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Attentional mechanisms in visual signal detection: The effects of simultaneous and delayed noise and pattern masks

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The attentional cuing effects in detection and some discrimination tasks depend on the use of backward masks and on the presence of external noise in the display. These effects have been attributed to an interruption masking mechanism, which terminates stimulus processing prematurely, and an external noise exclusion mechanism, which minimizes the perceptual effects of noise. To test whether the dependencies on masking and external noise are expressions of a single mechanism, observers detected grating patch stimuli, masked with noise masks or pattern masks, presented either simultaneously or after a delay of 60–90 msec. Contrary to an external noise exclusion account, but consistent with an interruption masking account, cuing effects were largest when the masks were delayed. However, weaker cuing effects were obtained with simultaneous masks, contrary to an interruption masking account. These results suggest that attentional effects in simple visual judgments are affected by mechanisms of both kinds.

Studies of the effects of attention on early visual processing have shown that attention and visual masking mechanisms are functionally interdependent: Attention reduces the effectiveness of some forms of masks (Enns & Di Lollo, 1997; Ramachandran & Cobb, 1995), and masking increases the effects of attention in some visual tasks (Giesbrecht & Di Lollo, 1998; Kawahara, Di Lollo, & Enns, 2001; Morgan, Ward, & Castet, 1998). For attention researchers, the link between attention and masking is an important one because of the light it can shed on how attention affects visual processing. To this end, in a series of recent studies we investigated the relationship between attention and masking in visual signal detection (Smith, 2000; Smith, Ratcliff, & Wolfgang, 2004; Smith & Wolfgang, 2004; Smith, Wolfgang, & Sinclair, 2004). These studies addressed the fundamental but still controversial question of whether detection sensitivity is increased locally for attended signals.

The idea that attentional effects can be identified theoretically with local increases in detection sensitivity is closely related to the classical idea of attention as a limited-capacity mechanism (Broadbent, 1958). As in the classical model, the benefits conferred by attention are necessarily selective and local because of the capacity-limited nature of the system. Capacity-limited effects need to be distinguished carefully, both theoretically and methodologically, from the statistical effects of stimulus uncertainty. Uncertainty effects will be present whenever observers lack foreknowledge of the location of the target stimulus in the visual field (Pelli, 1985; Tanner, 1961). This increases the number of visual channels that must be monitored to perform the task and so increases the noisiness of perceptual decision making. Because uncertainty often covaries with manipulations of attention and affects performance even in unlimited-capacity systems, capacity limitations can be inferred only from attentional effects exceeding those predictable on the basis of uncertainty alone (Eckstein, Thomas, Palmer, & Shimozaki, 2000; Palmer, Verghese, & Pavel, 2000; Shaw, 1984; Smith, 1998).

We have found that when stimuli are equated for detectability and uncertainty effects are properly controlled for, attentional cuing increases detection sensitivity only when stimuli are backwardly masked; when stimuli are not masked, cues do not change sensitivity. We refer to this as the *mask-dependent cuing effect*. We have shown that the effect is obtained for the range of stimulus–mask onset asynchronies over which Bloch's law (stimulus time–intensity reciprocity) holds (Smith, 2000). We have shown that it occurs across the entire psychometric function for contrast, with perhaps a slight tendency to decline at high contrasts (Smith, Wolfgang, & Sinclair, 2004). We have also shown that it is preserved and, indeed, somewhat enhanced under dichoptic viewing conditions, in which the target stimulus and the mask are presented to different eyes (Smith & Wolfgang, 2004). Any interaction between stimuli and masks under these conditions occurs only in the primary visual cortex or later, so this finding implies that the mask dependencies in the cuing effect reflect cortical, rather than peripheral, processes. Together, these findings appear to resolve the inconsistencies in the

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visual signal detection literature, in which the majority of studies showing significant attentional effects have been performed with masked stimuli, whereas the majority of studies showing no effect have been performed without masks (see Smith, 2000, Table 1).

We have proposed two different quantitative models of the mask-dependent cuing effect (Smith, Ratcliff, & Wolfgang, 2004; Smith & Wolfgang, 2004). The models assume different attentional mechanisms, but both assume that masks limit the time during which stimulus information is available to later processing stages; that is, they assume that masks act to *interrupt* stimulus processing (Kahneman, 1968). One model assumes that attention affects the rate at which stimulus information is accumulated by a sequential-sampling decision mechanism (Smith, 2000; Smith & Wolfgang, 2004; cf. Carrasco & McElree, 2001). The second model assumes that the act of orienting to a stimulus opens an attention window, admitting stimulus information into visual short-term memory (Smith, Ratcliff, & Wolfgang, 2004; cf. Posner, Snyder, & Davidson, 1980; Reeves & Sperling, 1986). Relative to attended stimuli, the opening of the attention window for miscued stimuli is delayed. In both models, attention interacts with the differential availability of stimulus information from masked and unmasked stimuli to produce mask-dependent cuing effects.

Visual Masking and External Noise Exclusion

In another series of studies on the role of attention in low-level visual tasks, Lu, Dosher, and colleagues have investigated the effects of attention on the discriminability of stimuli embedded in noisy backgrounds (Dosher & Lu, 2000a, 2000b; Lu & Dosher, 1998, 2000; Lu, Jeon, & Dosher, 2004; Lu, Lesmes, & Dosher, 2002). They have characterized performance in these tasks using a *perceptual template model*, an elaborated signal detection model that includes the effects of multiple noise sources, both internal and external. Although Dosher and Lu's experiments have focused on discrimination judgments and ours have focused on detection and its analogues, their results bear comparison with our own.

Perhaps the most striking finding from Dosher & Lu's studies is that the largest attentional effects are obtained with displays containing high levels of external noise. They attribute this to a general mechanism of *external noise exclusion*, which they characterize as an attention-dependent sharpening of the perceptual template that filters out noise at the target location. In noiseless displays, the attentional effects have typically been weaker and less systematic than those found when noise is present. They attribute these effects to a separate mechanism of *stimulus enhancement*, whose action is apparent only under low-noise conditions.

These findings lead to an obvious question: Are the mask-dependent cuing effects obtained in our studies merely another manifestation of external noise exclusion? That is, are mask-dependent cuing and external noise exclusion aspects of the same process? To the extent that the mask may be viewed as a source of external noise in the display, presented in close temporal proximity to the target, this identification is a plausible one, as has been argued by Lu et al. (2002). We investigate this question in this article.

The external noise exclusion mechanism proposed by Dosher, Lu, and colleagues is characterized by its properties under limiting high- and low-noise conditions. It predicts large attentional effects when stimuli are embedded in high levels of external noise and weak or no attentional effects when noise is absent. If performance in a given task is mediated by such a mechanism, reducing the level of external noise in spatiotemporal proximity to the stimulus should reduce the magnitude of the attentional effect. Or, to frame the prediction more conservatively, the magnitude of the attentional effect should not increase with decreases in the level of external noise. Since the mechanism's assumed function is to allow the extraction of stimulus information from a background of external noise, increasing the spatial or temporal separation between the noise and the stimulus and reducing the overall level of noise should reduce the magnitude of the external noise exclusion effect in a similar way. This characterization is supported by the results of Lu et al. (2004), who calculated that around 93% of the variance in the attentional effect in their data was explained by a temporally uniform reduction in the response of the perceptual template to external noise.

Table 1
Cuing Effects, Experiments 1–3

Observer	Stimulus Presentation: Successive	Simultaneous
	Experiment 1	
R.M.	38.98***	11.24*
S.W.	110.51***	2.57
C.A.	78.91***	21.58***
P.K.	134.00***	1.65
Group	90.60***	9.26*
	Experiment 2	
R.M.	81.06***	10.16*
S.W.	118.23***	0.27
C.A.	120.51***	16.28***
A.C.	57.59***	2.50
Group	94.35***	7.30
	Experiment 3	
R.M.	75.75***	5.78
S.W.	118.40***	8.07*
C.A.	131.99***	3.48
E.S.	111.60***	11.95**
Group	109.43***	7.32

Note—The test statistics are the difference in the goodness of fit of a single-function and a two-function Weibull model to the psychometric functions for cued and miscued conditions. The models were fitted by minimizing the chi-square statistic $\chi^2 = \sum[d'(c) - F(c)]^2 / \mathrm{var}[d'(c)]$. In this expression, var[$d'(c)$] is an asymptotic variance estimate for d' (Gourevitch & Galanter, 1967), and the summation extends over the 10 values of d' (five contrasts and two cue conditions) for a given stimulus configuration (successive or simultaneous). The fit statistics in the table were tested as chi-square variables with $df = 3$. *$p < .05$. **$p < .01$. ***$p < .001$.

EXPERIMENTS 1–3

We tested this prediction by varying the temporal separation between target and masking stimulus using two different forms of mask: a checkerboard pattern mask similar to that used in our previous studies, and a random noise mask similar to that used in a study of noise masking by Turvey (1973). The inclusion of the two forms of mask allowed a direct comparison with our previous studies, which used pattern masks, and with those of Lu, Dosher, and colleagues, which used noise masks.

We presented targets and masking stimuli either simultaneously, in interleaved frames, as in the studies by Lu, Dosher, and colleagues, or at a target–mask stimulus onset asynchrony (SOA) of 60 msec, as in our previous studies. These conditions were designed to promote *integration* masking and *interruption* masking, respectively. In the former, target and mask fuse to create a perceptual composite whose signal-to-noise ratio is lower than that of the target in isolation. In the latter, the mask interrupts processing of the target before it is completed (Breitmeyer, 1984). The aim of our experiments was to test whether increased temporal separation between target and mask would decrease the attentional effect, as predicted by an external noise exclusion account, or whether it would increase the effect, as predicted by an interruption masking account. Noise and pattern masks are known to behave differently under some conditions; for example, Turvey (1973) found that letters were masked by a dichoptic pattern mask, but not by a dichoptic noise mask. This raises the possibility that the two kinds of masks might interact differently with attention at different target–mask delays. The use of both kinds of masks in our study allowed us to investigate this possibility.

Method

Apparatus. Stimuli were presented on a linearized 17 in. Sony 200-PS monitor driven by a Cambridge Research Systems VSG 2/4 15-bit framestore housed in a Pentium computer. The frame rate of the VSG was set at 100 Hz, giving a frame duration of 10 msec. Stimulus presentation and response recording were controlled by software written in C++. Observers performed the task in a dimly

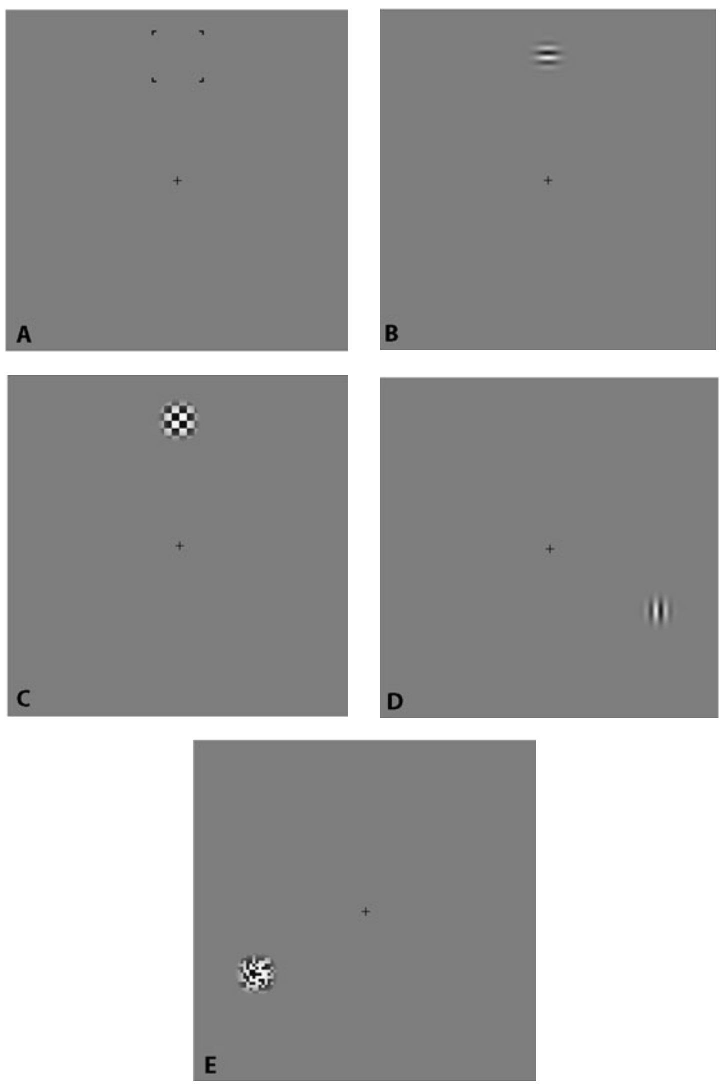

Figure 1. Example stimuli. (A) Peripheral cue. (B) Horizontal target at a cued location. (C) Pattern mask. (D) Vertical target at an uncued location. (E) Noise mask at the alternative uncued location.

lit laboratory at a viewing distance of 50 cm, with their viewing positions stabilized by a chinrest.

Stimuli and Display. Observers discriminated the orientations of horizontally and vertically oriented Gabor patches (Gaussian-vignetted sinusoidal gratings), presented on a 25º square, 30 cd/m^2, uniform field. The mathematical form of the Gabor patch stimuli was as given by Graham (1989, p. 53). The sinusoid had a spatial frequency of 3.5 cpd, and the Gaussian envelope had a space constant (full width at half height) of 0.463º, giving a bandwidth of 0.80 octaves. Examples of the stimuli are shown in Figure 1.

Perceptually, orthogonal discrimination and yes–no detection are similar tasks; both yield the same contrast thresholds (Thomas & Gille, 1979), implying that whenever a stimulus can be detected, its orientation can be discriminated and vice versa. A number of authors have argued that the two tasks are, therefore, also likely to be similar in their attentional resource demands (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lee, Koch, & Braun, 1997), suggesting that orthogonal discrimination can be used as a proxy for detection. Consistent with this, in Smith, Radcliff, and Wolfgang (2004), we showed that orthogonal discrimination yielded mask-dependent cuing effects identical to those found with yes–no detection in our previous studies. Methodologically, orthogonal discrimination has two advantages over yes–no detection: Response bias is typically small and independent of attentional manipulations, and sensitivity can be characterized using an equal-variance, rather than an unequal-variance, signal detection model (Green & Swets, 1966). These features simplify the task of obtaining reliable measures of sensitivity.

There were three potential stimulus locations on any trial, one cued and two miscued, located at an angular separation of 120º on the circumference of an imaginary 3.2º radius circle, centered on a fixation cross. On each trial, a randomly chosen angle, α ($0 < \alpha \leq 360$º), determined the position of the cued location. The possible uncued locations were at $\alpha \pm 120$º. The attentional cues consisted of four black right-angle markers that identified the corners of a 1.8º square centered on the target location. Cues were flashed for 60 msec at a cue–target SOA of 140 msec and then were extinguished. A weakly predictive cuing manipulation was used, in which stimuli appeared at the cued location with a probability of .50 and at either of the uncued locations with a probability of .25. The combination of a weakly predictive peripheral cue and a short SOA is likely to predominantly activate the *exogenous* (reflexive) orienting system. This manipulation was found to produce significant mask-dependent cuing effects by Smith, Ratcliff, and Wolfgang (2004). Evidence for external noise exclusion has been reported by Lu, Dosher, and colleagues with manipulations of both the exogenous orienting system and the *endogenous* (voluntary) orienting system (see Lu et al., 2004, for a summary).

The effects of two different mask configurations were compared. One was a 30% contrast, Gaussian-vignetted, checkerboard pattern mask, as used in our previous studies of mask-dependent cuing. The other was a 30% contrast random noise mask, constructed by applying a Gaussian vignette to an array of 2 × 2 pixel squares whose luminances were independently set to the minimum and maximum luminances of the display with a probability of .5. Examples of the two forms of masks are shown in Figure 1. Pattern masks were used in Experiment 1; noise masks were used in Experiments 2 and 3. The latter experiments were identical except for the temporal distributions of energy in the stimuli and masks, as described below. The noise masks presented on each trial of Experiments 2 and 3 were sampled with replacement from a set of 10 masks that were generated afresh at the beginning of each 20-trial experimental block.

Target stimuli and masks were presented in two conditions in each experiment: simultaneously (SIM) and successively (SUC). In the SIM condition, three target frames were presented in alternation with three mask frames (60-msec total stimulus duration) and combined by temporal integration. In the SUC condition, in Experiments 1 and 2, three consecutive target frames were followed by three blank frames and then by three consecutive mask frames to give a target–mask SOA of 60 msec. In the successive condition in Experiment 3, three target frames alternating with blank frames were followed by three mask frames, also alternating with blank frames, again giving an SOA of 60 msec. The latter configuration held the temporal distribution of target and mask energy constant across SIM and SUC trials. We did not expect the particular distribution of target energy on SUC trials to affect the results of these experiments, because of the temporal integration properties of the visual system, but we carried out Experiment 3 as verification. The frame sequence used to construct the various stimulus types is shown inset in Figure 2.

Design. The experiments were run using the method of constant stimuli in a three-way contrast (5 levels) × cue (cued, miscued) × mask (SIM, SUC) design. Five levels of stimulus contrast were chosen individually for each observer during practice to span a range of performance from near chance to near perfect. Stimulus contrast, cue condition, and mask condition were randomized across trials in each experimental session. Each of the observers in each experiment served in 5 practice sessions followed by 16 experimental sessions, each consisting of 400 trials, yielding a total of 6,400 trials per observer.

Procedure. Observers were instructed to try to perform the task accurately but not to spend too much time on each decision. They were instructed to maintain central fixation for the duration of each trial but to use the cue to direct their attention to the cued location. Each trial began, after a 3-sec intertrial interval, with presentation of the fixation cross 1 sec before the cue. This served as a warning signal and as an instruction to maintain fixation. The stimulus and mask were presented 140 msec after the onset of the cue. The observers indicated their decisions by pressing one of two microswitched response buttons and were given accuracy feedback auditorily by distinctive tones. Summary accuracy feedback was also provided on the visual display at the end of each 20-trial block. Because the time from cue onset to mask onset (200 msec) was too short to refixate the display (Robinson, 1965), eye movements were not monitored.

Observers. The observers were drawn from a pool of 6 paid undergraduates, all with normal vision, who were naive as to the purpose of the study. Three of the observers (R.M., S.W., and C.J.) served in all three experiments; the remaining observers (A.C., P.K., and E.S.) served in one experiment only, yielding 4 observers per experiment.

Results

The proportions of correct responses to horizontal and vertical stimuli, $P_H(C)$ and $P_V(C)$, for each observer in each stimulus condition were converted to d' sensitivity measures using the formula

$$d' = \frac{z[P_H(C)] + z[P_V(C)]}{\sqrt{2}},$$

where $z[.]$ denotes the inverse normal (z-score) transformation. The factor of $\sqrt{2}$ in the denominator in this expression puts d' values from a two-alternative forced choice task onto the same scale as those from a yes–no task (Green & Swets, 1966). The effects of cuing were evaluated by fitting Weibull functions to the psychometric functions for each observer, using the methods described in Smith, Wolfgang, and Sinclair (2004). These fits are shown in Figure 2. For the SIM and SUC conditions, two models of the psychometric functions for each observer were compared. One was a single-function model in which the same Weibull function was fitted to the data for cued and miscued stimuli; the other was a two-function model in which the cued and miscued stimuli were fitted with different functions. Cuing effects were inferred if the two-function model provided a better fit than the

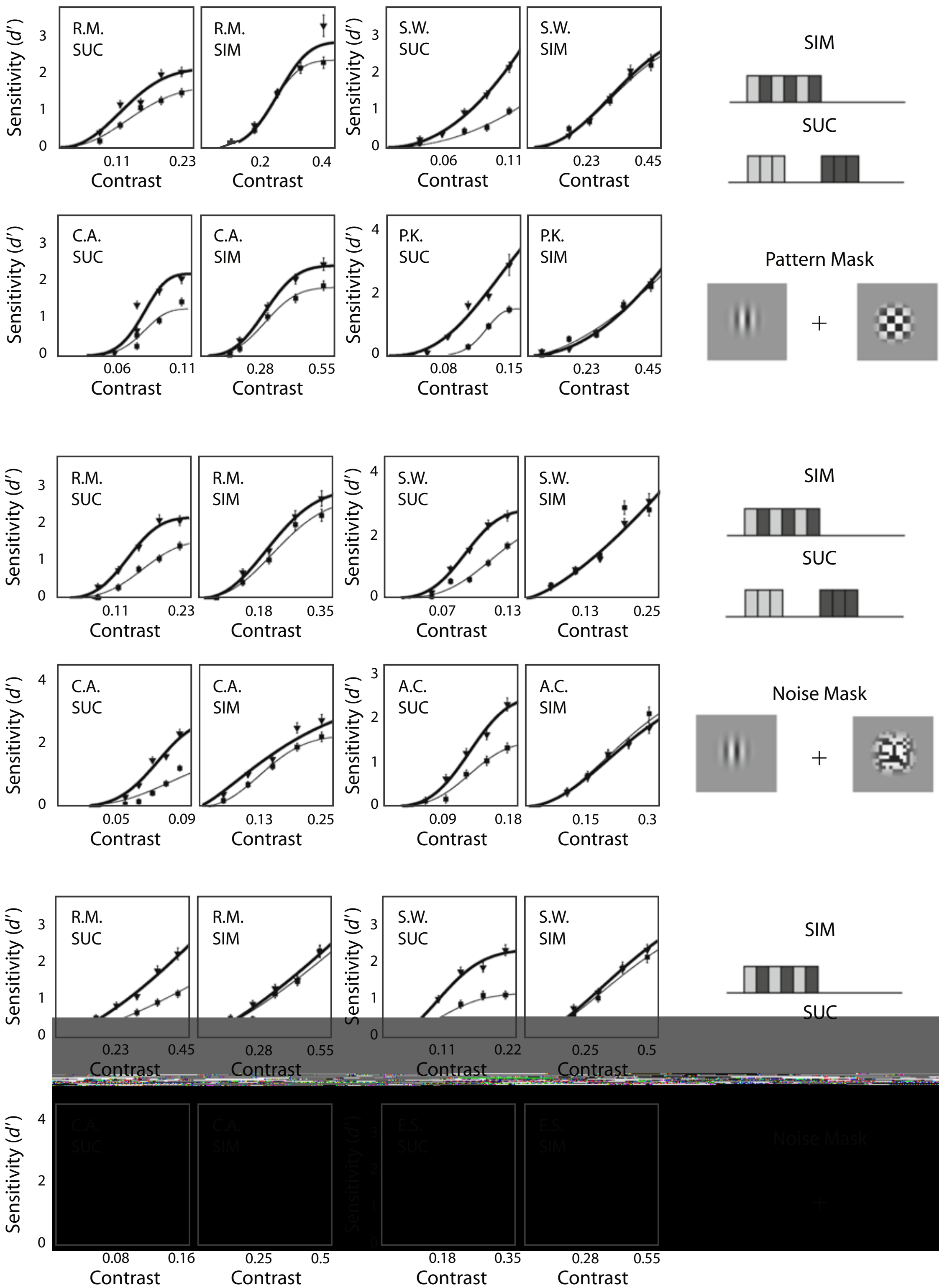

Figure 2. Results of Experiments 1–3. Top, Experiment 1; middle, Experiment 2; bottom, Experiment 3. Triangles and heavy lines are cued stimuli; squares and light lines are miscued stimuli. The insets on the right show the stimulus configurations. The icons at the top of each inset show the temporal structure of stimuli on simultaneous (SIM) and successive (SUC) trials. Each rectangle represents one 10-msec frame: Light rectangles are stimulus frames; dark rectangles are mask frames. The fitted curves are Weibull functions of the form $F(c) = \alpha\{1 - \exp[(c/\beta)^\gamma]\}$. In this expression, c is stimulus contrast, and α, β, and γ are amplitude, dispersion, and shape parameters, respectively. The error bars are $\pm SE\ (d')$. The standard errors were calculated using asymptotic variance estimates (see the note to Table 1).

stances, even when stimulus contrast is near threshold and no masks are used, the pedestal localizes the decision to a unique position in the display. Other investigators have used various forms of reporting cue, presented simultaneously with the stimulus (Eckstein, Pham, & Shimozaki, 2004; Lu et al., 2003) or delayed by several hundred milliseconds (Downing, 1988; Hawkins et al., 1990; Lu & Dosher, 1998; Müller & Humphreys, 1991; Smith, 1998), to localize decisions in a similar way. In all of the experiments we have carried out using the pedestal task, we have obtained reliable cuing effects with backwardly masked stimuli for all, or for a majority, of observers (Smith, 2000; Smith, Ratcliff, & Wolfgang, 2004; Smith & Wolfgang, 2004; Smith, Wolfgang, & Sinclair, 2004).

Because the onset and offset of the pedestal and stimulus coincide in the pedestal task, there is no delay in the availability of localizing information. The fact that reliable cuing effects are obtained with backwardly masked pedestal stimuli argues against the interpretation that the cuing effects found with trailing masks in Experiments 1–3 could be attributed to delays in stimulus localization. Nevertheless, our previous work does provide some hints that the timing of localizing information might influence the magnitude of the cuing effect with masked stimuli.

One hint comes from Experiments 1 and 2 of Smith (2000). These experiments investigated the cuing effect for backwardly masked stimuli, presented with or without pedestals (Experiments 1 and 2, respectively). All observers in both experiments showed significant cuing effects, consistent with the idea that, when stimuli are followed by backward masks, the presence or absence of the localizing information in the pedestal is not critical to whether a cuing effect is obtained. However, the average cuing effects for all three target–mask SOAs (30, 60, and 90 msec) were somewhat smaller when a pedestal was used, although the difference between pedestal and no-pedestal conditions was small, relative to the individual differences among observers. The second hint comes from the fact that the average gain estimates for SUC presentation in the present study (Figure 3) are roughly twice those typically obtained with the pedestal task (Smith, Wolfgang, & Sinclair, 2004).

One plausible interpretation of these findings is that both interruption masking and the timing of localizing information contribute to the cuing effect. When the sole source of localizing information is a trailing mask, large cuing effects are obtained; when there is an independent source of localizing information, coinciding with stimulus onset rather than offset, the magnitude of the cuing effect is reduced. We sought to characterize the relative contributions of localizing information and backward masking to the cuing effect in Experiments 4 and 5.

EXPERIMENTS 4 AND 5

Experiments 4 and 5 were designed to replicate the findings of Experiments 1–3 with stimuli that were localized at onset. The stimulus and mask configuration was similar to that of Experiment 3 except that the stimuli were localized with fiducial crosses. The fiducial cross, which we adapted from Eckstein et al. (2004), consisted of four white line segments that formed the arms of a cross, centered on the stimulus. The cross appeared at the same time as the Gabor patch and remained present for 60 msec. Examples of the resulting stimulus configuration are shown in the insets to Figure 4.

Because the fiducial cross plays the same role in localizing the stimulus as does the pedestal in the pedestal task, we expected the combination of fiducial cross and backward mask to produce cuing effects similar to those found previously in the pedestal task. We were therefore surprised to find that, with an initial sample of three observers and a target–mask SOA of 60 msec, none of the observers showed a cuing effect with either noise or pattern masks when fiducial crosses were present. One of the authors (P.S.) acted as an observer and confirmed this null result.

Taken at face value, the null results with a fiducial cross and a backward mask appear to imply that the large cuing effects obtained with SUC presentation in Experiments 1–3 could be attributed wholly to a delay in target localization. However, this conclusion is at odds with the findings from the pedestal task, in which reliable cuing effects are obtained with stimuli that are localized at onset. We therefore undertook extensive pilot testing to identify the reason for the discrepancy between the two paradigms. The factors that might potentially have been responsible for the difference were the way in which the stimuli were localized (pedestal vs. fiducial cross) and the contrast, form, and duration of the mask. Whereas the masks used in Experiments 1–3 and in the pilot testing for Experiments 4 and 5 were of comparatively low contrast and brief duration, the masks used in our previous studies with the pedestal task were of high contrast and long duration.

We found that the critical variable for obtaining a cuing effect was mask duration. Using an alternating-frame mask like that in Experiment 3, in which a 30% contrast checkerboard was interleaved with blanks, we were able to obtain a cuing effect with a mask in which 10 mask frames were interleaved with 9 blank frames (mask duration 190 msec). As the number of mask frames was reduced, the cuing effect began to break down. This occurred at around 4 or 5 mask frames (mask duration of 70–90 msec). At this point, the contours of the stimulus began to be visible through the mask. This "breaking through" of the mask by the target coincided with the breakdown of the cuing effect. We also found that we could restore the cuing effect by increasing target–mask SOA. With a three-frame mask, we were able to obtain a fairly reliable cuing effect by increasing the SOA from 60 to 90 msec. These observations parallel those of Macknik and Livingstone (1998), who found that maximum backward masking in a metacontrast masking paradigm occurred at shorter interstimulus intervals for longer duration masks.

We were motivated to explore the effects of changing the SOA by Francis's (2003) theory of *efficient masking*. Efficient masking is a form of interruption masking in which the masking effect depends on the time-varying difference in the encoded sensory representations of the stimulus and mask. Because the sensory representation of the stimulus decays exponentially after stimulus offset, maximum

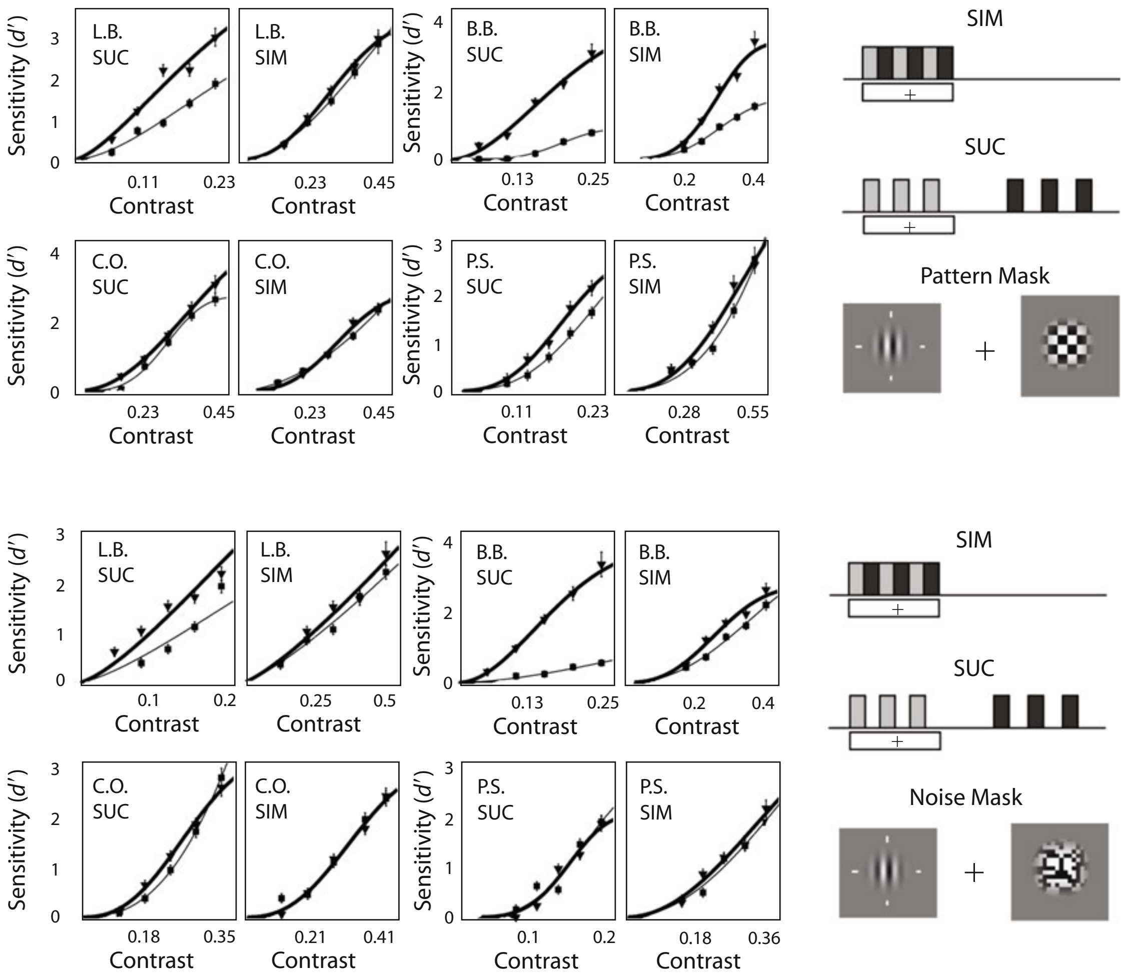

Figure 4. Results of Experiments 4 and 5. Top, Experiment 4; bottom, Experiment 5. Triangles and heavy lines are cued stimuli; squares and light lines are miscued stimuli. The insets on the right show the stimulus configurations. Light rectangles are stimulus frames; dark rectangles are mask frames. Masks were presented at an SOA of 90 msec. The fiducial cross consisted of four arms of a white cross centered on the Gabor patch. Fiducial crosses were presented for six frames (60 msec) beginning with the first stimulus frame. The rectangles labeled "+" below the stimulus frames shows the time course of the fiducial crosses on successive (SUC) and simultaneous (SIM) trials.

masking is obtained not when the mask immediately follows the stimulus, but when it is delayed. This allows time for the stimulus representation to decay, reducing its strength relative to that of the trailing mask. The finding that we could obtain a cuing effect with a three-frame mask if we increased the SOA to 90 msec allowed us to make a direct comparison of SIM and SUC presentation, as we did in Experiments 1–3. We therefore used this stimulus-mask configuration in Experiments 4 and 5.

Method

Stimuli. The stimuli for Experiments 4–5 and the associated event sequences are shown in Figure 4. In the SIM condition, the stimuli consisted of three Gabor patch frames interleaved with three mask frames, yielding a 60-msec target–mask composite. In the SUC condition, the stimuli consisted of three Gabor patch frames interleaved with blank frames, followed, after an SOA of 90 msec, by three mask frames interleaved with blanks. Checkerboard masks were used in Experiment 4, and noise masks were used in Experiment 5. The fiducial cross was composed of four 2.5 × 8 in. white lines, centered on the Gabor patch and located at a 9-in. separation from the edge of the Gaussian envelope. The fiducial crosses were presented for six consecutive frames (60-msec total), the first coinciding with the first frame of the target. Pilot testing ensured that the precues and fiducial crosses were perceptually distinct stimuli and that the precues had no subjectively perceivable forward-masking effect on the fiducial crosses. Apart from the addition of fiducial crosses and the increase in target–mask SOA, the cues, stimuli, cue–target contingencies, and the timing of the display were the same as those in Experiments 1–3.

Observers. Three paid graduate student volunteers (L.B., B.B., C.O.) and one of the authors (P.S.) served as observers. The volunteers were experienced psychophysical observers but were naive as to the purpose of the study. All 4 observers served in both experiments, in counterbalanced order.

Design and Procedure. The design and procedure for Experiments 4 and 5 were the same as those of Experiments 1 to 3. Following initial calibration sessions, each observer served in a total of 16 sessions per experiment, yielding a total of 6,400 trials per observer in each experiment.

Results and Discussion

Figure 4 shows Weibull function fits to the psychometric functions for each observer in each of the two experiments. The corresponding gain estimates are shown in Figure 5. As in the previous experiments, cuing effects were assessed by comparing the fits of a two-function model and a one-function model to the psychometric functions for cued and miscued stimuli. These fits are summarized in Table 2.

The psychometric functions in Figure 4 and the corresponding goodness-of-fit statistics in Table 2 show the same overall patterns that were found in Experiments 1–3, although the spread of individual differences is greater and the separation between SUC and SIM conditions is somewhat less pronounced. Whereas all 12 tests of the cuing effect with trailing masks in Experiments 1–3 were highly significant, only 9 of the 10 tests in Experiments 4 and 5 were significant. (The nonsignificant result was for P.S. with a trailing noise mask.) Two observers in each experiment showed significant cuing effects with simultaneous masks (B.B. and P.S. in Experiment 4; L.B. and B.B. in Experiment 5), replicating the findings of Experiments 1–3.

The greater magnitude of the cuing effect with trailing masks is reflected in the relative size of the goodness-of-fit statistics for SUC and SIM presentation. For six of the eight tests of the cuing effect in the two experiments, the chi-square values were appreciably larger with trailing masks than with simultaneous masks. This difference is also reflected in the average goodness-of-fit values. Although the average chi-squares were significant for both the SUC and the SIM conditions in both experiments, the SUC values were much larger than the corresponding SIM values.

The large standard errors for the gain estimates in Figure 5 reflect the comparatively large range of individual differences in the cuing effects in Experiments 4 and 5. Despite the individual differences, there is still a fairly clear separation between the gain curves for the SUC and SIM conditions. Except at high contrasts, where gain estimates for SUC and SIM presentation converge, average gain for SUC presentation exceeded that for SIM presentation, again replicating the results of Experiments 1–3.

The decrease in gain at high contrasts with SUC presentation in Experiments 1 and 2 was also found in Experiments 4 and 5. The decrease was particularly pronounced in Experiment 4, where pattern masks were used, and where gain showed a large and systematic decrease across the contrast range. In Experiment 5, where noise masks were used, gain initially increased before decreasing. It is tempting to ascribe the different patterns of gain at low contrast in the two experiments to differences in the interruption masking properties of noise and pattern masks (cf. Turvey, 1973). However, it is not clear how reliable these differences are, given the variability of estimates in this part of the gain curve. In contrast, the decrease in gain at high stimulus contrasts does appear to be systematic, appearing in four of the five experiments (with Experiment 3 being the exception). The magnitude of the decrease differs from the corresponding effect for the pedestal task, reported by Smith, Wolfgang, and Sinclair (2004). Although the gain estimates with backwardly masked stimuli reported in that study also tended to decrease at high contrasts, the size of the decrease found there was much smaller.

A likely reason for the different patterns of gain found by Smith, Wolfgang, and Sinclair (2004) and found here is the difference in mask energies and associated target–mask energy ratios. Whereas that study used high-energy masks (high contrast, long duration), the energy of the masks in the present study was much lower (low contrast, short duration). Consequently, the target-to-mask energy ratios in this study were much smaller than those in the study of Smith, Wolfgang, and Sinclair (2004). In pilot testing, with a target–mask SOA of 60 msec and a fiducial cross, we found that the cuing effect began to break down as mask duration was reduced. At short durations, the mask seems to have been acting primarily as an integration mask, fusing with the stimulus into an identifiable perceptual composite. Percepts of this kind have not been

Table 2
Cuing Effects, Experiments 4 to 5

Observer	Stimulus Presentation: Successive	Simultaneous
	Experiment 4	
L.B.	103.60***	3.73
B.B.	296.41***	133.82***
C.O.	13.09**	3.73
P.S.	22.74***	7.04*
Group	108.96***	37.08***
	Experiment 5	
L.B.	62.41***	6.64**
B.B.	309.89***	23.18***
C.O.	8.95*	0.08
P.S.	1.64	2.53
Group	95.73***	8.12*

Note—The test statistics are the difference in the goodness of fit of a single-function and a two-function Weibull model to the psychometric functions for cued and miscued conditions. The models were fitted by minimizing the chi-square statistic $\chi^2 = \sum[d'(c) - F(c)]^2 / \mathrm{var}[d'(c)]$. In this expression, var[$d'(c)$] is an asymptotic variance estimate for d' (Gourevitch & Galanter, 1967), and the summation extends over the 10 values of d' (five contrasts and two cue conditions) for a given stimulus configuration (successive or simultaneous). The fit statistics in the table were tested as chi-square variables with $df = 3$. $^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

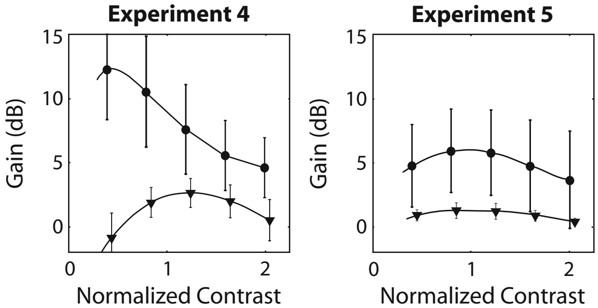

Figure 5. Average attentional gain for simultaneous trials (triangles) and successive trials (circles) in Experiments 4 to 5.

apparent with the long mask durations used in previous studies with the pedestal task.

The idea that the cuing effects break down at the kinds of target–mask energies that result in an identifiable target–mask composite is consistent with the finding that gain decreased at high contrasts with SUC presentation. A reduction of this kind occurred in all but one of the experiments reported here. It is also consistent with the finding, in both Experiments 4 and 5, that at high contrasts, the average gain estimates for SUC presentation converged toward those for SIM presentation. These results would be expected if short-duration, low-energy trailing masks acted as integration masks at high stimulus contrasts.

GENERAL DISCUSSION

The aim of this study was to ascertain whether mask-dependent cuing effects in detection could be attributed to the action of an external noise exclusion mechanism. If external noise exclusion is maximal when targets and noise are presented simultaneously and decreases as the separation between them is increased, our data allow this question to be answered in the negative. Contrary to this prediction, for all observers and all mask configurations the largest cuing effect was obtained when masks trailed targets by 60–90 msec, not when they were simultaneous. These conditions are optimal, or near optimal, for obtaining interruption masking (Turvey, 1973). Whereas integration masking effects are maximal at a target–mask SOA of zero and decrease symmetrically with increases in SOA for leading and trailing masks, interruption masking effects are maximal with masks that trail the target by a critical delay, usually 50–100 msec (Breitmeyer, 1984).

Further evidence that interruption masking is fundamental to the cuing effect in detection comes from our unexpected observation that the effect was abolished by the addition of a fiducial cross but could be restored by increasing the target–mask SOA from 60 to 90 msec. Although a parametric study is needed to characterize these effects fully, the fact that the cuing effect could be increased by increasing SOA also appears to implicate an interruption masking mechanism of some kind, as implied by Francis's (2003) theoretical analysis. We are currently undertaking a parametric study of this kind.

In implicating a specific, interruption masking dependent component of the attentional cuing effect, our results are consistent with those of Giesbrecht and Di Lollo (1998), who investigated the role of masking in the production of an attentional blink. They found that an attentional blink was obtained only if the second of two consecutive targets in a rapid serial visual presentation stream was masked by an interruption mask (i.e., by a subsequent character in the stream). Masking of the first target was also needed to obtain a blink, but, unlike for the second target, masking of the first target by an integration mask (zero target–mask SOA) and an interruption mask (100-msec target–mask SOA) were equally effective.

Our results are also consistent with those of Smith and Wolfgang (2004), who found greater cuing benefits with dichoptic than with monoptic masks. They argued that the strength of interruption masking under dichoptic conditions should exceed that obtained under monoptic or binocular conditions because targets and masks presented dichoptically cannot fuse in primary afferent pathways before reaching the visual cortex. Consequently, any cuing effect that depends on interruption masking for its occurrence should be maximal with dichoptic presentation.

Although the cuing effects here were largest in the SUC condition, significant cuing effects were found in the SIM condition for half of the observers in all five experiments. These effects cannot plausibly be attributed to an interruption masking mechanism. They also contrast with the results of our previous studies using spatially localized, unmasked stimuli, in which no cuing effects of any kind were obtained (Smith, 2000; Smith, Ratcliff, & Wolfgang., 2004; Smith & Wolfgang, 2004; Smith, Wolfgang, & Sinclair, 2004). Given the temporal properties of the SIM stimuli, the weaker cuing effects they produced may reflect the action of an external noise exclusion mechanism of the kind proposed by Dosher and Lu. Unlike Dosher and Lu, however, who have reliably found large external noise exclusion effects, the corresponding effects in our data are relatively weak and inconsistent.

A possible theoretical basis for these differences was suggested by Smith, Wolfgang, and Sinclair (2004). Their analysis suggests that the effects of external noise will be smaller in detection and its analogues, which we have studied here, than in discrimination, which has been studied by Lu, Dosher, and colleagues. Smith, Wolfgang, and Sinclair (2004) based their arguments on the model of Smith and Wolfgang (2004), in which attention affects the rate at which stimulus information is accumulated by a central decision mechanism and masks limit the informational persistence of the stimuli. In this model, cuing effects in sensitivity depend on the relative durations of two processes: the accumulation of stimulus information by the decision mechanism, and the iconic decay of the stimulus (or its rapid suppression by a trailing mask). If the accumulation time is less than the decay time, detection sensitivity will be unaffected by attention-dependent differences in accumulation rate. If the accumulation time exceeds the decay time, sensitivity will be greater for cued than for uncued stimuli, because information is accumulated more rapidly from attended than for unattended stimuli, and consequently, sensitivity will be greater for attended stimuli since more information can be accumulated about them before they decay.

Under the assumptions that (1) decay time is longer for unmasked than for backwardly masked stimuli, (2) the accumulation rate is slower for discrimination than for detection, and (3) external noise slows the accumulation rate for both detection and discrimination, the model predicts different-sized cuing effects in different tasks (see Smith & Wolfgang, 2004, Figure 10, or Smith, Wolfgang, & Sinclair, 2004, Figure 9). These predictions also assume that trailing masks interrupt stimulus processing, affecting the decay time, whereas simultaneous masks add noise to the stimulus, affecting the accumulation rate. Under these circumstances, the model predicts mask-dependent cuing effects for sensitivity in detection but unconditional effects in discrimination. Unconditional cuing effects in discrimination, independent of masks or noise, were reported by Cameron, Tai, and Carrasco (2002). The model also predicts that attentional effects in discrimination will be of greater magnitude than those in detection (Bonnel & Hafter, 1998; Brawn & Snowden, 2000; Kawahara et al., 2001) and that attentional effects will increase in the presence of external noise. Combined with the previous predictions, this implies weak external noise effects in detection and its analogues, as we have found, and strong external noise effects in discrimination, as found by Lu, Dosher, and colleagues.

Unlike us, Dosher and Lu have found little evidence for the involvement of an interruption-masking mechanism in the cuing effect. In the most relevant study (Lu et al., 2004), they varied the temporal separation between targets and noise but found scant evidence that the cuing effect changed with separation. Rather, they attributed most of the effect to a uniform reduction in the noise gain of the perceptual template. Only a small part of the cuing effect could be attributed to an increase in the efficiency with which noise from trailing masks was rejected.

It is likely that differences in the stimulus configurations used by Lu et al. (2004) and us may have contributed to the differences between their results and ours. Instead of trailing masks, they used a "noise sandwich" consisting of equal numbers of dynamically varying noise frames leading and trailing the stimulus. In comparison with our stimuli, this stimulus configuration is more likely to have produced integration masking, as they themselves remarked. In contrast, our stimuli, especially the trailing pattern masks, were specifically designed to produce interruption masking (Smith, 2000). Taken together, then, the findings from their studies and from ours suggest that masks may in fact engage two different kinds of mechanisms in attentional cuing tasks. One is an external noise mechanism in which masks affect signal-to-noise ratios, and, possibly, other, dynamic aspects of stimulus processing, such as rate of information accumulation, as well. The second is an interruption masking dependent mechanism that limits the availability of stimulus information to later processing stages.

AUTHOR NOTE

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REFERENCES

Bonnel, A.-M., & Prinzmetal, W. (1998). Dividing attention between simultaneous auditory and visual signals. *Perception & Psychophysics*, **60**, 113-124.

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.

Breitmeyer, B. G. (1984). *Visual masking: An integrative approach*. Oxford: Oxford University Press, Clarendon Press.

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

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.

Dosher, B. A., & Lu, Z.-L. (2000a). Mechanisms of perceptual attention in precuing of location. *Vision Research*, **40**, 1269-1292.

Dosher, B. A., & Lu, Z.-L. (2000b). 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.

Eckstein, M. P., Pham, B. T., & Shimozaki, S. S. (2004). The footprints of visual attention during search with 100% valid and 100% invalid cues. *Vision Research*, **44**, 1193-1207.

Eckstein, M. P., Thomas, J. P., Palmer, J., & Shimozaki, S. S, (2000). A signal detection model predicts the effects of set size on visual search accuracy for feature, conjunction, triple conjunction, and disjunction displays. *Perception & Psychophysics*, **62**, 425-451.

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

Francis, G. (2003). Developing a new quantitative account of backward masking. *Cognitive Psychology*, **46**, 198-226.

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.

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.

Kahneman, D. (1968). Methods, findings, and theory in studies of visual masking. *Psychological Bulletin*, **70**, 404-425.

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.

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., & Dosher, B. A. (2000). Spatial attention: Different mechanisms for central and peripheral precues? *Journal of Experimental Psychology: Human Perception & Performance*, **26**, 1534-1548.

Lu, Z.-L., Jeon, S.-T., & Dosher, B. A. (2004). Temporal tuning characteristics of the perceptual template and endogenous cuing of spatial attention. *Vision Research*, **44**, 1333-1350.

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.

Macknik, S. L., & Livingstone, M. S. (1998). Neuronal correlates of visibility and invisibility in the primate visual system. *Nature Neuroscience*, **1**, 144-149.

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

Palmer, J., Verghese, P., & Pavel, M. (2000). The psychophysics of visual search. *Vision Research*, **40**, 1227-1268.

Pelli, D. G. (1985). Uncertainty explains many aspects of visual contrast detection and discrimination. *Journal of the Optical Society of America A*, **2**, 1508-1532.

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.

Reeves, A., & Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review*, **93**, 180-206.

Robinson, D. A. (1965). The mechanics of human smooth pursuit eye movements. *Journal of Physiology*, **180**, 569-591.

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.

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

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

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.

Smith, P. L., & Wolfgang, B. J., & Sinclair, A. J. (2004). Mask-dependent attentional cuing effects in visual signal detection: The psychometric function for contrast. *Perception & Psychophysics*, **66**, 1056-1075.

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

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

Turvey, M. T. (1973). On peripheral and central processes in vision: Inferences from an information-processing analysis of masking with patterned stimuli. *Psychological Review*, **80**, 1-52.

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