Published in final edited form as:
*Vision Res*. 2000 ; 40(0): 1203–1215.

# Spatial covert attention increases contrast sensitivity across the CSF: support for signal enhancement☆

**Marisa Carrasco**[a,*], **Cigdem Penpeci-Talgar**[a], and **Miguel Eckstein**[b]

[a]Department of Psychology, New York University, 6 Washington Place, New York, NY 10003-6634, USA

[b]Department of Medical Physics and Imaging, Cedars-Sinai Medical Center, Los Angeles, CA, USA

## Abstract

This study is the first to report the benefits of spatial covert attention on contrast sensitivity in a wide range of spatial frequencies when a target alone was presented in the absence of a local post-mask. We used a peripheral precue (a small circle indicating the target location) to explore the effects of covert spatial attention on contrast sensitivity as assessed by orientation discrimination (Experiments 1–4), detection (Experiments 2 and 3) and localization (Experiment 3) tasks. In all four experiments the target (a Gabor patch ranging in spatial frequency from 0.5 to 10 cpd) was presented alone in one of eight possible locations equidistant from fixation. Contrast sensitivity was consistently higher for peripherally- than for neutrally-cued trials, even though we eliminated variables (distracters, global masks, local masks, and location uncertainty) that are known to contribute to an external noise reduction explanation of attention. When observers were presented with vertical and horizontal Gabor patches an external noise reduction signal detection model accounted for the cueing benefit in a discrimination task (Experiment 1). However, such a model could not account for this benefit when location uncertainty was reduced, either by: (a) Increasing overall performance level (Experiment 2); (b) increasing stimulus contrast to enable fine discriminations of slightly tilted suprathreshold stimuli (Experiment 3); and (c) presenting a local post-mask (Experiment 4). Given that attentional benefits occurred under conditions that exclude all variables predicted by the external noise reduction model, these results support the signal enhancement model of attention.

### Keywords

Attention mechanisms; Contrast sensitivity; Covert spatial attention; Signal enhancement; External noise reduction; Peripheral precue; Mask; Orientation discrimination; Detection; Localization

## 1. Introduction

In this study we employed spatial precueing to identify the mechanisms underlying the benefits produced by covert spatial attention. We explored whether directing observers' attention to a given location would improve their contrast sensitivity, as assessed by

☆Parts of this study were presented at the Annual Meeting Association for Research in Vision and Ophthalmology (ARVO, May 1999) and at the European Conference of Visual Perception (ECVP, August 1999) and published in Abstract format (Carrasco & Penpeci, 1999; Carrasco & Penpeci-Talgar, 1999).



*Corresponding author. Fax: +1-212-9954349. marisa@psych.nyu.edu (M. Carrasco).

orientation discrimination, detection and localization tasks. In comparison to previous studies dealing with the effects of attention on contrast sensitivity (Lee, Koch & Braun, 1997; Solomon, Lavie & Morgan, 1997; Foley & Schwartz, 1998; Lu & Dosher, 1998; Lee, Itti, Koch & Braun, 1999), the present study is unique for the following reasons: (1) the target (Gabor patch) appeared alone in the display (without distracters or a concurrent visual task) and covered a wide range of spatial frequencies (0.5–10 cpd); (2) it evaluated whether the attentional benefit would emerge in the following conditions: (a) in the presence or absence of a post-stimulus mask; (b) at different overall performance levels (82 versus 90% correct); (c) using different tasks — discrimination, detection and localization — at two discrimination levels (vertical versus horizontal or slightly tilted to the right versus to the left); and (3) the peripheral, exogenous precue provided no information in terms of response probability. These experimental manipulations allowed us to eliminate the conditions postulated by the model of external noise reduction to be necessary for an attentional effect to emerge.

According to the signal enhancement hypothesis, attention strengthens the stimulus' representation (e.g. Bashinski & Bacharach, 1980; Posner, 1980; Downing, 1988; Luck, Hillyard, Mouloua, Woldorff, Clark & Hawkins, 1996; Müller, Picton, Valdes-Sosa, Riera, Teder-Sälejärvi & Hillyard, 1998). Previous studies in which we have manipulated covert attention in a stimulus-driven fashion, via a peripheral, transient cue, have suggested that attention enhances spatial resolution at the attended location (Carrasco & Yeshurun, 1998; Yeshurun & Carrasco, 1998, 1999).

In contrast, the external noise reduction hypothesis maintains that attention diminishes the strength of the representation of stimuli that are outside the focus of attention.[1] Attentional effects have emerged when distracters appeared with the target, but not when the target was presented alone (Shiu & Pashler, 1994, 1995), and are more pronounced as the number of distracters increases (e.g. Palmer, 1994; Foley & Schwartz, 1998; Morgan, Ward & Castet, 1998). These studies sustain that attention allows us to exclude distracters that differ along some relevant dimension from the signal by narrowing a filter that is processing the stimulus. Accordingly, precues also allow observers to monitor only the relevant location(s) instead of all possible ones. This reduction of statistical noise is also known as reduction of spatial uncertainty with respect to the target location (e.g. Kinchla, 1980; Davis, Kramer & Graham, 1983; Shaw, 1984; Sperling & Dosher, 1986; Palmer, 1994; Shiu & Pashler 1994; Solomon et al., 1997; Eckstein, 1998; Foley & Schwartz, 1998).

Some proponents of the external noise reduction hypothesis have attributed previous attentional effects to the use of multiple masks, which introduce decisional noise (Shiu & Pashler, 1994). However, when a suprathreshold target appears alone in the display and is followed by a local mask which covers only the target location, a spatial precue improves performance in a variety of tasks (Henderson, 1996; Luck et al., 1996; Yeshurun & Carrasco, 1999). Yet, it has been proposed that the effects of a local backward mask can be modulated by attention. Enns and Di Lollo (1997) have proposed that targets at unattended locations are coded with low spatio-temporal resolution and are thus vulnerable to substitution by a four-dot mask. Smith (in press) maintains that the rate of approach to asymptotic performance is faster at attended than unattended locations, but the asymptotic activation is the same at all locations. According to these studies, in the absence of a local

[1]In this paper the term external noise reduction is used to refer to the effect of uncertainty. The term should not be confused with the concepts of noise reduction (reduction of internal multiplicative noise) or that of external noise exclusion (also known as sampling or calculation efficiency, referring to a better match between the human filter/template and the ideal optimal filter) used by Lu and Dosher (1998).

mask no attentional effect should emerge. Experiment 1 was conducted to test this prediction.

Transient covert attention improves observers' performance in tasks that rely on detection or discrimination of high-spatial frequencies (Nakayama & Mackeben, 1989; Balz & Hock, 1997; Yeshurun & Carrasco, 1999). However, the visual system codes images containing a wide range of spatial frequencies. It extracts information by means of many 'channels' or quasi-independent mechanisms whose bandwidths are about 1–2 octaves in spatial frequency and about 15° in orientation (e.g. Graham, 1989). Outputs from these individual filters appear to be processed simultaneously and jointly determine detection and discrimination of spatial patterns. The human contrast sensitivity function illustrates that the highest sensitivity is in the mid-spatial frequency range with a sharp drop-off in sensitivity at high spatial frequencies and a more gradual drop-off at low frequencies (Robson & Graham, 1981). The present study examined whether attention improves contrast sensitivity over a wide range of spatial frequencies.

Spatial attentional benefits in contrast sensitivity have been shown when the target appears with distracters or when observers perform a concurrent task: (a) the target was displayed simultaneously with distracters and observers had to indicate whether the target had an increment or decrement in contrast (Foley & Schwartz, 1998; Solomon et al., 1997); (b) observers judged the orientation of two Gabor patches that appeared simultaneously when one location was cued and the other was not (Lu & Dosher, 1998); and (c) the target was displayed simultaneously with information pertaining to a concurrent task (Lee et al., 1997, 1999). In contrast to these studies, in the present experiments a Gabor pattern was presented alone in the display to evaluate the role that the factors identified by the external noise reduction and signal enhancement mechanisms play in the cueing effect.

## 2. Experiments

The effects of precueing were assessed by comparing the stimulus contrast necessary for observers to perform an orientation discrimination task (Nachmias, 1967) at a given performance level. We assessed attentional effects across a wide range of spatial frequencies (0.5–10 cpd). To eliminate the effect of distracters and masks, we explored whether attention would increase contrast sensitivity when the stimulus was presented alone (Experiment 1). To evaluate attentional effects under reduced location uncertainty conditions, observers performed: (a) detection and discrimination tasks at a higher overall performance level (Experiment 2); (b) discrimination, detection and localization tasks at two levels of discriminability (Experiment 3); and (c) a discrimination task when a local post-mask was presented (Experiment 4). These manipulations allowed us to rule out the conditions postulated by the model of external noise reduction to underlie attentional effects.

In psychophysical studies, the target's location has been usually specified by either a 'central' ('endogenous', 'sustained') cue presented at the center of the visual field, or a 'peripheral' ('exogenous', 'transient') cue presented at the relevant location. The maximum attentional benefit occurs at about an stimulus-onset-asynchrony (SOA) of 300 ms for the former and of 100 ms for the latter (Jonides, 1981; Nakayama & Mackeben, 1989).

To maximize attentional participation and to prevent eye movements, we used a peripheral precue in half of the total trials of the following four experiments. To prevent forward spatial masking effects, the precue appeared adjacent to the target location. Some authors have suggested that precues encourage observers to adopt a more liberal decisional criterion or to assign more weight to information extracted from the cued location (e.g. Kinchla, 1992). Because the precue cue always indicated target location (100% valid) and appeared equally often adjacent to a Gabor of either orientation, it did not associate a higher probability with one of the responses and observers could not rely on its presence to reach a decision. In the other 50% of the trials, a small circle (neutral cue) appeared in the middle of the screen indicating that the target was equally likely to appear in any of eight possible locations.

## 3. Experiment 1

Experiment 1 was designed to examine whether an attentional benefit could be found when a Gabor target of a wide range of frequencies was presented alone in one of eight possible locations, and was not followed by either a global or a local mask. Observers had to indicate the orientation of the Gabor patch, vertical versus horizontal.

### 3.1. Method

**3.1.1. Observers—**Six individuals (three graduate, two undergraduate students and one postdoctoral fellow) from NYU acted as observers; two are lab members, the other four were naïve as to the purposes of the study.[2] All had normal or corrected to normal vision.

**3.1.2. Apparatus—**Stimuli were displayed on a gamma-corrected computer monitor (Pelli & Zhang, 1991) in a dark room. A video attenuator drove only the green gun of the Apple 17 in. Multiscan color monitor, whose frame duration is 13.4 ms.

**3.1.3. Stimuli and design—**The stimuli were created on a Power Macintosh 7500/100 computer using MATLAB 5.2 and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Background luminance was set to the middle of the monitor's range, about 16 cd/m$^2$. All Gabor patches (sinusoidal gratings embedded in a Gaussian window) subtended 1.5° of visual angle. The Gabor stimuli were oriented vertically or horizontally and had a center spatial frequency of 0.5, 1, 2, 4, 8 or 10 cpd. On each trial, the Gabor patch appeared with equal probability at one of eight random locations at 3.2° eccentricity. Cue onset was always indicated. On half of the blocks a precue appearing 2° away from the center of the Gabor patch ('cued trials') also indicated location. The precue was a black circle, subtending a radius of 0.25° of visual angle. On the remainder of the blocks ('neutral trials'), this circle appeared at the center of the display to indicate that the stimulus had equal probability of appearing at any location. Half of the cued trials and half of the neutral trials contained a vertical Gabor. The rest of the trials contained a horizontal Gabor. A small fixation square (0.2 × 0.2° of visual angle) was present at the center of the screen throughout the block, except when the circular neutral cue appeared (Fig. 1).

**3.1.4. Procedure—**Observers viewed the display binocularly. They were instructed to fixate on the fixation point throughout the trial and to report the target orientation. Each observer was then given ten practice blocks of trials and performed 60 experimental blocks in a random order over ten 1-h sessions. On each of the trials the cue appeared for 40 ms, and after an ISI of 60 ms (i.e. an SOA of 100 ms), the stimulus was presented for 100 ms. Given that about 250 ms are needed for saccades to occur (Mayfrank, Kimmig & Fischer, 1987), goal or target directed eye movements could not take place between the cue onset and the stimulus offset. Observers responded by pressing a key on the computer keyboard using the index or middle finger of their dominant hand to indicate whether the stimulus was vertical or horizontal, respectively. Feedback for a correct response was given by a high-frequency tone while a low-frequency tone signaled an incorrect response. Contrast thresholds at 82% correct were measured for each block using the improved QUEST

[2]One observer only completed three instead of five observations per data point. We included her data in the analysis because her standard error was very low and her pattern of results was exactly the same as that of the other observers.

sequential estimation procedure over 75 trials (Watson & Pelli, 1983; King-Smith, Grigsby, Vingrys, Benes & Supowit, 1994).

### 3.2. Results and discussion

Fig. 2 illustrates the observers' averaged contrast sensitivity function for the neutral trials in which attention was not manipulated. Peak sensitivity was observed at about 1–4 cpd and declined towards higher spatial frequencies, consistent with previous studies (Graham, 1989). Individual CSFs are depicted in Fig. 3.

To quantify the attentional effect, we calculated the ratio of sensitivity when a peripheral cue preceded the target to that when a neutral cue did. No difference in sensitivity between the two conditions would yield a ratio of one. If the peripheral cue increased contrast sensitivity, the ratio would be greater than one. The ratios for each of the six spatial frequencies tested are shown in Fig. 4a. A single sample one-tailed *t*-test revealed that these ratios were significantly greater than one [$t(5) = 3.07$, $P < 0.03$].

This cueing benefit in a 2AFC orientation discrimination task used to assess contrast sensitivity is consistent with previous studies (Lee et al., 1997, 1999; Solomon et al., 1997; Foley & Schwartz, 1998; Lu & Dosher, 1998), and extends the findings to a wide range of spatial frequencies. Attention may modulate the degree of mask suppression (Enns & Di Lollo, 1997; Smith, in press), but these results show that its effects are not limited to such a scope.

Even though in this discrimination task no additional visual information (distracters or masks) had to be filtered out, observers could perform this task with low stimulus contrast. Because this stimulus could have been confused with the background, the cueing effect could reflect reduction of location uncertainty (Cohn & Lasley, 1974; Graham, Kramer & Haber, 1985). Thus, we investigated whether a signal detection model could account for these results. Signal detection theory (SDT) based models assume that each element in the display elicits inherently noisy internal responses in the observers (Shaw, 1980). Accuracy degradation with increasing set-size is caused by the increasing probability that any distracter will exceed the response of the target, rather than due to capacity limitations; i.e., reductions in the perceptual quality of the processing of each item in the display or in a serial processor. SDT models predict the effects of set-size on detection when a target differs from distracters along one (feature tasks, Palmer, 1994) or many (conjunctions, Eckstein, 1998) physical attributes, as well as when a target is localized on uniform (Shaw, 1980; Eckstein, Beutter, Bartroff & Stone, 1999), noisy (Swensson & Judy, 1981) or complex (Eckstein & Whiting, 1996) backgrounds. However, SDT models have failed to predict performance in more complex tasks such as line bisection and tasks involving memory (Palmer, 1994). The model used in this paper (Appendix A) is an extension of these SDT models to an orientation-identification task, which incorporates intrinsic uncertainty (i.e. the observers inability to perfectly use information about the elements' spatial or temporal position, size, or spatial frequency; Pelli, 1985).

Based on the contrast threshold estimates predicted by the orientation-identification SDT model, we obtained the peripheral:neutral ratio of sensitivity. The model accounts for the present data; it marginally over-predicts the sensitivity ratio [$t(4) = 2.52$, $P < 0.10$; Fig. 4a]. This result indicates that the cueing effect found in this experiment can be explained by reduction of location uncertainty.

## 4. Experiment 2

According to noise-limited models performance decreases as uncertainty and distracter number increase, because the noise they introduce can be confused with the target signal. As uncertainty is reduced, observers can base their decisions on only the relevant locations and thereby avoid errors caused by noisy irrelevant locations (e.g. Davis et al., 1983; Palmer, 1994; Eckstein, 1998; Foley & Schwartz, 1998). Given that the effect of target location uncertainty produces a more noticeable degradation at low than at high performance levels (Pelli, 1985), one would expect the attentional benefit to be reduced when observers' overall performance is higher. To investigate this possibility, the overall performance level for the discrimination task was increased to 90% correct, while the rest of the design remained the same as in Experiment 1.

We obtained contrast detection thresholds to further address the idea of location uncertainty. Thomas and Gille (1979) reported that if two low contrast stimuli differ in orientation by about 20–30°, they are discriminated from one another as accurately as each is detected or discriminated from noise (blank locations). They concluded that detection and orientation discrimination occur concomitantly, and that these results are consistent with tuned-channel models. Likewise, Watson and Robson (1981) presented stimuli at a contrast near to detection threshold, and found that some pairs of stimuli differing in spatial frequency were correctly identified as often as they were detected. They postulated that the detectors of these stimuli are 'labeled' (i.e. the observer can distinguish the response of each detector from that of any other). Other near-detection threshold studies have also shown that discrimination depends on detectability for orientation (Thomas & Shimamura, 1975), spatial frequency (Furchner, Thomas & Campbell, 1977) and phase relationships (Nachmias & Weber, 1975). In short, we explored whether the cueing effect would emerge when the performance level was increased to 90% correct in both detection and discrimination tasks, and evaluated the predictions of the orientation-identification SDT model.

### 4.1. Method

**4.1.1. Observers—**Five observers (one high School, two undergraduate and two graduate students) from NYU participated in the discrimination experiment. One observer had participated in the previous experiment, and the other four observers were naïve to the purposes of the study. Three of these observers also participated in the detection experiment. All had normal or corrected to normal vision.

**4.1.2. Stimuli, design, apparatus and procedure—**For the discrimination task, the stimuli, design, apparatus and procedure were the same as in Experiment 1, except that the contrast thresholds for each block was measured at 90% correct using the improved QUEST sequential estimation procedure over 60 trials (Watson & Pelli, 1983; King-Smith et al., 1994). In the 2AFC detection task, the vertical Gabor patches were presented in half of the trials and the observers indicated whether the target had been presented or not. The procedure was the same as in the discrimination task.

### 4.2. Results and discussion

The data were analyzed as in the previous experiment. Fig. 2 depict the observers' average contrast sensitivity for the Gabor patches in the neutral cue condition for the discrimination and detection tasks. Fig. 4b and c illustrate the cueing effect for the respective conditions. For each of the spatial frequencies tested, the ratios revealed a significant increased sensitivity due to the cueing manipulation [$t(4) = 5.32$, $P < 0.01$ and $t(2) = 5.06$, $P < 0.05$, respectively]. For the three observers that participated in both the discrimination and detection tasks, sensitivity was somewhat higher in the former than in the latter. The finding that frequency discrimination is sometimes better than detection (Nachmias & Sansbury, 1974) has been attributed to inhibitory interactions or correlated noise among responding mechanisms (e.g. Olzak & Thomas, 1981).

The present results show that when the overall performance level was increased from 82 to 90% correct, cueing still enhanced contrast sensitivity for a Gabor patch at a wide range of spatial frequencies. As in Experiment 1, the cueing effect cannot be due to a mask suppression effect. We obtained the peripheral:neutral ratio of sensitivity predicted by the orientation-identification SDT model. For this discrimination data the observers' sensitivity ratio is higher than that predicted by the model [$t(4)= 3.37$, $P< 0.05$; Fig. 4b]. Although the effect of target location uncertainty produces a more noticeable degradation at low than at high performance levels (Pelli, 1985), increasing the stimulus contrast to achieve a higher overall performance level did not decrease the overall attentional modulation. Whereas in Experiment 1 the model marginally over-predicted the human sensitivity ratio, in this experiment, the model under-predicted such a ratio (except for the 8 cpd Gabor target where the difference was not statistically significant). Thus, the cueing effect cannot be explained by the mere reduction of location uncertainty. As stimulus contrast increased to attain a higher performance level, the predictability of the SDT model decreased.

## 5. Experiment 3

To systematically investigate the role that stimulus contrast plays in the cueing effect, we compared observers' performance at two different levels of discriminability requiring different stimulus contrasts, for discrimination, detection and localization tasks. To be able to characterize performance in the three tasks, we used the method of constant stimuli. There were two phases. In Phase 1, it was expected that observers would require low stimulus contrast to perform the vertical-horizontal discrimination task ('easy-level'). As mentioned above, Thomas and Gille (1979) reported that if two low-contrast 5 cpd stimuli, presented foveally, differ in orientation by at least 20–30°, they are discriminated from one another as accurately as each is detected or discriminated from noise (blank locations). In contrast, it was expected that observers would require higher stimulus contrast to discriminate whether the Gabor patch was tilted slightly to the left or to the right ('hard-level'). To directly assess the ease with which observers can localize the stimulus, a localization task was also performed. Superior performance at detecting and localizing the tilted stimuli would indicate that the target location is less confusable from the non-target locations reducing the effect of location uncertainty; indeed, close to perfect performance in these tasks would indicate negligible uncertainty levels. It is critical to assess if under such a condition observers' performance in the discrimination task would still benefit from the peripheral cue.

### 5.1. Phase A — discrimination, detection and localization tasks with vertical–horizontal stimuli

**5.1.1. Observers—**An NYU graduate student, who had participated in the previous experiments, and a high-school student who had participated in Experiment 2, were the observers.

**5.1.2. Stimuli and apparatus—**The stimuli and apparatus were the same as in the previous experiments, except that the Gabor patch was presented at 4.5° of eccentricity.[3]

[3]We had conducted an experiment that differed from Experiment 1 only in that the stimulus eccentricity was 4.5° instead of 3.2°. The same pattern of results was obtained in both experiments.

**5.1.3. Design and procedure—**The method of constant stimuli was used. Observers performed one practice block and three experimental blocks of 100 trials per each of eight experimental conditions: spatial frequency (1, 2, 4 or 8 cpd) X cue (neutral versus peripheral). Stimulus contrast was adjusted such that observers would perform at about 80–85% correct in the neutral condition of the discrimination task, in which observers reported the orientation of the Gabor patch. (This level of performance was attained before applying the correction factor for guessing; see below). In the detection task, observers indicated the presence or absence of the target. In the localization task, the stimulus was always present; observers were asked to indicate the position in which the stimulus had appeared by using eight keys of the number keypad corresponding to those locations. Both the order of the three tasks and the order of the eight conditions within each task were randomized for each observer.

**5.1.4. Results and discussion—**Given that chance performance was 50% for detection and discrimination, but 12.5% for the localization task, we used a correction factor to account for guessing across tasks: $P$[processed]= [($N \times P$ [correct])− 1]/($N$–1), where $P$[correct]= measured value, $P$[processed]=actual value of detection, discrimination or localization task, and $N$=number of response alternatives. Observers' performance for the localization task was better than for discrimination, which in turn was better than for detection (Fig. 5a; the better performance in discrimination than in detection tasks was discussed in the previous experiment). The detection and discrimination peripheral:neutral sensitivity ratios for each of the three spatial frequencies tested are highly significant (Fig. 6a).[4] However, the imperfect performance on localization and detection tasks could suggest that the cueing effect resulted from a reduction of location uncertainty. To assess this possibility the difficulty of the task was increased in Phase B; consequently, stimulus contrast was increased.

### 5.2. Phase B — discrimination, detection and localization tasks with slightly tilted stimuli

**5.2.1. Observers—**Four observers participated in this Phase. One observer from NYU who had participated in all previous experiments, one High School student who had participated in Experiments 2 and 3a, and two naïve observers — an NYU graduate student who had participated in Experiment 2 and one observer that had not participated in psychophysical experiments.

**5.2.2. Stimuli, apparatus, design and procedure—**All were the same as in Phase A, except that the Gabor patches were slightly tilted, 4° to the right or to the left from vertical.

**5.2.3. Results and discussion—**Fig. 5b shows the observers' average performance for the detection, discrimination and localization tasks with the tilted stimuli. In contrast to Phase A, performance was far superior for detection and localization than for discrimination. In fact, localization was practically perfect. Moreover, the cueing effect for the discrimination task was significant [$t(3)= 3.20$, $P< 0.05$, Fig. 6b]. This result indicates that even when all the variables that the external noise reduction mechanism holds to be responsible for an attentional effect — distracters, global and local masks, and location uncertainty — have been eliminated, this effect still emerged. (The cueing effect for the detection task was not graphed in Fig. 6b because performance in the neutral condition was close to ceiling and there was no room for improvements.)

[4]The larger attentional benefit for the 2 cpd than for the other two frequencies resulted from a lower performance level for the 2 cpd than for the other frequencies in the neutral condition, but a similar performance for the three frequencies in the peripheral condition.

## 6. Experiment 4

In Experiment 3, tilted stimuli were detected and localized more effectively than they were discriminated, and an attentional effect emerged even under conditions of such reduced spatial uncertainty. To further explore the effects of reducing spatial uncertainty on attention, in this experiment we included a local post-mask. Smith (in press) has pointed out that a single backward mask not only limits the signal-to-noise ratio at the attended location, but also reduces spatial uncertainty by indicating the location where the target has appeared. The only difference between this experiment and Experiment 1 was the presence of the local post-mask.

### 6.1. Method

**6.1.1. Observers—**Six observers (three graduate and two undergraduate students and 1 postdoctoral fellow) from NYU participated in this experiment. Three observers are members of our lab, one of them had participated in all experiments; the remaining three were naive as to the purpose of the study. All had normal or corrected to normal vision.

**6.1.2. Stimuli, design, apparatus and procedure—**All were the same as in Experiment 1, except for the following: the target was followed by a 200 ms broadband white-noise mask, subtending the same degree of visual angle as the stimulus (1.5 × 1.5° of visual angle).

**6.1.3. Results and discussion—**The data were analyzed as in Experiment 1. Fig. 2 depicts the observers' average contrast sensitivity function for the Gabor patches in the neutral cue condition, and Fig. 7 illustrates individual CSFs for two observers. In the presence of a mask, the peripheral-to-neutral sensitivity ratio revealed a significant benefit due to the attentional manipulation [$t(5)= 3.34$, $P<0.025$; Fig. 4d]. Note that according to the SDT model, this sensitivity ratio should not differ from 1, because in both cue conditions observers are considered to monitor only the target location, thus eliminating noise from the other locations. However, the attentional effect that emerged was not less pronounced than that of Experiment 1, where no mask was presented; i.e. where spatial uncertainty was not reduced.

## 7. General discussion

The present results are consistent with previous studies that have demonstrated an attentional benefit for contrast sensitivity (Lee et al., 1997, 1999; Solomon et al., 1997; Foley & Schwartz, 1998; Lu & Dosher, 1998), and extend their findings to situations where the target was presented alone, appeared in both masked or unmasked displays, at a wider range of spatial frequencies, and had to be processed fairly accurately. According to the external noise reduction mechanism, an attentional effect is not likely to occur under such display conditions. These results indicate that an enhanced signal must have increased contrast sensitivity for a wide range of spatial frequencies.

Several studies have attributed attentional facilitation to an efficient reduction of external noise, either because a suprathreshold target could be confused with distracters (e.g. Palmer, 1994; Shiu & Pashler, 1994, 1995; Morgan et al., 1998), or because a near-threshold target presented alone could be confused with empty locations (e.g. Cohn & Lasley, 1974; Graham et al., 1985). These authors have suggested that precues reduce the number of locations that have to be monitored, thus reducing the statistical noise that is introduced at these locations. Such an SDT based model accounted for the cueing effects in the discrimination task (Experiment 1) when low-contrast vertical and horizontal stimuli were used, i.e. when detection and discrimination thresholds were similar (e.g. Thomas & Gille, 1979). This noise reduction model, however, would predict no attentional benefit when a high-contrast target presented in isolation is detected and localized almost perfectly (Experiment 3) or a post-local mask reduces the target's spatial uncertainty (Experiment 4). The target could neither be confused with the blank at the other locations or with distracters, since there were none. Indeed, the extent of the attentional benefit was the same regardless of whether a local post-mask was used or not. This indicates that attention not only operates on the processing of the mask (Enns & Di Lollo, 1997; Smith, in press), but also on that of the stimulus.

Our results differ from those of Smith (in press) who found that attention increased contrast sensitivity only when a mask followed the target. In Smith's study, the combination of a central and a peripheral cue, as well as the SOA between the cue and the display may not have been optimal for an attentional effect to emerge. In addition, for the attentional effect to be equally likely to occur, it would have been desirable to have had observers' contrast sensitivity equated across experiments. In any case, the findings of the present study showing an attentional benefit regardless of the presence of a mask, clearly indicate that the increased contrast sensitivity induced by transient attention is not merely due to mask suppression.

Furthermore, although location uncertainty produces a more noticeable degradation at low than at high performance levels (Pelli, 1985), the extent of the attentional effect was similar when we decreased the likelihood that the pattern would be confused with the blank locations. This was accomplished by either increasing the overall performance level (Experiment 2), increasing stimulus contrast to enable finer discriminations (Experiment 3), or presenting a local post-mask (Experiment 4).[5] Other recent studies have also found limitations to location or spatial uncertainty models. For instance, Lee et al.'s (1999) findings regarding the way in which spatial visual thresholds are influenced by the near absence of attention cannot be accounted for by such a spatial uncertainty model. Similarly, when Morgan et al.'s (1998) orientation displays were briefly presented (100 ms), the improvement produced by cueing the target location is greater than that predicted from the signal-detection model of spatial uncertainty.

The present study is consistent with Lu and Dosher (1998), who interpreted their finding of an attentional effect in an orientation discrimination task at low levels of external noise, but not at high levels, as providing support for the signal enhancement mechanism. The present results are also consistent with Lee et al.'s (1999) recent computational model for attentional modulation of spatial vision, which suggests that attention strengthens the interactions among visual spatial filters, resulting in both sharpening of tuning and increased gain.

The attentional facilitation reported here reflects more than just an efficient inhibition of the non-relevant information. An enhanced processing of the relevant information may result from improved quality of the stimulus representation corresponding to the cued location. Experiments 2, 3 and 4 support the hypothesis that a signal enhancement mechanism is responsible for the finding that attention increases sensitivity across the contrast sensitivity function. Yeshurun and Carrasco (1999) showed that attention improves performance in visual acuity tasks when a supra-threshold target appears alone in the display and is followed by a local mask. The present study extends those findings to situations where the target ranges across a spectrum of spatial frequencies and is or is not followed by a local mask.

[5]Although the extent of the attentional effect was similar, the pattern of this effect varied somewhat. For the discrimination tasks at 82% correct (Experiments 1 and 4) the attentional benefit seems to have increased as a function of spatial frequency, but this was not the case for the discrimination and detection tasks at 90% correct (Experiment 2). It would be premature to draw conclusions from this pattern difference; currently, we are exploring the interaction of spatial frequency, performance level and target eccentricity.

In conclusion, manipulating transient covert attention by using a peripheral precue significantly improved observers' contrast sensitivity for a range of spatial frequencies. It is reasonable to assume that attentional facilitation in visual tasks reflects a combination of mechanisms such as signal enhancement, external noise reduction and decisional factors. However, given the experimental conditions of this study the models of decisional factors or external noise reduction (distracter exclusion, mask suppression, and location uncertainty) cannot explain the attentional benefit found in all four experiments. This study supports the hypothesis that attention can enhance the signal representation at the cued location.

## Acknowledgments

This study was supported by the National Science Foundation (NYI Grant SBR-9528197), a Cattell Fellowship and a Guggenheim Fellowship to MC. We thank Leslie Cameron for her thoughtful contributions to this project, and Yaffa Yeshurun, Karen Frieder, Suleyman Penbeci, Michael Landy and the two anonymous reviewers for comments on a draft of this manuscript.

## References

Balz GW, Hock HS. The effect of attentional spread on spatial resolution. Vision Research. 1997; 37(11):1499–1510. [PubMed: 9205711]

Bashinski HS, Bacharach VR. Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. Perception & Psychophysics. 1980; 28:241–248. [PubMed: 7433002]

Brainard DJ. The psychophysics toolbox. Spatial Vision. 1997; 10:433–436. [PubMed: 9176952]

Carrasco M, Penpeci-Talgar C. Attention affects orientation discrimination of Gabor patches of different frequencies. Investigative Ophthalmology and Visual Sciences (Suppl). 1999; 40:806.

Carrasco M, Penpeci C. Covert attention improves orientation discrimination across the contrast sensitivity function. Perception (Suppl). 1999; 28:57A.

Carrasco M, Yeshurun Y. The contribution of covert attention to the set-size and eccentricity effects in visual search. Journal of Experimental Psychology: Human Perception and Performance. 1998; 24(2):673–692. [PubMed: 9554103]

Cohn TE, Lasley DJ. Detectability of a luminance increment: effect of spatial uncertainty. Journal of the Optical Society of America. 1974; 64:1715–1719. [PubMed: 4443844]

Davis ET, Kramer P, Graham N. Uncertainty about spatial frequency, spatial position, or contrast of visual patterns. Perception & Psychophysics. 1983; 33(1):20–28. [PubMed: 6844089]

Downing CJ. Expectancy and visual-spatial attention: effects on perceptual quality. Journal of Experimental Psychology: Human Perception and Performance. 1988; 14:188–202. [PubMed: 2967876]

Eckstein MP. The lower efficiency for conjunctions is due to noise and not serial attentional processing. Psychological Science. 1998; 9:111–118.

Eckstein MP, Whiting JS. Visual signal detection in structured backgrounds: I. Effect of number of possible spatial locations and signal contrast. Journal of the Optical Society of America A. 1996; 9:1777–1787.

Eckstein MP, Beutter BR, Bartroff L, Stone LS. Guided search vs. signal detection theory in target localization tasks. Investigative Ophthalmology & Visual Science (Suppl). 1999; 40:1836.

Enns JT, Di Lollo V. Object substitution: a new form of masking in unattended visual locations. Psychological Science. 1997; 8(2):135–139.

Foley JM, Schwartz W. Spatial attention: effect of position uncertainty and number of distractor patterns on the threshold-versus-contrast function for contrast discrimination. Journal of the Optical Society of America. 1998; 15(5):1036–1047.

Furchner CS, Thomas JP, Campbell FW. Detection and discrimination of simple and complex patterns at low spatial frequencies. Vision Research. 1977; 17:827–836. [PubMed: 898688]

Graham, N. Visual pattern analyzers. New York: Oxford University Press; 1989.

NIH-PA Author Manuscript

NIH-PA Author Manuscript


Graham, N.; Kramer, P.; Haber, N. Attending to the spatial frequency and spatial position of near-threshold visual patterns. In: Posner, MI.; Marin, OS., editors. Attention and performance XI. Hillsdale, NJ: Erlbaum; 1985.

Henderson JM. Spatial precues affect target discrimination in the absence of visual noise. Journal of Experimental Psychology: Human Perception & Performance. 1996; 22(3):780–787. [PubMed: 8666963]

Jonides, J. Voluntary vs. automatic control over the mind's eye's movement. In: Long, JB.; Baddeley, AD., editors. Attention and performance IX. Hillsdale, NJ: Erlbaum; 1981. p. 187-204.

Kinchla, RA. The measurement of attention. In: Nikerson, RS., editor. Attention and performance IX. Hillsdale, NJ: Erlbaum; 1980.

Kinchla RA. Attention. Annual Review of Psychology. 1992; 43:711–742.

King-Smith PE, Grigsby SS, Vingrys AJ, Benes SC, Supowit A. Efficiency and unbiased modifications of the QUEST threshold method: theory, simulations, experimental evaluation and practical implementation. Vision Research. 1994; 34:885–912. [PubMed: 8160402]

Lee DK, Itti C, Koch C, Braun J. Attention activates winner-take-all competition among visual filters. Nature Neuro-science. 1999; 2(4):375–381.

Lee DK, Koch C, Braun J. Spatial vision thresholds in the near absence of attention. Vision Research. 1997; 37(17):2409–2418. [PubMed: 9381676]

Lu Z, Dosher BA. External noise distinguishes attention mechanisms. Vision Research. 1998; 38:1183–1198. [PubMed: 9666987]

Luck SJ, Hillyard SA, Mouloua M, Woldorff MG, Clark VP, Hawkins HL. Effects of spatial cuing on luminance detectability: psychophysical and electrophysiological evidence for early selection. Journal of Experimental Psychology: Human Perception and Performance. 1996; 20(4):887–904. [PubMed: 8083642]

Mayfrank, L.; Kimmig, H.; Fischer, B. The role of attention in the preparation of visually guided saccadic eye movements in man. In: O'Regan, JK.; Levy-Schoen, BA., editors. Eye movements: from physiology to cognition. New York: North-Holland; 1987. p. 37-45.

Morgan MJ, Ward RM, Castet E. Visual search for a tilted target: tests of spatial uncertainty models. The Quarterly Journal of Experimental Psychology. 1998; 51A(2):347–370. [PubMed: 9621843]

Müller MM, Picton TW, Valdes-Sosa P, Riera J, Teder-Sälejärvi WA, Hillyard SA. Effects of spatial attention on the steady-state visual evoked potential in the 20–28 Hz range. Cognitive Brain Research. 1998; 6:249–261. [PubMed: 9593922]

Nachmias J. Effect of exposure duration on visual contrast sensitivity with square wave gratings. Journal of the Optical Society of America A. 1967; 57(3):421–427.

Nachmias J, Sansbury RV. Grating contrast: discrimination may be better than detection. Vision Research. 1974; 14:1039–1042. [PubMed: 4432385]

Nachmias J, Weber A. Discrimination of simple and complex gratings. Vision Research. 1975; 15:217–223. [PubMed: 1129978]

Nakayama K, Mackeben M. Sustained and transient components of focal visual attention. Vision Research. 1989; 29:1631–1646. [PubMed: 2635486]

Olzak LA, Thomas JP. Gratings: why frequency discrimination is sometimes better than detection. Journal of the Optical Society of America. 1981; 71:64–70. [PubMed: 7218069]

Palmer J. Set-size effects in visual search: the effect of attention is independent of the stimulus for simple tasks. Vision Research. 1994; 34:1703–1721. [PubMed: 7941377]

Pelli DG. Uncertainty explains many aspects of visual contrast detection and discrimination. Journal of the Optical Society of America A. 1985; 2:1508–1530.

Pelli DG. The videotoolbox software for visual psychophysics: transforming numbers into movies. Spatial Vision. 1997; 10:437–442. [PubMed: 9176953]

Pelli DG, Zhang L. Accurate control of contrast on microcomputer displays. Vision Research. 1991; 31:1337–1350. [PubMed: 1891822]

Posner MI. Orienting of attention. Quarterly Journal of Experimental Psychology. 1980; 32:3–25. [PubMed: 7367577]

Robson JG, Graham N. Probability summation and regional variation in contrast sensitivity across the visual field. Vision Research. 1981; 21:409–418. [PubMed: 7269319]

Shaw, ML. Identifying attentional and decision making components in information processing. In: Nickerson, RS., editor. Attention and performance VIII. Hillsdale, NJ: Erlbaum; 1980. p. 277-296.

Shaw, ML. Division of attention among spatial locations: a fundamental difference between detection of letters and detection of luminance. In: Bouma, H.; DG, editors. Attention and performance X. Hillsdale, NJ: Erlbaum; 1984. p. 109-120.

Shiu L, Pashler H. Negligible effect of spatial precuing on identification of single digits. Journal of Experimental Psychology: Human Perception and Performance. 1994; 20(5):1037–1054.

Shiu L, Pashler H. Spatial attention and vernier acuity. Vision Research. 1995; 35:337–343. [PubMed: 7892729]

Smith PL. Attention and luminance detection: effects of cues, masks, and pedestals. Journal of Experimental Psychology: Human Perception and Performance. in press.

Solomon JA, Lavie N, Morgan MJ. Contrast discrimination function: Spatial cuing effects. Journal of the Optical Society of America. 1997; 14(9):2443–2448. [PubMed: 9291612]

Sperling, G.; Dosher, BA. Strategy and optimization in human information processing. In: Boff, KR.; Kaufman, L.; Thomas, JP., editors. Handbook of perception and human performance. Vol. 1. New York: Wiley; 1986. p. 1-65.

Swensson RG, Judy PF. Detection of noisy visual targets: models for the effects of spatial uncertainty and signal to noise ratio. Perception and Psychophysics. 1981; 29:521–534. [PubMed: 7279581]

Thomas JP, Gille J. Band widths of orientation channels in human vision. Journal of the Optical Society of America. 1979; 69(5):652–660. [PubMed: 479968]

Thomas JP, Shimamura KK. Inhibitory interaction between visual pathways tuned to different orientations. Vision Research. 1975; 15:1373–1380. [PubMed: 1210021]

Watson AB, Pelli DG. QUEST: a Bayesian adaptive psychometric method. Perception & Psychophysics. 1983; 33:113–120. [PubMed: 6844102]

Watson AB, Robson JG. Discrimination at threshold: labelled detectors in human vision. Vision Research. 1981; 21:1115–1122. [PubMed: 7314490]

Yeshurun Y, Carrasco M. Attention improves or impairs visual performance by enhancing spatial resolution. Nature. 1998; 396(6706):72–75. [PubMed: 9817201]

Yeshurun Y, Carrasco M. Spatial attention improves performance in spatial resolution tasks. Vision Research. 1999; 39(2):293–305. [PubMed: 10326137]

## Appendix A. Mathematical expressions for performance prediction

The observer is monitoring two filters: the vertical and horizontal tuned filters. For the trials where a vertical target is displayed there are two types of responses to each of the two filters: (a) the vertical filter to the vertical Gabor target; (b) the vertical filter to the blank spaces; (c) the horizontal filter to the vertical Gabor target; and (d) the horizontal filter to the blank spaces. We denote the response of a filter to a given stimulus (Gabor or blank) with two subscripts (the first one referring to the filter and the second one to the stimulus). For example $f_{v,v}(x)$ is the response of the vertically tuned filter to the vertical Gabor. With this notation for the trial where the vertical Gabor is the target we have four types of responses: $f_{v,v}(x)$; $f_{h,v}(x)$; $f_{v,b}(x)$; $f_{h,b}(x)$ where the subscript b refers to the blank spaces. The responses of all filters are assumed to be Gaussian. The response of the vertical filter that matches the vertical orientation of the target is assumed to have a $d'_{v,v}$ response mean. The response of the horizontal filter to the vertically oriented target is assumed to have a mean $d'_{v,h}$ and the response of both filters to blank spaces are assumed to have 0 mean. The responses are therefore given by:

$$f_{\mathrm{v,v}}(x)=g(x-d'_{\mathrm{v,v}}),\ f_{\mathrm{h,v}}(x)=g(x-d'_{\mathrm{v,h}}),\ f_{\mathrm{v,b}}(x)=f_{\mathrm{h,b}}(x)=g(x) \quad \text{(A1)}$$

where the $g(x)$ is the Gaussian probability function given by:

$$g(x)=1/\sqrt{2\pi}\exp(-x^2/2)$$

The observer is then correct if the response of any of the vertical tuned filters takes the maximum value. The probability that the observer is correct is the sum of two probabilities: (1) the probability that the vertical filter responding to the Gabor target takes a value $x$ while the horizontal filter response to the Gabor target and the horizontal and vertical filter responses to the blanks and the additional uncertainty locations take a value less than $x$; and (2) the probability that any one of the vertical filters responding to the blanks or additional uncertainty locations take the maximum value:

$$\begin{aligned}Pc=\int_{-\infty}^{+\infty}&+g_{\mathrm{v}}(x-d'_{\mathrm{v,v}})G_{\mathrm{h}}(x-d'_{\mathrm{h,v}})G_{\mathrm{v}}(x)^{(UM+M-1)}\\&\times G_{\mathrm{h}}(x)^{(UM+M-1)}\\&+(UM+M-1)(g_{\mathrm{v}}(x)G_{\mathrm{v}}(x)^{(UM+M-2)}G_{\mathrm{h}}(x)^{(UM+M-1)}\\&\times G_{\mathrm{v}}(x-d'_{\mathrm{v,v}})G_{\mathrm{h}}(x-d'_{h,v})\,\mathrm{d}x\end{aligned} \quad \text{(A2)}$$

Eq. (A2) simplifies to:

$$\begin{aligned}Pc=\int_{-x}^{+x}&[g_{\mathrm{v}}(xd'_{\mathrm{v,v}})G(x)^{2(UM+M-1)}\\&+(UM+M-1)g_{\mathrm{v}}(x)G(x)^{2(UM+M)-3}G_{\mathrm{v}}(x-d'_{\mathrm{v,v}})]\\&\times G_{\mathrm{h}}(x-d'_{h,v})\,\mathrm{d}x\end{aligned} \quad \text{(A3)}$$

where $M$ is the number of monitored locations, and $U$ is the intrinsic uncertainty number corresponding to the number of additional irrelevant statistically independent decision variables per location monitored by the observer.

## A.1. Neutral condition versus peripheral condition

In the neutral condition where the cue did not give any information about target location we set the number of possible target locations ($M$) to 8. In the peripheral cue condition where the cue was 100% of the times indicative of the target location, the model assumed that the observer can perfectly use this information and therefore the model used an $M$ value of 1.

## A.2. Fitting the models to the data

For each condition, the data from the QUEST adaptive procedure resulted in different number of trials at different contrast levels. For each observer and condition (spatial frequency) the percent correct versus contrast data points were simultaneously fit to the peripheral and neutral cue conditions with Eq. (A3) ($M$=8 for neutral cue and $M$=1 for the peripheral cue). The index of detectability was assumed to be related to the contrast by a proportionality constant: $d'_{\mathrm{v,v}}=k_{\mathrm{v,v}}c$ and $d'_{\mathrm{v,h}}=k_{\mathrm{v,h}}c$. In addition, the uncertainty number ($U$) was assumed to be the same for the two conditions (peripheral and neutral). There were therefore three fitting parameters: $k_{\mathrm{v,v}}$, $k_{\mathrm{v,h}}$ and $U$. The fit was done using a maximum likelihood criteria. From the best-fit psychometric function a contrast threshold for the experimental performance criteria was then obtained. The contrast thresholds obtained for the model could then be compared to those obtained for the human observers by fitting the psychometric data for each cue condition (neutral versus peripheral) separately using the QUEST algorithm.



NIH-PA Author Manuscript

NIH-PA Author Manuscript

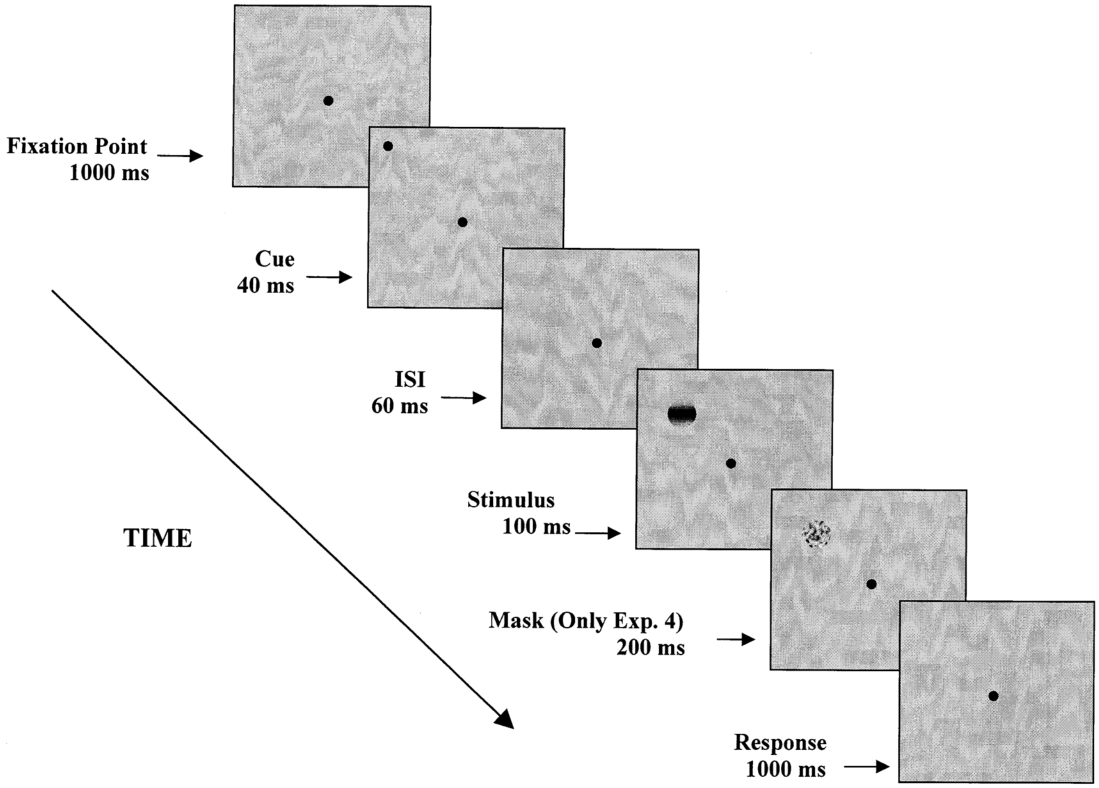


**Fig. 1.**

A schematic representation of a trial sequence. In half the blocks, the target was preceded by a peripheral cue (as shown here) and the rest of the blocks were preceded by a neutral cue (a circle in the center of the display; not shown here). In Experiments 1, 2, and 3, no local post-mask appeared; in Experiment 4, a local post-mask appeared.

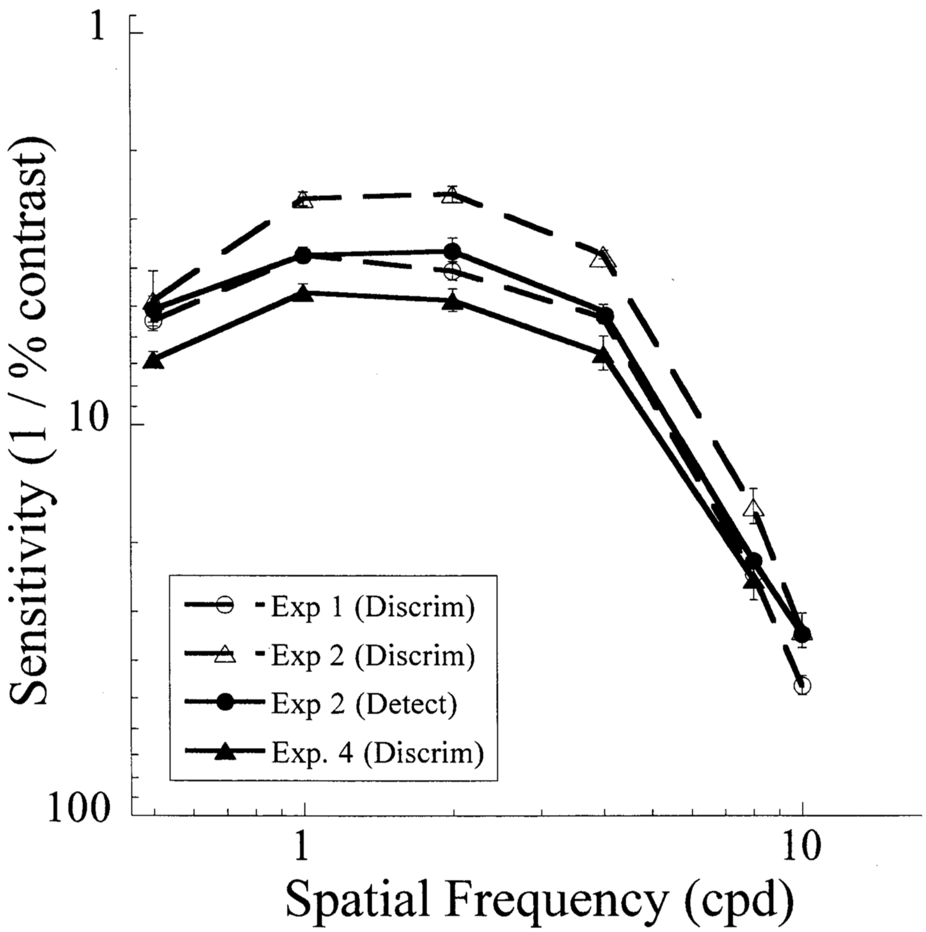


**Fig. 2.**

Contrast sensitivity as a function of spatial frequency in the neutral condition. The functions depict the average of observers sensitivities in (a) Experiment 1 (discrimination task, *n*=6); (b) Experiment 2a (discrimination task, *n*=5); (c) Experiment 2b (detection task, *n*=3); and (d) Experiment 4 (discrimination, *n*=6).

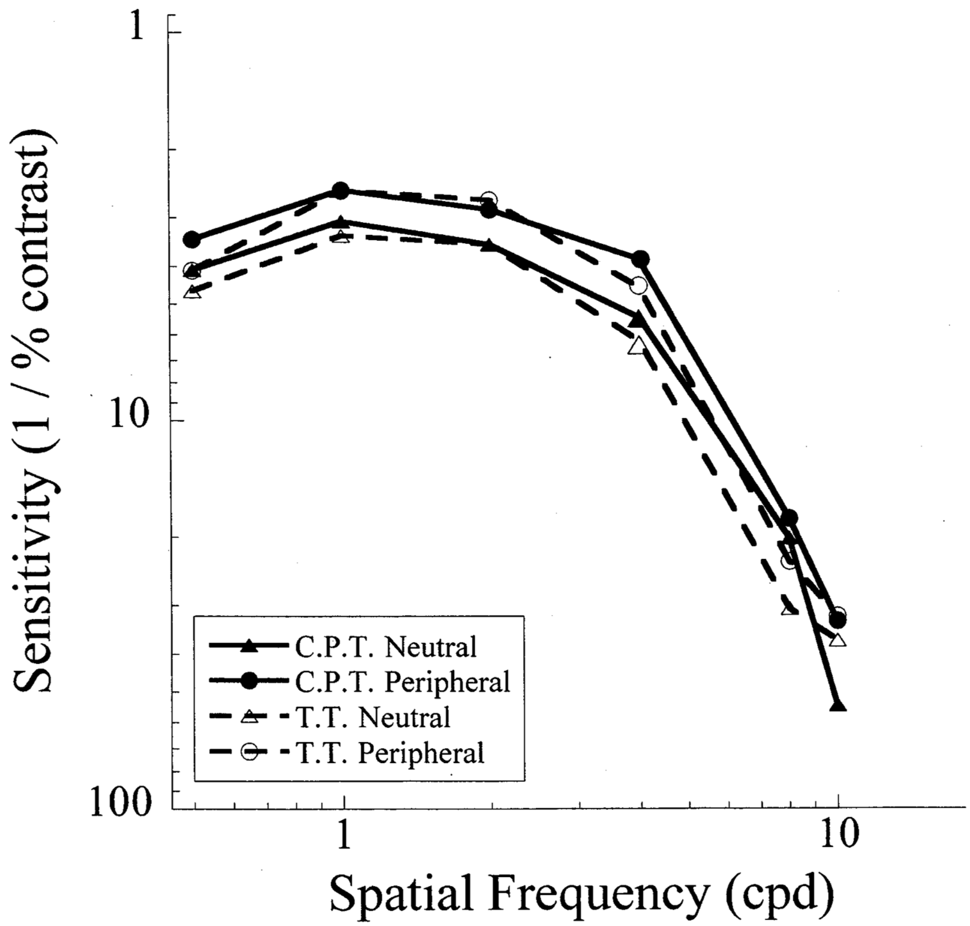


**Fig. 3.**
Contrast sensitivity as a function of spatial frequency in both neutral and peripheral conditions for two observers in Experiment 1.

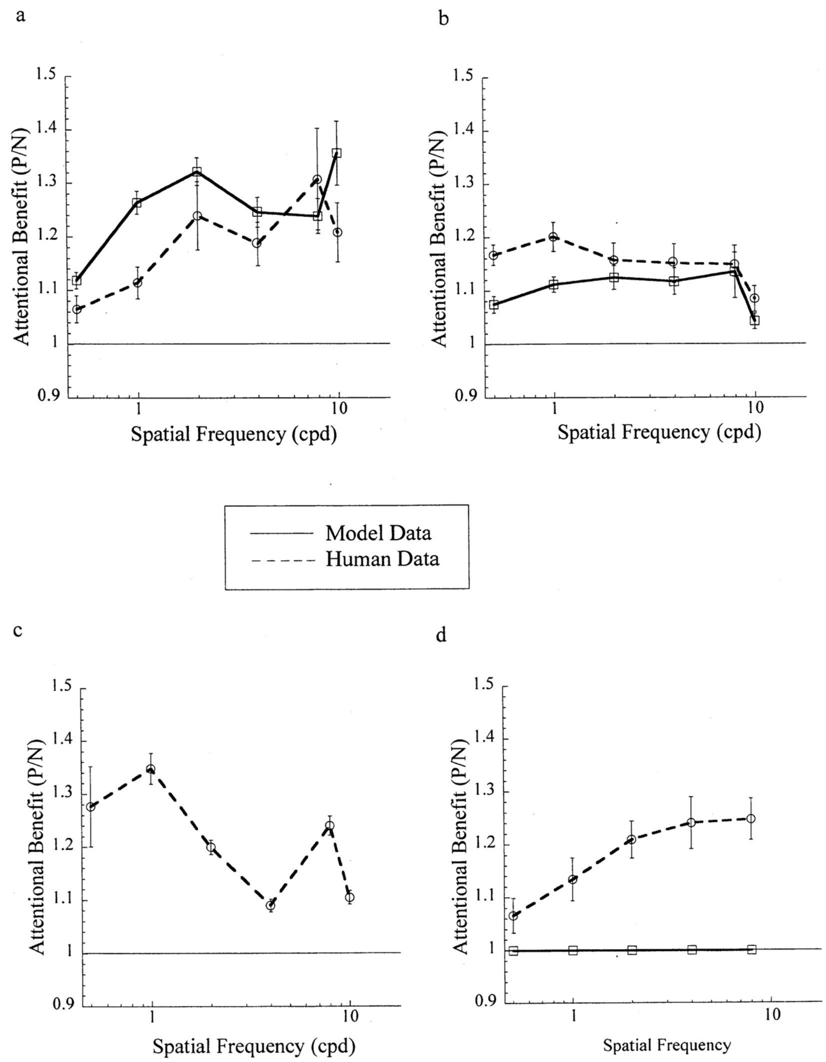


**Fig. 4.**

To quantify the attentional effect on contrast sensitivity, we plotted the ratio of contrast sensitivity in the peripheral cued condition to the neutral cued condition (*P*/*N*). Values above 1 illustrate an attentional benefit. The functions depict both the averages of observers sensitivity ratios (dotted line) as well as those predicted by the SDT model (solid line) under the same conditions, for (a) Experiment 1 (discrimination task at 82% correct); (b) Experiment 2a (discrimination task at 90% correct); (c) Experiment 2b (detection task at 90% correct); (d) Experiment 4 (discrimination task with local post-mask at 82% correct. The SDT model lies along the line corresponding to a ratio of 1).

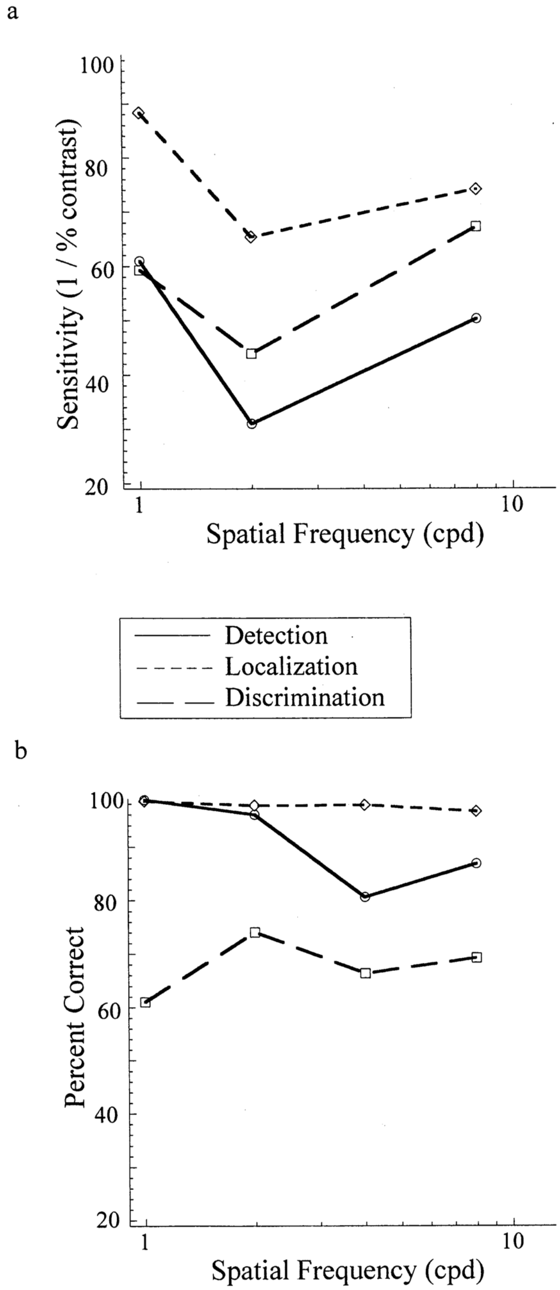


**Fig. 5.**
Average percent correct (corrected for guessing) for the detection, localization, and discrimination tasks for (a) Experiment 3a (vertical versus horizontal stimuli; $n$=2); and (b) Experiment 3b (tilted stimuli; $n$=4).

NIH-PA Author Manuscript

NIH-PA Author Manuscript

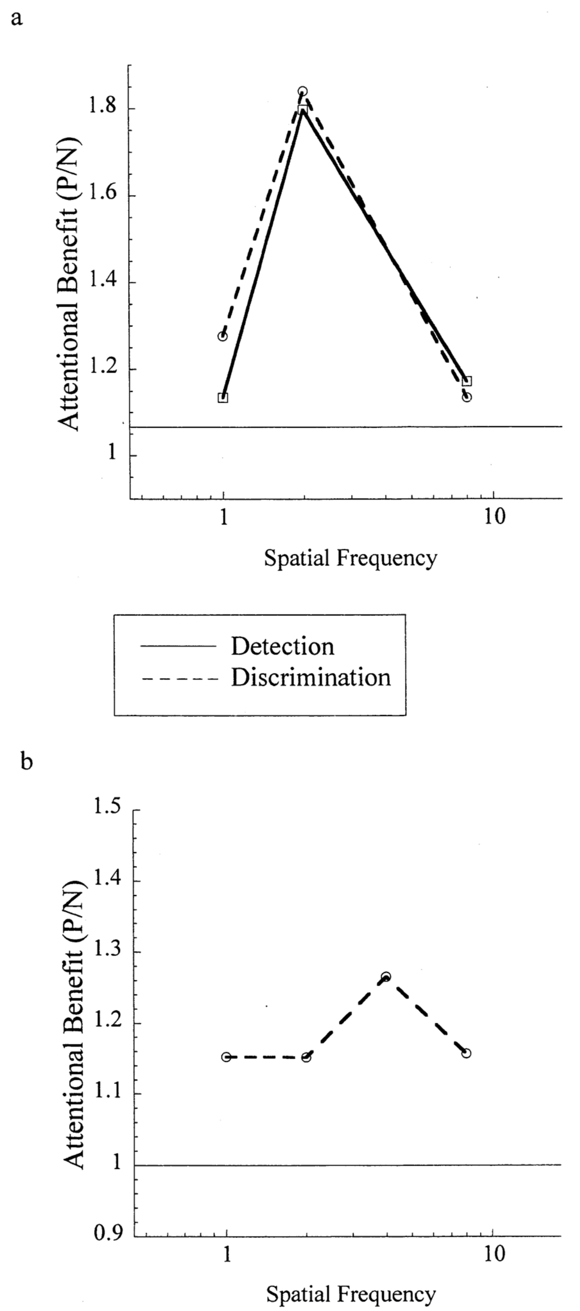


**Fig. 6.**

To quantify the attentional effect on contrast sensitivity, we plotted the ratio of percent correct in the peripheral cued condition to the neutral cued condition (*P*/*N*). Values above 1 illustrate an attentional benefit. The functions depict both the averages of observers ratios for (a) Experiment 3a (vertical versus horizontal stimuli; *n*=2); and (b) Experiment 3b (tilted stimuli; *n*=4).

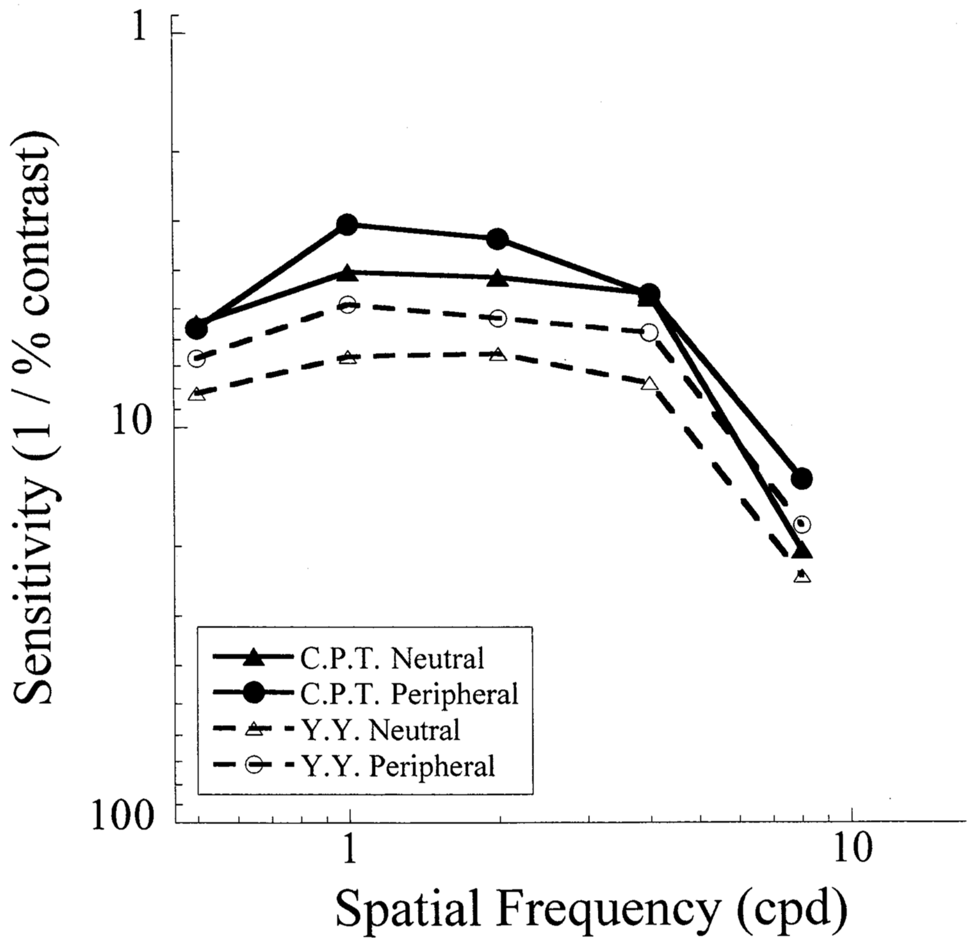


**Fig. 7.**
Contrast sensitivity as a function of spatial frequency in both neutral and peripheral conditions for two observers in Experiment 4.