

# Covert attention increases spatial resolution with or without masks: Support for signal enhancement

**Marisa Carrasco**

Psychology & Center for Neural Science,  
New York University, New York, NY, USA



**Patrick E. Williams**

Center for Neural Science,  
New York University, New York, NY, USA



**Yaffa Yeshurun**

Psychology, University of Haifa, Haifa, Israel



Visual attention can increase spatial resolution even when it leads to a decrease in performance. Whether this effect is mediated by reduction of external noise or by signal enhancement is an unsettled question. Although we previously demonstrated that attention can improve speed and accuracy in an acuity task, those experiments made use of a local postmask, which could be considered a source of external noise. In this work, a peripheral cue improved observers' abilities to indicate which side of a Landolt-square target had a gap whether or not a local postmask was used and with both central- and spread-neutral cues. In addition, we documented the presence of visual field inhomogeneities in a resolution task. Given that these experiments presented the target alone with no external noise added (i.e., without distracters or masks), our results indicate that transient attention enhanced the quality of the stimulus representation. Furthermore, because performance in the Landolt-square task indexes resolution, this attentional benefit indicates that transient attention can produce signal enhancement through finer spatial resolution.

**Keywords:** covert attention, masking, signal enhancement, spatial resolution

## Introduction

Visual attention allows us to select a certain aspect of a visual scene and grant it priority in processing. Spatial covert attention is the selective processing of visual information at a given location in the absence of eye movements to that location (e.g., Posner, 1980). Covert attention can be either voluntarily allocated to a given location according to goals (sustained attention) or involuntarily allocated, in a reflexive manner, in response to a cue that appears suddenly in the visual field (transient attention). Several authors have characterized these sustained and transient aspects of attention (e.g., Cheal & Lyon, 1991; Jonides, 1981; Nakayama & Mackeben, 1989).

Studies manipulating observers' covert attention by precueing the location of the relevant item have shown that visual performance is modulated in a variety of visual tasks, such as contrast sensitivity (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lu & Dosher, 1998; Prinzmetal, Amiri, Allen, & Edwards, 1998), acuity (Mackeben & Nakayama, 1993; Shiu & Pashler, 1995; Yeshurun & Carrasco, 1999), texture segmentation (Yeshurun & Carrasco, 1998, 2000), visual search (Carrasco & Yeshurun, 1998; Nakayama & Mackeben, 1989), and letter identification (Juola, Bouwhuis, Cooper, & Warner, 1991; Prinzmetal, Presti, & Posner, 1986). Several explanations have been suggested to account for this modulation.

We have been particularly interested in characterizing the effects of transient attention on early visual processes and have found that attention has the capacity to increase both contrast sensitivity (Carrasco et al., 2000; Carrasco, Talgar, & Cameron, 2001; Cameron, Tai, & Carrasco, 2002) and spatial resolution (Talgar & Carrasco, 2002; Yeshurun & Carrasco, 1998, 1999, 2000). Central to this work is the finding that directing observers' attention to a target location improves their performance in tasks designed specifically to probe spatial resolution, such as indicating which side of Landolt-square targets had a gap (acuity) or the offset direction of vernier targets (hyperacuity; Yeshurun & Carrasco, 1999). We found this attentional effect even when the suprathreshold target appeared alone in the display without distracters and no multiple masks followed the display. Given that these experimental manipulations eliminated all known sources of added external noise as well as spatial uncertainty associated with stimuli at contrast threshold, we concluded that covert attention enhanced the signal through enhancement of spatial resolution (Yeshurun & Carrasco, 1999).

However, Smith (2000) attributed the finding of an attentional effect on Landolt acuity (Yeshurun & Carrasco, 1999) to the presence of a local mask in that experiment. This proposal was based on his finding that attention improves performance in a detection task only in the presence of a local postmask (a mask appearing at

the target location after the target's offset). He proposed that although the local mask acts as a source of external noise by limiting the signal to noise ratio (SNR) of masked locations, it also reduces spatial uncertainty by indicating the location where a target has appeared.

Information about a target (or equivalently, the probability of making a correct response) accrues as some function of time after a target's onset. When the target is not followed by a mask, this information naturally accumulates to some maximal level determined by target parameters (e.g., contrast, eccentricity, and stimulus duration); however, processing may be interrupted before reaching that maximum if a mask is presented quickly enough after target offset (Figure 1a) or if observers are forced to respond quickly. If a mask is used to interrupt processing at a pre-asymptotic level, any performance advantage measured in the attended condition could be the result of attention either speeding the rate of information accrual or of raising its asymptote over the neutral condition (cf., Carrasco & McElree, 2001). However, in the absence of a postmask and time pressure, a performance benefit will be found only if peripheral cueing raises the asymptotic level of performance (Figure 1b). Consequently, removing the local mask allows us to measure the cueing effect at the signal's asymptotic level.

Prominent hypotheses that have been proposed to explain attentional effects include external noise reduction and signal enhancement. The external noise reduction hypothesis maintains that attention diminishes the impact of stimuli that are outside its focus (Baldassi & Burr, 2000; Doshier & Lu, 2000; Morgan, Ward, & Castet, 1998; Palmer, 1994; Prinzmetal et al., 1998; Shiu & Pashler, 1994). Noise-limited models incorporate external noise resulting from distracters and masks, as well as internal noise arising from such sources as spatial and temporal uncertainty of targets and distracters. According to these models, performance decreases as number of distracters and spatial uncertainty increase, because the noise they introduce can be confused with the target signal (e.g., Eckstein, 1998; Foley & Schwartz, 1998; Palmer, 1994).

The signal enhancement hypothesis proposes that attention directly improves the quality of the stimulus representation, either by enhancing contrast or spatial resolution (Carrasco et al., 2000; Lu & Doshier, 1998; Müller et al., 1998; Posner, 1980; Yeshurun & Carrasco, 1999). Recent neurophysiological (Reynolds, Pasternak & Desimone, 2000) and psychophysical (Cameron et al., 2002) studies have shown that attention improves contrast sensitivity by boosting the gain within the dynamic range of the contrast response function. Covert attention can increase contrast sensitivity either via external noise reduction (in the presence of added external noise; Doshier & Lu, 2000) or via signal enhancement (in the absence of added external noise: distracters, global mask, or a local mask<sup>1</sup>; Cameron et al., 2002; Carrasco et al., 2000, 2001). We have shown that

attention can also increase spatial resolution in a texture segmentation task in which the target elements are presented amidst background elements (distracters) (e.g., Talgar & Carrasco, *in press*; Yeshurun & Carrasco, 1998); here we investigated whether attention can enhance spatial resolution via signal enhancement.

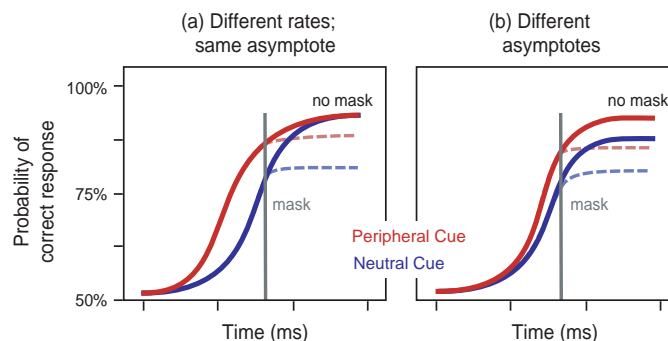


Figure 1. Different cues may cause an observer's information about a target to (a) accumulate at different rates or (b) accumulate to different asymptotes. When the information accrual is interrupted by a postmask, these two cases may be indistinguishable because an advantage of the peripheral cue is measured in each case. To properly assess the cueing effect, performance should be allowed to asymptote in the absence of a mask.

Specifically, we asked whether covert attention could enhance spatial resolution in a visual acuity task even without the local postmask. Here we excluded all added noise sources that we had identified in the previous acuity experiment (i.e., distracters and global masks; Yeshurun & Carrasco, 1999). We also omitted the local postmask to rule out the possibility that a postmask is required to obtain an attentional effect (Smith, 2000) and to allow information to be accrued up to its maximum. In the Yeshurun and Carrasco study, processing could also have been curtailed by pressing observers to respond as quickly as possible. Here we assessed performance at asymptote by measuring accuracy as the primary dependent variable; although we did not press observers to respond fast, we also recorded response time to evaluate the possibility of a speed-accuracy trade-off. In fact, given that speed and accuracy do not always reflect the same perceptual process, the convergence of these measures should be demonstrated empirically rather than taken for granted (Santee & Egeth, 1982).

## Experiment 1

### Methods

#### Observers

Twenty observers participated. Thirteen were undergraduates from the New York University (NYU) Subject Pool and seven were members of the Carrasco lab. All had normal or corrected to normal vision. All

observers except for two of the lab members were naive as to the purpose of the study. All participants signed an informed consent approved by NYU Institutional Review Board.

### Apparatus

The stimuli were presented using VScope™ (Enns & Rensink, 1992), whose response timing has an accuracy of 1 ms (Rensink, 1990). The stimuli appeared on a 21" monitor of a Power Macintosh 7500/100 computer, whose frame duration equaled 13.4 ms and resolution was set to 1024 x 768.

### Stimuli and Design

A white square appeared on a gray background and subtended  $1^\circ \times 1^\circ$  of visual angle (Michelson contrast = .8). On each trial this square was presented in one of 16 possible locations, with its center positioned along the horizontal or vertical meridian at  $1.5^\circ$ ,  $3.5^\circ$ ,  $5.5^\circ$ , or  $7.5^\circ$  from the fixation point. A gap of one of three sizes,  $3.1'$ ,  $3.9'$ , or  $7.8'$ , was embedded equally often in the middle of the square's left or right side (Figure 2). On one half of the total trials, a 100% valid precue appeared  $0.37^\circ$  above the top of the Landolt-square (peripheral cue trials). The precue was a green horizontal bar, subtending  $0.68^\circ$  width x  $0.26^\circ$  height of visual angle. On the other half (central-neutral cue trials), instead of the bar, a green circle, whose diameter subtended  $0.39^\circ$  of visual angle, appeared in the center of the display. For both cues, the left- and right-side gaps occurred equally often. Both cues signaled the target onset but did not indicate on which side of the square the gap would appear. Whereas the peripheral cue indicated the location where the Landolt-square would appear, the neutral cue indicated that the Landolt-square had equal probability of appearing at any location. A small fixation dot was present in the center of the screen throughout the experiment. A plus ( $0.5^\circ$  height x  $0.5^\circ$  width) or a minus ( $0.5^\circ$  width x  $0.1^\circ$  height) sign served as the feedback, and was presented in the center of the screen. In one half of the blocks, a  $1.6^\circ$  wide x  $1.5^\circ$ -high rectangular local postmask composed of randomly oriented lines was presented at the target location.

### Procedure

Each observer participated in two conditions; one included the local postmask and the other did not. The order of these two conditions was counterbalanced across observers. Observers sat 85 cm from the monitor and viewed the display binocularly. They were instructed to fixate on the fixation point throughout the experiment. In this 2-alternative forced-choice (2AFC) task, observers were asked to indicate, as accurately as possible, on which side of the square the gap was located, left or right. Observers were given 192 practice trials before each of the two conditions. Each condition

consisted of 6 blocks of 96 trials, for a total of 1,152 trials per observer. The order of the trials was randomized.

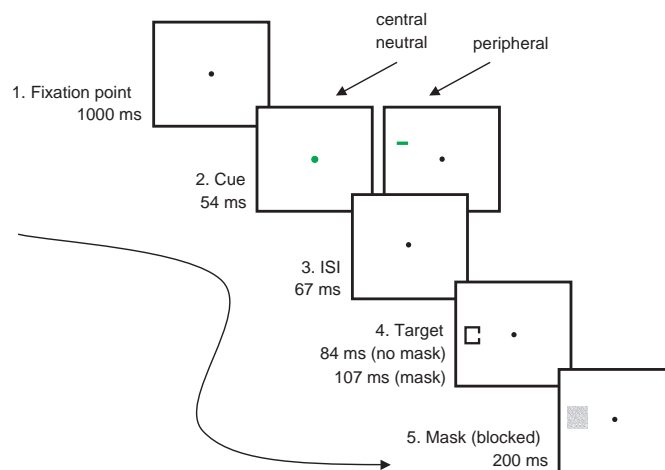


Figure 2. This diagram depicts the sequence of presentation of each experimental trial in both experiments of this study. Note that the mask and the neutral cue shown here were included only in Experiment 1.

Figure 2 shows that in each of the trials the cue appeared for 54 ms, and after an interstimulus interval (ISI) of 67 ms, the Landolt-square was presented for a variable duration. For each observer, performance on the practice trials was used to estimate the target duration that would yield 70%-75% correct performance in each condition, so that ceiling and floor effects would be avoided. The mean target duration was 107 ms for the masked and 84 ms for the unmasked conditions.

The interval between the cue onset and the target onset was 121 ms. This timing maximizes the effect of the peripheral cue, which triggers transient attention to the target location in a reflexive, involuntary manner (Cheal & Lyon, 1991; Jonides, 1981; Nakayama & Mackeben, 1989). Furthermore, the interval between the cue onset and the stimulus offset was brief enough to prevent goal- or target-directed eye movements, as about 250 ms are needed for a saccade to occur (Mayfrank, Kimmig, & Fischer, 1987). The local postmask, when presented, lasted 200 ms (Figure 2).

Observers responded by pressing one of two keys on the computer keyboard to indicate whether the gap was on the right or left. Accuracy was the main dependent variable but response time was also recorded to evaluate speed-accuracy trade-offs. Although observers were not pressed to respond quickly, they had to respond within 1.5 s. Immediately after observers responded, the appropriate feedback sign was presented for 1 s. In addition, at the end of each experimental block, observers received feedback about their error rate for that block.

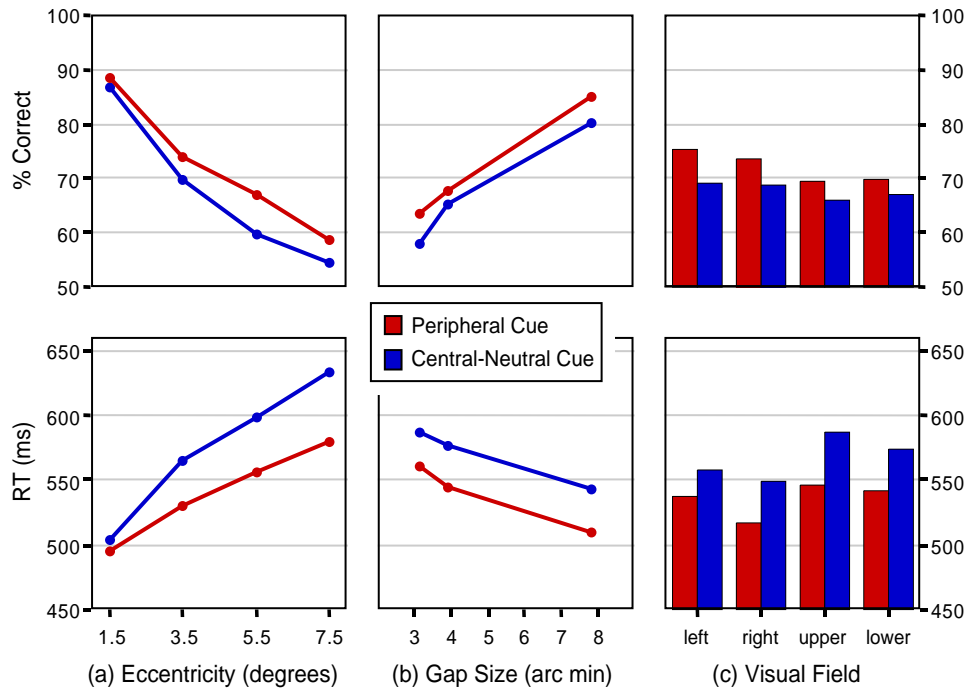


Figure 3. Percentage of trials correctly discriminated (top row) and the associated mean response times (bottom row) for both central-neutral and peripheral trials, as a function of (a) eccentricity, (b) gap size, and (c) visual field. All trials included a local postmask (Experiment 1).

### Results

The main goal of this experiment was to evaluate the cueing effect in the presence and absence of a local postmask. In addition, because performance across the visual field is often inhomogeneous (e.g., Carrasco et al., 2001; Rijdsdijk, Kroon, & van der Wilt, 1980; Rovamo & Virsu, 1979), we also analyzed whether performance in this acuity task would differ across the visual field.

A within-observers four-way ANOVA (cue: neutral vs. peripheral; X eccentricity: 1.5°, 3.5°, 5.5° and 7.5°; X meridian: vertical vs. horizontal; X gap size: 3.1', 3.9', or 7.8') was performed for each condition, masked and unmasked, on the primary dependent variable (accuracy) and on the secondary dependent variable (response time [RT]) data for correct responses.<sup>2</sup> All effects reported below were statistically significant at  $p < .01$ . (The standard errors are plotted in all figures, but are too small to be visible in some).

In the masked condition, all accuracy and speed main effects were significant, with the exception that accuracy was not found to be significantly different between the horizontal and vertical meridians. Discrimination was more accurate and faster in the peripheral- than in the neutral-cue trials (Figure 3). Accuracy decreased and RT increased as target eccentricity grew (Figure 3a) and as gap size shrank (Figure 3b). The main effect of meridian indicated that performance was significantly faster (and more accurate, although not statistically significant) at the horizontal than vertical locations (Figure 3c).

Both accuracy and speed analyses revealed a 3-way interaction of eccentricity X meridian X gap size (Figure 4); the eccentricity effect was more pronounced along the vertical than horizontal meridian, in particular for small

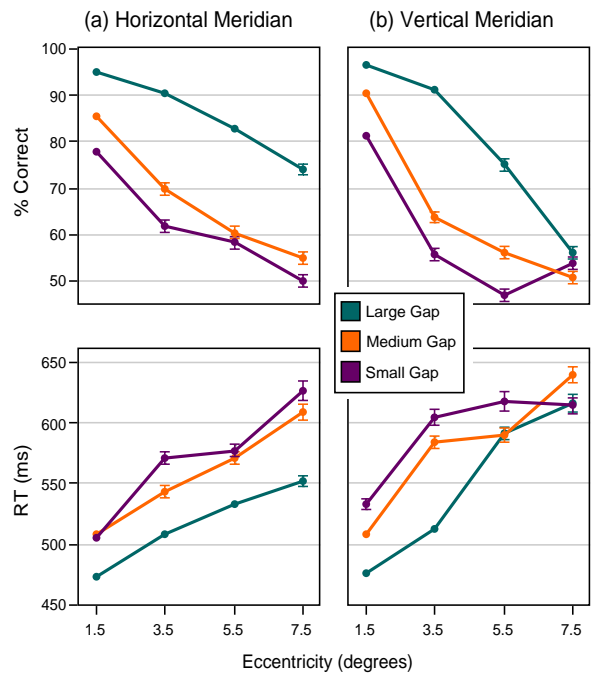


Figure 4. Percentage of trials correctly discriminated (top row) and the associated mean response times (bottom row) for different gap sizes as a function of eccentricity, when the target appeared along the (a) horizontal or (b) vertical meridian. All trials included a local postmask (Experiment 1).

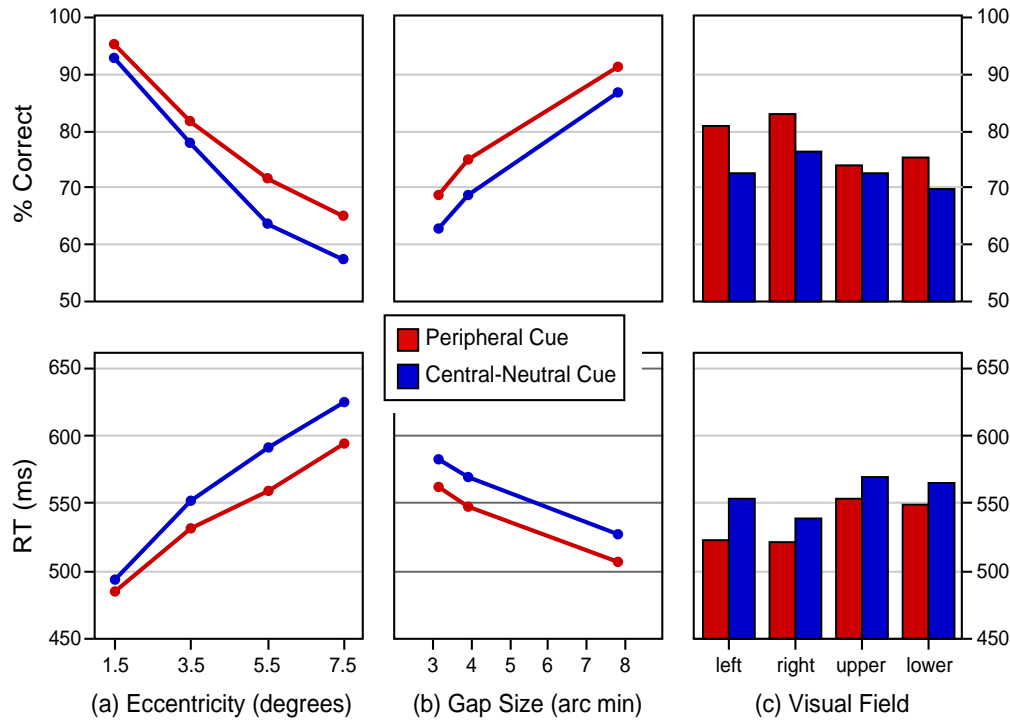


Figure 5. Percentage of trials correctly discriminated (top row) and the associated mean response times (bottom row) for both central-neutral and peripheral trials, as a function of (a) eccentricity; (b) gap size; and (c) visual field. No local postmask was used (Experiment 1).

gap sizes. In sum, the overall pattern of results is consistent with our previous study in which a local postmask was used and RT was the primary dependent variable (Yeshurun & Carrasco, 1999).

The more relevant analysis for this work deals with the nonmasked condition. As in the masked condition, all accuracy and speed main effects were significant (Figure 5). In particular, the peripheral-cue yielded better performance than the neutral-cue trials, as manifested in both higher accuracy and shorter RT: performance deteriorated with increasing target eccentricity (Figure 5a) and decreasing gap size (Figure 5b), and performance was better along the horizontal than along the vertical meridian (Figure 5c).

The speed analyses revealed a significant 3-way interaction of eccentricity  $\times$  meridian  $\times$  gap size, which also emerged as a trend in the accuracy analysis (Figure 6): the eccentricity effect was more pronounced along the vertical than the horizontal meridian, in particular for small gap sizes. In addition, the RT cue  $\times$  eccentricity  $\times$  gap size interaction indicated that the eccentricity effect was more pronounced for the neutral than for the peripheral cue, in particular for small gap sizes.

In short, the masked and nonmasked conditions produced similar patterns of results both in terms of the cueing effects and visual field inhomogeneities. Note that the magnitude of these effects was at least as pronounced without a local postmask as it was with one.

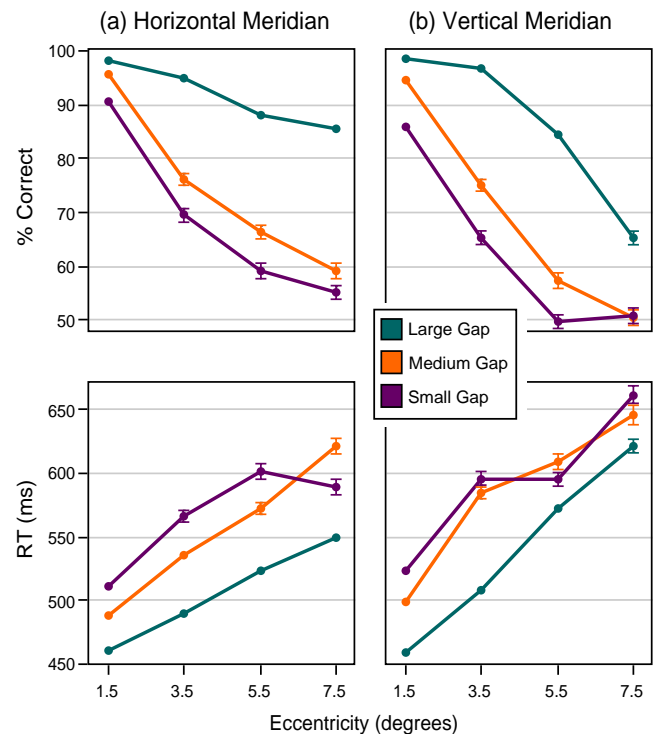


Figure 6. Percentage of trials correctly discriminated (top row) and the associated mean response times (bottom row) for different gap sizes as a function of eccentricity, when the target appeared along the (a) horizontal or (b) vertical meridian. No local postmask was used (Experiment 1).

## Experiment 2

It has been proposed that the central-neutral cue could reduce the extent of the attentional spread (Pashler, 1998). That is, a central-neutral cue may attract attention to its location, away from the more peripheral locations in which the target is presented. Had this been the case in Experiment 1, the condition that was intended to be neutral would have been one in which attention was focused at a nontarget location; thus, the difference in performance would not necessarily reflect a benefit of the peripheral precue, but rather a cost of the central-neutral cue.

To rule out this alternative explanation, in Experiment 2 we modified the neutral cue. The cue was designed to spread observers' attention across the possible target locations. We refer to this as the spread-neutral cue.

## Methods

### Observers

Eighteen undergraduates from the NYU Subject Pool participated as observers. All had normal or corrected to normal vision and were naive as to the purpose of the study.

### Apparatus, stimuli and design

They were identical to those of the nonmask condition of Experiment 1, except for the neutral cue. The neutral cue consisted of four copies of the peripheral precue, simultaneously presented at the centers of each of the four

quadrants  $4.5^\circ$  from both the horizontal and vertical meridians. We refer to this as the spread-neutral cue.

### Procedure

The procedure was identical to that of Experiment 1. A mean target duration of 65 ms was required for individual observers to reach the 70%-75% overall performance level.

## Results

As in the previous experiment, within-observers four-way ANOVAs (cue  $\times$  eccentricity  $\times$  meridian  $\times$  gap size) revealed that all accuracy and speed main effects were significant. As illustrated in Figure 7, discrimination was more accurate and faster in the peripheral- than in the neutral-cue trials. Accuracy decreased and RT increased as target eccentricity grew and as gap size shrank. The main effect of meridian indicated that performance was more accurate and faster at the horizontal than vertical locations.

The accuracy analysis revealed several interactions. Cue and eccentricity interacted because the peripheral cue diminished the eccentricity effect; this finding is also supported by a significant RT interaction.

The cue also interacted with gap size because the peripheral cue relieved the detrimental effect of shrinking gap size on accuracy. In addition, the gap size  $\times$  eccentricity interaction revealed that the detrimental effect of eccentricity on accuracy was more pronounced for smaller gap sizes.

Given that the 3-way interaction of eccentricity  $\times$

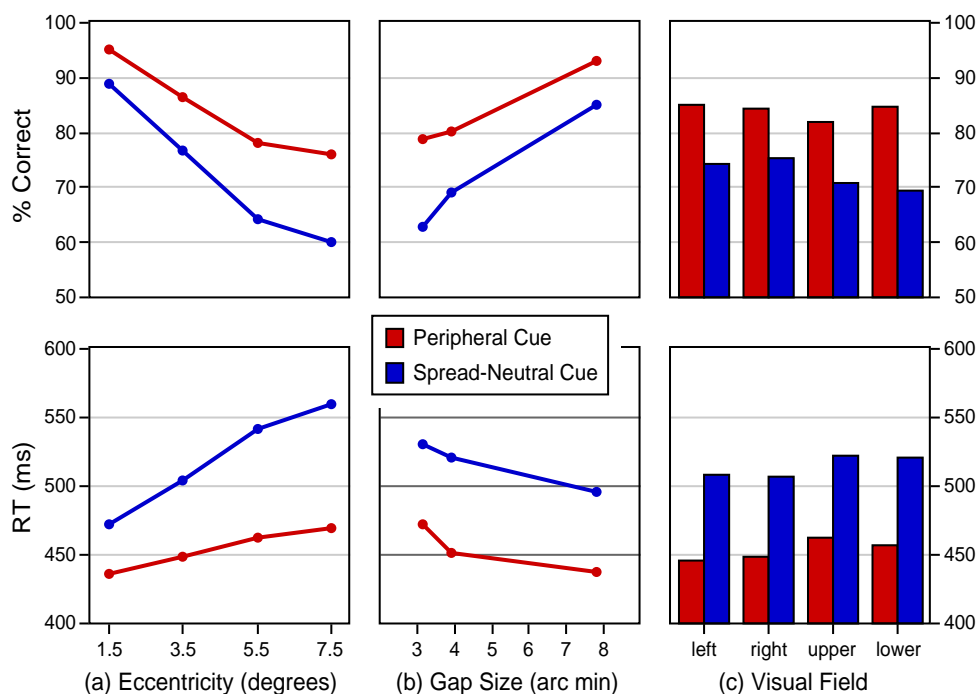


Figure 7. Percentage of trials correctly discriminated (top row) and the associated mean response times (bottom row) for spread-neutral and peripheral trials, as a function of (a) eccentricity, (b) gap size, and (c) visual field (Experiment 2).

gap size  $\times$  meridian was significant in both masked and unmasked conditions of Experiment 1, we chose to explore this interaction in Experiment 2. As can be seen in Figure 8a, the results show a pattern qualitatively consistent (although not statistically significant) with the previous experiment. This preplanned comparison indicated that the eccentricity effect was more pronounced along the vertical than the horizontal meridian, in particular for small gap sizes, in agreement with Experiment 1. In addition, Figure 8b illustrates that performance is more accurate for the lower than the upper region of the vertical meridian, and that the eccentricity effect is more pronounced for the latter.

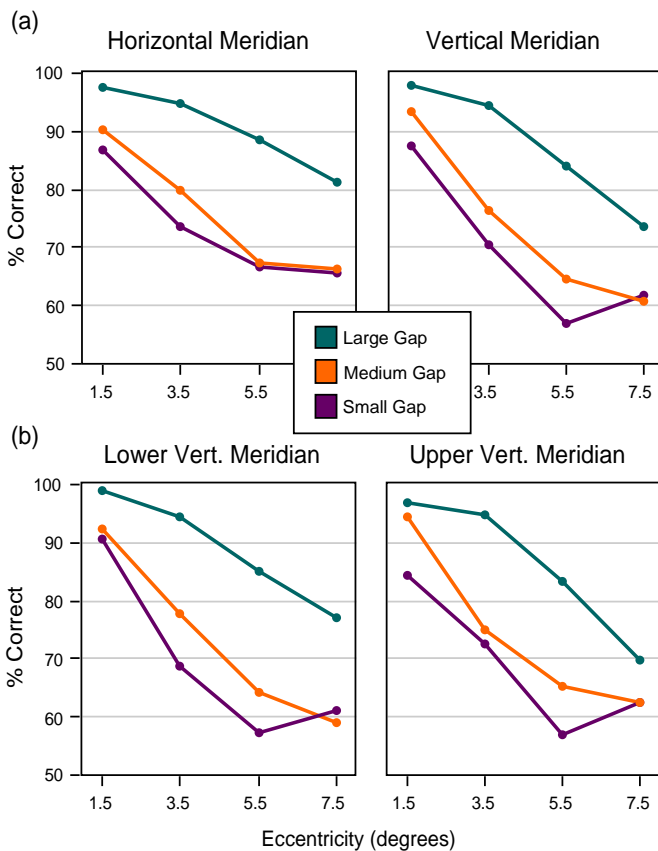


Figure 8. Percentage of trials correctly discriminated for different gap sizes as a function of eccentricity, when the target appeared along the (a) horizontal or vertical meridian or (b) along the lower or upper vertical meridian (Experiment 2).

There was also a 3-way accuracy interaction of cue  $\times$  eccentricity  $\times$  meridian (Figure 9). The peripheral cue minimized the difference in the eccentricity effect between the vertical and the horizontal meridian to the point that the effect of eccentricity was quite similar for both meridians. The speed analysis reflected a consistent pattern.

In sum, the advantage of the peripheral cue over the spread-neutral cue was at least as pronounced as the advantage produced by the peripheral cue over the central-

neutral cue. Furthermore, this experiment revealed the same visual inhomogeneities as Experiment 1.

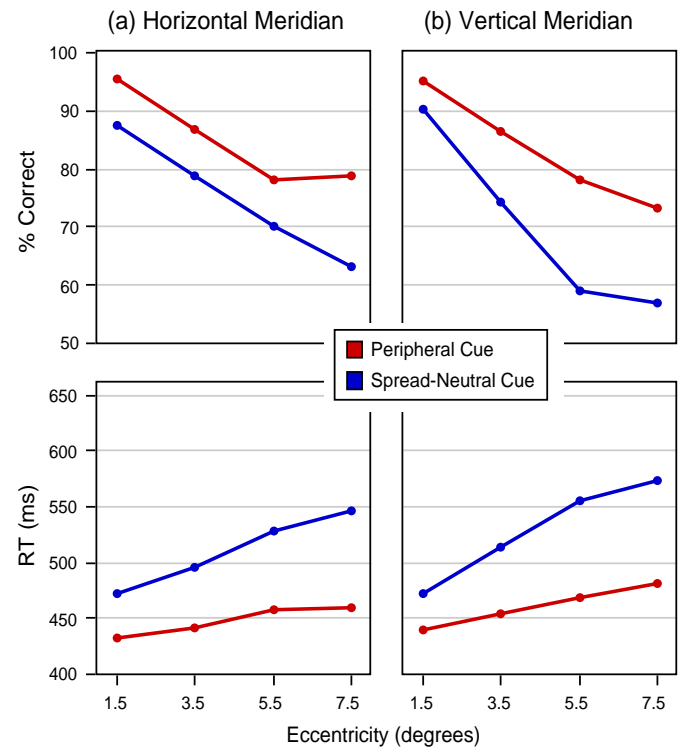


Figure 9. Percentage of trials correctly discriminated (top row) and the associated mean response times (bottom row) for spread-neutral and peripheral trials, as a function of eccentricity, when the target appeared along the (a) horizontal and (b) vertical meridian (Experiment 2).

## Discussion

It is reasonable to assume that attentional modulation may reflect a combination of mechanisms, such as reduction of external noise (Lu, Liu, & Doshier, 2000; Palmer, 1994; Shiu & Pashler, 1994, 1995; Solomon, Lavie, & Morgan, 1997; Sperling & Doshier, 1986) and signal enhancement (e.g., Carrasco et al., 2000; Lu & Doshier, 2000; Lu et al., 2000; Müller et al., 1998). Indeed, by using the external noise plus attention paradigm, in which target and distracter stimuli are embedded in varying amounts of external noise, it has been found that stimulus enhancement may play a prominent role in low-noise displays when the target location is peripherally (transiently) cued, whereas external noise exclusion plays a prominent role in high-noise displays with central (sustained) cues (Doshier & Lu, 2000; Lu & Doshier, 2000).

These hypotheses find support in a growing body of physiological studies that have shown the instantiation of attention at the level of sensory representation. Single-cell recordings have demonstrated that directing attention toward the stimulus can alter responses of V1 neurons

and results in stronger and more selective responses in both V4 and MT/MST neurons (e.g., Desimone & Duncan, 1995; McAdams & Maunsell, 1999; Reynolds & Desimone, 1999; Treue & Martinez-Trujillo, 1999) and fMRI studies have shown attentional modulation in striate and extrastriate visual cortex (e.g., Brefczynski & DeYoe, 1999; Gandhi, Heeger, & Boynton, 1999; Martinez et al., 1999; Somers, Dale, Seiffert, & Tootell, 1999).

## Signal enhancement and spatial resolution

Several studies have attributed attentional facilitation to reduction of external noise, either because a suprathreshold target could be confused with suprathreshold distracters (e.g., Morgan et al., 1998; Palmer, 1994; Shiu & Pashler, 1994, 1995), or because a near-threshold target presented alone could be confused with empty locations (e.g., Cohn & Lasley, 1974; Graham, Kramer, & Haber, 1985). We have shown that covert attention can enhance contrast sensitivity with or without added external noise (Cameron et al. 2002; Carrasco et al., 2000, 2001). However, although our texture segmentation task has shown conclusively that attention enhances spatial resolution (Talgar & Carrasco, *in press*; Yeshurun & Carrasco, 1998, 2000), given that in this task the target elements appeared amidst background elements, these studies were agnostic as to whether the attentional effect was due to external noise reduction, to signal enhancement, or to both. Here we investigated whether covert attention enhances spatial resolution in a visual acuity task. The display consisted of a suprathreshold target, whose high contrast diminishes the spatial uncertainty associated with stimuli at contrast threshold. The display lacked distracters, multiple masks, and local masks, which are sources of added external noise (e.g., Eckstein, 1998; Foley & Schwartz, 1998; Morgan et al., 1998; Palmer, 1994; Shiu & Pashler, 1994, 1995; Smith, 2000; Sperling & Doshier, 1986). Hence, using an acuity task to probe spatial resolution, we show that covert attention can enhance resolution in the absence of external noise, indicating that the attentional effect is due to signal enhancement.

This work suggests that signal enhancement can be accomplished by increasing spatial resolution. In both experiments, we used a Landolt-square, a stimulus specifically designed to assess visual acuity. The peripheral cue improved accuracy and reduced response time across gap size and eccentricity. Moreover, the finding that the attentional benefit improved more as a function of eccentricity indicates that attention helped the most where resolution is poorest. This finding is consistent with our previous studies in visual search (Carrasco & Yeshurun, 1998) and acuity (Yeshurun & Carrasco, 1999) and with the studies showing that in a texture segmentation task, attention enhances resolution even

when performance is hampered by heightened resolution (Talgar & Carrasco, *in press*; Yeshurun & Carrasco, 1998, 2000).

The finding that attention can enhance resolution is in line with other psychophysical studies suggesting that attention allows a finer-scale analysis. For instance, Morgan and his colleagues (Morgan et al., 1998) measured orientation thresholds in a visual search task. They presented a Gabor patch in one of two possible orientations, with or without distracters, and found that when distracters were present, spatially cueing target location reduced orientation thresholds to the level found when the target was presented alone. The authors suggested that focusing attention on the target location reduced thresholds through the operation of a smaller-scaled “stimulus analyzer” (Morgan et al., 1998). Likewise, when Tsai and Shalev (1996) studied the effects of cueing attention on the perceived length of short lines, they found that a briefly presented line is judged to be shorter when its location was known in advance. They suggested that the attended line was perceived as shorter because the processing of an attended stimulus is mediated by smaller “attentional receptive fields” (Tsai & Shalev, 1996).

A possible neural correlate for enhanced spatial resolution is provided by studies showing that attention increases spatial resolution by contracting a neuron’s receptive field around the attended stimulus (e.g., Desimone & Duncan, 1995; Luck, Chelazzi, Hillyard, & Desimone, 1997; Moran & Desimone, 1985; Reynolds & Desimone, 1999; Reynolds, Chelazzi, & Desimone, 1999). The authors proposed that such attentional modulation of sensory processing is accomplished in two stages. Initially, top-down signals bias activity in favor of the neurons representing the relevant location. Then these favored neurons compete with and ultimately suppress other neurons’ responses. This competition may be due to mutual inhibition between cells or between the inputs to the cell, and its outcome could effectively reduce the cell’s receptive field size.

Finally, the idea that attention enhances resolution has inspired a recent neuronal model that implements the role that visual attention plays in object recognition (Deco & Zihl, 2001) and has also been captured in a computational model proposing that interactions among visual spatial filters result in both increased gain and sharpened tuning (Lee, Itti, Koch, & Braun, 1999).

## Does the mask matter?

We examined the cueing effect on target discriminability in two conditions: the target followed by a local mask, or the target alone. The results clearly showed that removing the local mask did not diminish the benefit brought about by the peripheral cue (Figure 3 and Figure 5). The peripheral cue was used to draw attention to the target location in a stimulus-driven,



reflexive fashion (e.g., Cheal & Lyon, 1991; Jonides, 1981; Nakayama & Mackeben, 1989). Thus, given that the cue benefit occurred in the absence of added external noise, the present results support signal enhancement as a central mechanism for attention in these experiments.

The finding that attention enhances sensitivity across the entire contrast sensitivity function in the absence of distracters and masks (Carrasco et al., 2000) provides parallel evidence for signal enhancement. In that study as in this work, the attentional benefit was manifested not only in higher accuracy at the attended location but also in faster RTs. The attentional benefit found in these studies contradict Smith's (2000) hypothesis that once the process runs to completion, without a postmask, the attended and unattended conditions would reach the same asymptote. Although other studies have found that attention can modulate the degree of mask suppression (e.g., Enns & Di Lollo, 1997), the results of Experiment 1 show unequivocally that the mask is not necessary for an attentional benefit; attention benefits performance even when observers respond without time pressure, and information accrual could, in principle, have reached asymptotic levels.

Note that we do not reject the possibility that in addition to improving discriminability, attention may speed information accrual. Indeed, to assess directly whether attention speeds information accrual, we have used the response-signal speed-accuracy tradeoff (SAT) procedure to investigate the effects of precueing on feature and conjunction searches (Carrasco & McElree, 2001). The SAT procedure is used to obtain conjoint measures of discriminability and rate of information accrual. We showed that covert attention does accelerate the rate of information processing, but it also increases the asymptotic level reflecting improved discriminability.

## Does the type of neutral cue matter?

To assess the effect of transient attention in any given task, it is necessary to compare performance when the target follows a peripheral precue and a neutral cue. Several authors have used a central-neutral cue that indicates the target onset but conveys no information regarding the target location (e.g., Carrasco et al., 2000, 2001; Jonides, 1981; Nakayama & Mackeben, 1989; Yeshurun & Carrasco, 1999).

Some authors have suggested that this central-neutral cue may reduce the extent of the attentional spread (e.g., Pashler, 1998). To rule this out, in Experiment 2 we used a neutral cue designed to spread observers' attention across the display. The results clearly indicate that the performance difference between the peripheral cue and the spread-neutral cue was at least as pronounced as the difference between the peripheral cue and the central-neutral cue. The peripheral cue maintained its advantage in accuracy and RTs across all gaps and eccentricities over the spread-neutral cue (Figure 7). Given that there were

no added sources of external noise, this result lends further support to the interpretation that the peripheral cue enhances the stimulus representation.

## Spatial uncertainty

Given that spatial uncertainty is known to affect performance in cueing tasks, we designed both experiments to minimize spatial uncertainty. First, because uncertainty has little effect for suprathreshold stimuli (Pelli, 1985), we intentionally used high-contrast stimuli to preclude the spatial uncertainty created by confusing threshold-level targets with the background. Second, the local mask (as used in Experiment 1) can reduce target location uncertainty (Smith, 2000). Nonetheless, our results indicate that the magnitude of the attentional effect was similar with and without a mask, suggesting that the targets were well localized regardless of the presence of the mask. Similarly, in the absence of added external noise, attention has been shown to improve contrast sensitivity to the same degree, regardless of whether or not the target is followed by a mask (Carrasco et al., 2000).

SDT models provide additional support for the idea that presenting a high-contrast target with no distracters minimizes spatial uncertainty. These models assume that all elements in the display are processed in parallel and they each elicit a noisy independent response. When target-distracter discriminability is low, performance decreases with increasing set size because the likelihood of choosing a distracter increases as the number of nontarget noisy responses monitored by the observer increases. However, performance remains practically constant across set size when discriminability is high (Eckstein, Thomas, Palmer, & Shimozaki, 2000; Verghese, 2001). With regard to our experiments, SDT models would consider the neutral-cue condition as a set size of 16 (1 target and 15 distracter locations), and the peripheral-cue condition as a set size of 1 (because the cue would eliminate possible distracter locations). Because the high-contrast target presented alone would result in a high target-distracter discriminability, the number of empty locations would have a negligible effect on performance. Hence, even though the peripheral cue would reduce set size from 16 to 1 by excluding the empty locations, it could not affect performance substantially.

Other studies also support the finding that the attentional effect goes beyond the reduction of location uncertainty. For instance, although location uncertainty produces a greater degradation at low than at high performance levels (Pelli, 1985), the magnitude of the attentional benefit is similar regardless of the likelihood of observers confusing the target with blank locations. Attention increases sensitivity throughout the psychometric function of contrast sensitivity to the same extent for stimuli that differ in spatial uncertainty (Cameron et al., 2002) or even when localization performance indicates that there is no uncertainty with

regard to the target location (Carrasco et al., 2000).<sup>3</sup> Likewise, with brief displays (100 ms), other authors have found that cueing the target location improves performance more than predicted by a signal-detection model of spatial uncertainty (Morgan et al., 1998). Moreover, a spatial uncertainty model does not account for the effects of the near absence of attention on visual thresholds (Lee et al., 1999). Together, these studies indicate that even though spatial uncertainty can play a role in performance, it cannot be the sole source of the attentional effect reported here.

## Visual field

For contrast sensitivity we have previously reported the existence of a horizontal-vertical anisotropy (HVA) – better performance on the horizontal than vertical meridian – as well as a vertical meridian asymmetry (VMA) – better performance in the lower than upper vertical meridian. We have shown that both of these inhomogeneities become more pronounced with eccentricity, spatial frequency, and number of distracters (Carrasco et al., 2001), and that attention heightens contrast sensitivity similarly at all iso-eccentric locations in the visual field (Cameron et al., 2002; Carrasco et al., 2001).

Here we assessed whether these inhomogeneities are present in a resolution task. The results show that the Landolt-square acuity task used to assess resolution also revealed an HVA. In every condition, accuracy was higher and RTs were faster along the horizontal meridian than along the vertical meridian. In addition, the eccentricity effect was more pronounced along the vertical than horizontal meridian, in particular for the small gap sizes, which tax resolution more than the largest gap size. This acuity task also exhibited a VMA in Experiment 2: performance was more accurate for the lower than the upper vertical meridian, and the eccentricity effect was more pronounced along the upper vertical meridian. This VMA also emerges in a resolution-limited texture segmentation task (Talgar & Carrasco, *in press*). Attention improved performance at all iso-eccentric locations among the vertical and horizontal meridians to a similar degree (Figure 2c, Figure 4c, and Figure 6c). In agreement with our previous studies (Cameron et al., 2002; Carrasco et al., 2001; Talgar & Carrasco, *in press*), we conclude that performance asymmetries result from visual rather than attentional constraints.

The HVA is consistent with previous psychophysical studies (e.g., Carrasco & Frieder, 1997; Mackeben, 1999; Rijdsdijk et al., 1980; Rovamo & Virsu, 1979; Yeshurun & Carrasco, 1999). Anatomical and physiological findings in macaque monkeys provide a possible neural correlate for the visual constraints underlying the HVA. Along the vertical meridian in the retina, there is a lower density of ganglion cells (Curcio & Allen, 1990; Perry & Cowey, 1985) and a faster decline of cone density with increasing distance from the fovea (Curcio, Sloan, Packer,

Hendrickson, & Kalina, 1987) than along the horizontal meridian. Evidence of such an HVA also exists in LGN (Connolly & Van Essen, 1984) and V1 (Tootell, Switkes, Silverman, & Hamilton, 1988; Van Essen, Newsome, & Maunsell, 1984).

The VMA is also consistent with an advantage of the lower visual field reported in a variety of psychophysical tasks (e.g., Previc, 1990; Rijdsdijk et al., 1980; Rubin, Nakayama, & Shapley, 1996). Possible neural correlates for this asymmetry include the greater cone and ganglion cell densities in the lower visual field than in the upper visual field (Perry & Cowey, 1985), and the fact that slightly more area is devoted to the inferior than superior visual field in the LGN (Connolly & Van Essen, 1984) and V1 (Tootell et al., 1988; Van Essen et al., 1984).

## Conclusions

In both experiments, the peripheral cue improved observers' abilities to indicate which side of a Landolt-square target had a gap. This attentional benefit was found with and without the presence of a local mask and with both types of neutral cue, central and spread. Given that these experiments did not include any sources of added external noise (distracters or masks), the signal enhancement model is the only one that can account for this attentional benefit. Furthermore, because we chose a task specifically designed to measure spatial resolution, this attentional benefit indicates that transient attention can enhance the signal through finer spatial resolution. In addition, we documented the presence of both HVA and VMA in a resolution task.

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## Footnotes

<sup>1</sup>Note that some sources of external noise cannot be eliminated (e.g. random photon fluctuations).<sup>2</sup>Observers whose performance did not reach 66% correct response (excluding the farthest eccentricity and the smallest gap size, which were difficult for most observers) in either condition were removed from the entire analysis. Stimulus duration could not be increased to improve performance because presenting the target for longer than 120 ms could allow eye movements between the cue onset and the stimulus offset. Six observers (two lab members) were excluded in Experiment 1 and one observer was

excluded in Experiment 2.<sup>3</sup>A recent paper stating that most of the targets in these studies were low contrast and that observers were uncertain of the target location (Lu, Lesmes & Doshier, 2002) failed to appreciate that when stimulus contrast was high enough for observers to localize the targets perfectly, the cueing benefit did not differ from conditions when the contrast was lower. These studies demonstrate that attention affects performance in the absence of location uncertainty.

## References

- Baldassi, S., & Burr, D. C. (2000). Feature-based integration of orientation signals in visual search. *Vision Research*, *40*, 1293-1300. [PubMed]
- Brefczynski, J. A., & DeYoe, E. A. (1999). A physiological correlate of the 'spotlight' of visual attention. *Nature Neuroscience*, *2*, 370-374. [PubMed]
- Cameron, E. L., Tai, J., & Carrasco, M. (2002). Covert attention affects the psychometric function of contrast sensitivity. *Vision Research*, *42*, 949-967. [PubMed]
- Carrasco, M., & Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Research*, *37*, 63-82. [PubMed]
- Carrasco, M., & McElree B. (2001). Covert attention speeds the accrual of visual information. *Proceedings of the National Academy of Science*, *98*, 5363-5367. [PubMed]
- Carrasco, M., Penpeci-Talgar, C., & Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity along the CSF: Support for signal enhancement. *Vision Research*, *40*, 1203-1215. [PubMed]
- Carrasco, M., Talgar, C., & Cameron, E. L. (2001). Characterizing visual performance fields: Effects of transient covert attention, spatial frequency, eccentricity, task and set size. *Spatial Vision*, *14*, 61-75. [PubMed]
- Carrasco, M., & Yeshurun, Y. (1998). The contribution of covert attention to the set-size and eccentricity effects in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 673-692. [PubMed]
- Cheal, M. L., & Lyon, D. R. (1991). Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology*, *43A*, 859-880.
- Cohn, T. E., & Lasley, D. J. (1974). Detectability of a luminance increment: Effect of spatial uncertainty. *Journal of the Optical Society of America A*, *64*, 1715-1719. [PubMed]
- Connolly, M., & Van Essen, D. (1984). The representation of the visual field in parvocellular and magnocellular layers of the lateral geniculate nucleus in the macaque monkey. *Journal of Comparative Neurology*, *266*, 544-564.
- Curcio, C. A., & Allen, K. A. (1990). Topography of ganglion cells in human retina. *Journal of Comparative Neurology*, *300*, 5-25. [PubMed]
- Curcio, C. A., Sloan, K. R., Packer, O., Hendrickson, A. E., & Kalina, R. E. (1987). Distribution of cones in human and monkey retina: Individual variability and radial asymmetry. *Science*, *236*, 579-582. [PubMed]
- Deco, G., & Zihl, J. (2001). A neurodynamical model of visual attention: Feedback enhancement of spatial resolution in a hierarchical system. *Journal of Computational Neuroscience*, *10*, 231-253. [PubMed]
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193-222. [PubMed]
- Doshier, B. A., & Lu, Z. -L. (2000). Mechanisms of perceptual attention in precuing of location. *Vision Research*, *40*, 1269-1292. [PubMed]
- Eckstein, M. P. (1998). The lower efficiency for conjunctions is due to noise and not serial attentional processing. *Psychological Science* *9*, 111-118.
- Eckstein, M. P., Thomas, J. P., Palmer, J., & Shimozaki, S. S. (2000). A signal detection model predicts the effects of set size on visual search accuracy for feature, conjunction, triple conjunction, and disjunction displays. *Perception & Psychophysics* *62*, 425-451. [PubMed]
- Enns, J. T., & Di Lollo, V. (1997). Object substitution: A new form of masking in unattended visual locations. *Psychological Science*, *8*, 135-139.
- Enns, J. T., & Rensink, R. A. (1992). *VScope (TM) software and manual: Vision testing software for the Macintosh*. Micropsych Software. Vancouver, British Columbia, Canada: University of British Columbia.
- Foley, J. M., & Schwartz, W. (1998). Spatial attention: Effect of position uncertainty and number of distracter patterns on the threshold-vs.-contrast function for contrast discrimination. *Journal of the Optical Society of America A*, *15*, 1036-1047.
- Gandhi, S. P., Heeger, D. J., & Boynton, G. M. (1999). Spatial attention affects brain activity in human primary visual cortex. *Proceedings of the National Academy of Sciences*, *96*, 3314-3319. [PubMed]
- Graham, N., Kramer, P., & Haber, N. (1985). Attending to the spatial frequency and spatial position of near-threshold visual patterns. In M. I. Posner & O. S. Marin (Eds.), *Attention and performance XI* (pp. 269-284). Hillsdale, NJ: Erlbaum.

- Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 187-204). Hillsdale, NJ: Erlbaum.
- Juola, J. F., Bouwhuis, D. G., Cooper, E. E., & Warner C. B. (1991). Control of Attention around the fovea. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 125-141. [PubMed]
- Lee, D. K., Itti, L., Koch, C., & Braun, J. (1999). Attention activates winner-take-all competition among visual filters. *Nature Neuroscience*, *2*, 375-381. [PubMed]
- Lu, Z. -L., & Doshier, B. A. (1998). External noise distinguishes attention mechanisms. *Vision Research*, *38*, 1183-1198. [PubMed]
- Lu, Z. L., & Doshier, B. A. (2000). Spatial attention: Different mechanisms for central and peripheral temporal precues? *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1534-1548. [PubMed]
- Lu, Z. -L., Lesmes, L. A., & Doshier, B. A. (2002). Spatial attention excludes external noise at the target location. *Journal of Vision*, *2*, 312-323, <http://journalofvision.org/2/4/4/>, DOI 10.1167/2.4.4. [Link]
- Lu, Z. -L., Liu, C. Q., & Doshier, B. A. (2000). Attention mechanisms for multi-location first- and second-order motion perception. *Vision Research*, *40*, 173-186. [PubMed]
- Luck, S. J., Chelazzi, L., Hillyard, S. A., & Desimone, R. (1997). Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *Journal of Neurophysiology*, *77*, 24-42. [PubMed]
- McAdams, C. J., & Maunsell, J. H. R. (1999). Effects of attention on orientation-tuning functions of single neurons in macaque cortical area V4. *Journal of Neuroscience*, *19*, 431-441. [PubMed]
- Mackeben, M. (1999). Sustained focal attention and peripheral letter recognition. *Spatial Attention*, *12*, 51-72.
- Mackeben, M., & Nakayama, K. (1993). Express attentional shifts. *Vision Research*, *33*, 85-90. [PubMed]
- Martinez, A., Anllo-Vento, L., Sereno, M. I., Frank, L. R., Buxton, R. B., Dubowitz, D. J., Wong, E. C., Hinrichs, H., Heinze, H. J., & Hillyard, S. A. (1999). Involvement of striate and extrastriate visual cortical areas in spatial attention. *Nature Neuroscience*, *2*, 364-369. [PubMed]
- Mayfrank, L., Kimmig, H., & Fischer, B. (1987). The role of attention in the preparation of visually guided saccadic eye movements in man. In J. K. O'Regan & A. Levy-Schoen (Eds.), *Eye movements: From physiology to cognition* (pp. 37-45). New York, NY: North-Holland.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, *229*, 782-784. [PubMed]
- Morgan, M. J., Ward, R. M., & Castet, E. (1998). Visual search for a tilted target: Tests of spatial uncertainty models. *Quarterly Journal of Experimental Psychology*, *51A*, 343-370.
- Müller, M. M., Picton, T. W., Valdes-Sosa, P., Riera, J., Teder-Sälejärvi, W. A., & Hillyard, S. A. (1998). Effects of spatial selective attention on the steady-state visual evoked potential in the 20-28 Hz range. *Cognitive Brain Research*, *6*, 249-261. [PubMed]
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631-1646. [PubMed]
- Palmer, J. (1994). Set-size effects in visual search: The effect of attention is independent of the stimulus for simple tasks. *Vision Research*, *34*, 1703-1721. [PubMed]
- Pashler, H. E. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.
- Pelli, D. G. (1985). Uncertainty explains many aspects of visual contrast detection and discrimination. *Journal of the Optical Society of America A*, *2*, 1508-1530. [PubMed]
- Perry, V. H., & Cowey, A. (1985). The ganglion cell and cone distribution in the monkey retina: Implications for central magnification factors. *Vision Research*, *25*, 1795-1810. [PubMed]
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3-25. [PubMed]
- Previc, F. H. (1990). Functional specialization in the lower and upper visual fields in humans: Its ecological origins and neurophysiological implications. *Behavioral and Brain Sciences*, *13*, 519-575.
- Prinzmetal, W., Amiri, H., Allen, K., & Edwards, T. (1998). Phenomenology of attention. 1. Color, location, orientation, and spatial frequency. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1-22.
- Prinzmetal, W., Presti, D. E., & Posner, M. I. (1986). Does attention affect visual feature integration? *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 361-369. [PubMed]

- Rensink, R. A. (1990). Toolbox-based routines for Macintosh timing and display. *Behavior Research Methods, Instruments, & Computers*, *22*, 105-117.
- Reynolds, J. H., Chelazzi, L., & Desimone, R. (1999). Competitive mechanisms subserve attention in macaque areas V2 and V4. *Journal of Neuroscience*, *19*, 1736-1753. [PubMed]
- Reynolds, J. H., & Desimone, R. (1999). The role of neural mechanisms of attention in solving the binding problem. *Neuron*, *24*, 19-29. [PubMed]
- Reynolds, J. H., Pasternak, T., & Desimone, R. (2000). Attention increases sensitivity of V4 neurons. *Neuron*, *26*, 703-714. [PubMed]
- Rijsdijk, J. P., Kroon, J. N., & van der Wilt, G. J. (1980). Contrast sensitivity as a function of position on the retina. *Vision Research*, *20*, 235-241. [PubMed]
- Rovamo, J., & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research*, *37*, 495-510.
- Rubin, N., Nakayama, K., & Shapley, R. (1996). Enhanced perception of illusory contours in the lower versus upper visual hemifields. *Science*, *271*, 651-653. [PubMed]
- Santee, J. L., & Egeth, H. E. (1982). Do reaction time and accuracy measure the same aspects of letter recognition? *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 489-501. [PubMed]
- Shiu, L., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1037-1054.
- Shiu, L., & Pashler, H. (1995). Spatial attention and vernier acuity. *Vision Research*, *35*, 337-343. [PubMed]
- Smith, P. L. (2000). Attention and luminance detection: Effects of cues, masks, and pedestals. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1401-1420. [PubMed]
- Solomon, J. A., Lavie, N., & Morgan, M. J. (1997). Contrast discrimination function: Spatial cuing effects. *Journal of the Optical Society of America A*, *14*, 2443-2448. [PubMed]
- Somers, D. C., Dale, A. M., Seiffert, A. E., & Tootell, R. B. H. (1999). Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proceedings of the National Academy of Sciences*, *96*, 1663-1668. [PubMed]
- Sperling, G., & Doshier, B. A. (1986). Strategy and optimization in human information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1* (pp. 1-65). New York, NY: Wiley.
- Talgar, C., & Carrasco, M. (in press). Vertical meridian asymmetry in spatial resolution: Visual and attentional factors. *Psychonomic Bulletin Review*.
- Tootell, R. B. H., Switkes, E., Silverman, M. S., & Hamilton, S. L. (1988). Functional anatomy of macaque striate cortex. II. Retinotopic organization. *Journal of Neuroscience*, *8*, 1531-1568. [PubMed]
- Treue, S., & Martinez-Trujillo, J. C. (1999). Feature-based attention influences motion processing gain in macaque visual cortex. *Nature*, *399*, 575-579. [PubMed]
- Tsal, Y., & Shalev, L. (1996). Inattention magnifies perceived length: The attentional receptive field hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 233-243. [PubMed]
- Van Essen, D. C., Newsome, W. T., & Maunsell, J. H. R. (1984). The visual field representation in striate cortex of the macaque monkey: Asymmetries, anisotropies, and individual variability. *Vision Research*, *24*, 429-448. [PubMed]
- Verghese, P. (2001). Visual search and attention: A signal detection theory approach. *Neuron*, *31*, 523-535. [PubMed]
- Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature*, *396*, 72-75. [PubMed]
- Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Research*, *39*, 293-305. [PubMed]
- Yeshurun, Y., & Carrasco, M. (2000). The locus of attentional effects in texture segmentation. *Nature Neuroscience*, *3*, 622-627. [PubMed]