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Mask-dependent attentional cuing effects in visual signal detection: The psychometric function for contrast

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A spatial-cuing paradigm was used to test the hypothesis of Carrasco, Penpeci-Talgar, and Eckstein (2000) that the mask-dependent cuing effects found in visual signal detection by Smith (2000a) were caused by submaximal activation of the transient-orienting system. Mask-dependent cuing was found with a range of stimulus contrasts with pure peripheral cues and with the mixed central–peripheral cues of Smith (2000a), contrary to the predictions of the submaximal activation hypothesis. The use of a pedestal detection task to control spatial uncertainty showed that the cuing effect was due to signal enhancement. A model of mask-dependent cuing is described, which assumes that attention affects the rate of information accumulation from the display and that masks limit the visual persistence of the stimulus. The model correctly predicts differential mask dependencies in sensitivity for detection and discrimination and the associated patterns of response times.

Strong interactions between spatial attention and visual masking have recently been reported in a number of perceptual tasks. In metacontrast masking and object substitution paradigms, the magnitude of the masking effect varies in strength with attention (Ramachandran & Cobb, 1995; Enns & Di Lollo, 1997; Tata, 2002). In orientation discrimination (Morgan, Ward, & Castet, 1998), character recognition (Giesbrecht & Di Lollo, 1998), and oddball form and motion judgments (Kawahara, Di Lollo, & Enns, 2001), the magnitude of the attentional effects have been found to depend on whether backwardly masked displays are used.

In visual signal detection, the idea that attention enhances the detectability of weak visual stimuli only when they are backwardly masked has provided an explanation for the inconsistent results previously obtained in such studies. One of the enduring questions in the detection literature is whether detection is carried out without attentional involvement or whether it is enhanced by focal attention. The idea that detection differs in its attentional demands from other, more complex forms of perceptual decision is one that goes back to the earliest auditory experiments of Cherry (1953) and to the filter theory of Broadbent (1958). More recently, the same idea has been given expression in the proposals that attention is required only to discriminate between similar stimuli (Duncan & Humphreys, 1989) or to identify stimuli in which multiple features have been conjoined (Treisman & Gelade, 1980).

Although the idea that detection differs qualitatively from other forms of perceptual decision has a long history in the attention literature, the experimental evidence for this has been inconclusive. Whereas some studies have shown that attention has little or no effect on detection sensitivity or effects that could be attributed to the statistical effects of uncertainty reduction alone (Bonnel, Stein, & Bertucci, 1992; Davis, Kramer, & Graham, 1983; Foley & Schwarz, 1998; Graham, Kramer, & Haber, 1985; Lee, Koch, & Braun, 1997; Müller & Findlay, 1987; Palmer, 1994; Palmer, Ames, & Lindsey, 1993; Shaw, 1984), others have shown that detection sensitivity is selectively enhanced for signals at attended locations (Bashinski & Bacharach, 1980; Brawn & Snowden, 2000; Downing, 1988; Hawkins et al., 1990; Luck et al., 1994; Müller & Humphreys, 1991; Smith, 1998). With few exceptions, however, studies that have shown enhanced detection sensitivity for attended stimuli have been performed with backwardly masked displays, whereas those showing no enhancement have been performed without masks (Smith, 2000a, Table 1).

Direct experimental support for the idea that masking is the critical variable that distinguishes among these findings has been provided by recent studies by Smith (2000a) and Smith and Wolfgang (2004). In these studies, the effects of spatial cues on visual signal detection were investigated, using both masked and unmasked stimuli. In both of these studies *mask-dependent cuing effects* were found: When signals were masked by backward pattern masks, detection sensitivity was enhanced

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Table 1
Experimental Manipulations

	Pure Peripheral Cues
Masked	Experiment 1
	1A (1-element central neutral cue)
	1B (3-element peripheral neutral cue)
Unmasked	Experiment 2
	Mixed Central–Peripheral Cues
Masked	Experiment 3
Unmasked	Experiment 4
	Pure Peripheral Cues, No Pedestal
Unmasked	Experiment 5

for signals at attended locations; when no masks were used, sensitivity at attended and unattended locations did not differ.

However, a recent study by Carrasco, Penpeci-Talgar, and Eckstein (2000) has cast doubt on the generality of these findings. In their study, the effects of attention on luminance detection were investigated, using two different spatial-cuing tasks. One was a yes/no task, similar to that used by Smith (2000a), in which observers detected the presence or absence of sinusoidal grating patches presented at cued or uncued locations. The other was a two-alternative forced choice task in which observers discriminated the orientation of orthogonal (horizontal vs. vertical) grating patches. Because contrast thresholds for the detection and discrimination of grating patches become indistinguishable once the angular separation exceeds 20°–30° (Thomas & Gille, 1979), the authors suggested, as Lee et al. (1997) had proposed previously, that this task may be used as a proxy for detection.

Carrasco et al. (2000) found, in both of these tasks, that contrast sensitivity was enhanced for cued, unmasked stimuli. Indeed, they found little difference in the magnitude of the cuing effect in these two tasks and in that obtained in an orientation discrimination task in which stimuli were presented at an angular separation of ±4°. They also found little difference in the magnitude of the cuing effect in masked and unmasked versions of the orthogonal discrimination task. They attributed the differences between their findings and those of Smith (2000a) to differences in the form of the attentional cues and the cue–target asynchronies used in the two studies.

The cues used in Smith's (2000a) study, which combined the features of central and peripheral cues (Jonides, 1981; Müller & Rabbitt, 1989; Posner, 1980), were presented at stimulus onset asynchronies (SOAs) of 150 msec and remained present until the response. The cues used by Carrasco et al. (2000) were pure peripheral cues, which were flashed briefly at the target location at an SOA of 100 msec and then extinguished. Carrasco et al. argued that their cues may have activated the transient-orienting system (Nakayama & Mackeben, 1989) more effectively than did the cues used by Smith (2000a) and, consequently, may have produced a more pronounced attentional effect.

The study by Kawahara et al. (2001) also yielded results that were, in one important respect, different from those of Smith (2000a) and Smith and Wolfgang (2004). In an attentional blink (AB) paradigm, they found mask-dependent attentional effects for both form and motion judgments in a detection task of moderate difficulty. When the detection task was made very difficult, however, they obtained an AB even with unmasked stimuli. This pattern of results differed from that found in a discrimination task using the same stimuli, in which an AB occurred with unmasked stimuli, irrespective of task difficulty. Together, the results of Carrasco et al. (2000) and Kawahara et al. suggest that any conclusions about the relationship between attention and backward masking in detection may need to be qualified, in relation both to how attention is controlled and to the difficulty of the task. Our aim in the experiments reported here was to ascertain whether the mask-dependent cuing effects reported by Smith (2000a) and Smith and Wolfgang (2004) would occur with different forms of attentional cue and at different levels of task difficulty. To this end, we compared the efficacy of the combined central and peripheral cues of Smith (2000a) and the purely peripheral cues of Carrasco et al. (2000).

To investigate the effects of task difficulty, we examined the effects of these two cue types across the entire psychometric function for stimulus contrast. As well as providing us with information about the three-way relationship between attention, masking stimuli, and task difficulty, this procedure avoided the calibration problems involved in attempting to have the task performed at a fixed level of difficulty under masked and unmasked conditions—a feature of Smith's (2000a) study that was criticized by Carrasco et al. (2000). Because the present experiments yielded entire psychometric functions for each condition, the interpretation of results was unaffected by small calibration differences between conditions. Psychometric functions for orientation discrimination were obtained in a later study by Cameron, Tai, and Carrasco (2002) from a task in which stimuli were presented at angular separations of ±4° and ±15°. Our study differed from theirs in that we sought to investigate the effects of masking on the psychometric function in a yes/no detection task. We discuss the relationship between our results and theirs in the General Discussion section.

Signal Enhancement and Uncertainty Reduction

When a weak signal is presented at an unknown location against an otherwise uniform background, attention may benefit performance in either of two main ways. First, it may selectively amplify or enhance signal strength for stimuli occurring at attended locations. Metaphorically speaking, attention may act to "turn up the volume" for selected stimuli. This process is known as *signal enhancement* or *stimulus enhancement* (Lu & Dosher, 1998; Shiu & Pashler, 1994). Selective enhancement in the processing of attended stimuli is a reflection of the limited-capacity nature of the attentional system and is predicted for perceptual decision tasks that cannot be performed preattentively (Henderson, 1996).

Second, attention may act to reduce the impact of noise from surrounding regions of the display on the observer's decision. Implicit in this idea is a distinction between what we term *reducible* and *irreducible* noise. Irreducible noise is inherent in the structure of the stimulus itself and in the way it is processed in the visual system. Such noise imposes fundamental limits on the observer's performance, irrespective of attentional set or prior knowledge of the stimulus identity or location. It may be distinguished from reducible noise, whose level varies with attention and prior knowledge. In tasks in which stimuli are presented at suprathreshold levels of contrast, reducible noise comes primarily from distractor stimuli elsewhere in the display (Lu & Dosher, 1998; Shiu & Pashler, 1994). In tasks in which the stimuli are presented at near-threshold levels of contrast against an otherwise empty background, reducible noise comes primarily from activity in visual mechanisms that encode surrounding nontarget regions of the display. Under these conditions, cuing a particular location may benefit performance because it decreases the likelihood that noise from a nontarget location will trigger a false alarm. Performance benefits that come from reducing an observer's uncertainty about the likely location of a target stimulus are known as *noise reduction*, or *uncertainty reduction*, benefits (Nachmias, 2002; Shiu & Pashler, 1994).[1]

Uncertainty reduction benefits are predicted in any situation in which target stimuli are confusable with their surroundings, even in unlimited-capacity systems (Cohn & Lashley, 1974; Swets, 1984; Tanner, 1961). This means that the occurrence of attention-dependent variations in sensitivity cannot in itself be used to infer anything about the preattentive status of detection. As a result, the main methodological problem in this area has been to try to distinguish signal enhancement effects from uncertainty reduction effects to determine if and when signal enhancement actually occurs.

Two distinct approaches have been developed to deal with this problem. In one, performance on the task is modeled mathematically, using some form of multichannel signal detection theory (SDT) model (e.g., Eckstein, Thomas, Palmer, & Shimozaki, 2000; Foley & Schwarz, 1998; Kinchla, Chen, & Evert, 1995; Lu & Dosher, 1998; Palmer, 1994; Palmer et al., 1993; Shaw, 1982, 1984; Smith, 1998). Such models attempt to specify quantitatively how performance is affected by noise from multiple display locations. Signal enhancement effects are identified in such models as variations in the parameters that describe signal-to-noise ratios (SNRs) at attended and unattended display locations. Signal enhancement may be inferred if a model that assumes that SNRs are higher at attended than at unattended locations provides a better description of the data than does one in which SNRs at attended and unattended locations are equal.

Model-based inferences of this kind have the advantage that they not only provide a characterization of the effects of attention on performance, but also offer insights into other processes involved in carrying out the task. Their disadvantage is that any conclusions that are drawn about the magnitude of attentional effects are necessarily model bound; that is, they rely on the assumed model being the true one.

In the alternative approach, an attempt is made to eliminate or to control for the effects of uncertainty reduction experimentally. To the extent that performance in different experimental conditions is unaffected by differences in uncertainty, any differences in detection sensitivity can plausibly be attributed to signal enhancement. In one version of this approach, devised by Luck et al. (1994), the display contains only a single backwardly masked stimulus, which may occur at either a cued or an uncued location. In this task, the mask does double duty, serving both to limit the detectability of the target and to localize the observer's decision to a single position in the display. This has the effect of decoupling variations in location uncertainty from variations in cuing condition, because the region of the display on which the observer's judgment is based is equally well localized on cued and uncued trials. It is reasonable to assume that judgments made under such conditions will be largely unaffected by noise arising from elsewhere in the display.

To allow masked and unmasked stimuli to be compared in the same experimental paradigm, Smith (2000a) and Smith and Wolfgang (2004) used an extension of Luck et al.'s (1994) single-mask procedure, in which the stimulus to be detected was presented atop a luminance pedestal, rather than directly against a uniform field. The observers' task in these experiments was to detect a single Gabor patch stimulus (a Gaussian vignetted sinusoidal grating) that could occur at either a cued or an uncued location. On signal trials, both the pedestal and the Gabor patch were presented (cf. Figure 1); on noise trials, only the pedestal was presented. In response, observers made a yes/no (patch present/absent) detection judgment.

The logic of this procedure is that the pedestal, like the mask in the single-mask procedure of Luck et al. (1994), is a suprathreshold stimulus, whose location in the display is always clearly visible. It therefore serves the same function as the mask, of localizing the observer's decision to a single position in the display. Using this procedure, Smith (2000a) and Smith and Wolfgang (2004) found that detection sensitivity was enhanced for attended signals only when they were backwardly masked. In contrast, the study of Carrasco et al. (2000), which showed attentional effects even with unmasked signals, presented Gabor patch stimuli directly against a uniform field. We hypothesized that it was this variable, not differences in the kinds of cues used, that was responsible for the differences between the results of Carrasco et al. and those reported by us. We will return to this issue subsequently.

The Pedestal Detection Task

In this article, we report five visual signal detection experiments that were carried out using the pedestal de-

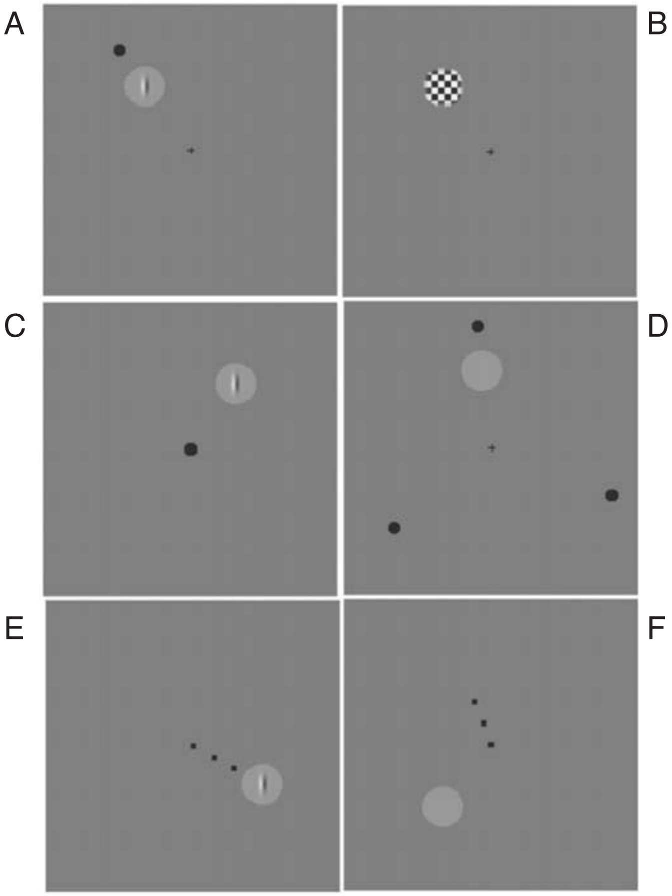

Figure 1. Example stimuli. (A) Signal and peripheral cue (Experiments 1, 2, and 5). (B) Backward mask (Experiments 1A, 1B, and 3). (C) Signal and central neutral cue (Experiments 1A, 2, and 5). (D) Noise and peripheral neutral cue (Experiment 1B). (E) and (F) Cued and miscued signal and noise with mixed central–peripheral cue (Experiments 3 and 4).

tection task of Smith (2000a) and two different kinds of attentional cues: the central–peripheral cues of Smith (2000a) and the pure peripheral cues of Carrasco et al. (2000). Figure 1 shows examples of the cues, stimuli, and backward masks used in these experiments, and Table 1 summarizes the main experimental manipulations. In the experiments, the effects of different cue configurations, backward masks, and the presence or absence of pedestals were investigated.

A further aim of these experiments was to collect receiver operating characteristic (ROC) data for each observer in each experimental condition. Many studies in which the effects of attention on visual signal detection have been investigated (including our own) have used yes/no or two-alternative forced choice tasks and have quantified performance, using d' or an equivalent measure. In contrast, many of the classical experiments in the signal detection literature have been carried out with rating scale tasks, in which a confidence rating was made on each trial and from which an ROC curve could be estimated for each condition. The advantage claimed for ROC analysis in SDT is that it provides information about the relative variances in the underlying noise and signal distributions. These may be used to obtain a more complete picture of the observer's sensitivity than is possible using d' from two-choice tasks (e.g., Green & Swets, 1966; Macmillan & Creelman, 1991). The studies of Smith (2000a) and Smith and Wolfgang (2004) both used d' statistics that were corrected for unequal noise and signal distributions. In this article, we instead used a rating scale task to investigate the ROC space directly.

GENERAL METHOD

Observers

A total of 16 observers participated in the study, including two of the authors (P.S. and A.S.) and 14 paid undergraduate volunteers who were naive as to the purposes of the study. Ages ranged from 18 to 48 years, and all had normal or corrected-to-normal vision.

Five observers were used in each experiment, with the observers serving in from one to three experiments, depending on availability. The observers in Experiments 1, 2, and 5 served in six experimental sessions; the observers in Experiments 3 and 4 served in eight experimental sessions. (The reason for this difference was that the relative frequencies of cued and uncued stimuli were manipulated only in the latter two experiments.) The observers completed at least five practice sessions on the task before data collection began, during which the range of stimulus contrasts for the task was set. Those observers who participated in more than one experiment completed an additional two or three practice and calibration sessions, as required, before each new experiment.[2]

Apparatus

The stimuli were presented on a 17-in. Sony 200PS monitor (P22 phosphor) driven at a frame rate of 100 Hz by a Cambridge Research Systems VSG 2/4 15-bit frame store housed in a Pentium computer. The display response was linearized (gamma corrected) from measurements made with a Pritchard PR880 photometer. Stimulus presentation and response recording were controlled by software written in C++. The observers performed the task in a dimly lit laboratory at a viewing distance of 50 cm. Viewing position was stabilized with a chinrest.

Stimuli

The stimuli were circularly symmetrical, sine-phase Gabor patches presented on a 25° square, 30 cd/m^2 uniform yellow field. The mathematical form of the stimuli was as given by Graham (1989, p. 53). The stimuli were constructed by in-phase modulation of the red and green guns of the monitor in a 3:1 ratio to obtain a yellow-black, luminance-modulated grating patch. The sinusoid had a period of 8 pixels; the Gaussian envelope had a space constant (full width at half height) of 10 pixels, giving a bandwidth of 1.06 octaves. At the specified viewing distance, the spatial frequency of the sinusoid was 2.5 cycles/deg, and the width of the Gabor patch (half height) was 28 arc min.

In Experiment 5, the stimuli were presented directly against a uniform field; in the remaining experiments, they were presented atop a circular, 15% contrast luminance pedestal of 1.37° (30 pixel) diameter. The backward masks used in Experiments 1 and 3 consisted of alternating 17 arc min (6-pixel) squares whose contrasts were modulated by a circularly symmetrical Gaussian vignette with a space constant of 42 arc min (15 pixels) and a peak contrast, relative to the luminance of the pedestal, of 95%.

The attentional cues used in Experiments 1, 2, and 5 were the pure peripheral cues of Carrasco et al. (2000). The cue consisted of a black 0.25° disk that appeared at a point adjacent to the target location on the radius extending from the fixation point through the center of the target location, at an eccentricity of 5.2° from fixation (i.e., the center-to-center separation of the cue and the target was 2°). This was flashed for 60 msec at an SOA of 100 msec and then extinguished. The cues used in Experiments 3 and 4 were the combined central–peripheral cues of Smith (1998, 2000a). These consisted of a row of two black squares located equidistantly along the radius extending from a fixation square to the target location. They were presented at an SOA of 150 msec and remained present until the observer responded. (The use of different SOAs with the different cue configurations reflects the differences in the original studies.)

On any trial there were three potential target locations, one cued and two uncued, located at an angular separation of 120° on the circumference of an imaginary 3.2° radius circle centered on the fixation point. On each trial, a randomly chosen angle α ($0 < \alpha \leq 360°$) determined the position of the cue. The possible uncued locations were at $\alpha \pm 120°$, these locations being chosen on uncued location trials with equal frequency. This display configuration, which was used by Smith (1998, 2000a), has the property that the two possible uncued locations are equidistant from the cued location and, thus, according to a symmetrical model of attentional gradient effects, should receive equal processing resources.

Procedure

The experiments were run in sessions of 360 trials, divided into 12 blocks, each with 30 trials. Half of the trials were signal trials, on which a Gabor patch was presented; the remainder were noise trials (a luminance pedestal without a patch in Experiments 1–4, a blank display in Experiment 5). To allow psychometric functions to be obtained, signals were presented at five equally spaced contrasts. The range of stimulus contrasts was set individually for each observer during the practice sessions and was chosen to produce a range of performance that varied from near chance to near perfect.

Experiments 1, 2, and 5 were run with no probabilistic manipulation of stimulus frequencies, following the procedure of Carrasco et al. (2000). Half of the trials were cued trials; the other half were neutral trials. On cued trials, the cue was 100% predictive. On such trials, the stimulus always occurred at the cued location. On neutral trials, the stimulus could occur at one of three possible display locations, the particular location being chosen at random on each trial.

Experiments 3 and 4 were run with probabilistic manipulation of stimulus frequencies, following the procedure of Smith (1998, 2000a). In these experiments, the attentional cue had the same form on every trial. The ratio of valid to invalid cues was 5:1. On 83% of the trials, the stimulus appeared at the cued location; on the remaining 17% of the trials, it appeared at one of the two possible uncued locations, the particular location being chosen at random on each trial.

Apart from SOAs, the timing of stimulus events during a trial was the same for all the experiments. The trial began with the presentation of the fixation point (a cross in Experiments 1, 2, and 5 and a small square in Experiments 3 and 4.) This served both as an alerting signal and as an instruction to the observer to maintain fixation throughout the course of the trial. One second after the fixation point, the cue appeared, and after an SOA of 100 or 150 msec, the stimulus was presented for 50 msec. In experiments in which a backward mask was used (Experiments 1 and 3), the mask was presented at the stimulus location 50 msec after the onset of the stimulus and remained present until the observer responded. In the remaining experiments, the stimulus was extinguished after 50 msec, and the uniform field with the fixation point remained present until the response. After the response, the fixation point was extinguished and then presented again after a 3-sec interstimulus interval to signal the beginning of a new trial.

Responses were recorded on a linear array of six microswitched buttons. The observers were instructed to interpret the buttons as a confidence rating scale running from *extremely confident noise* on the left to *extremely confident signal* on the right. They were told to treat the three buttons on the right, which were a different color from those on the left, as signal responses of varying confidence and those on the left as noise responses of varying confidence. After each response, they were provided with accuracy feedback auditorily. Responses on signal trials were deemed correct if they pressed any of the three *signal* buttons, irrespective of confidence, and incorrect if they pressed any of the three *noise* buttons. In addition, at the end of each block, they were provided with summary feedback on the visual display, informing them of the number of correct responses and the number of signal responses for the block. The observers were instructed at the beginning of the experiment to try to use the full range of the rating scale when making their responses and were shown histograms of their confidence ratings at the end of each practice session to reinforce this.

The observers were instructed to maintain central fixation during the course of each trial, but to use the cues to direct their attention. Eye movements were not monitored, since the combined SOA and exposure duration was too short to allow effective refixation of the display. During the instruction phase, all of the display contingencies and all aspects of display timing were fully explained.

EXPERIMENT 1

The observers in Experiment 1 detected backwardly masked, pedestal Gabor patch stimuli, which were presented using the pure peripheral cues of Carrasco et al. (2000). Two versions of this experiment were run (Experiments 1A and 1B), using different forms of neutral cue. On cued trials, in both Experiments 1A and 1B, a 100% predictive peripheral cue was flashed for 60 msec at one of the display locations. On neutral trials, in Experiment 1A, a single cue disk was flashed centrally, at the fixation point, following the procedure of Carrasco et al. In Experiment 1B, peripheral cues were flashed at the three possible stimulus locations: α°, $\alpha - 120^\circ$, and $\alpha + 120^\circ$ (see Figure 1). On these trials, targets could appear at any of the three possible display locations with equal probability.

The two different forms of neutral cue were used because they provided controls for different features of the prestimulus luminance transient. The use of a single central cue, like that in Carrasco et al. (2000), ensures that the total prestimulus transient is the same on cued and neutral trials. The use of multiple peripheral cues ensures that the magnitude of the local luminance transient proximal to the target is the same on cued and neutral trials. Although it is difficult to say, a priori, which form of cue provides the more appropriate control in experiments of this kind, if the magnitude of the cuing effect is affected by forward (paracontrast) masking of the stimulus by the cue, as has been suggested by Smith (2000a) and others, it may be more important to control the local luminance transient. This is especially so when disk stimuli are used as cues and when they are presented at greater eccentricity than the targets, as here, because the magnitude of any masking effect produced by the cue is likely to increase with cue size and eccentricity. We ran Experiment 1B, using the three-element neutral cue, to ensure that the magnitude of the cuing effect was not underestimated in Experiment 1A.

In both versions of the task an equal number of cued and neutral trials and an equal number of noise and signal stimuli were presented, in random order, during each 60-trial (two-block) segment of the experiment. Each of the observers in both experiments completed a total of 2,520 experimental trials in six experimental sessions: 630 cued noise trials, 630 neutral noise trials, and 126 cued signal trials and 126 cued noise trials at each level of signal contrast.

Results

Detection sensitivity for cued and neutral stimuli was quantified for each observer, using the measure d_a (Macmillan & Creelman, 1991, chap. 3), which describes the area under the ROC curve in z-score space. For a yes/no task, d_a may be written

$$d_a = \beta_0 \sqrt{\frac{2}{1+\beta_1^2}}, \tag{1}$$

where β_1 and β_0 are the slope and intercept, respectively, of the best-fitting straight line in zROC space. When the standard normal, equal-variance, signal detection model holds, the zROC plot is linear with a slope of unity. Under these conditions, d_a reduces to d', which measures the distance from the origin to the zROC line in both a horizontal and a vertical direction. When the distributions of noise and signal are normal but their variances are unequal, as is often found in yes/no tasks, the zROC is still linear, but with a slope equal to the ratio of the standard deviations of the noise and signal distributions. Under these circumstances, d_a is proportional to the minimum Euclidian distance from the zROC to the origin (i.e., the length of the line segment perpendicular to the zROC running from the zROC to the origin).

We obtained the slope and intercept of the zROC, using a generalized regression procedure that assumes that both the predictor and the criterion variable are subject to measurement error and that the ratio of the measurement errors in the two variables is known (Draper & Smith, 1998). Values of d_a were calculated for cued and neutral trials for each of the five levels of contrast for each observer. Figure 2 shows examples of the zROCs obtained for 1 observer, using this method. A resampling (bootstrap) procedure was used to estimate standard errors for each value of d_a. Further details of the procedure used to estimate sensitivity are given in the Appendix.

Figure 3 shows the resulting sensitivity estimates for the 5 observers in Experiment 1A, in which a central neutral cue was used. Figure 4 shows the corresponding estimates from Experiment 1B, in which a three-element, peripheral neutral cue was used. To quantify the change in sensitivity as a function of stimulus contrast, c, a three-parameter Weibull function

$$F(c) = \alpha\left\{1-\exp\left[-\left(\frac{c}{\beta}\right)^{\gamma}\right]\right\}, \tag{2}$$

was fitted to the empirical sensitivity estimates by minimizing a chi-square statistic

$$\chi^2 = \sum \frac{\left[d_a(c)-F(c)\right]^2}{\mathrm{var}\left[d_a(c)\right]}, \tag{3}$$

where $\mathrm{var}[d_a(c)]$ is the bootstrap variance estimate of d_a at contrast level c. To quantify the magnitude of the cuing effect, two models were fitted to the data for each observer: a three-parameter null model, in which a single Weibull function was fitted to the psychometric functions for both cued and neutral stimuli, and a six-parameter model, in which separate Weibull functions were fitted to the psychometric functions for the cued and the neutral conditions. The smooth curves in Figures 3 and 4 are fits of the latter model.

The difference between the fit of the single-function model and that of the two-function model (a chi-square with three degrees of freedom) was used to test for the presence of cuing effects. To the extent that the two-function model provides a better description of the data than does the single-function model, the psychometric functions for cued and neutral conditions can be consid-

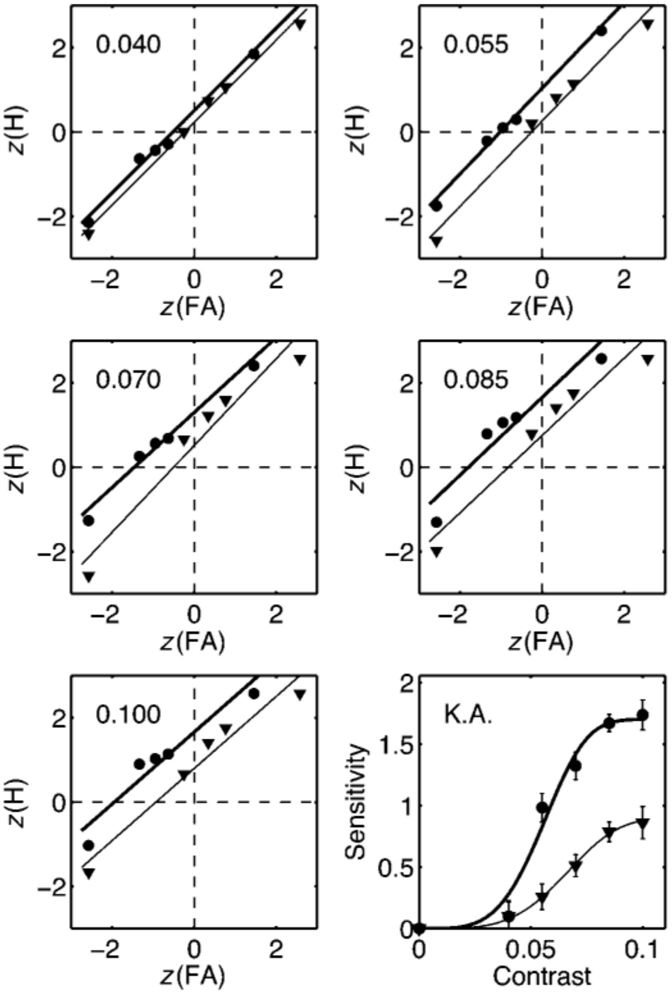

Figure 2. Example *z*ROCs for one observer (K.A., Experiment 1B). Circles are responses to cued stimuli; triangles are responses to neutral stimuli. The heavy and light lines are *z*ROCs for cued and neutral stimuli, respectively, calculated using Equations 2 and 3. The level of stimulus contrast is inset in each panel. The panel at the lower right shows Weibull function fits (Equation 4) to d_a sensitivity measures calculated from the *z*ROCs, using Equation 1. Error bars are bootstrap standard errors.

ered to differ from one another. The results of these tests are reported in Table 2. As may be seen in the table, significant cuing effects were obtained for 3 of the observers in Experiment 1A (L.D., E.K., and M.S.). Of the remaining 2 observers, L.M. showed no effect of the cue; N.W. showed some evidence of a reversal, but the effect was nonsignificant. In Experiment 1B, 4 of the observers showed significant cuing effects (P.S., K.P., A.S., and K.A.), and none showed any evidence of a reversal. The last row of the table (labeled "Group") is the average of the chi-squares for the 5 observers. We use this measure, which is significant for both experiments, to characterize the average cuing effect for each experiment as a whole.

Another measure of the average effect across the observers in each experiment is shown in Figures 3 and 4. For each observer, an *attentional gain* function was defined as 20 log[$F_A(c)/F_N(c)$], the logarithm of the ratio of the psychometric functions for the cued and neutral conditions, estimated from the two-function Weibull model and expressed in decibels. The gain functions were reexpressed as a function of normalized contrast (the value of contrast at which d_a for cued stimuli equalled 1.0), to make them comparable across observers, and then were averaged. The average gain functions are plotted in the lower right panel of each figure. The error bars in this panel are standard errors of the mean. As may be seen from a comparison of the two figures, the gain was of a similar magnitude in the two experiments and was roughly constant across a range of normalized contrasts, perhaps showing a slight tendency to decline (by less than 2 dB) from the lowest to the highest contrast. However, the magnitude of the effect is small, relative to the standard errors.

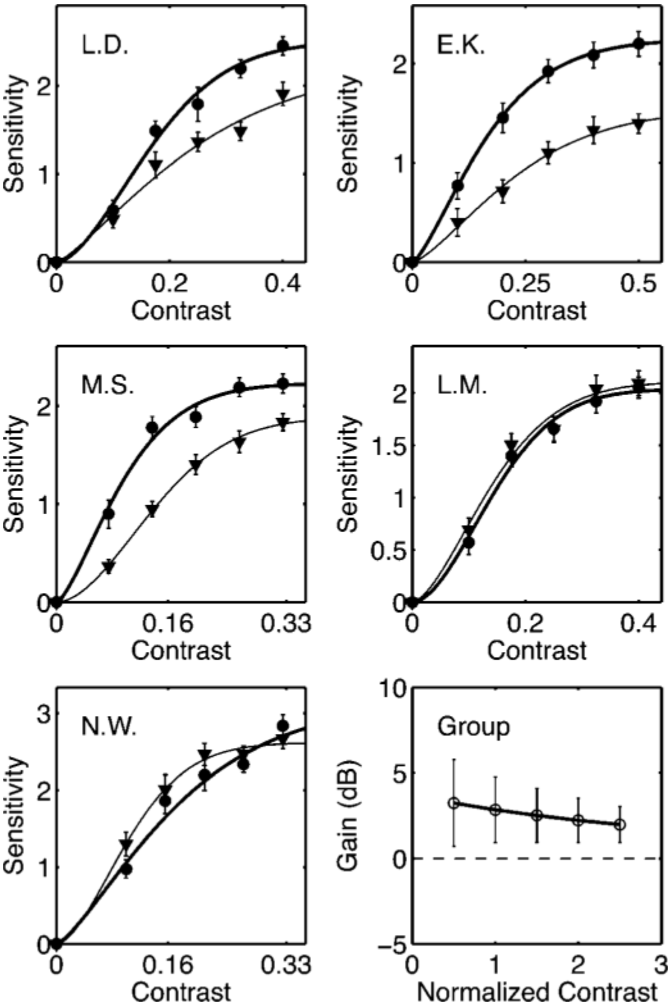

Figure 3. Sensitivity (d_a) for Experiment 1A (peripheral cues, backward masks, and single-element neutral cue). Circles and triangles are responses to cued and neutral stimuli, respectively; solid lines are Weibull function fits. The heavy line is the cued condition; the light line is the neutral condition. The panel at the lower right shows the attentional gain as a function of normalized contrast, averaged across observers.

Discussion

The results of this experiment replicated the main findings of Smith (2000a) and Smith and Wolfgang (2004), showing evidence for signal enhancement when backwardly masked stimuli were detected—at least for the majority of observers. They also extend the findings of the previous studies, showing that the magnitude of the signal enhancement effect does not depend on signal contrast. There is a slight tendency for gain to decrease as a function of normalized contrast, but the effect is small, relative to the differences among observers. These findings complement those of Smith (2000a), who found no systematic effect of exposure duration on signal enhancement with masked stimuli. However, in Smith's (2000a) study, stimulus contrast and exposure duration were covaried to try to keep overall detectability constant. Experiment 1 showed that there is no appreciable variation in the signal enhancement effect across a wide range of detectabilities.

One feature of the results that we had not predicted, which differs from the results of both Smith (2000a) and Smith and Wolfgang (2004), was the significant individual differences in the magnitude of the cuing effect. In those studies, all of the observers in all of the experiments in which masked signals were used showed significant cuing effects of some kind. (No direct comparison with the results of Carrasco et al., 2000, is possible, because their statistical tests were carried out on averaged effects across observers.) The finding that only 3 of the 5 observers showed significant cuing effects in Experiment 1A led us to suspect that forward masking of the stimulus by the cue may have attenuated the cuing effect, and for this reason, we ran Experiment 1B as a

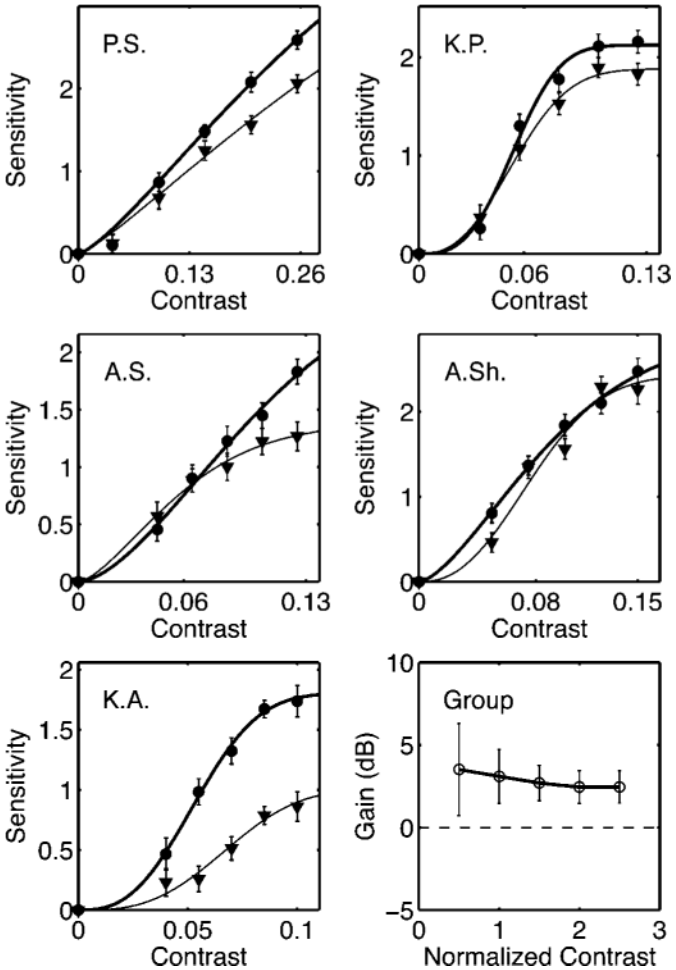

Figure 4. Sensitivity (d_a) for Experiment 1B (peripheral cues, backward masks, and three-element neutral cue). Other details are the same as those for Figure 3.

control experiment. Since in this experiment, identical peripheral disk cues were used in the cued and the neutral conditions, the magnitude of any forward-masking effect in the two conditions should have been the same. Although there is some evidence that this cue configuration yielded a more consistent cuing effect, overall, the similarities between the two experiments outweighed the differences. In particular, the estimates of average gain in the lower right-hand panel of Figures 3 and 4 are virtually identical. Because of the overall similarity in the results of Experiments 1A and 1B, in the remaining two experiments with peripheral cues (Experiments 2 and 5), we used the single, central neutral cue of Experiment 1A for consistency with the procedure of Carrasco et al.

Table 2
Tests of Cuing Effect, Experiments 1A, 1B, and 2

Experiment 1A			Experiment 1B			Experiment 2		
Observer	$\Delta\chi^2(3)$	*p*	Observer	$\Delta\chi^2(3)$	*p*	Observer	$\Delta\chi^2(3)$	*p*
L.D.	38.86	0**	P.S.	23.63	0**	P.S.	5.12	.16
E.K.	75.52	0**	K.P.	8.44	.04*	A.S.	3.01	.39
M.S.	66.19	0**	A.S.	12.91	.01**	C.B.	1.87	.60
L.M.	1.04	.78	A.Sh.	4.21	.24	K.J.	4.48	.21
N.W.	4.76	.20	K.A.	122.97	0**	A.Sh.	0.01	.99
Group	37.27	0**	Group	34.43	0**	Group	2.98	.46

$^*p < .05$. $^{**}p < .01$. *p* values with no asterisks, nonsignificant.

EXPERIMENT 2

The observers in Experiment 2 detected unmasked, pedestal Gabor patches presented for 50 msec. Apart from the absence of backward masks, all other aspects of the procedure were the same as those in Experiment 1A.

Results and Discussion

Psychometric functions and estimates of average gain are shown in Figure 5. Tests of the signal enhancement effect for individual observers are shown in Table 2. The results of this experiment are very clear: Under unmasked conditions, no observer showed any evidence of signal enhancement. Average gain was zero, except at the lowest level of contrast, where it became positive. However, the error of estimate in this region of the function is large, so the estimate is not reliable.

The results of Experiments 1 and 2 replicated the mask-dependent cuing effects of Smith (2000a) and Smith and Wolfgang (2004), using a cue configuration that differed from those used in either of those studies. In addition, they also suggest that the effect is fairly constant across a wide range of display contrasts. They do not support the interpretation of Carrasco et al. (2000), that Smith (2000a) failed to find a cuing effect with unmasked stimuli because the cue configuration used in that study did not activate the transient-orienting system effectively. Rather, using the same peripheral cue as that in Carrasco et al., we found a cuing effect for the majority of the observers in Experiments 1A and 1B, but none in Experiment 2.

In Experiments 3 and 4, we investigated the effects of spatial cuing under masked and unmasked conditions, respectively, using the mixed central–peripheral cues of Smith (2000a). Although mask-dependent cuing effects have already been shown to occur with this cue configuration, they were obtained at a single level of stimulus detectability. Experiments 3 and 4 were designed to extend these results by investigating the effects of cuing across the entire psychometric function.

EXPERIMENT 3

The observers detected masked, pedestal Gabor patches that were presented for 50 msec, using the *radial* (mixed

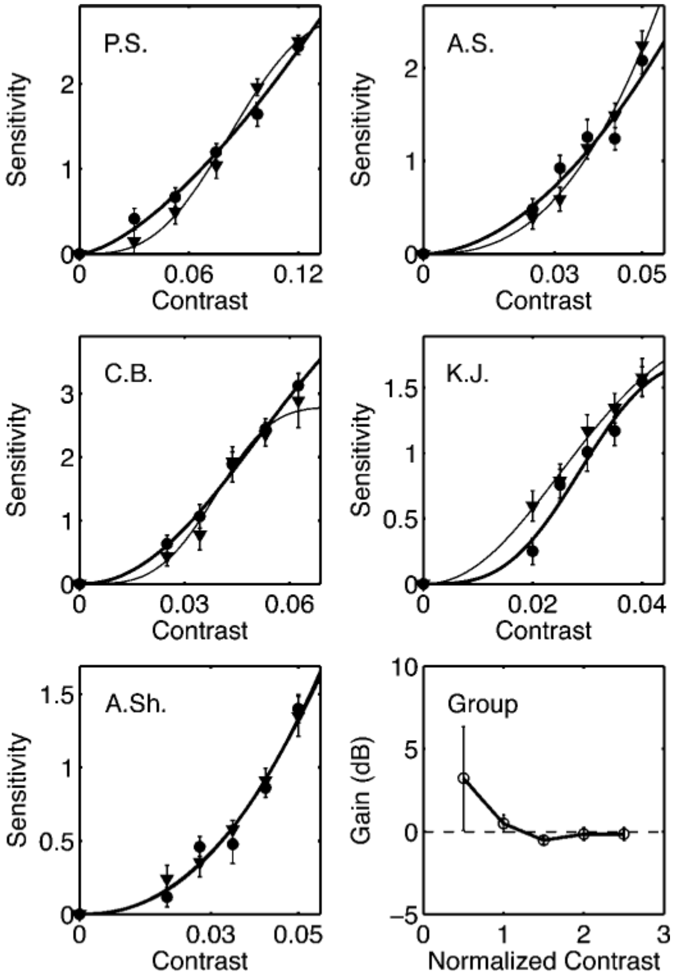

Figure 5. Sensitivity (d_a) for Experiment 2 (peripheral cues, no backward masks). Details are the same as those for Figures 3 and 4.

central–peripheral) cue shown in Figure 1. On each trial, a randomly chosen angle, α, determined the position of the cue. On 83% of the trials, the target stimulus appeared at the cue location. On the remaining 17% of the trials, it appeared at one of the locations, $\alpha \pm 120°$, the particular location being chosen at random on each trial. Note that with this cue configuration, a control condition was used to test for the presence of signal enhancement effects that was different from the one used in previous experiments. In Experiments 1 and 2, performance in the cued condition was tested against a neutral (i.e., a diffuse, or divided) attention condition, whereas in Experiments 3 and 4, it was tested against a miscued condition, in which attention was directed away from the stimulus location. These procedural differences reflect those in the original articles of Carrasco et al. (2000) and Smith (2000a).

Each observer served in eight, 360-trial experimental sessions, divided into 30-trial blocks, as in the previous experiments, yielding a total of 2,880 trials per observer. There were a total of 1,200 cued noise trials, 240 miscued noise trials, 240 cued signal trials at each of five levels of signal contrast, and 48 miscued signal trials at each level of contrast.

Results and Discussion

Psychometric functions and estimates of gain are shown in Figure 6; tests of the signal enhancement effect are shown in Table 3. For all the observers in this experiment, a significant signal enhancement effect was obtained. As in the previous experiments with backward masks, average gain was fairly constant as a function of contrast, showing a slight tendency to decrease as a function of normalized contrast.

The finding of a consistent signal enhancement effect for all the observers at a cue–target SOA of 150 msec does not support the interpretation of Carrasco et al. (2000), that the radial cue of Smith (2000a) activated the transient-orienting system only weakly. They are, however, consistent with the finding of Smith (1998), who

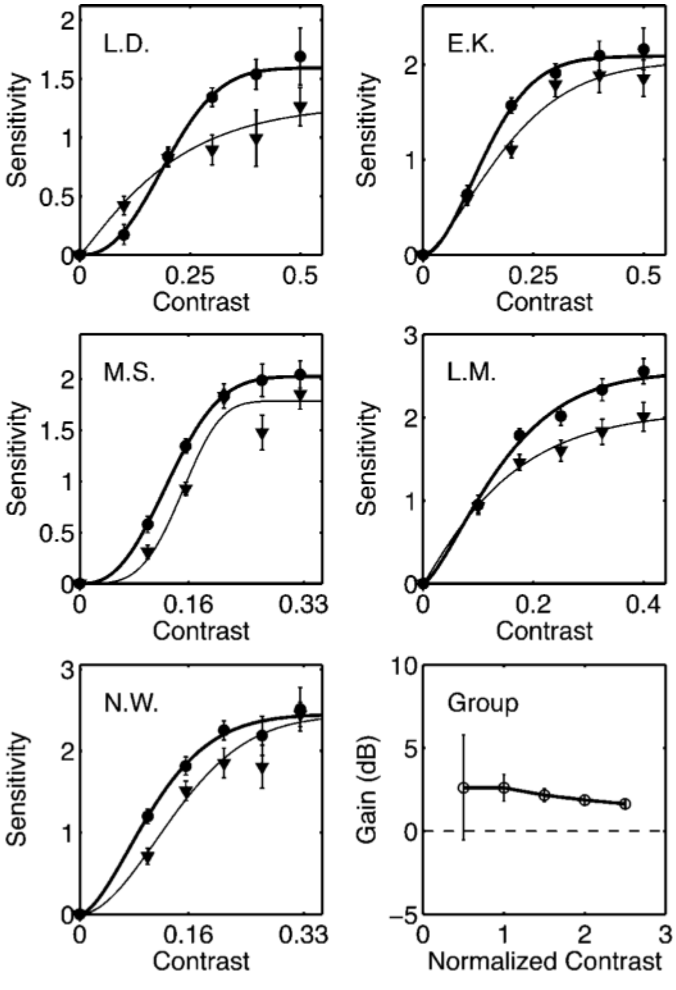

Figure 6. Sensitivity (d_a) for Experiment 3 (mixed central–peripheral cues, backward masks). Circles and triangles are responses to cued and miscued stimuli, respectively. Other details are the same as those for Figures 3–5.

Table 3
Tests of Cuing Effect, Experiments 3, 4, and 5

Experiment 3			Experiment 4			Experiment 5		
Observer	$\Delta\chi^2(3)$	*p*	Observer	$\Delta\chi^2(3)$	*p*	Observer	$\Delta\chi^2(3)$	*p*
L.D.	15.20	0**	L.D.	2.47	.48	P.S.	1.95	.58
E.K.	11.71	.01**	E.K.	5.45	.14	H.F.	23.45	0**
M.S.	23.24	0**	M.S.	13.41	.01**	P.G.	10.22	.01**
L.M.	20.84	0**	L.M.	1.23	.74	A.L.	4.77	.18
N.W.	16.94	0**	N.W.	4.01	.26	K.L.	7.87	.05*
Group	17.59	0**	Group	5.31	.15	Group	9.65	.02*

$^*p < .05$. $^{**}p < .01$. *p* values with no asterisks, nonsignificant.

showed, using a poststimulus probe method (Downing, 1988), that the radial cue was as effective as a *landmark* cue, in which four dots were flashed at the corners of an imaginary 1.2° square surrounding the target. Like the flashed disk used by Carrasco et al. and in Experiments 1 and 2 here, the landmark cue is a peripheral cue that should selectively activate the transient-orienting system. Smith's (1998) finding that similar cuing effects were obtained with radial and landmark cues was interpreted by him as evidence that the mixed central–peripheral form of the radial cue was an effective stimulus for the transient-orienting system.

It might be tempting to infer, on the basis of the greater consistency of the cuing effect found in Experiment 3, as compared with those in Experiments 1A and 1B, that the radial cue activated the transient-orienting system more effectively than did the peripheral disk. However, these effects are more likely to reflect differences in the control conditions used to test for the presence of signal enhancement effects. As was noted previously, a neutral condition was used as a control condition in Experiments 1A and 1B, whereas a miscued condition was used in Experiment 3. In studies in which cued and neutral conditions have been included, both attentional costs and benefits have usually been obtained (Müller & Humphreys, 1991; Smith & Wolfgang, 2004). The former measures sensitivity differences between focused and divided attention; the latter measures differences between divided and misdirected attention. The consistent cuing effect found in Experiment 3 is likely to have arisen because it compared two extreme attentional states, rather than comparing one extreme with the intermediate state. Although it is a matter of some theoretical interest, we have not attempted to distinguish further the individual contributions of the physical cue configuration, the predictability of the target, and the choice of control condition to the overall cuing effect, since these questions are incidental to the purposes of this study.

EXPERIMENT 4

The observers detected unmasked, pedestal Gabors that were presented for 50 msec and then extinguished. The stimuli were presented at either cued or miscued locations, using the radial cue configuration in Experiment 3. All other details of the stimulus display and the procedure were identical to those in Experiment 3.

Results and Discussion

Psychometric functions and average gain are shown in Figure 7; tests of the signal enhancement effect are shown in Table 3. For 1 of the observers (L.D.), the empirical psychometric functions were not well described by Weibull functions. For this observer, the estimated psychometric functions for the best two-function model separate at high contrasts, but the difference between them is not significant, due to the large standard errors in the data, and it does not accurately reflect the growth of sensitivity in the two conditions. This observer's empirical psychometric functions were better described by a shifted Weibull function of the form $F(c - .05)$ (not shown), where .05 is the minimum level of contrast at which the observer performed the task. Once again, however, there was no significant difference in the goodness of fit of a two-function model and a single-function model, suggesting that there is no evidence of a systematic cuing advantage.

The psychometric functions for 1 observer (M.S.) were better described by a two-function than by a one-function model, but the difference reflects shape differences (a sensitivity reversal at high contrast), rather than a systematic cuing effect. For neither this observer nor the others (E.K., L.M., and N.W.) was there evidence of signal enhancement. The test of the average chi-square is nonsignificant, and average gain is equal to or less than zero at all signal contrasts.

Together, the results of Experiment 3 and 4 replicated the mask-dependent cuing effect found in Experiments 1 and 2 with a different form of attentional cue. Although there were individual differences in each experiment, the overall pattern is fairly clear: In detection, signal enhancement is found with backwardly masked stimuli, but not with unmasked stimuli. The magnitude of the average signal enhancement effect is largely independent of display contrast, although there may be a tendency for it to decline slightly at high contrasts. The finding that mask-dependent cuing occurs with both forms of cues shows that these effects are not due to a failure to activate the transient-orienting system effectively, as has been previously suggested. Rather, they appear to reflect a more fundamental interaction between masking and attentional mechanisms.

Previously, we hypothesized that the reason why Carrasco et al. (2000) found a cuing effect with unmasked stimuli was that they presented their stimuli directly against a uniform field, rather than atop a luminance

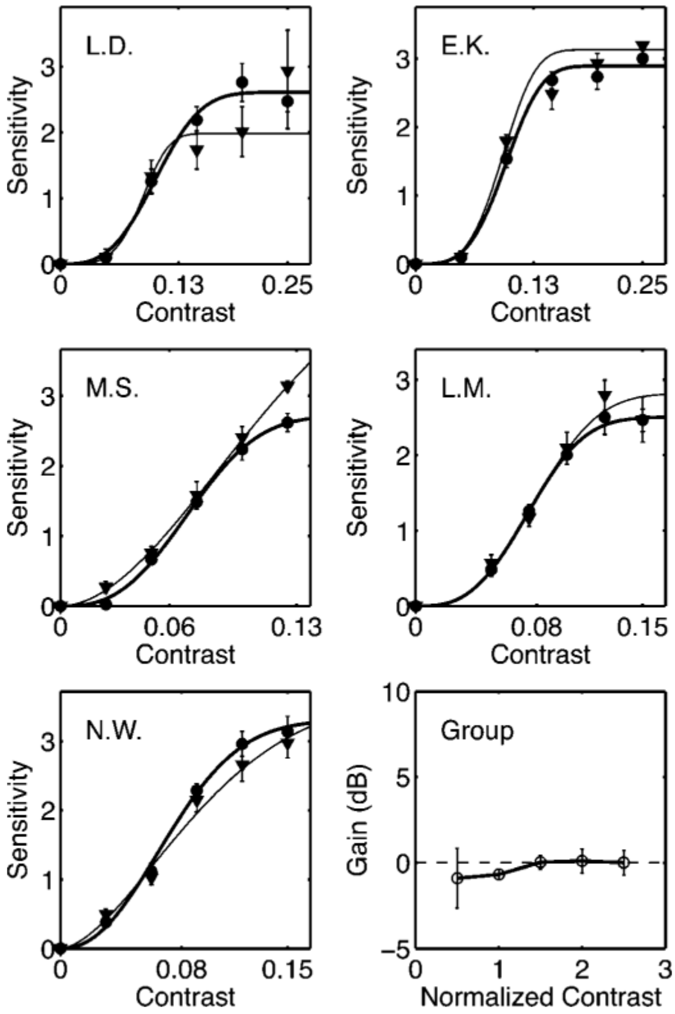

Figure 7. Sensitivity (d_a) for Experiment 4 (mixed central–peripheral cues, no backward masks). Details are the same as those for Figure 6.

pedestal, as we have done. Because noise reduction effects may play a significant role under these circumstances, any cuing effect that is found cannot be attributed uniquely to signal enhancement. To test this possibility, we replicated the detection task in Experiment 2 without luminance pedestals.

EXPERIMENT 5

The observers detected Gabor patch targets that were presented for 50 msec, directly against a uniform field, and then extinguished. The attentional cues were identical to those in Experiment 1A. All other aspects of the display and procedure were the same as those in the preceding experiments.

Results and Discussion

Psychometric functions and estimates of average gain are shown in Figure 8; tests of the cuing effect for individual observers are shown in Table 3. The psychometric functions for cued and neutral stimuli differed significantly for 3 observers (H.F., P.G., and K.L.), but only the first two showed a systematic cuing advantage. The cued and neutral psychometric functions for K.L. differ in shape, but the differences do not appear to reflect an overall cuing advantage. The average gain shows a systematic trend, decreasing from around 2 dB at low contrasts to 0 at high contrasts. Although the average reflects only the minority of observers who showed systematic cuing effects, the pattern is consistent with the predictions of a noise reduction account. This account predicts that decisions will be more affected by noise from the surrounding display regions at low signal strengths, because activity from the signal becomes submerged in the "floor" of uniform field noise. Taken together, the results of Experiments 2 and 5 are consistent with the idea that signal enhancement does not occur with unmasked displays and that a weak or inconsistent noise reduction effect may also operate when the decision task is not localized by the pedestal.

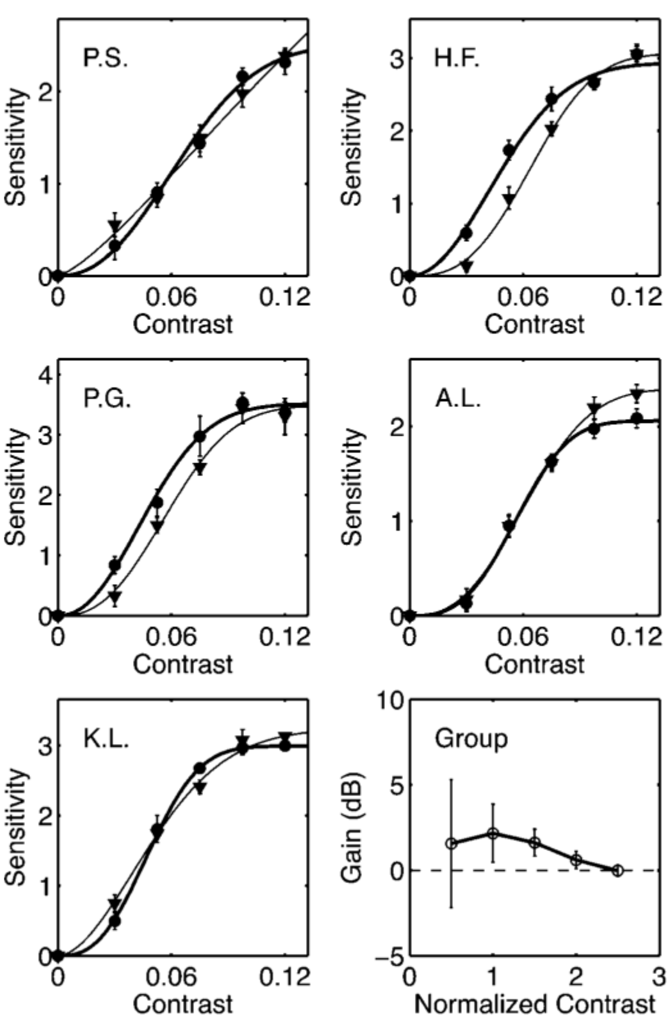

Figure 8. Sensitivity (d_a) for Experiment 5 (peripheral cues, no backward masks, or pedestals). Details are the same as those for the previous figures.

GENERAL DISCUSSION

Consistent with the results of Smith (2000a), Smith and Wolfgang (2004), and other studies in the literature, signal enhancement occurred in our experiments only when stimuli were backwardly masked. These findings differ from those in Carrasco et al. (2000), who reported signal enhancement even with unmasked displays. In this discussion, we first will consider possible reasons for the discrepancy between our findings and those in Carrasco et al. and then will describe a mechanism that provides a theoretical basis for the mask-dependent cuing effect.

An important feature of our procedure was the use of a luminance pedestal to identify the location of the target stimulus in the display. This ensured that the decision task was equally well localized with masked and unmasked stimuli, allowing them to be compared within the same experimental paradigm. We hypothesized that noise reduction would produce significant cuing effects when unmasked stimuli were presented without pedestals, as in Experiment 5. Although there was some evidence of effects of this kind, they were significant only for a minority of the observers.

In a related study, Foley and Schwarz (1998) investigated the effects of attentional cuing on contrast discrimination in a spatial, two-alternative forced choice task. In their task, a contrast increment was added to one of two sinusoidal luminance pedestals, whose contrast relative to the background was itself variable, and observers identified the location of the (unmasked) contrast increment. When there were no distractor elements present in the display, attentional cuing improved performance only at low levels of pedestal contrast, when the pedestals themselves were not well localized relative to the background. At suprathreshold levels of pedestal contrast, when the pedestals were well localized in the display, cuing had no effect on performance (see their Figure 3A). The data were well described by a multichannel

SDT model similar to that used by Palmer et al. (1993), Smith (1998), and others, in which the effects of cuing were explained solely by noise reduction.

Taken together, the results of Foley and Schwarz (1998) and Experiment 5 here suggest that noise reduction or uncertainty reduction mechanisms affect performance when a weak, unmasked contrast increment to be detected is presented directly against a uniform field, but the magnitude of these effects and the conditions under which they occur have yet to be established clearly. Thus, it is not clear whether the significant cuing effects obtained with unmasked stimuli by Carrasco et al. (2000) can be attributed to noise reduction alone, as we hypothesized. We will consider their results in more detail in the following section.

The Data of Carrasco et al. (2000) and Cameron et al. (2002)

Carrasco et al. (2000) were aware of the problems of noise and uncertainty and of the difficulties involved in ascribing cue-related variations in sensitivity unambiguously to signal enhancement. As was described previously, they used two different tasks to investigate the effects of spatial cuing on detection sensitivity: a yes/no detection task and an orthogonal orientation discrimination task. The evidence they presented for signal enhancement with unmasked stimuli was of two kinds. First, they showed that contrast sensitivity was higher for cued than for neutral stimuli across a wide range of stimulus spatial frequencies. However, as was noted previously, because their stimuli were presented directly against a uniform field, this procedure was not able to distinguish cuing effects caused by noise reduction or uncertainty reduction from those caused by signal enhancement. Furthermore, the use of adaptive procedures to assess sensitivity in yes/no tasks may confound sensitivity differences and criterion differences, because the proportion of correct responses in such tasks varies with both sensitivity and criterion.

Second, to try to control for the effects of uncertainty, they fitted a maximum-outputs SDT model to the empirical threshold estimates from the orthogonal discrimination task. This model, which is similar to models that have been used successfully to model performance in related tasks (e.g., Eckstein et al., 2000; Foley & Schwarz, 1998; Palmer, 1994; Palmer et al., 1993; Shaw, 1982; Smith, 1998) assumed that independent horizontal and vertical filters encode the stimulus at each display location and that the observer's response is based on the most active filter in the set. To test for signal enhancement, the authors fitted a model that assumed that the only mechanism distinguishing cued from neutral performance was noise or uncertainty reduction. They then compared the difference in cued and neutral performance obtained empirically with that predicted by the model. With this procedure, signal enhancement could be inferred if the difference between cued and neutral sensitivities in the data exceeded that predicted by the model (i.e., by uncertainty reduction alone).

This procedure yielded conflicting results. The data to which Carrasco et al. (2000) applied their SDT model were contrast sensitivity thresholds estimated from two different experiments. In these experiments, the adaptive procedure estimated the levels of stimulus contrast needed for 82% and 90% correct responding, respectively. The main results of these model fits (Carrasco et al., 2000, Figures 4A and 4B) were as follows. (1) At high spatial frequencies (around 8–10 cpd), the cuing benefit predicted by the noise reduction model was in close agreement with the data for both the 82% and the 90% accuracy conditions. (2) At lower spatial frequencies, the model systematically overpredicted the cuing benefit in the 82% condition and underpredicted it in the 90% condition. (3) The overprediction and the underprediction were of similar magnitude, although the latter was significant only at the $p < .10$ level.[3] This can probably be attributed to the fact that the threshold estimates were more variable in the 82% than in the 90% condition and the statistical tests were of low power (t tests with four degrees of freedom).

These results suggest that at high spatial frequencies, the sole determinant of the cuing effect was noise or uncertainty reduction. At low spatial frequencies and high stimulus discriminability, the cuing effect exceeded that predicted by uncertainty reduction, which is consistent with the action of an additional mechanism of signal enhancement. However, at low spatial frequencies and low levels of stimulus discriminability, the cuing effect was less than that predicted by uncertainty reduction alone. This result is not consistent with the assumptions of the model, regardless of whether or not signal enhancement occurred, and may indicate that the model itself was misspecified.

Like other, similar model-based inferences, Carrasco et al.'s (2000) inference of signal enhancement for this task relied on their being able to quantify the attentional benefit from uncertainty reduction in an accurate way. This quantification rested on assumptions about the total number of noise sources in the display, how these changed with cue condition, and how effective signal strength varied with signal contrast. In particular, because their stimuli were presented directly against a uniform field, it relied on their being able to obtain an accurate estimate of the so-called *intrinsic uncertainty* of the display, a quantity that reflects the combined effects of noise in all of the visual mechanisms stimulated by the uniform field surrounding the target locations. Because intrinsic uncertainty functions as a constant background on which other, cue-related variations in uncertainty are superimposed, it cannot be brought under direct experimental control. As a result, if the assumptions made about the properties of intrinsic uncertainty in the model were incorrect, the uncertainty reduction benefit attributable to spatial cuing would not have been predicted accurately, which, in turn, could have led to an inference of signal enhancement when none in fact was present.

In their discussion of signal enhancement, Carrasco et al. (2000) emphasized the results from the 90% accuracy condition and the fact that the observed cuing benefit from that experiment exceeded the benefit predicted by an uncertainty reduction account. However, our view, based on the fact that the underprediction of the cuing effect in one experiment was of a similar magnitude to the overprediction in the other, is that it is difficult to draw firm conclusions about the mechanism responsible for the cuing effect from data of this kind. For this reason, rather than attempting to quantify the effects of uncertainty reduction within the framework of a particular model, we used the pedestal detection task, since we believe that it provides the most direct way to test for signal enhancement in detection with the minimum of additional assumptions. The results we obtained with this task supported the claim that signal enhancement in detection occurs only with backwardly masked stimuli. We also showed that the signal enhancement effect is largely unaffected by the particular form of the cue and is of a similar magnitude for a fairly wide range of display contrasts.

As was noted previously, in a later study Cameron et al. (2002) obtained psychometric functions for contrast for an orientation discrimination task in which stimuli were presented at ±15º and ±4º to the vertical. Like the study of Carrasco et al. (2000), the stimuli in this task were presented without masks, directly against a uniform field. In both of these tasks, discrimination performance was found to be significantly better for stimuli at cued locations. To investigate the effects of uncertainty, the authors investigated how well observers could localize the stimulus on each trial of the experiment, reasoning that uncertainty effects should be manifested as imperfect localization. In the ±15º task, which was performed at lower levels of contrast, localization was imperfect and tightly coupled to discrimination performance, suggesting that uncertainty may have played a significant role in limiting performance on this task. In the ±4º task, which was performed at higher levels of contrast, localization at the upper end of the psychometric function was virtually perfect, but discrimination nevertheless varied systematically with spatial cuing.

The results of Cameron et al. (2002) suggest that discrimination, especially in difficult tasks, is enhanced by attentional cues, irrespective of masking, under conditions in which spatial uncertainty effects appear not to be significant. Their results, combined with those we have reported here, provide evidence for a three-way cue × mask × task interaction in spatial-cuing tasks: Cues produce signal enhancement only with backwardly masked stimuli in detection tasks but produce an unconditional effect in discrimination tasks. In the following section, we will describe a mechanism that predicts effects of this kind.

A Model of Mask-Dependent Cuing

Smith and Wolfgang (2004) showed that the three-way cue × mask × task interaction emerges as a natural prediction from a stochastic, dynamic model of attention called the *attention gated stochastic integrator* (AGSI). This model, which is an extension of the model of simple reaction time proposed by Smith (1995; see also Smith, 2000a, 2000b), is a stochastic version of a continuous-flow system of the kind investigated by McClelland (1979). In the AGSI model, stimuli are encoded by an array of spatial frequency and orientation-tuned filters, similar to those typically assumed in models of visual encoding (e.g., Watson, 1986). The outputs of these filters are perturbed by noise and accumulated by a decision mechanism that is modeled mathematically as a diffusion process (Ratcliff, 1978; Ratcliff & Smith, 2004; Smith, 2000b).[4]

To model the effects of attention, the AGSI model assumes that attention controls, or *gates*, the rate at which stimulus information flows from early sensory encoding mechanisms to the decision mechanism. Information from attended locations accumulates rapidly; information from unattended locations accumulates more slowly. Consequently, when stimuli are attended, the decision mechanism requires less time to accumulate the criterion amount of information needed for a response. The idea that attention selectively affects the rate of information accumulation in a sequential sampling decision mechanism was proposed by Smith (2000a) to explain the mask-dependent cuing effects in detection. Direct experimental support for this idea was subsequently obtained by Carrasco and McElree (2001), using a response signal task.

An important property of the model, which derives from its sequential-sampling assumptions, is that although the rate of information accumulation differs for attended and unattended stimuli, their asymptotic SNRs are identical. That is, if the accumulation of stimulus information is allowed to run to completion without interruption, detection sensitivity for attended and unattended stimuli will be the same. This property is shown in Figure 9, which depicts how information in the decision stage grows as a function of stimulus-processing time. The decoupling of the rate of information growth from asymptotic SNR shown in the figure is reminiscent of a similar decoupling of rate and asymptotic activation variables in the deterministic, continuous-flow systems studied by McClelland (1979) and occurs for similar reasons.

To explain the mask-dependent cuing effects, the model assumes that masks limit the visible persistence of the stimuli (Coltheart, 1980; Sperling, 1960). When no masks are used, stimulus information persists in the visual system for some time after stimulus offset, whereas when masks are used, that information is rapidly suppressed (Kovács, Vogels, & Orban, 1995). When stimuli are not masked and stimulus persistence is comparatively long, as indicated by the dashed vertical lines on the right of the figure, the process of information accumulation is able to run to completion. Under these conditions, detection sensitivity for attended and unattended stimuli will not differ. When stimulus information is suppressed by the mask before accumulation is complete, however, as indicated by the dashed vertical lines on the left of the figure, detection sensitivity will be greater for attended than for unattended stimuli. This occurs because infor-

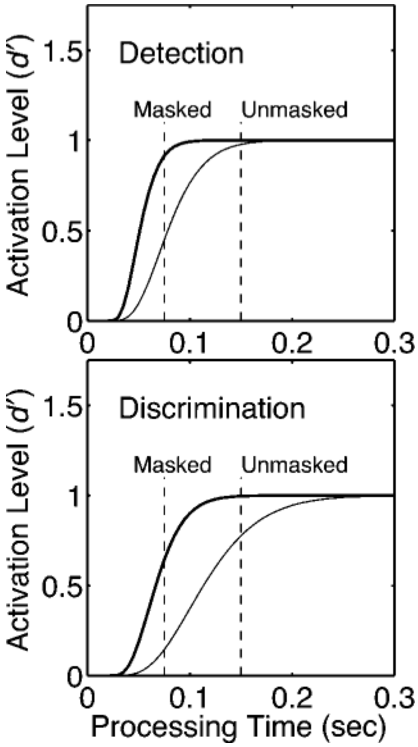

Figure 9. Activation dynamics of the attention gated stochastic integrator model. Decision stage activation grows rapidly at cued locations (the heavy line) and slowly at uncued locations (the light line), but both grow to the same asymptote. When stimuli are masked, the information in the stimulus is suppressed before asymptote is attained, as is shown by the dashed vertical line on the left-hand side. When no mask is used, the information in the stimulus decays relatively slowly, and accumulation continues until the point represented by the vertical line on the right-hand side of the figure. In detection, information accumulates comparatively rapidly, allowing the accumulated information to reach asymptote. At this point, the difference between cued and uncued sensitivity functions is abolished, whereas on the shoulder of the function, sensitivity for cued stimuli exceeds that for uncued stimuli. In discrimination, information accumulates more slowly, so the point at which accumulation ceases for unmasked stimuli occurs while the accumulation functions are still on the shoulder of the curve. Mask-dependent cuing effects are therefore predicted for detection, but an unconditional cuing effect is predicted for discrimination.

mation accumulates more rapidly when stimuli are attended and, as a result, more information is accumulated before the stimulus trace is suppressed by the mask.

Mask-dependent cuing effects in the model thus arise through an interaction of two factors: an increased rate of information accumulation from stimuli at attended locations and greater persistence of stimulus information when the stimuli are unmasked. However, the precise pattern of mask dependencies that is predicted depends on the overall rate of information accumulation and on its relationship to the rate at which the stimulus trace degrades. If information accumulates more slowly in discrimination than in detection, as is implied, for example, by the reaction time data of Brawn and Snowden (2000), cuing effects may occur independently of masking, as a comparison of the upper and lower panels of Figure 9 shows. In this figure, the effect of reducing the rate of information accumulation in discrimination is represented by a simple dilation of the time scale of the associated accumulation function. Under these circumstances, the point at which no further information can be extracted from unmasked stimuli falls on the rising part of the curve, rather than on its shoulder. As a result, cuing effects in discrimination are predicted for both masked and unmasked stimuli.

As well as predicting a three-way cue × mask × task interaction in sensitivity, the model also predicts the cuing benefits that have been found in visual simple reaction time by Posner, Snyder, and Davidson (1980) and others. This prediction, which is an immediate consequence of the assumption that information is accumulated more rapidly from attended locations, holds irrespective of whether stimuli are masked. Also, under the assumption that information accumulates more slowly in discrimination than in detection, the model predicts the cue × task interaction found in reaction time by Brawn and Snowden (2000): Mean reaction times are longer and the magnitude of the cuing effect is greater in discrimination than in detection. This occurs because the difference in the time required to accumulate a criterion amount of information for cued and uncued stimuli increases as overall accumulation rates slow.

A further interesting property of the model is that it provides a novel account of the effects of attention in high external noise displays. Lu, Dosher, and co-workers have carried out a number of studies within the framework of a perceptual template model (Lu & Dosher, 1998), in which they have investigated the effects of external noise on orientation discrimination judgments in spatial-cuing tasks. One of the mechanisms they identified as making a large and systematic contribution to the cuing effect in several studies is *external noise exclusion* (Dosher & Lu, 2000; Lu, Lesmes, & Dosher, 2002). The signature of this mechanism is an increase in the magnitude of the cuing effect with the amount of external noise in the display. The perceptual template model explains these effects by assuming that attention allows the perceptual template to weight the stimulus more efficiently, so the activity in spatial frequency channels not containing the target are excluded from the observer's decision.

The same mechanism that is used to explain the differences between detection and discrimination in the AGSI model provides an alternative account of why cuing effects may be larger in high-noise displays. A likely effect of adding noise to the display is to degrade the stimulus representation and, thereby, to slow the rate of information accumulation. The effect of slowing the rate is to dilate the time scale of the accumulation function, as is shown in Figure 9. This will shift the point at which accumulation terminates down the shoulder of the curve, increasing the magnitude of the cuing effect. Consequently, the magnitude of the cuing effect will increase with increases in the amount of noise in the display.

CONCLUSION

The point of departure for these experiments was the report by Carrasco et al. (2000) that signal enhancement could be obtained in cued detection tasks with unmasked stimuli and their conjecture that the mask-dependent cuing effects reported by Smith (2000a) were due to a failure to activate the transient-orienting system. Contrary to this conjecture, we replicated the mask-dependent cuing effect, using both the pure peripheral cues of Carrasco et al. and the mixed central–peripheral cues of Smith (2000a). Furthermore, we showed, with both forms of cue, that the magnitude of the cuing effect was approximately constant across a wide range of stimulus contrasts, at least for the particular stimuli used here. As the mask-dependent cuing effect has now been replicated in several different studies using different forms of attentional cues, we believe the effect is a real one. It emerges as a natural prediction of a stochastic, dynamic model of detection, the AGSI model, which assumes that attention affects the rate at which stimulus information accumulates and backward masks limit the persistence of the stimulus information in the visual system.

Although the AGSI model as described by Smith and Wolfgang (2004) was developed to account for performance in two-choice tasks, it may be extended to provide an account of ROC data of the kind collected here, using the *balance of evidence* theory of response confidence of Vickers (1978), in a similar way as was done for recognition memory by Van Zandt (2000). We are currently comparing the performance of this model with that of an alternative attention-orienting model (Smith, Ratcliff, and Wolfgang, 2004), in which miscuing delays the entry of stimulus information into visual short-term memory. Mask-dependent cuing occurs in the orienting model, as in the AGSI model, due to the differing visual persistence of masked and unmasked stimuli. When stimuli are unmasked, the effects of delaying the entry of stimuli into short-term memory are small, because a stimulus representation can be formed from the information in the iconic trace. When stimuli are masked, delaying the entry of the stimulus into short-term memory causes the stimulus information to degrade, and so a miscuing cost results.

REFERENCES

Bashinski, H. S., & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. *Perception & Psychophysics*, **28**, 241-248.

Bonnel, A.-M., Stein, J.-F., & Bertucci, P. (1992). Does attention modulate the perception of luminance changes? *Quarterly Journal of Experimental Psychology*, **44A**, 601-626.

Brawn, P. M., & Snowden, R. J. (2000). Attention to overlapping objects: Detection and discrimination of luminance changes. *Journal of Experimental Psychology: Human Perception & Performance*, **26**, 342-358.

Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon.

Busemeyer, J., & Townsend, J. T. (1993). Decision field theory: A dynamic-cognitive approach to decision making in an uncertain environment. *Psychological Review*, **100**, 432-459.

Cameron, E. L., Tai, J. C., & Carrasco, M. (2002). Covert attention affects the psychometric function of contrast sensitivity. *Vision Research*, **42**, 949-967.

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences*, **98**, 5363-5367.

Carrasco, M., Penpeci-Talgar, C., & Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity across the CSF: Support for signal enhancement. *Vision Research*, **40**, 1203-1215.

Cherry, E. C. (1953). Some experiments on the recognition of speech with one and two ears. *Journal of the Acoustical Society of America*, **25**, 975-979.

Cohn, T. E., & Lashley, D. J. (1974). Detectability of a luminance increment: Effect of spatial uncertainty. *Journal of the Optical Society of America*, **64**, 1715-1719.

Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics*, **27**, 183-228.

Davis, E. T., Kramer, P., & Graham, N. (1983). Uncertainty about spatial frequency, spatial position, or contrast of visual patterns. *Perception & Psychophysics*, **33**, 20-28.

Dorfman, D. D., & Alf, E., Jr. (1969). Maximum likelihood estimation of parameters of signal detection theory and determination of confidence intervals-rating-method data. *Journal of Mathematical Psychology*, **6**, 487-496.

Dosher, B. A., & Lu, Z.-L. (2000). Noise exclusion in spatial attention. *Psychological Science*, **11**, 139-146.

Downing, C. J. (1988). Expectancy and visual–spatial attention: Effects on perceptual quality. *Journal of Experimental Psychology: Human Perception & Performance*, **14**, 188-202.

Draper, N. R., & Smith, H. (1998). *Applied regression analysis* (3rd ed.). New York: Wiley.

Duncan, J., & Humphreys, G. W. (1989). Visual search and visual similarity. *Psychological Review*, **96**, 433-458.

Eckstein, M. P., Thomas, J. P., Palmer, J., & Shimozaki, 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.

Efron, B., & Gong, G. (1983). A leisurely look at the bootstrap, the jackknife, and cross-validation. *American Statistician*, **37**, 36-48.

Enns, J. T., & Di Lollo, V. (1997). Object substitution: A new form of masking in unattended visual locations. *Psychological Science*, **8**, 135-139.

Foley, J. M., & Schwarz, W. (1998). 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*, **15**, 1036-1047.

Giesbrecht, B., & Di Lollo, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 1454-1466.

Gourevitch, V., & Galanter, E. (1967). A significance test for one parameter isosensitivity functions. *Psychometrika*, **32**, 25-33.

Graham, N. V. S. (1989). *Visual pattern analyzers*. New York: Oxford University Press.

Graham, N. [V. S.], Kramer, P., & Haber, N. (1985). Attending to the spatial frequency and spatial position of near-threshold visual patterns. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 269-284). Hillsdale, NJ: Erlbaum.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.

Hawkins, H. L., Hillyard, S. A., Luck, S. J., Mouloua, M., Downing, C. J., & Woodward, D. P. (1990). Visual attention modulates signal detectability. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 802-811.

Henderson, J. M. (1996). Spatial precues affect target discrimination in the absence of visual noise. *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 780-787.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye. In J. [B.] Long & A. [D.] Baddeley (Eds.), *Attention and performance IX* (pp. 187-203). Hillsdale, NJ: Erlbaum.

Kawahara, J., Di Lollo, V., & Enns, J. T. (2001). Attentional requirements in visual detection and identification: Evidence from the attentional blink. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 969-984.

Kinchla, R. A., Chen, Z., & Evert, D. (1995). Precue effects in visual search: Data or resource limited? *Perception & Psychophysics*, **57**, 441-450.

Kovács, G., Vogels, R., & Orban, G. A. (1995). Cortical correlate of backward pattern masking. *Proceedings of the National Academy of Sciences*, **92**, 5587-5591.

Lee, D. K., Koch, C., & Braun, J. (1997). Spatial vision thresholds in the near absence of attention. *Vision Research*, **37**, 2409-2418.

Lu, Z.-L., & Dosher, B. A. (1998). External noise distinguishes attentional mechanisms. *Vision Research*, **38**, 1183-1198.

Lu, Z.-L., Lesmes, L. A., & Dosher, B. A. (2002). Spatial attention excludes external noise at the target location. *Journal of Vision*, **2**, 312-323.

Luck, S. J., Hillyard, S. A., Mouloua, M., Woldorff, M. G., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: Psychophysical and electrophysical evidence. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 887-904.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. Cambridge: Cambridge University Press.

McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Review*, **86**, 287-330.

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**, 347-370.

Müller, H. J., & Findlay, J. M. (1987). Sensitivity and criterion effects in the spatial cuing of visual attention. *Perception & Psychophysics*, **42**, 383-399.

Müller, H. J., & Humphreys, G. W. (1991). Luminance-increment detection: Capacity-limited or not? *Journal of Experimental Psychology: Human Perception & Performance*, **17**, 107-124.

Müller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 315-330.

Nachmias, J. (2002). Contrast discrimination with and without spatial uncertainty. *Vision Research*, **42**, 41-48.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, **29**, 1631-1646.

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.

Palmer, J., Ames, C. T., & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **19**, 108-130.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, **32**, 3-25.

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, **109**, 160-174.

Ramachandran, V. S., & Cobb, S. (1995). Visual attention modulates metacontrast masking. *Nature*, **373**, 66-68.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, **85**, 59-108.

Ratcliff, R., & Smith, P. L. (2004). A comparison of sequential-sampling models for two-choice reaction time. *Psychological Review*, **111**, 333-367.

Shaw, M. I. (1982). Attending to multiple sources of information: I. The integration of information in decision making. *Cognitive Psychology*, **14**, 353-409.

Shaw, M. I. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and the detection of luminance increments. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 109-121). Hillsdale, NJ: Erlbaum.

Shiu, L.-P., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 1037-1054.

Smith, P. L. (1995). Psychophysically-principled models of visual simple reaction time. *Psychological Review*, **102**, 567-593.

Smith, P. L. (1998). Attention and luminance detection: A quantitative analysis. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 105-133.

Smith, P. L. (2000a). Attention and luminance detection: Effects of cues, masks, and pedestals. *Journal of Experimental Psychology: Human Perception & Performance*, **26**, 1401-1420.

Smith, P. L. (2000b). Stochastic dynamic models of response time and accuracy: A foundational primer. *Journal of Mathematical Psychology*, **44**, 408-463.

Smith, P. L., Ratcliff, R., & Wolfgang, B. J. (2004). Attention orienting and the time course of perceptual decisions: Response time distributions with masked and unmasked displays. *Vision Research*, **44**, 1297-1320.

Smith, P. L., & Wolfgang, B. J. (2004). The attentional dynamics of masked detection. *Journal of Experimental Psychology: Human Perception & Performance* **30**, 119-136.

Sperling, G. (1960). The information available in brief stimulus presentations. *Psychological Monographs*, **74**, 1-29.

Swets, J. A. (1984). Mathematical models of attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 183-242). New York: Academic Press.

Tanner, W. P. (1961). Physiological implications of psychophysical data. *Annals of the New York Academy of Sciences*, **89**, 752-765.

Tata, M. S. (2002). Attend to it now or lose it forever: Selective attention, metacontrast masking, and object substitution. *Perception & Psychophysics*, **64**, 1028-1038.

Thomas, J. P., & Gille, J. (1979). Band widths of orientation channels in human vision. *Journal of the Optical Society of America*, **69**, 652-660.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.

Van Zandt, T. (2000). ROC curves and confidence judgments in recognition memory. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **26**, 582-600.

Vickers, D. (1978). An adaptive module for simple judgments. In J. Requin (Ed.), *Attention and performance VII* (pp. 599-618). Hillsdale, NJ: Erlbaum.

Watson, A. B. (1986). Temporal sensitivity. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and performance* (Vol. 1, pp. 6.1-6.85). New York: Wiley.

NOTES

1. Along with signal enhancement and noise reduction, some authors consider an additional mechanism of *distractor exclusion*. As has been shown by Shiu and Pashler (1994) and Foley and Schwarz (1998), there may be a large distractor exclusion effect when there are multiple distractor stimuli in the display. We use the term *reducible noise* to refer to the effects of all sources of nontarget stimulation that vary with uncertainty. This includes the effects both of distractor stimuli and of internal and external noise. Since there were no distractor stimuli in our displays, the distinction between these various noise sources is incidental to the purpose of our study.

2. Where the same observers served in multiple experiments, we attempted, as far as was possible, to counterbalance the order in which the experiments were performed. There was no indication that the magnitude of the cuing effects shown by any observer depended on task order.

3. Carrasco et al. (2000) tested whether the cuing effect obtained empirically, averaged across spatial frequencies, differed from that predicted under noise reduction by the SDT model, using a t test. In view

of the pattern of spatial frequency dependencies apparent in their plots, which show good agreement between data and model at high spatial frequencies but systematic discrepancies at low frequencies, it may have been more diagnostic to have tested the condition × spatial frequency interaction with an analysis of variance.

4. The decision mechanism in the AGSI model was formulated by Smith and Wolfgang (2004) as an Ornstein–Uhlenbeck (OU) diffusion process, which is similar to the decision mechanism proposed in the successful model of Ratcliff (1978), except that the accumulation mechanism is an imperfect, or "leaky," one, which bounds the growth of the SNR on each experimental trial (Busemeyer & Townsend, 1993; Smith 1995, 2000b). At present the issue of decay in decision models is a controversial one. A number of recent models have included decay on theoretical grounds, to reflect the saturation properties of the underlying neural mechanisms. However, in a recent evaluation of sequential-sampling models, Ratcliff and Smith (2004) found little or no empirical evidence for decay. The AGSI model's predictions of mask-dependent cuing do not depend on the assumption of decision stage decay. They do, however, depend on the assumption that the decision mechanism samples from a decaying perceptual trace.

APPENDIX
Calculation of Sensitivity Measures

We considered a number of sensitivity measures based on the ROC space in addition to d_a, including A_g, which measures the area under a polygonal approximation to the ROC curve (Macmillan & Creelman, 1991; Equation 4.10), and $P(A)$, the area under the ROC curve obtained by fitting a normal, unequal variance signal detection model using maximum likelihood (Dorfman & Alf, 1969). Although the latter is arguably the most direct measure of this kind, in our data it failed to provide a good description of the empirical ROC curves at high levels of contrast for some observers. These failures to fit appeared to be due to errors in the predicted frequencies of use of high-confidence responses. Such discrepancies are emphasized by maximum likelihood's sensitivity to prediction errors in the tails of the noise and signal distributions. Although d_a also assumes a normal, unequal signal detection model, it differs from $P(A)$ in that it weights prediction errors at high and low levels of confidence equally. As a result, it is less sensitive to prediction errors associated with high-confidence responses. The measure A_g has the advantage that, unlike both $P(A)$ and d_a, it does not assume a parametric model for the noise and signal distributions but has the disadvantage that it underestimates the area under the ROC curve.

We considered two different methods for obtaining the slope and intercept of the *z*ROC line: simple linear regression, which assumes that scores on the predictor variable are measured without error, and a generalized regression procedure, which assumes the ratio of the measurement errors on the predictor and criterion variables are known (Draper & Smith, 1998). Under these circumstances, the slope and intercept of the best-fitting straight line are

$$\beta_1 = \frac{S_{YY} - \lambda S_{XX} + \left[\left(S_{YY} - S_{XX}\right)^2 + 4\lambda S_{XY}^2\right]^{1/2}}{2S_{XY}} \tag{A1}$$

and

$$\beta_0 = \overline{Y} - \beta_1 \overline{X}, \tag{A2}$$

respectively. In these equations, S_{YY}, S_{XX}, and S_{XY} are the sums of squares of the Y and X variables (i.e., the hits and false alarms) and the sum of cross products, respectively. The values $\overline{Y}$ and $\overline{X}$ are the means of the Y and X variables and $\lambda = \sigma_\epsilon^2/\sigma_\delta^2$, the ratio of the variances of the measurement errors in the Y and X variables.

To apply Equations A1 and A2 to *z*ROC data, we calculated asymptotic variance estimates for the observed *z*-transformed proportions of hits and false alarms, using the method of Gourevitch and Galanter (1967; see also Smith, 2000a, Appendix.) We then set σ_ϵ^2 and σ_δ^2 equal to the averages of the variance estimates for hits and alarms, respectively. Values of d_a obtained in this way showed fairly good agreement with the values obtained by simple linear regression. This agreement was expected because there were five times as many noise trials as signal trials in the design. This meant that the measurement errors in the estimated proportions of false alarms were much smaller than those in the estimated proportions of hits.

Values of d_a were calculated for cued and neutral trials for each of the five levels of contrast for each observer. A resampling (bootstrap) procedure was used to estimate standard errors for each value of d_a (Draper & Smith, 1998; Efron & Gong, 1983). To do this, 250 sets of simulated confidence ratings were generated by sampling, with replacement, from the distributions of experimentally obtained confidence ratings. Each set of simulated ratings was based on the same number of trials as was its empirical counterpart. For each of the 250 simulated data sets, a value of d_a was calculated, and the standard deviation of the resulting set of values was used as an empirical estimate of the standard error of d_a. These estimates were used to calculate goodness-of-fit statistics in Equation 3.

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