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# Signal detection theory applied to three visual search tasks — identification, yes/no detection and localization

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**Abstract**—Adding distracters to a display impairs performance on visual tasks (i.e. the set-size effect). While keeping the display characteristics constant, we investigated this effect in three tasks: 2 target identification, yes-no detection with 2 targets, and 8-alternative localization. A Signal Detection Theory (SDT) model, tailored for each task, accounts for the set-size effects observed in identification and localization tasks, and slightly under-predicts the set-size effect in a detection task. Given that sensitivity varies as a function of spatial frequency (SF), we measured performance in each of these three tasks in neutral and peripheral precue conditions for each of six spatial frequencies (0.5–12 cpd). For all spatial frequencies tested, performance on the three tasks decreased as set size increased in the neutral precue condition, and the peripheral precue reduced the effect. Larger set-size effects were observed at low SFs in the identification and localization tasks. This effect can be described using the SDT model, but was not predicted by it. For each of these tasks we also established the extent to which covert attention modulates performance across a range of set sizes. A peripheral precue substantially diminished the set-size effect and improved performance, even at set size 1. These results provide support for distracter exclusion, and suggest that signal enhancement may also be a mechanism by which covert attention can impose its effect.

*Keywords*: Visual search; signal detection theory; transient covert attention; yes/no detection; discrimination; localization.

## INTRODUCTION

The visual system is constantly confronted with more information than can be efficiently processed at one time. To overcome this overload of information, visual

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attention is the process by which one grants priority among sources of visual information. In the study of visual attention, one of the central phenomena is the *set-size effect* of visual search. The set-size effect is the decrease in accuracy or increase in reaction time as a function of the number of distracters. This effect, traditionally observed in conjunction but not feature searches, has been taken as evidence that resources are limited and that attention is required and deployed serially for such tasks (e.g. Treisman, 1993; Treisman and Gelade, 1980; Wolfe, 1994). This explanation of the set-size effect has been challenged by many (e.g. Carrasco and Yeshurun, 1998; Eckstein, 1998; McElree and Carrasco, 1999; Nakayama and Joseph, 1998; Palmer *et al.*, 2000; Verghese, 2001). For example, performance may improve with smaller set sizes because of the removal of misleading information from irrelevant distracters (distracter exclusion; e.g. Palmer *et al*. 1993).

*Signal detection theory applied to visual search*

A formal theory to calculate set-size effects and the attentional effects of distracter exclusion on performance comes from signal detection theory (SDT) models that take into consideration noise in the visual and decision systems. These models attribute the set-size effect to the noisy quality of the sensory impressions, which increases the risk of confusing the target with a distracter as the number of distracters increases. The set-size effect, then, is the result of an increase in the probability of the noise from one of the distracters exceeding that of the signal, causing the observer to choose a distracter instead of the target. These models account for the set-size effect in some feature and conjunction searches (Eckstein, 1998; Eckstein *et al.*, 2000; Foley and Schwartz, 1998; Kinchla, 1974; Palmer, 1994; Palmer *et al.*, 1993, 2000; Shaw 1982). Note that neither serial processing nor limited-capacity attentional resources are required to explain the set-size effect. On the other hand, when observers are cued to a location or element, these models assume that the precue allows the observer's attention to ignore noisy responses arising from irrelevant distracters (distracter exclusion) and therefore improve performance.

Typically, performance on visual search tasks has been assessed by using either yes-no detection tasks with reaction time as the main or only dependent variable (e.g. Egeth *et al.*, 1984; Treisman, 1993; Treisman and Gormican, 1988; Wolfe, 1994) or discrimination tasks with accuracy as the dependent variable (Baldassi and Burr, 2000; Morgan *et al.*, 1998; Solomon and Morgan, 2001). This study examines human performance on three different tasks (yes/no detection with 2-targets, 2-target identification (Baldassi and Verghese, 2002; Carrasco *et al.*, 2000, 2003) and 8-alternative localization) with accuracy as the primary dependent variable, and applies an SDT model to search performance on the three different tasks.

### *The role of sensory factors in visual search*

Performance on visual search tasks can be affected by sensory factors. For example, the set-size effect becomes more pronounced as eccentricity increases (Carrasco *et al.*, 1995) and this effect is neutralized for features and substantially diminished for conjunctions when stimulus visibility is equated across eccentricity (i.e. with a cortical magnification factor; Carrasco and Frieder, 1997). The finding that search performance for orientation, spatial frequency (SF) and color is closely related to discrimination thresholds for the respective dimensions suggests that early visual processes determine search performance (Verghese and Nakayama, 1994). Likewise, stimulus content and spatial resolution predict search time in multiple fixation searches for both features and conjunctions (Geisler and Chou, 1995).

In most visual search studies whose results have been interpreted in terms of a serial deployment of attention, the display is presented until observers respond (e.g. Treisman, 1993; Treisman and Gelade, 1980; Wolfe, 1994). Therefore, it is impossible to discriminate between the effects of eye movements and those of covert attention. To assess the effects of covert attention, it is necessary to present short duration displays so as to prevent the possibility of eye movements while the display is present (e.g. Carrasco *et al.*, 1995, 2004; McElree and Carrasco, 1999). Here, we used brief displays and placed the stimuli at a constant eccentricity, to equate retinal and field eccentricity and to try to equate for discriminability (*cf.* Carrasco and McElree, 2001; Eckstein, 1998), and with an inter-stimulus distance designed to prevent masking and crowding effects (Bouma, 1970; Toet and Levi, 1992).

### *The role of attention in visual search*

Search studies have shown that although performance in some feature searches is impaired in the presence of distracters, directing attention to the target location reduces this effect (e.g. Baldassi and Burr, 2000; Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998; Foley and Schwartz, 1998; Morgan *et al.*, 1998; Palmer, 1994). A ‘peripheral’ (exogenous, transient) precue, which appears adjacent to the location of an upcoming target, has been shown to draw attention effectively and to result in enhanced performance in detection, discrimination and visual search tasks (e.g. Baldassi and Burr, 2000; Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998; Carrasco *et al.*, 2004; Kahneman *et al.*, 1983; Morgan *et al.*, 1998; Nakayama and Mackeben, 1989).

Previous studies have shown that transient covert attention improves performance on tasks that rely on the detection or discrimination of high spatial frequencies (e.g. Balz and Hock, 1997; Nakayama and Mackeben, 1989; Yeshurun and Carrasco, 1999). However, relatively less is known about how transient covert attention improves performance on tasks that examine a range of spatial frequencies (SFs). Previous studies from our laboratory (Cameron *et al.*, 2002; Carrasco *et al.*, 2000, 2001) have shown that attention improves performance across the entire contrast sensitivity function when a single target is presented without distracters. However, in the few visual search experiments in which SF has been manipulated, only one or two spatial frequencies were tested (e.g. Baldassi and Burr, 2000; Carrasco *et al.*, 1998; Foley and Schwartz, 1998; Morgan *et al.*, 1998). Given that contrast sensitivity varies across the range of SF that we perceive (Campbell and Robson, 1968) and that a search asymmetry has revealed that a low SF target is detected among high SF distracters faster and more accurately than the opposite condition (Carrasco *et al.*, 1998), here we investigated whether SF affects either the extent of the set-size effect, the effect of peripheral precueing or their interaction.

Whereas most studies in the visual search literature have inferred the role of attention (e.g. Treisman and Gelade, 1980; Treisman and Gormican, 1988; Wolfe, 1994, 2000; Wolfe *et al.*, 1989), in this study we examined its role directly by peripherally precueing the target location (*cf.* Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998; Carrasco *et al.*, 2004). This is the first study to examine the effect of a peripheral precue in three different visual search tasks: 2-target yes/no detection, 2-target identification and 8-alternative localization.

## MODELING

### *Signal detection models for search tasks*

Signal detection based models are often used to calculate the performance degradation with increasing set size or performance enhancement with decreasing set size, expected from the effect of independent noise associated with the observers' internal response to each relevant item in the visual search task. The models can be used as a benchmark to test whether set-size effects can be accounted for without resorting to limited attentional resources. These types of models have been successfully used to predict human performance for detection and localization of targets in a variety of conditions (Burgess and Ghandeharian, 1984; Eckstein and Whiting, 1996; Foley and Schwartz, 1998; Green and Swets, 1966; Palmer *et al.*, 1993; Shaw, 1980; Solomon *et al.*, 1997; Sperling and Dosher, 1986; Swensson and Judy, 1981). For complex tasks and those involving memory, human performance often degrades beyond what is expected from the independent noise prediction (Palmer *et al.*, 1993; Shaw, 1980).

### *Single filter models for single target tasks*

In most simple search tasks a single target may appear among distracters (all distracters being identical). In the typical yes/no task, a single array of elements is presented to the observer on each trial and the target has a 50% probability of being present. The observer's task is to decide whether the signal was present. In the 2-interval forced choice task (2 IFC), two arrays of elements are presented to the observer sequentially through time. One of the two intervals consists of a target and distracters while the other interval consists of only distracters. The observer's task is to decide which interval contained the target.

For these tasks, the standard SDT model assumes that the observer monitors a single filter or detector tuned to the target (or tuned to discriminate maximally between the target and distracter). The filter elicits a higher response to the target than the distracter; however, its response is stochastic due to internal noise (e.g. neural noise and/or decision noise).

In a yes/no task the model responds 'target present' if the internal response exceeds a decision threshold or criterion. The proportion of trials in which the model correctly responds 'target present' in a target present trial (hit rate, $h$) is calculated by computing the probability of the target or any of the distracters in the display exceeding the criterion. Similarly, the false alarm rate (proportion of trials in which the model incorrectly responds 'target present' in a target absent trial) is calculated by computing the probability of any one of the distracters exceeding the criterion (see Table 1, yes/no detection of orientation with one oriented target among vertical distracters).

In a 2-interval forced choice task, the model chooses the interval associated with the highest (maximum) response. Performance (proportion of correct selection of the target present interval) is calculated by computing the probability of the filter's response to the target taking the maximum value (see Table 1, 2-interval forced choice detection).

*Two filter models for two-target tasks*

In this study, as in some previous work (Baldassi and Burr, 2000; Baldassi and Verghese, 2002; Carrasco and McElree, 2001, Carrasco *et al.*, 2003, 2004; Morgan *et al.*, 1998), the search task involves one of two possible targets appearing among a single type of distracter. The observer's task is to decide which of two targets has appeared (identification task), whether either of the two targets has appeared (detection task), or to identify the spatial location of either of the targets (localization task).

Given that two types of targets can appear, it is reasonable to assume that the observer must monitor two filters, one tuned to each of the possible targets (or alternatively each filter tuned to discriminate between each of the targets and the distracters; Carrasco *et al.*, 2000). The model performance is then determined by the response of two filters to each element in the display rather than a single filter's response. In the following sections we develop two-filter SDT models for each of the tasks: (a) 2-target identification; (b) 2-target yes/no detection; (c) 8-alternative localization. The mathematical expressions for each of the tasks are summarized in Table 1. In addition, for comparison, Table 1 also includes the traditional SDT expressions corresponding to tasks in which there is only one type of target and the observer is assumed to monitor the response of a single perceptual filter to the elements in the display. Related treatments of the 2-target identification task taking into account the two possible targets have been previously developed in Carrasco *et al.* (2000) and Baldassi and Verghese (2002) (see Note 1). In the neutral condition where the precue did not give any information about target location, we set $n$ to the

**Table 1.**
Expressions for maximum response signal detection model

| Task | Target/distracters | Closed form expressions |
|---|---|---|
| 2-interval forced choice | One oriented target among vertical distracters | $Pc = \int_{-\infty}^{+\infty} g_{\mathrm{r,r}}(x - d')[G_{\mathrm{r,v}}(x)]^{2n-1} + (n-1) g_{\mathrm{r,v}}(x)[G_{\mathrm{r,v}}(x)]^{2n-2} G_{\mathrm{r,r}}(x - d')\,\mathrm{d}x$ (E.1) <br> (Shaw, 1980; Palmer *et al*., 1993; Eckstein, 1998) |
| Yes/no detection of orientation | One oriented target among vertical distracters | $h = 1.0 - G_{\mathrm{r,r}}(\lambda - d')[G_{\mathrm{r,v}}(\lambda)]^{n-1}$ <br> $f_a = 1.0 - [G_{\mathrm{r,v}}(\lambda)]^n$ (E.2) <br> (Green and Swets, 1966) |
| | One of two oriented targets (leftward or rightward) among vertical distracters* | $h = 1.0 - G_{\mathrm{r,r}}(\lambda - d'_{\mathrm{r,v}}) G_{\mathrm{l,r}}(\lambda + d'_{\mathrm{l,v}})[G_{\mathrm{r,v}}(\lambda)]^{n-1}[G_{\mathrm{l,v}}(\lambda)]^{n-1}$ <br> $f_a = 1.0 - [G_{\mathrm{r,v}}(\lambda)]^n [G_{\mathrm{l,v}}(\lambda)]^n$ (E.3) |
| Identification of orientation | One of two oriented targets (leftward or rightward) among vertical distracters* | $Pc = \int_{-\infty}^{+\infty} g_{\mathrm{r,r}}(x - d'_{\mathrm{r,v}})[G_{\mathrm{r,v}}(x)]^{n-1} G_{\mathrm{l,r}}(x + d'_{\mathrm{l,v}})[G_{\mathrm{l,v}}(x)]^{n-1} + (n-1) g_{\mathrm{r,v}}(x)[G_{\mathrm{r,v}}(x)]^{\lvert n-2 \rvert}[G_{\mathrm{l,v}}(x)]^{n-1} G_{\mathrm{l,r}}(x + d'_{\mathrm{l,v}}) \times G_{\mathrm{r,r}}(x - d'_{\mathrm{r,v}})\,\mathrm{d}x$ (E.4) |
| Localization | One oriented target among vertical distracters | $Pc = \int_{-\infty}^{+\infty} g_{\mathrm{r,r}}(x - d'_{\mathrm{r,v}})[G_{\mathrm{r,v}}(x)]^{n-1}\,\mathrm{d}x$ (E.5) <br> (Green and Swets, 1966) |
| | One of two oriented targets (leftward or rightward) among vertical distracters* | $Pc = \int_{-\infty}^{+\infty} g_{\mathrm{r,r}}(x - d'_{\mathrm{r,v}})[G_{\mathrm{r,v}}(x)]^{n-1} G_{\mathrm{l,r}}(x + d'_{\mathrm{l,v}})[G_{\mathrm{l,v}}(x)]^{n-1} + g_{\mathrm{l,r}}(x + d'_{\mathrm{l,v}}) G_{\mathrm{r,r}}(x - d'_{\mathrm{r,v}})[G_{\mathrm{r,v}}(x)]^{n-1}[G_{\mathrm{l,v}}(x)]^{n-1}\,\mathrm{d}x$ (E.6) |

**Definition of symbols:**

$d'$: index of detectability.

$d'_{\mathrm{r,v}}$: discriminability between the response of the rightward tuned detector to the rightward tilted Gabor and its response to the vertical distractor.

$d'_{\mathrm{l,v}}$: discriminability between the response of the left tuned detector to the rightward tilted Gabor and its response to the vertical distractor.

$n$: number of distracters.

$g(x) = (1/\sqrt{2\pi})\exp(-x^2/2)$, Gaussian probability density function.

$G(x) = \int_{-\infty}^{x} g(y)\,\mathrm{d}y$ is the Gaussian cumulative probability.

Subscripts to $g(x)$ and $G(x)$ correspond to: (1) first subscript identifies the filter (tuned to rightward or leftward orientation); (2) second subscript identifies the element to which the filter is responding; (3) subscripts, r: rightward tilted Gabor; l: leftward tilted Gabor; v: vertical Gabor.

Example: $g_{\mathrm{r,v}}$ response of the filter tuned to the rightward titled Gabor to the vertical distractor.

**Note*: Percent correct expressions is for trials in which the rightward tilted Gabor is the target. The percent correct expressions for the trials in which the leftward tilted Gabor is the target are identical to E.3, E.4 and E.6 with these changes: subscripts r, r replaced by l, l, subscripts r, v replaced by l, v and subscripts l, v replaced by r, v.

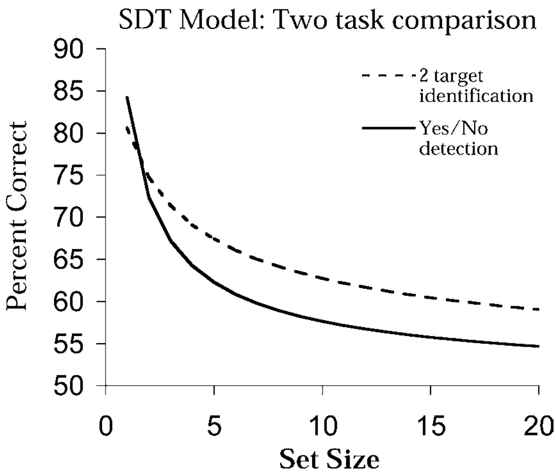


**Figure 1.** Comparison of the predictions of the expected set-size effect for a single filter/single target 2 IFC task *vs.* a two filter/two target orientation identification task (with the assumption that the discriminability, $d'_{\mathrm{lr}}$, between the tilted Gabor targets is double that between each of the tilted Gabor targets and the vertical distractors, $d'_{\mathrm{v}}$).

number of elements (number of distracters + 1) in the condition. We shall outline the details of the fitting routines including number of free parameters for each of the tasks in the results section of each experiment.

Figure 1 shows performance for an SDT model as a function of set-size for the standard 1-target 2 IFC detection task and for the present 2-target orientation identification task where the discriminability between tilted Gabors (rightward and leftward) was assumed to be double of that between any of the tilted Gabors and the vertical distracters (see Table 1 for mathematical expressions). The results show that a model consistent with noisy independent coding of the elements for the present 2-target orientation identification task (and no limited resources) can result in larger set-size effects than the same model for the standard 1-target 2 IFC task. Therefore, if one were to use the standard 1-target 2 IFC model prediction to evaluate human performance as a function of set size for some of the present orientation discrimination task results, one could potentially erroneously conclude that human performance degradation with set size was consistent with limited resources. This example stresses the point that SDT model predictions are task-specific and directly generalizing predictions across different tasks can lead to erroneous conclusions.

The aims of the present study were threefold: First, to extend SDT models to evaluate their ability to account for set-size effects in three different tasks (2-targets yes/no detection, 2-target identification and 8-alternative localization). Second, to examine the extent to which spatial frequency affects search performance in those three tasks. Third, to assess the effects of directing transient covert attention to the target location on the set-size effect in the same three tasks. To accomplish these goals we kept the display as constant as possible in all three tasks: the targets, distracters, orientation, spatial frequency, set size, eccentricity and locations were identical.

## EXPERIMENT 1: TWO–TARGET IDENTIFICATION TASK

We examined the effect of distracters in a 2-target identification task in neutral and peripheral precue conditions. This task required observers to decide which of the two possible targets was present on each trial.

### *Methods*

Four observers participated in this experiment (see Note 2). Two were authors (LC and JT), one was a graduate student (CPT), and the fourth observer (TT) was naïve to the purposes of the experiment. All observers had normal or corrected-to-normal vision.

*Stimuli and design.* Stimuli were generated in HIPS (Landy *et al.*, 1984) and presented in VScope™ (Enns and Rensink, 1992) on a Macintosh G3 computer with a 17-inch gamma-corrected color monitor. The refresh rate of the monitor was 13.4 ms and the mean luminance was 47 cd/m$^2$. Observers sat in a dark room with their head stabilized by a chin rest. Viewing was binocular at 114 cm. Observers performed an orientation identification task with visual feedback. The target was a 2° Gabor patch (cosine-wave grating in a Gaussian vignette) tilted 15° clockwise or counterclockwise, and was present on every trial. Targets were presented either alone or in the presence of 1, 3 or 7 vertically oriented Gabor patches (distracters) for ~54 ms. These distracter conditions corresponded, respectively, to set sizes of 1, 2, 4, and 8. Given that there were always 8 possible target locations, increasing set size did increase density as we kept eccentricity constant. To avoid crowding, we presented 2° stimuli at 4.5° eccentricity and positioned targets and distracters at maximal separation from each other. Hence, the distance between stimuli was 3.4° for set size 8, and for the smaller set sizes, the distance between the stimuli was larger (see Note 3).

The observer performed an orientation identification task (Nachmias, 1967) by reporting (with a key-press) whether the target was tilted to the left or right. Observers were instructed to perform the task as accurately and quickly as possible. Responses longer than 2500 ms were coded as incorrect, and were exceedingly rare (under 1% of all trials). Stimuli were one of 6 spatial frequencies (0.5, 1, 2, 4, 8 or 12 cpd). The SF of the target and the number of distracters were blocked. The target and distracters were presented randomly at one of 8 locations at 4.5 deg eccentricity, equally spaced around the circumference of an imaginary circle (see Fig. 2). In the Set Size 2 condition, the distracters appeared at the location directly opposite to the target. In the Set Size 4 condition, the target and distracters were presented at four equally spaced locations. In the Set Size 8 condition, the distracters were presented

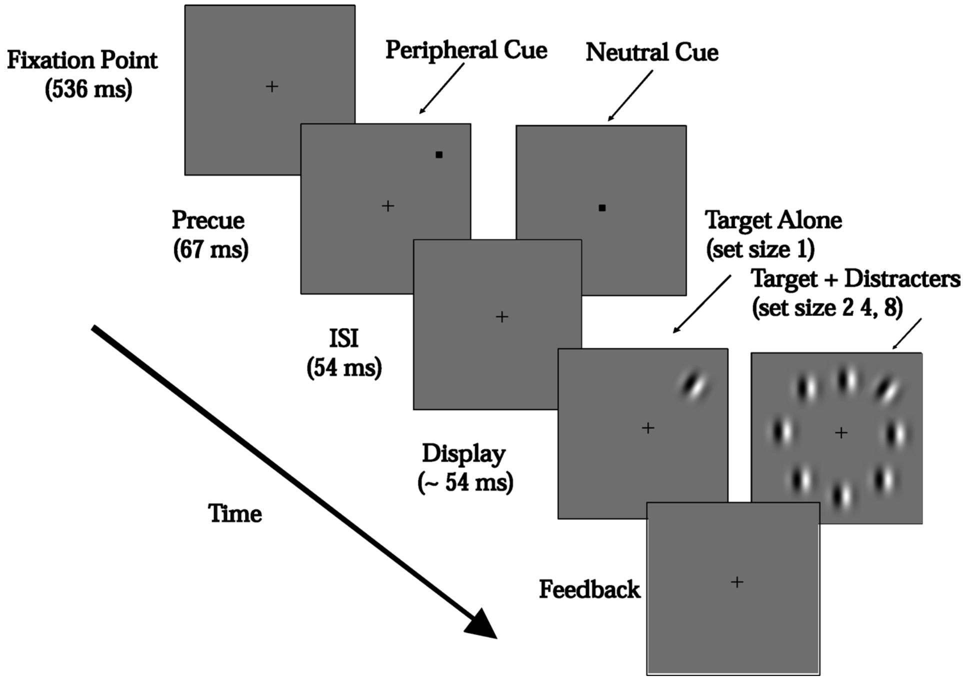


**Figure 2.** A schematic representation of a trial. Each trial began with a cross in the center of the screen that the observers were instructed to fixate. The fixation was replaced with a small black square (neutral precue condition) or disappeared and a small black square appeared just beyond the location of the target, 1.3 deg from the center, and on the same radius as the Gabor patch (peripheral precue condition). The peripheral precue was 100% valid in terms of location; it always indicated target location. The target was either presented alone (set size 1) or in the presence of 1, 3 or 7 distracters (set sizes 2, 4 and 8 respectively). Observers received visual feedback after each trial, and error rate at the end of each block of 100 trials.

in the remaining 7 locations. Either a neutral or peripheral precue preceded targets. The neutral precue (0.13 deg $\times$ 0.13 deg black square) replaced the fixation in the center of the screen, and indicated the time at which the upcoming target would appear, but not its location. The peripheral precue (0.13 deg $\times$ 0.13 deg black square) was presented at 5.8° eccentricity, 1.3° beyond the center of the upcoming Gabor stimulus, and indicated both the time and the location at which the upcoming target would appear.

*Procedure.* On each trial, a fixation cross appeared at the center of the computer monitor for 536 ms. The fixation was followed by a precue that remained present for 67 ms. There was a 54 ms interval between the precue offset and the stimulus display onset. No mask followed the stimulus display. The stimulus onset asynchrony (SOA) of 120 ms was chosen to maximize the precueing effect (e.g. Cheal and Lyon, 1991; Jonides, 1981; Nakayama and Mackeben, 1989), and to prevent eye movements to the target; it takes about 250 ms for a target directed saccade to be initiated (e.g. Carpenter, 1988; Mayfrank *et al.*, 1987).

Each observer performed 14,400 experimental trials (300 per 2 precue types, 6 spatial frequencies, and 4 set sizes). Observers performed about eight blocks of 100 trials per day (about an hour) and they performed 10 practice trials prior to each block of trials. Set size, precue condition, and SF were held constant throughout blocks of 100 trials. Each of the 48 conditions was presented in a different random order for each observer, and was repeated 3 times. We computed the mean and standard error of the percent correct of the three blocks of trials for all distracter conditions for each observer individually (see Note 4).

### *Results and discussion*

*Baseline performance.* We first established the stimulus contrast required for each observer, in each SF condition, to perform at about 80% correct when the target was presented alone (randomly at one of 8 locations), following a neutral precue. If manipulating only stimulus contrast could not attain this performance level, the stimulus duration was also varied (between 40 and 67 ms). Whenever possible, contrast was held constant across observers. The contrast sensitivity function for each of the 4 observers (data not shown) was established to be in the normal range (Campbell and Robson, 1968). Once we determined the parameters that yielded performance at about 80% correct, we kept these stimulus parameters constant for each observer in each condition as we manipulated the set size and precue condition. These baseline data were used only to establish contrast and duration to be used in the main experiment, and were not used in any of the analyses described below.

*Experimental results.* Figure 3 shows average percent correct (see Note 5) for the four observers as a function of set size for the neutral (open symbols and dotted lines) and peripheral (closed symbols and solid lines) precue conditions. There were 1200 trials per data point (300 from each of 4 observers). The fits to the data in the neutral precue condition reflect the average of the model fits to individual observer's data, as described below. For all spatial frequencies the data were well captured by this model. We compared the results of those averages with the averages derived from mean parameter values from individual observers, described below, and the results were practically the same. Therefore, we used the average of fits to individual data in this and the next two experiments. In this condition, accuracy decreased monotonically, but the cost of adding a distracter was greater at smaller than at larger set sizes. In contrast, in the peripheral precue condition, accuracy decreased only slightly with set size and typically in a linear way.

We conducted a repeated-measures ANOVA (2 precue types $\times$ 6 spatial frequencies $\times$ 4 set sizes). All effects reported here were significant at $p < 0.05$. There were main effects of set size and precue. Accuracy decreased as a function of set size, and the peripheral precue improved overall performance. SF was not significant, as we had equated performance in the baseline condition.

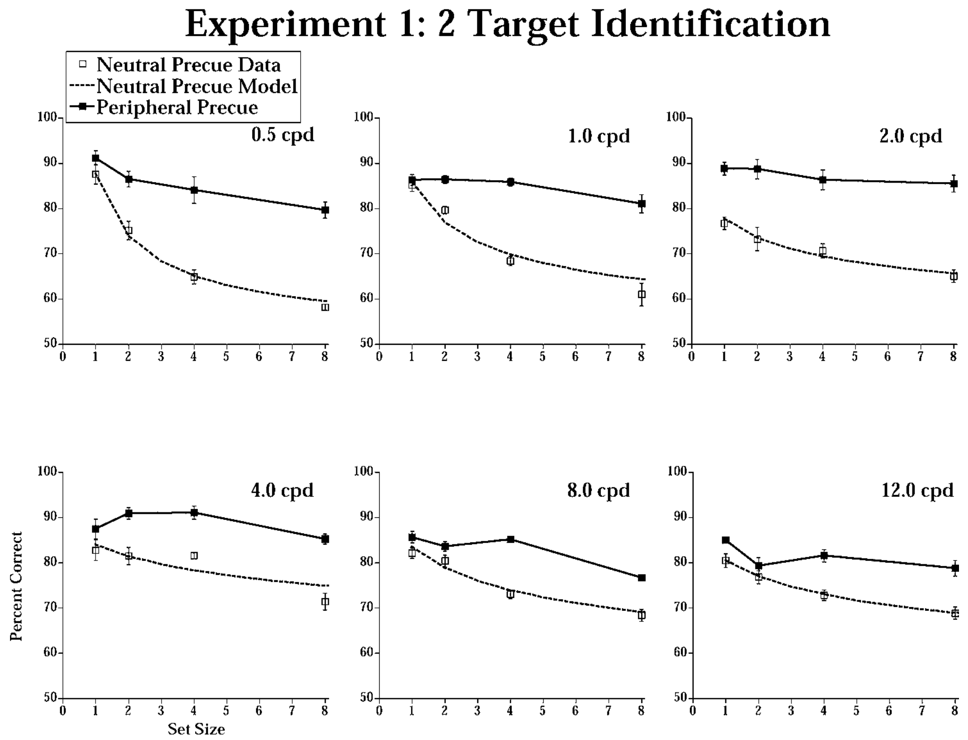


**Figure 3.** Mean accuracy (percent correct) as a function of set size for 6 spatial frequencies (0.5–12 cpd) for the 2-target identification task. The error bars reflect standard error of the mean of the four observers. Open symbols represent data from the neutral precue condition, filled symbols represent data from the peripheral precue condition. Dotted lines indicate the average of the SDT model fits to individual observer's data.

The set-size x precue interaction confirmed that, as predicted by the SDT model, performance decreased more in the neutral than peripheral precue condition as set size increased. Thus, there was a significantly larger precue effect at larger set sizes. The set-size x–SF interaction indicated that there was a larger decrease in performance as a function of set size for low than for high SFs. Finally, the precue x–SF interaction revealed that the peripheral precue reduced the set-size effect more for low than for high spatial frequencies. The 3-way interaction was not significant.

*Modeling of two-target identification*

In this task the target is a rightward or leftward oriented Gabor and the distracters are all vertical Gabors. The model assumes that the observer monitors two perceptual filters: one tuned to the rightward oriented target and one tuned to the leftward oriented target. The observer supposedly compares the scalar responses of the perceptual filters and chooses the stimulus associated with the filter that elicited the highest response. That is, if a filter tuned to the rightward oriented target elicits the highest response then the observer responds ‘right oriented’, otherwise they respond ‘left oriented’. Obtaining model accuracy in trials in which the rightward oriented target was present requires computing the probability that the maximum of rightward tuned filter responses exceeds the maximum of the leftward tuned filter responses. The mathematical closed form expression for the particular task and particular target and distracter configuration is given in Table 1 (see, identification of two orientations). A particular property of the target/distracter configuration used in this orientation identification task is that, for set-size 1, the display contains one of two types of elements (a rightward or leftward tilted target, but no vertical distracters). In the set-size 1 condition, performance identifying the orientation is determined by the observers’ ability to discriminate between the rightward and leftward tilted Gabors ($d'_{\mathrm{l,r}}$). For set-size 2 and higher set-sizes, the display contains two of three types of elements (a rightward or leftward target, and vertical distracters). Therefore, for set-size 2 and higher, performance is determined not only by the observers’ ability to discriminate between the rightward and leftward tilted Gabors but also their ability to discriminate between the rightward tilted Gabors and the vertical distracter Gabors ($d'_{\mathrm{r,v}}$). This situation is different from the typical single target search task where the elements in the display are the same across set-size conditions. As a result of the difference in element configuration, one expects that the SDT model for the current task to predict different set-size effects than expected in the standard single target 2 IFC tasks used by others (Eckstein, 1998; Palmer, 1994; Shaw, 1980).

In contrast to the single target model, the 2-target model has two fitting parameters: the discriminability between the two tilted Gabors and the discriminability between each of the tilted Gabors and the vertical Gabors. Different set-sizes can be accommodated by the different combinations of discriminabilities (two tilted Gabor discriminability and tilted Gabor/vertical Gabor discriminability). The value of the two discriminabilities was left free to vary as a function of spatial frequency and therefore accommodate the dependency of the set-size effect of SF. No attempts were made to parameterize the relationship between discriminabilities as a function of spatial frequency, which might be a worthwhile goal of future studies.

*Modeling orientation identification of tilted Gabors among vertical Gabor distracters.* For each observer and task we fit human proportion correct using the corresponding model for the task (see Table 1). All fits were done using $\chi^2$ goodness-of-fit criteria. No assumptions were made about the relationship of the discriminability between two tilted Gabors and that between the tilted Gabors and the vertical distracters. The two discriminabilities ($d'_{\mathrm{r,l}}$ and $d'_{\mathrm{r,v}}$) were fitting parameters in the model.

The estimated values of the two $d'$ parameters varied with spatial frequency. In particular, to accommodate the larger set-size effects with lower frequencies, the discriminability ($d'$) between the left tilted and right tilted Gabors was estimated to be over double that of the discriminability between the left (or right) tilted Gabor and the vertical distracters (averaged across observers: $d' = 1.75$ *vs* $d' = 0.695$). The shallower set-size effects with the other spatial frequencies were accounted for with discriminabilities between the left-tilted and right-tilted Gabors that were closer to the discriminabilities between the left of right-tilted Gabor and the vertical distracters.

*Speed–accuracy tradeoff analysis*

Whereas most RT visual search studies have not explicitly ruled out speed-accuracy trade-offs (e.g. Cavanagh *et al.*, 1990; Jonides and Yantis, 1988; Treisman, 1991; Wolfe *et al.*, 1989), and accuracy search studies typically do not report RT (e.g. Baldassi and Burr, 2000; Eckstein, 1998; Morgan *et al.*, 1998; Palmer *et al.*, 1993), we have measured both accuracy and reaction time (RT). This allowed us to assess how sensitivity changes with set size and to ensure that there was no trade-off between speed and accuracy.

Figure 4 shows average RT for correct responses plotted as a function of set size. RT increased as set size increased in the neutral precue condition at all spatial frequencies, but remained relatively constant (and relatively short) in the peripheral precue condition. This analysis indicates that, in addition to being more accurate, observers were faster at the task in the peripheral precue condition. Given that there

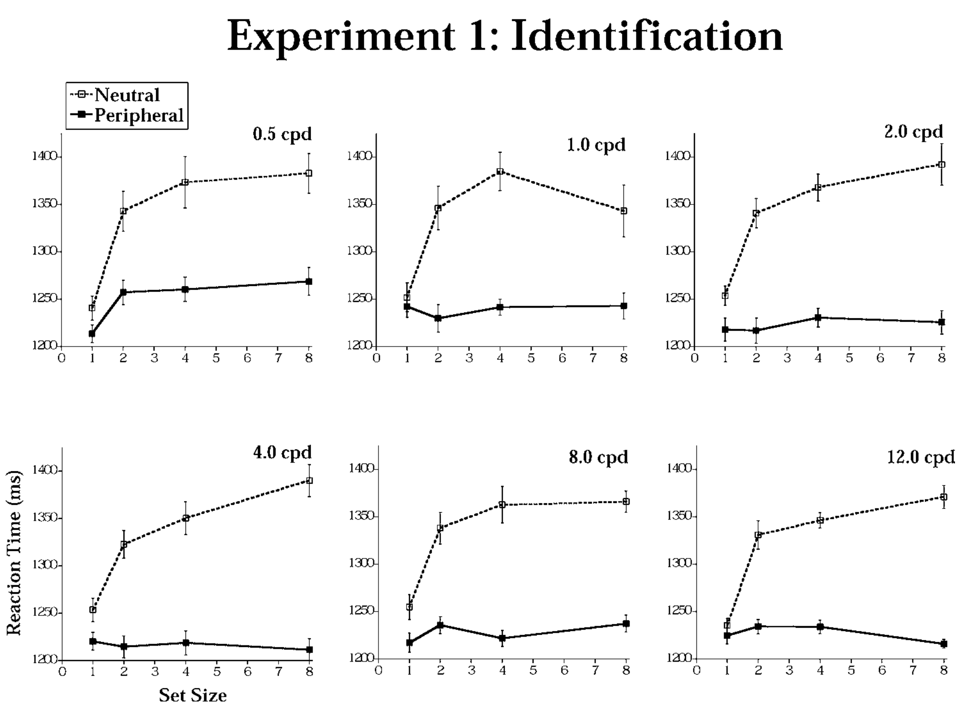


**Figure 4.** Reaction time data for the 2-target identification task, plotted as accuracy was plotted in Fig. 3.

was both a decrease in accuracy and an increase in RT with set size, no speed–accuracy tradeoff was present. Thus, the effects of set size and of the precue cannot be due to a speed–accuracy tradeoff.

## EXPERIMENT 2: YES/NO DETECTION TASK WITH TWO-TARGETS

We examined the effect of distracters in a 2-target yes-no detection task in neutral and peripheral precue conditions. This task, most similar to a conventional visual search task, examined the ability of observers to detect whether a stimulus, a target tilted clockwise or counter-clockwise, was present or absent in a display of vertical distracters.

### *Methods*

Four observers participated in this experiment — two of the authors (same as in Experiment 1) and two (MI trained, UW, not trained) who were naïve to the purposes of the experiment, and had not participated in Experiment 1. All observers had normal or corrected-to-normal vision.

The methods were identical to Experiment 1 except for the task of the observer. Observers performed a yes/no detection task in which half of the trials contained a tilted (clockwise or counter-clockwise) target and the other half contained only vertical distracters. Observers had to report whether the target was present or absent, regardless of its orientation. On target-absent trials the precue cued a vertical distracter. Baseline performance was obtained as in Experiment 1, but with the 2-target yes/no detection task. Stimulus duration varied between 27 and 80 ms to attain an overall performance level of about 80% correct (with no distracters present). Baseline data confirmed that the contrast sensitivity of all 4 observers was in the normal range (Campbell and Robson, 1968).

### *Results*

Figure 5 shows the average percent correct (see Note 6) of the four observers as a function of set size for neutral (open symbols and dotted lines) and peripheral (closed symbols and solid lines) precue conditions. Although accuracy decreased with set size, the cost of adding a distracter was greater at smaller than at larger set sizes in the neutral precue condition. Accuracy decreased only slightly with set size in the peripheral precue condition and this effect was more linear. This pattern of results is consistent with that of Experiment 1.

We conducted a repeated-measures ANOVA (2 precue types $\times$ 6 spatial frequencies $\times$ 4 set sizes). All main effects (precue, set size and SF) were significant. That is, sensitivity decreased as a function of set size in the neutral precue condition, the peripheral precue improved performance, and performance varied as a function of SF (see Note 7). The only significant interaction — set size $\times$ precue — confirmed that performance decreased more in the neutral than in the peripheral precue

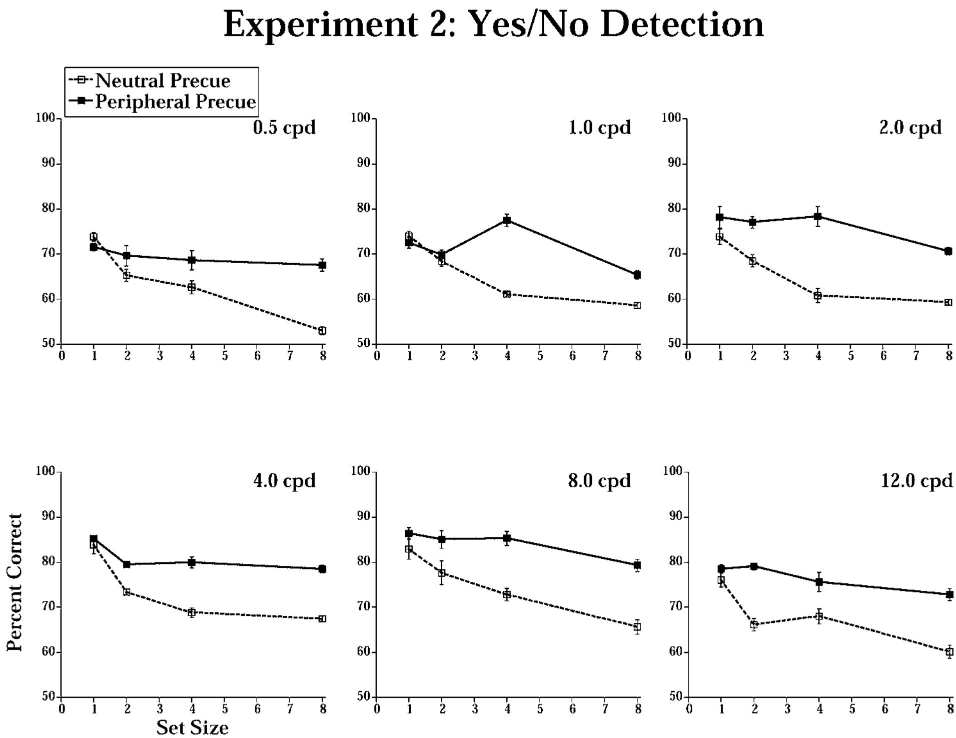


**Figure 5.** Mean percent correct as a function of set size for 6 spatial frequencies (0.5 to 12 cpd) in the 2-target yes/no detection task. The error bars reflect standard error of the mean of the four observers. Open symbols represent data from the neutral precue condition, and filled symbols represent data from the peripheral precue condition.

condition as set size increased and thus there was a significantly larger precue effect at larger set sizes. This is consistent with our previous findings showing that the peripheral precue allows the observer to minimize, albeit not eliminate completely, the effect of irrelevant information. Thus the set-size effect is diminished but not eliminated (Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998; Morgan *et al.*, 1998).

*Modeling of 2-target yes/no detection*

The SDT model assumes that the observer monitors two perceptual filters tuned to each of the two possible targets. The output of each perceptual filter is a stochastic variable due to the effects of internal noise. The observer compares the scalar output of the two filters to a decision threshold (a scalar value, $\lambda$). The observer responds ‘target present’ if either of the two filter responses exceeds the decision threshold. The hit rate (i.e. proportion of trials on which the model correctly responds target present) for this model is given by the probability that the response of either of the two perceptual filters to any of the elements in the display (rightward or leftward

**Table 2.**
Parameter estimates for yes/no detection task

| Set size | | UW | MI | LC | JT |
|---|---|---|---|---|---|
| 0.5 cpd | 1 | 1.16 | 1.28 | 0.84 | 0.93 |
| | 2 | 1.16 | 0.95 | 1.05 | 1.1 |
| | 4 | 1.81 | 1.19 | 1.6 | 1.36 |
| | 8 | 1.72 | 1.85 | 1.59 | 1.66 |
| 1.0 cpd | 1 | 1.11 | 1.5 | 0.84 | 1.06 |
| | 2 | 1.46 | 1.07 | 1.09 | 1.12 |
| | 4 | 1.6 | 1.37 | 1.48 | 1.37 |
| | 8 | 1.83 | 1.55 | 1.79 | 1.7 |
| 2.0 cpd | 1 | 0.71 | 1.46 | 0.78 | 1.28 |
| | 2 | 1.55 | 1.14 | 1.19 | 1.41 |
| | 4 | 1.71 | 1.51 | 1.39 | 1.75 |
| | 8 | 2.06 | 1.64 | 1.75 | 2.08 |
| 4.0 cpd | 1 | 2.05 | 1.68 | 1.22 | 1.38 |
| | 2 | 1.37 | 1.69 | 1.48 | 1.55 |
| | 4 | 1.69 | 2.02 | 1.66 | 1.69 |
| | 8 | 2.22 | 2.16 | 1.95 | 2.05 |
| 8.0 cpd | 1 | 2.17 | 2.17 | 1.35 | 0.89 |
| | 2 | 1.94 | 2.23 | 1.48 | 1.43 |
| | 4 | 2 | 2.08 | 1.83 | 1.81 |
| | 8 | 2.2 | 2.25 | 1.93 | 1.92 |
| 12.0 cpd | 1 | 1.42 | 1.87 | 1.19 | 0.86 |
| | 2 | 1.43 | 1.82 | 1.5 | 1.21 |
| | 4 | 1.85 | 2.08 | 1.73 | 1.67 |
| | 8 | 1.87 | 2.27 | 1.7 | 1.78 |

oriented target or vertical distracter) exceeds the decision threshold, $\lambda$. The hit rate ($h$) is given by 1 minus the probability that the responses of both perceptual filters to the target and the distracters are below the decision threshold. The false alarm rate for the task is given by the probability that either of the two perceptual filters responses in the target absent display (where all $n$ elements are distracters) exceeds the decision threshold. Note that the expressions are different than those corresponding to a yes/no task with one oriented target among vertical distracters (see Table 1).

*Modeling yes/no detection of one of two tilted Gabors.* For the detection task, we assumed that the decision threshold, $\lambda$, could vary with set size so that an individual decision threshold was used for each set-size condition. Parameter estimates ($\lambda$) are shown in Table 2 for each observer in each SF and set-size condition. For each set size, the criterion was found so that the model false alarm rate matched the human false alarm rate. Two discriminabilities were used as fitting parameters to

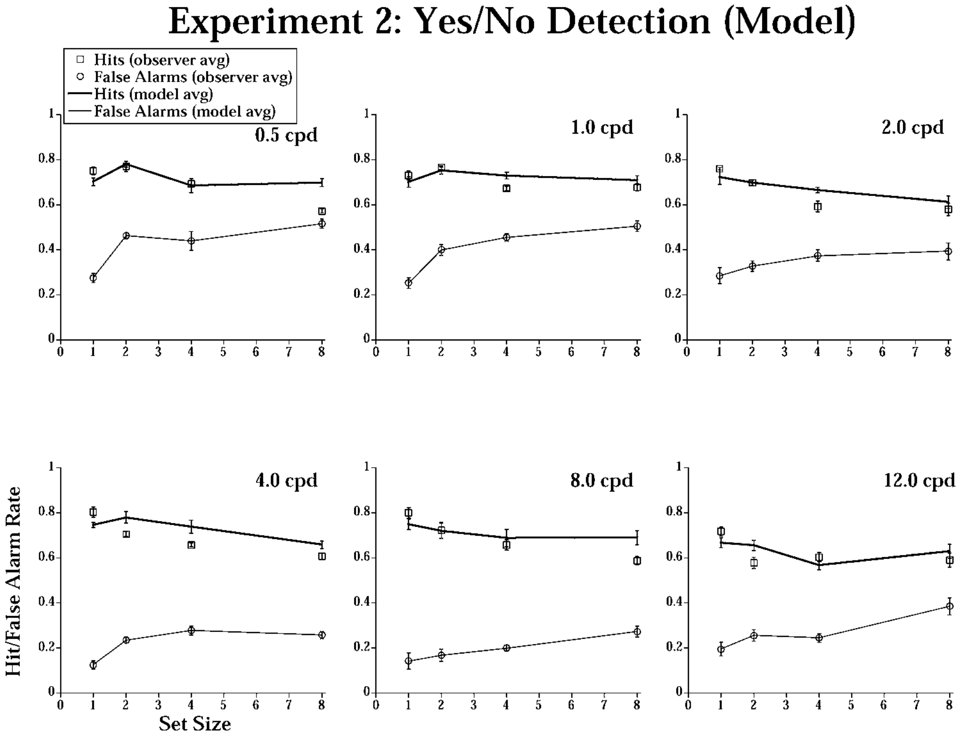


**Figure 6.** Average hits (square symbols) and false alarms (circle symbols) of the four observers, with standard error of the mean, are shown along with the model fits (lines) for the yes/no detection task. See text for details.

minimize the error between the model's predicted hit rate and the human measured hit rate. As in the orientation identification task no assumptions were made about the relationship of the discriminability between the two tilted Gabors and that between each of the tilted Gabors and the vertical distracters.

Figure 6 shows hits and false alarm rates, averaged across 4 observers. Solid symbols are the averaged hit rates and the bold solid line is the model estimate of the hit rate. The open symbols (observer averages) and thin solid line (model predictions) reflect false alarm rates that, by definition, are perfectly captured by the model. The model under-predicts the observed set-size effect, i.e. performance decreased more than predicted by the model across spatial frequencies.

*Speed–accuracy tradeoff analysis*

Figure 7 shows average RT for correct responses plotted as a function of set size. RT increased with set size in the neutral precue condition at all spatial frequencies, although not as dramatically as in Experiment 1. As in Experiment 1, in addition to being more accurate, observers were faster at the task in the peripheral precue condition. There was no evidence of a speed–accuracy tradeoff. Thus, the effects of set size and of precue cannot be due to a speed–accuracy tradeoff.

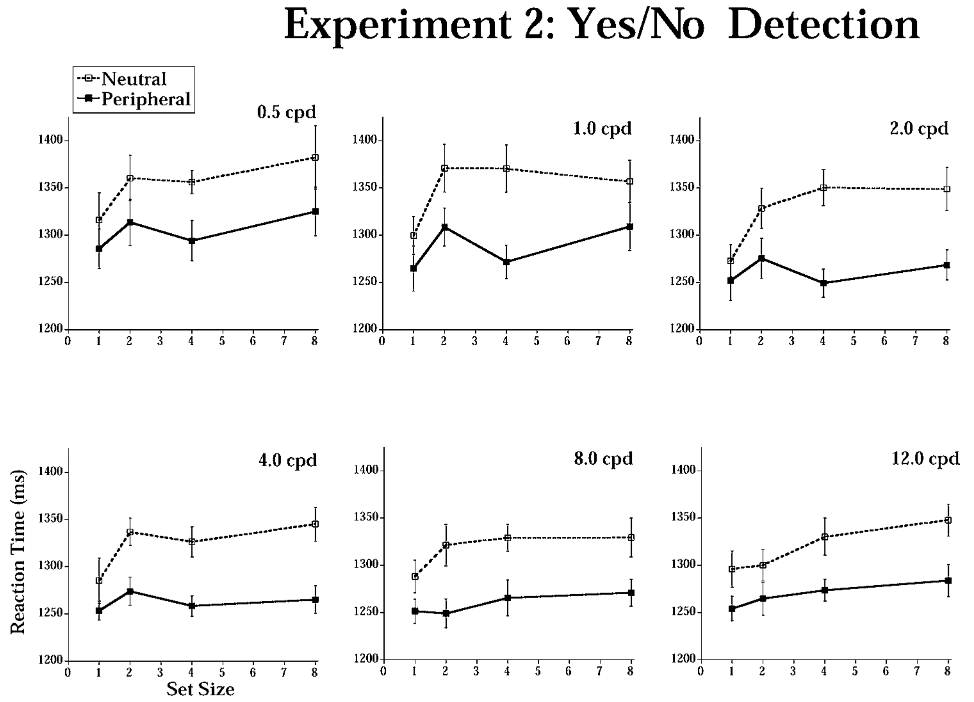


**Figure 7.** Reaction time data for the yes/no detection task, plotted as accuracy was plotted in Fig. 5.

## EXPERIMENT 3: 8-ALTERNATIVE LOCALIZATION TASK

We examined the effect of distracters in an 8-alternative localization task in the neutral precue condition. This task examined the ability of observers to specify target location. We characterized the types of mislocalizations that observers made and were able to assess spatial uncertainty, which is important for understanding possible mechanisms underlying the set-size effect and for placing constraints on potential models.

### *Methods*

Four observers participated in this experiment. Two were authors (same as in Experiments 1 and 2) and two were untrained and naïve to the purpose of the experiment (AR and SF), and had not participated in either of the two previous experiments. All observers had normal or corrected-to-normal vision.

The methods were identical to Experiments 1 and 2 except for the task of the observers. Observers performed a localization task in which they had to press one of 8 buttons on a numeric keypad, corresponding to a target location, to indicate where the target had appeared. The stimulus presentation in this experiment was identical to Experiment 1 — the target, a Gabor patch tilted clockwise or counterclockwise, was present on every trial (see Note 8).

The localization task with a 100% valid precue (i.e. always indicating target location) was not informative because it amounted to the observer indicating the location of the precue. Therefore, for each observer we randomly selected six unique conditions (100 trials per condition) to ensure that performance was perfect on such a task, but were not included in any analyses. As expected, performance was at or very near 100% correct in this task for all conditions and all observers (data not shown).

*Results*

A repeated-measures ANOVA (6 spatial frequencies $\times$ 4 set sizes) was conducted. The ANOVA revealed a main effect of set size, but not SF. For all spatial frequencies and all observers, performance decreased as set size increased in the neutral precue condition. The set size x–SF interaction was significant, indicating that there was a larger decrease in performance as a function of set size for low than for high SFs.

Figure 8 shows average performance (percent correct, corrected for guessing — see Note 9) of the four observers as a function of set size for the neutral precue

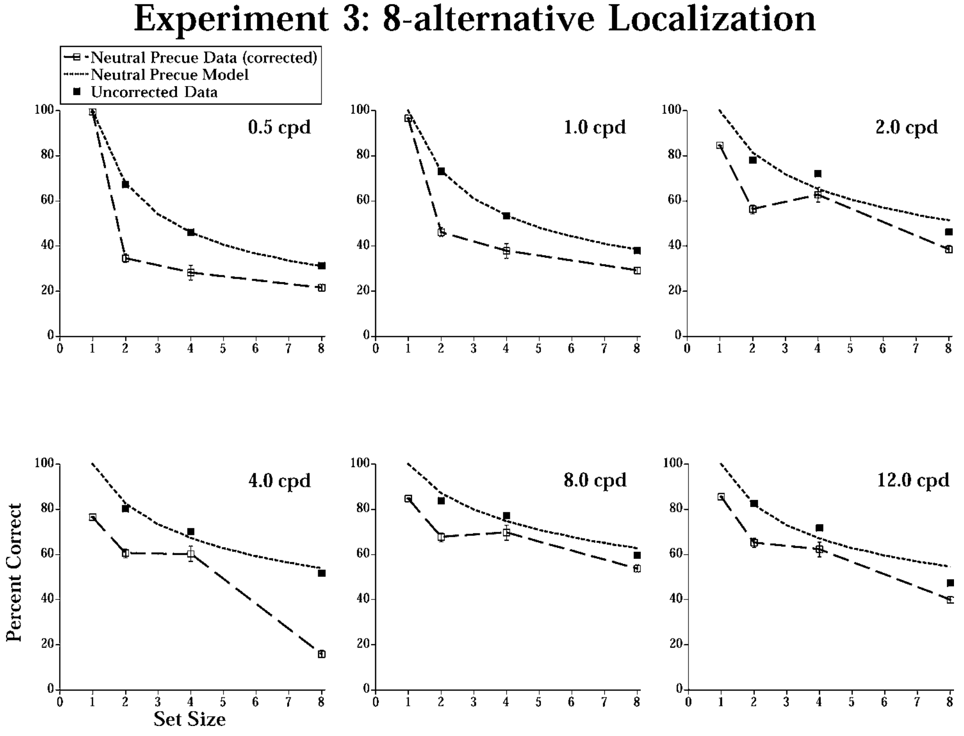


**Figure 8.** Performance as a function of set size for the 8-alternative localization task for 6 spatial frequencies (0.5 to 12 cpd). Corrected percent correct is shown with open symbols and dashed line for comparison with other tasks. Note that data are shown only for the neutral precue condition. In the peripheral precue condition this task amounted to indicating the location of the precue (see text for details). Solid symbols and dotted line show uncorrected percent correct and model fits.

condition (dashed lines) for each spatial frequency. Again, there was a non-linear effect of set size, particularly at the lowest spatial frequencies. Note that the large decrease in performance with set size is not simply the result of the fact that performance in the set size 1 condition was close to ceiling. Even though performance was near 100% correct (0.5 and 1.0 cpd) at set size 1, it was about 20–30% correct at set size 8 (chance = 12.5%). At higher SFs, performance at set size 1 was lower, but often did not decrease to such low levels of performance.

### *Modeling of 8-alternative localization task*

In this task, the observer had to select the spatial location of the target (whether rightward or leftward oriented). The SDT model for this task therefore assumes that the observer monitors two outputs per location corresponding to the rightward and leftward tuned filters. The observer compares the maximum response for each location and chooses the location associated with the maximum response. Obtaining model accuracy in this task requires calculating the probability that either of the two filter responses at the target location exceeds the responses of the filters to all other locations. The mathematical closed form expressions for model's accuracy prediction for the localization task are summarized in Table 1 and are compared to the standard single filter/single target localization task given by Green and Swets (1966).

*Modeling localization of one of two tilted Gabors.* For the localization task, we used a single index of detectability as a fitting parameter. We assumed that the discriminability between the rightward and leftward tilted Gabors was twice the discriminability of any of the tilted Gabors and the vertical distracters ($d'_{\mathrm{l,r}} = 2d'_{\mathrm{r,v}}$). For the localization task, the model prediction is less sensitive to the relationship between $d'_{\mathrm{l,r}}$ and $d'_{\mathrm{r,v}}$.

Figure 8 shows the model fits (dotted lines) to average percent correct data (for set sizes 2 through 8), uncorrected for guessing. The model results shown here are averages of the model outputs of individual observer's data. The model accounts for most of the set-size effect and the data are particularly well fit at low SFs.

### *Speed–accuracy tradeoff analysis*

Figure 9 shows average RT of correct responses plotted as a function of set size. RT increased as set size increased in the neutral precue condition at all spatial frequencies. As in the accuracy data, the largest increase in RT usually appeared between set sizes 1 and 2, reflecting the relatively greater cost of adding distracters at small set sizes. There was no evidence for a speed–accuracy tradeoff with regard to the effects of set size and of precue.

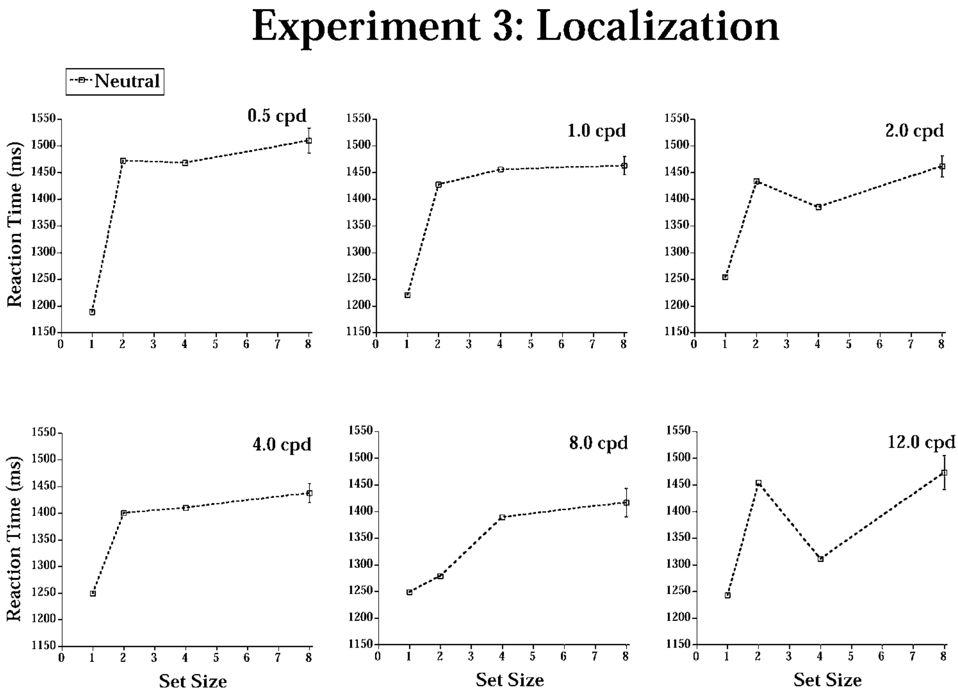


**Figure 9.** Reaction time data for the localization task, plotted as accuracy was plotted in Fig. 8.

### *Localization errors*

We characterized localization errors because we were particularly interested in determining whether observers chose locations in which there were no stimuli (i.e. 'empty' locations), since this would be an index of spatial uncertainty. We found no evidence for such confusion. When observers made errors, they chose empty spaces (specifically Set Size 2 and 4) on less than 10% of error trials, which is less often than predicted by chance. This indicates that the stimulus contrast that we used largely eliminated the effect of stimulus location uncertainty, which is known to produce a more pronounced degradation at low than at high performance levels (Pelli, 1985). This is important for modeling the data, since it indicates that empty locations are not effectively acting as distracters and need not be accounted for in the signal detection modeling (see Carrasco *et al.*, 2000).

## GENERAL DISCUSSION

The aims of the present study were threefold: First, to extend SDT models to evaluate their ability to account for set-size effects in three different tasks (2-target identification, 2-target yes/no detection, and 8-alternative localization). Second, to examine the extent to which spatial frequency affects search performance. Third, to assess the effects of directing transient covert attention to the target location on the set-size effect in the same three tasks.

We applied psychophysical techniques to the study of visual search. In particular, we kept eccentricity and contrast constant across set size and assessed performance at different SFs. In many instances, set-size effects have been attributed to sensory factors, such as target eccentricity and lateral inhibition (e.g. Carrasco and Yeshurun, 1998; Carrasco *et al.*, 1995). In this study, the display characteristics allowed us to rule out sensory factors as possible contributors to the set-size effect in these tasks.

We observed a decrease in performance as a function of set size in three tasks — identification, yes/no detection, and localization — at all spatial frequencies tested. In some cases the effect was very pronounced. Given that in the present study observers performed feature searches with homogeneous distracters and that sensory factors were ruled out, the fact that a set-size effect was still observed indicates that these feature searches were not performed ‘preattentively’ and are incompatible with traditional visual search models (e.g. Treisman, 1993; Treisman and Gormican, 1988; Wolfe, 1994). This finding is consistent with previous studies that have questioned the dichotomy between preattentive and attentive processes by showing a cost of performing a concurrent task (Joseph *et al.*, 1997; Lee *et al.*, 1997, 1999) or a benefit of precueing the target location (Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998; Carrasco *et al.*, 2004) in feature searches.

Set-size effects have been observed with homogeneous distracters (i.e. feature search) when target–distracter discriminability is low (e.g. Cave and Wolfe 1990; Duncan and Humphreys, 1989). The orientation tasks used here required making judgements about oriented stimuli that were at minimum 15° apart, and thus presumably were subserved by separate mechanisms (channels in V1) (DeValois and DeValois, 1988). Whereas this could result in high discriminability, stimulus contrast was manipulated to attain a performance level of about 80% correct. Thus, these tasks could be considered to have a relatively low target-distracter discriminability and hence are consistent with the account of search efficiency as a continuum, as proposed by Duncan and Humphreys (1989). That is, set-size effects increase as target-distracter discriminability decrease with no simple division between the presence and absence of a set-size effect or preattentive and attentive search.

### *Does SDT explain the set-size effect in visual search?*

In SDT models, as distracters are added to the display, the likelihood of erroneously choosing a distracter increases as the number of non-target noisy responses monitored by the observer increases. Hence performance decreases as set size increases (e.g. Eckstein, 1998; Kinchla, 1974; Palmer *et al.*, 2000; Verghese, 2001). The SDT model we applied can account for the set-size effects observed in the 2-target identification and 8-alternative localization tasks, and slightly under-predicts some of the set-size effects that were observed in the 2-target yes/no detection task at most spatial frequencies. These results provide additional support for the notion that a serial deployment of attention is not required to explain the set-size effect.

The set-size effect has also been attributed to spatial uncertainty (e.g. Palmer *et al.*, 1993; Solomon *et al.*, 1997). That is, an increase in set size simply increases the uncertainty about target location, which results in a decrease in performance. However, Morgan *et al.* (1998) and Baldassi and Burr (2000) found a performance degradation with set size that was larger than predicted by the standard 1-target 2IFC SDT model (Palmer *et al.*, 1993). One model that predicted the larger set-size effect included suboptimal integration of irrelevant information (Baldassi and Burr, 2000). More recently it has been demonstrated that if the modeling had taken into consideration the fact that the task involved two possible targets (i.e. targets were either tilted clockwise or counterclockwise; e.g. Carrasco *et al.*, 2000; Baldassi and Verghese, 2002), performance might have been accounted for by uncertainty (Baldassi and Verghese, 2002).

Notwithstanding the differences between tasks and some of the complexities of comparison, it is worth noting that the SDT model predicted the set-size effects in all tasks, although it slightly under-predicted the yes/no detection results. Hence, we argue that it is noise in the sensory system that is responsible for these set-size effects. It is interesting to note that there was a smaller set-size effect in the 2 targets yes/no detection task (most similar to typical search tasks) than in the 2-target identification task or 8-alternative localization task. Moreover, the SDT model *under*-predicts the set-size effect in the detection task even though a speed-accuracy tradeoff was ruled out. The fact that the SDT model often under-predicts the set-size effect in the detection task suggests that the residual effect could be due to limited resources (e.g. McElree and Carrasco, 1999).

The effect of set size on performance in the neutral precue condition was a nonlinear one; there was a greater cost of adding a distracter when the display contained none or few distracters than when it contained several distracters. This finding is consistent with SDT models (Eckstein *et al.*, 2000), and with other feature (Bacon and Egeth, 1991; Carrasco and Yeshurun, 1998) and conjunction (Carrasco *et al.*, 1995; Palmer *et al.*, 2000; Wolfe *et al.*, 1989) searches, whose slopes are steeper for the smaller than the larger set sizes. This pattern has been attributed to distracter grouping and display density: The larger the set size, the more crowded the display and the more opportunity there would be for distracter grouping. Distracters tend to group as a function of their similarity and proximity (Duncan and Humphreys, 1989, 1992), and adding distracters strengthens perceived grouping (Banks and Prinzmetal, 1976), which, in turn, improves observers' performance in search tasks (Carrasco and Chang, 1995; Carrasco *et al.*, 1995; Farmer and Taylor, 1980; Humphreys *et al.*, 1989; Poisson and Wilkinson, 1992).

*Comparison across tasks.* As described above, we measured both accuracy and RT in the three tasks (identification, detection and localization) when stimulus conditions were identical (as we manipulated SF and precue condition). Two observers were common in the three experiments and the target duration and contrast were typically the same across tasks. (Note: we compared individual observer data where stimulus conditions were identical in all three tasks and the data were qualitatively similar to the average data.) The other 2 observers were different in each task (and the duration and contrast of the targets were not identical). Thus, these comparisons must be made with caution. The averaged data shown in Figs 3, 5 and 8 suggest that detection was overall more difficult than identification (as overall percent correct was lower). Moreover, there appears to be a larger set-size effect at low spatial frequencies (0.5 and 1.0 cpd) in the identification and localization tasks than in the detection task. The smaller set-size effect in the detection task (particularly at low spatial frequencies) may be a result of the fact that overall baseline performance was lower. In general, accuracy was higher in the identification and localization tasks than in the detection task. The largest differences were observed at low SFs (0.5 and 1.0 cpd). At these frequencies, observers were able to perform the 2-target identification and 8-target localization tasks with greater accuracy than they could perform the yes/no detection task.

*The effect of spatial frequency on visual search tasks*

In general we found that an SDT model predicts most of the set-size effect observed in all tasks at all spatial frequencies. This is the first study to address the effect of SF on search performance systematically. Performance decreased as a function of set size at all spatial frequencies tested, indicating that whatever mechanism is responsible for the set-size effect affects a wide range of SF channels. However, the larger set-size effect for low than for high SFs in the identification and localization tasks suggests that such a mechanism does not affect all SF channels equally. Although the SDT model accounted for the variation in SF, due to the fact that there were two fitting parameters, as described above, it does not predict an SF dependence. This is an issue for further research.

*How does directing attention to the target location affect the set-size effect?*

In this study covert attention diminished the set-size effect in all tasks at all SFs. A peripheral precue improves performance when a single target is present in the display (Cameron *et al.*, 2002; Carrasco *et al.*, 2000, 2002; Yeshurun and Carrasco, 1999), and decreases (e.g. Baldassi and Burr, 2000; Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998; Foley and Schwartz, 1998; Morgan *et al.*, 1998) or eliminates (e.g. Davis *et al.*, 1983; Palmer, 1994) the effect of distracters. Although SDT models predict that the precue would eliminate the set-size effect, there was a small decrease in performance with increasing set size in the peripheral precue condition in the identification and yes/no detection tasks; that is, the precue diminished, but did not eliminate, the set-size effect. These results are consistent with parallel processing. Even when the target location was precued, performance was still affected by irrelevant information. Notwithstanding the effectiveness of the precue (see Note 10), some information was processed beyond the focus of attention (e.g. Carrasco and McElree, 2001; Cave and Pashler, 1995; Eriksen, 1990; Tsal and Lavie, 1993).

As mentioned in the Introduction, most studies of transient attention have examined effects on high SF stimuli. Here we show that transient attention improves performance across a range of SFs, consistent with Cameron *et al*. (2002) and Carrasco *et al*. (2000).

Early accounts of the effect of covert attention on performance revolved around the notion that attention was a limited resource. Moreover, improvements in performance with attention were characterized by a serial deployment of attention (e.g. Posner, 1980; Treisman and Gelade, 1980; Wolfe, 1994). The effect of precueing observed in these feature tasks argues against a dichotomy between preattentive and attentive search. Recently, other mechanisms have been suggested to account for the improvement in performance when attention is activated under peripheral precue conditions. Based on a statistical argument, some authors have argued that a precue results in uncertainty reduction or distracter exclusion (Eckstein, 1998; Foley and Schwartz, 1998; Palmer, 1994; Shiu and Pashler, 1994, 1995; Solomon *et al*., 1997). Increasing the number of stimuli or target locations increases the probability of an error, but precueing target location reduces this effect by decreasing uncertainty. However, for short stimulus durations, a peripheral precue improves performance more than would be predicted by uncertainty alone (Carrasco *et al*., 2000, 2002; Morgan *et al*., 1998). Some authors have supported the notion that peripheral precues affect decision mechanisms (Kinchla, 1974; Palmer *et al*., 1993; Shaw, 1980). Some have suggested that precuing results in a better match between the perceptual template and the target (i.e. external noise exclusion; Dosher and Lu, 2000). There is also evidence for signal enhancement (e.g. Carrasco *et al*., 2000, 2002; Downing, 1988; Lu and Dosher, 1998 (internal noise reduction)).

Two attentional mechanisms that are likely to be responsible for the precuing effect observed in the present data are signal enhancement and distracter exclusion. The data reported here for set size 1 — when the suprathreshold target was presented alone, in the absence of a post-mask, and all sources of external noise were eliminated — are nearly identical to some of the conditions reported in Carrasco *et al*. (2000). In that paper, the improvement in performance under such conditions was modeled with SDT. Improvement in performance that exceeds that predicted by SDT model was attributed to signal enhancement. Thus the results for set size 1 presented here provide support for signal enhancement, consistent with previous studies (e.g. Cameron *et al*., 2002; Carrasco *et al*., 2000, 2002; Yeshurun and Carrasco, 1999). When distracters are present, although distracter exclusion accounts for the bulk of the effect, signal enhancement may also contribute to the effect of attention (e.g. Carrasco and McElree, 2001; Palmer, 1994; Shiu and Pashler, 1994).

## CONCLUSION

We have used a theoretical and methodological framework from visual psychophysics to investigate visual search and the way it is affected by transient covert attention. We found a pronounced set-size effect in three different tasks. Notwithstanding the differences between tasks and some of the complexities of comparison, it is worth noting that the SDT model we applied can account fully for the set-size effect observed in the identification and localization tasks, and for a large extent of the set-size effect observed in the detection task in most neutral precue conditions. This indicates that the set-size effect can be accounted for by noise in the visual system. We found an interaction between set size and spatial frequency; the set-size effect was larger at low SFs in identification and localization tasks. Transient covert attention diminished the set-size effect in all tasks for all spatial frequencies. In the set size 1 condition this effect supports signal enhancement. At larger set sizes, although distracter exclusion accounts for the bulk of the effect, signal enhancement may also be a mechanism by which the peripheral precue imposes its effect.

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Some of the results of these experiments were reported at ARVO (Cameron *et al*., 2000).

## NOTES

1. The present 2-target identification SDT model, also used in Carrasco *et al*. (2000), differs slightly in the way in which it makes decisions from the signed-max SDT model proposed by Baldassi and Verghese (2002). In the latter model, the decision is based on the difference between the two detector outputs.

2. A fifth naïve observer participated in this experiment. The overall pattern of her results was consistent with the other observers, but we excluded her data because her performance was at chance for all targets presented below the horizontal meridian, and nearly perfect for all targets presented above the horizontal meridian. All other observers showed a vertical meridian asymmetry (performance was higher in the upper than in the lower visual field, on the vertical meridian) and a horizontal–vertical anisotropy (performance was higher on the horizontal than the vertical meridian). See Carrasco *et al*. (2001).

3. Our stimulus arrangement avoids crowding according to Toet and Levi's (1992) estimate of a center-to-center spacing of stimuli of 1/10th the target eccentricity in the radial direction, and to Bouma's (1970) rule of 1/2 target eccentricity. In addition, given that the cost of adding distracters is greater at smaller set sizes, it is unlikely that crowding contributes to the observed set-size effects.

4. We identified all conditions that had a standard error greater than one standard deviation from the mean of all 24 conditions for each precue (4 set sizes $\times$ 6 spatial frequencies), and re-ran one block (of 100 trials) for those conditions. For each observer, this meant collecting one more block of 100 trials in about 8 conditions to replace the outlier data points.

5. The results had the same pattern when data were analyzed with $d' = z(\text{hits}) - z(\text{false alarms})$. A 'hit' was categorized as a correct response to a target tilted to the right. Criterion or bias (measured with 'c', Macmillan and Creelman, 1991) was $< \pm 0.5$ for all observers and did not vary systematically with set size or spatial frequency.

6. Note that the standard $d'$ (equation: $d' = z(\text{hits}) - z(\text{false alarms})$) is inappropriate for the task performed in this experiment, as it does not take into account set size. We measured criterion or bias (measured with 'c', Macmillan and Creelman 1991), which was an absolute value of less than 0.5 for all observers and did not vary systematically with set size or spatial frequency.

7. The significant effect of spatial frequency indicates that performance was not perfectly well equated in the baseline condition.

8. The stimulus contrast and duration in the localization task were based on baseline conditions in the detection task for two observers and the discrimination task for the other two observers.

9. The data graphed here are an average across the four observers. We corrected for guessing by applying the following formula to the averaged data: PC (corrected) $= ((N \times \text{PC (observed)}) - 1)/(N - 1)$, where $N$ is the number of alternatives (8). In the ANOVA we corrected for guessing for each individual observer's data.

10. The spatial and temporal characteristics of the peripheral precue were designed to maximize its effect. This precue has been effective in visual search (Carrasco *et al.*, 2004; Carrasco and McElree, 2001; Carrasco and Yeshurun, 1998), contrast sensitivity (e.g. Cameron *et al.*, 2002; Carrasco *et al.*, 2000, 2001), acuity (Carrasco *et al.*, 2002; Yeshurun and Carrasco, 1999), and texture segmentation (e.g. Yeshurun and Carrasco, 1998; 2000) tasks.

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