

# Spatial attention excludes external noise at the target location

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To investigate the nature of external noise exclusion, we compared central spatial precuing effects in 16 conditions that varied the amount of external noise, the number of signal stimuli, the number of locations masked by external noise, and the number and style of frames surrounding potential target locations. In the absence of external noise, precuing produced only marginal performance improvements in a small number of display conditions. In the presence of high external noise, precuing improved task performance in all the display conditions. The magnitude of these spatial attention effects, as gauged by contrast threshold reduction, is nearly constant across all the display conditions. This suggests that spatial attention mostly excludes external noise at the target location; the presence of external noise and/or signal stimuli in non-target regions has little effect on spatial performance when location uncertainty is eliminated by report cues. However, the presence of other potential locations for the target is critical, because if target location is known in advance, attention can be focused on that location with or without a cue.

**Keywords:** spatial attention, mechanisms of attention, external noise exclusion, stimulus enhancement, internal noise reduction

## Introduction

Covert spatial attention allows the visual system to process information from selected spatial regions without eye movements (Beck & Ambler, 1973; Cohn & Lasley, 1974; Helmholtz, 1911; Hoffman & Nelson, 1981; Posner, 1980; Sperling & Melchner, 1978; Wolford & Morrison, 1980). Under certain circumstances, responses to stimuli in the attended regions, compared to those in the unattended regions, are faster (e.g., Egly & Homa, 1991; Eriksen & Hoffman, 1972; Henderson & Macquistan, 1993; Posner, 1980; Posner, Nissen, & Ogden, 1978) and/or more accurate (e.g., Cheal & Lyon, 1991; Henderson, 1991; Lyon, 1990). How does spatial attention improve human performance? It has been postulated that two functionally separate attention systems, an endogenous system and an exogenous system, are involved in central and peripheral spatial cuing, respectively (Briand & Klein, 1987; Posner, 1980; Posner & Cohen, 1984). Lu and Doshier (2000) documented a mechanistic difference between the two attention systems: external noise exclusion for the endogenous system (central cuing); external noise exclusion plus stimulus enhancement for the exogenous system (peripheral cuing). A pure mechanism of external noise exclusion has been associated with central cuing of spatial attention (Doshier & Lu, 2000a, 2000b; Lu & Doshier, 2000). Here,

we use central cuing to investigate the nature of external noise exclusion in covert spatial attention. We focus on one particular question: Does spatial attention (with central cuing) exclude external noise in the target region, in the distractor region(s), in both the target and distractor regions, or instead the non-target signal stimuli in distractor regions?

## Mechanisms of Spatial Attention

Several mechanisms of spatial attention have been proposed, including facilitation of perceptual processing at the attended location (Cheal, Lyon, & Gottlob, 1994; Corbetta, Miezin, Shulman, & Petersen, 1993; Mangun, Hillyard, & Luck, 1993; Posner et al., 1978), allocation of limited capacity (Broadbent, 1957; Broadbent, 1971; Henderson, 1996; Henderson & Macquistan, 1993), reduction of stimulus uncertainty (Eckstein, Shimozaki, & Abbey, 2002; Palmer, 1994; Palmer, Ames, & Lindsey, 1993; Shaw, 1984; Sperling & Doshier, 1986), elimination of interference from masks or distractors in unattended locations (Shiu & Pashler, 1994), suppression of masking at the attended location (Enns & Di Lollo, 1997), and both facilitation of responses to attended objects and inhibition of responses to other objects (Cheal & Gregory, 1997).

We developed the external noise plus attention paradigm and related theoretical framework to

quantitatively analyze and distinguish various mechanisms of attention (Doshier & Lu, 2000a, 2000b; Lu & Doshier, 1998, 2000; Lu, Liu, & Doshier, 2000). Within this framework, effects of spatial attention are attributed to three mechanisms: *stimulus enhancement*, *external noise exclusion*, and (multiplicative) *internal noise reduction*. Although these three mechanisms do not map exactly onto the proposed mechanisms in the literature, they are closely related. Stimulus enhancement is related to the verbal notion of facilitation of perceptual processing; external noise exclusion is related to elimination of interference from masks, suppression of masking, and/or inhibition of response to other objects.

The external noise plus attention paradigm has been applied to study the mechanisms of spatial attention in cue validity effects (Doshier & Lu, 2000a, 2000b) and temporal precuing advantages (Lu & Doshier, 2000). Both studies found that, with central cuing (endogenous attention), accuracy improvements due to spatial attention were largely restricted to high external noise conditions; there was no significant precuing effect on performance accuracy in the absence of external noise. With peripheral cues (exogenous attention), Lu and Doshier (2000) found that, in addition to its effect in the presence of high external noise, spatial attention improved response accuracy to a smaller extent in the absence of external noise. Peripheral spatial cuing effects in the absence of external noise were also reported by Carrasco, Penpeci-Talgar, and Eckstein (2000) and Cameron, Tai, and Carrasco (2002). Doshier and Lu (2000a) concluded that the primary mechanism of spatial attention is external noise exclusion.

## External Noise Exclusion

If we assume that high-contrast poststimulus masking has effects similar to those of high external noise, our conclusion that spatial attention excludes external noise is consistent with other findings from postmasking paradigms in the literature (e.g., Cheal & Lyon, 1991; Enns & Di Lollo, 1997; Henderson, 1991, 1996; Lyon, 1990; Shiu & Pashler, 1994; Smith, 2000). In fact, some authors (e.g., Cheal & Lyon, 1992) identified poststimulus masking as a critical condition for performance improvements in spatial attention.<sup>1</sup> However, the nature of external noise/mask exclusion is still under debate (Henderson, 1996; Shiu & Pashler, 1994). In particular, does spatial attention exclude external noise in the target region, in the distractor region(s), in both the target and distractor regions, or instead the non-target signal stimuli in distractor regions (a form of noise with regard to the target stimulus)?

Henderson (1991) and Henderson and Macquistan (1993) studied effects of spatial attention in shape identification. A target stimulus appeared briefly in only one of eight possible locations. High-contrast pattern masks immediately followed the target presentation at all

eight (target + non-target) locations. Henderson (1991) reported that a 100-ms valid peripheral cue improved two-alternative forced-choice accuracy by approximately 10%. In a similar task, Shiu and Pashler (1994) manipulated the number of masks following the target presentation. They found that peripheral precuing significantly improved identification accuracy (by about 15%-60% in different conditions) *only* when all the possible target locations were masked – it had little or no effect when only the target was masked. Shiu and Pashler (1994) concluded that spatial precuing excludes external noise in non-target locations from entering decision (and possibly perception). Henderson (1996) refuted this notion of noise reduction. In one experiment, he found that valid peripheral cuing improved two-alternative forced-choice accuracy by about 5%-6% compared to invalid cuing even when only one mask followed the target. He concluded that exclusion of external noise from non-target regions could not be the only mechanism of spatial attention.

It seems that the magnitude of cuing effects is much larger in experiments with multiple masks (Shiu & Pashler, 1994). However, as pointed out by Shiu and Pashler, the benefit of valid precuing in the multi-mask condition in their study may be “nothing more than reducing the probability that one of the distractors is being mistaken for a target.” This is so because in invalid trials, the observers were not explicitly informed of the target location. This introduced “statistical uncertainty” (the possibility that responses are based on non-target locations) into the decision process. In valid trials, the spatial cue explicitly informed the observers of the target location, and the probability that a distractor was mistaken for a target was greatly reduced. Therefore, the benefits of valid cuing may have merely reflected a reduction of the uncertainty effect in the decision process rather than changes in the quality or processing of the target stimulus (Eckstein et al., 2002; Palmer et al., 1993; Shaw, 1984; Sperling & Doshier, 1986). In comparison, experiments involving a single mask at the target location (e.g., Henderson, 1996) do not suffer from this uncertainty confound because the high-contrast mask marks the target location clearly, even in the invalid trials. To compare attention effects (other than uncertainty reduction) between single- and multi-mask conditions, the statistical uncertainty confound must be removed. This can be achieved by explicitly cuing the target region in all the conditions before response (Cheal & Lyon, 1992; Cheal et al., 1994; Lyon, 1990).<sup>2</sup> In this study, we conducted a direct comparison between single- and multi-mask/external noise conditions with explicit cuing to target regions. For an ideal observer with no functional capacity limitation (Palmer et al., 1993), this procedure eliminates *structural uncertainty*. However, cuing cannot eliminate capacity limitations in the observer (Doshier & Lu, 2000b). Thus, any observed performance variation due to cue-target stimulus onset asynchrony (SOA)

changes or cue validity manipulations reflects some form of capacity limitations of the human observers.

Note that both [Henderson \(1991; 1996\)](#) and [Shiu and Pashler \(1994\)](#) used peripheral cues. [Lu and Doshier \(2000\)](#) found that peripheral cues improved response accuracy via a mixture of stimulus enhancement and external noise exclusion, whereas central cues improved response accuracy via a pure mechanism of external noise exclusion. Because we are concerned with the nature of external noise exclusion in this study, we chose to use central rather than peripheral cuing.

In addition to cuing the target region, a common practice in spatial cuing experiments is to precisely mark the potential target locations to further reduce spatial uncertainty. This is typically accomplished with some spatial markers, such as frames centered at each potential target location. The markers themselves may be a form of external noise because they can potentially mask the target stimulus ([Enns & Di Lollo, 1997](#)). In other words, the existence and style of the markers could contribute to the magnitude of spatial cuing effects, especially in the “zero” external noise condition. We explicitly varied the number and style (stationary versus flashed versus elaborated) of markers in this study.

Another source of errors in a spatial cuing experiment is distractor stimuli, potentially mistaken as signal stimuli, in non-target regions. [Chastain and Cheal \(1997\)](#) conducted three experiments to determine whether the identity of irrelevant items presented outside the focus of attention would affect the identification of a precued target. They found that there was an effect of the identity of the characters at the seven non-cued locations (the non-targets) on the accuracy of identification of the target in certain special cases. When there were more non-targets identical to the target, accuracy was higher than when there were fewer non-targets identical to the target. The repeated distractor contexts consistently affected performance despite incentives to focus only on the target. [Chastain and Cheal \(1997\)](#) suggested that the observers processed information from the distractor locations in spite of instructions to process information at only target locations. However, an alternative interpretation of the [Chastain and Cheal \(1997\)](#) result is that somewhat different processes (e.g., configural) were involved in processing the display when most of the distractors were identical to the target. In this study, the target and the distractors on every trial were all selected from the same list randomly and independently (no correlation between the identity of the signal at the cued location and that at the uncued locations). Thus, statistically, in identifying the target, any “cross-talk” from the locations containing distractors is in principle uncorrelated and can be treated as random noise. We directly assessed the impact of distractor identity on target report with a target-reported versus distractor-identity contingency analysis. In addition, we

examined the impact of spatial cuing with different numbers of potential signal stimulus.

## Summary and Overview

To investigate the nature of external noise exclusion in spatial attention, we compared spatial precuing effects in 16 conditions that varied the amount of external noise, the number of signal stimuli, the number of locations masked by external noise, and the number and style of frames surrounding potential target locations. A full psychometric function sampled at seven signal contrast values was measured in each condition. We found that, in the absence of external noise, precuing produced only marginal performance improvements in a small random subset of display conditions; in the presence of high external noise, precuing improved task performance in all the display conditions; and the magnitude of spatial attention effects, as gauged by contrast threshold reduction, is nearly constant across all the display conditions.

## Methods

### Stimuli

All the experiments were controlled by a 7500/100 PowerPC Macintosh computer running programs based on PsychToolbox ([Brainard, 1997; Pelli, 1997](#)). The stimuli were presented on a Nanao Technology FlexScan-6600 monitor with a P4 phosphor and a refresh rate of 120 Hz. A special circuit ([Pelli & Zhang, 1991](#)) combined the outputs of two 8-bit graphic channels to produce 6,144 distinct gray levels (12.6 bits). The luminance levels of the display were gamma-corrected using a psychophysical procedure ([Lu & Sperling, 1999](#)). The background luminance of the display was set at 27 cd/m<sup>2</sup>, with the minimum luminance at 1 cd/m<sup>2</sup> and the maximum luminance at 53 cd/m<sup>2</sup>. All displays were viewed binocularly with natural pupil at a viewing distance of approximately 70 cm in a dimly lit room.

Four pseudocharacters (rotated Ts), pointing either up, down, left, or right, were created using line segments of  $3.35 \times 0.20$  deg and  $1.68 \times 0.20$  deg ([Figure 1](#)). The contrast of the pseudocharacters was set at seven levels in each experimental condition based on pilot studies.

The fixation cross was made of two  $0.80 \times 0.04$ -deg black line segments (contrast = -1.0). Four report cues, each pointing to one of the four fixed spatial locations, were made of black arrows (contrast = -1.0) located in the center of the display with a length of 1.2 deg. One and only one cue appeared in each trial.

External noise images ( $5.3 \times 5.3$  deg) were made of  $4 \times 4$  pixel patches ( $0.16 \times 0.16$  deg). The contrast of each pixel patch was sampled randomly and independently from a Gaussian distribution with mean 0 and standard deviations 0 in the noiseless condition and 0.32 in the high external noise condition. External noise with a

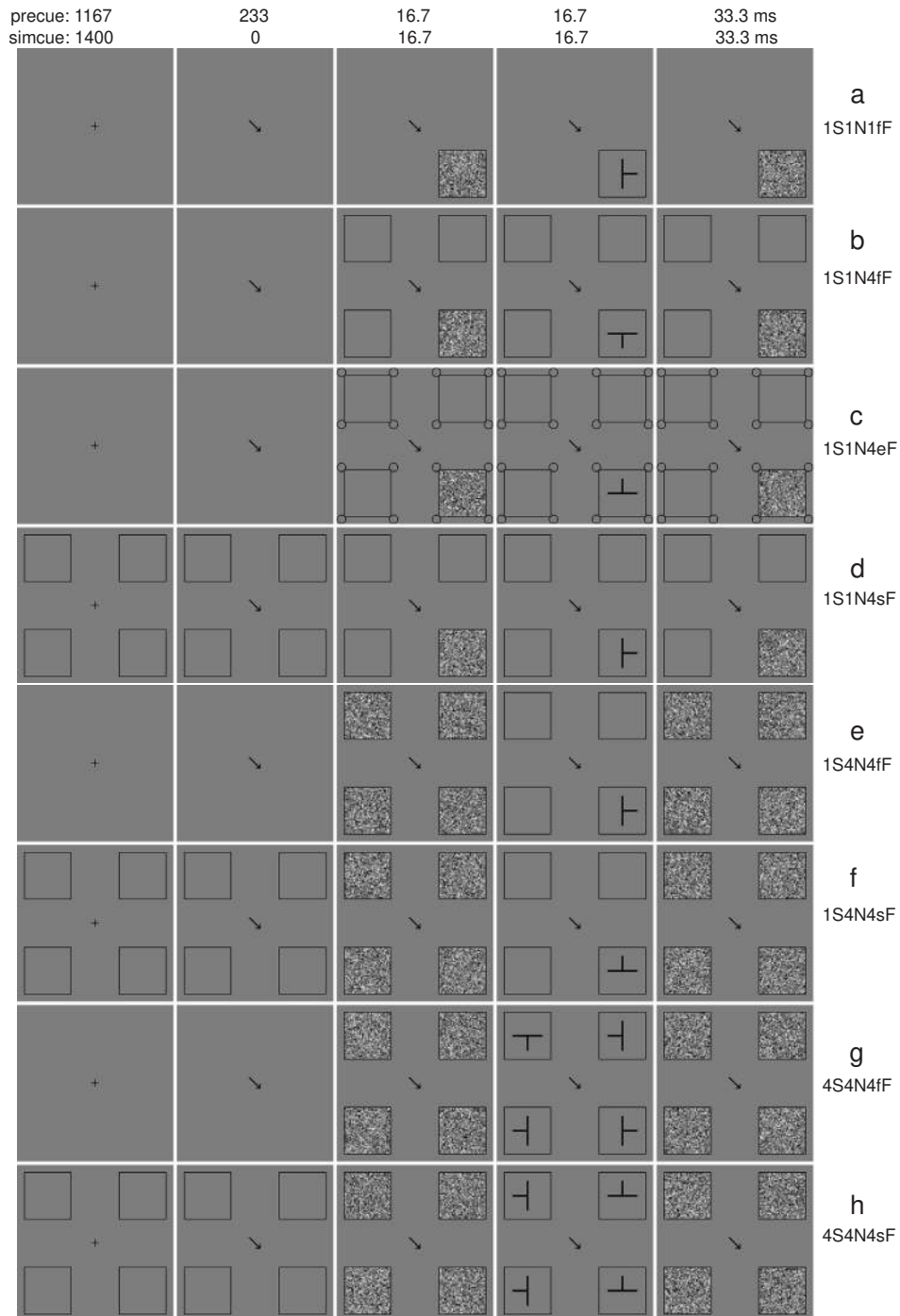


Figure 1. Eight display conditions. The conditions are labeled by the number of locations that contained signal stimulus (1 or 4), the number of external noise masked locations (1 or 4), and the number (1 or 4) and style (flash, elaborated, or stationary) of boxes centered on the stimulus locations. The duration of each display frame is indicated on the top of the figure. Note the different time lines for the pre- and simultaneous cue conditions

standard deviation of 0.32 is the highest level we could achieve in order to conform to the Gaussian distribution because the maximum contrast in the display is  $\pm 1.0$ . In different conditions, the stimuli occurred in all or a subset of four fixed  $5.3 \times 5.3$ -deg square regions, centered  $\pm 5.3$  deg horizontally and vertically, yielding

stimuli on a 7.5-deg radius circle around the fixation point. All or a subset of these square regions were framed with boxes made of  $5.3 \times 0.04$ -deg black line segments (contrast = -1.0). The T-junction of pseudo-characters always coincided with the centers of the square regions.

## Design

The experiment was blocked by eight display conditions (Figure 1). They are described by  $jSkNltF$ , in which  $j = 1$  or  $4$  denotes the number of locations that contained signal stimulus,  $k = 1$  or  $4$  and  $k \geq j$  denotes the number of external noise masked locations, and  $l = 1$  or  $4$  and  $l \geq k$  and  $t = \textit{stationary, flash, or elaborated}$  denote the number and style of the frames centered on the target locations. A stationary frame occurs with the fixation point (1400 ms before the onset of the first noise frame) and stays on until the end of a trial (Figures 1d, 1f, and 1h). A flash frame occurs simultaneously with the first frame of external noise and stays on until the end of a trial (Figures 1a, 1b, 1e, and 1g). An elaborated frame is a flash box with additional circles around its corners (Figure 1c).

For each display condition, two external noise levels (zero and high contrast) and two cue-target SOAs (a precue at 250 ms and a simultaneous cue at 0 ms) were studied in a mixed-list design.<sup>3</sup> The method of constant stimuli (Woodworth & Schlosberg, 1954) was used to measure psychometric functions. Each psychometric function was sampled at seven signal contrast levels.

In summary, there were a total of  $(8 \text{ display}) \times (2 \text{ external noise}) \times (2 \text{ SOA}) \times (7 \text{ signal contrast}) = 224$  conditions.

## Procedure

In a precue trial, the fixation was highlighted for 1167 ms. A cue arrow pointing to one of the four spatial regions replaced the fixation point in the center of the display and stayed on until the end of the trial. The first noise frame appeared 233 ms after the precue, followed by a signal frame, and another two noise frames. Each of the signal/noise-frames lasted 16.7 ms. Thus, the SOA between the cue and the first signal frame is 250 ms, precluding voluntary saccades to the target location (Hallett, 1986). In a simultaneous cue trial, the display sequence was exactly the same as that in a precue trial except that the fixation was replaced by the cue at a later time when the first noise frame occurred. Observers were required to identify the orientation of the pseudocharacter at the cued location by pressing one of four keys ('d' for left, 'f' for up, 'j' for right, and 'k' for down). A brief beep followed every correct response.

Each experimental session consisted of eight blocks, one for each of the eight display conditions. Each block contained 112 trials, four for each of the 28 intermixed noise  $\times$  SOA  $\times$  signal contrast conditions. A session thus consisted of 896 trials and lasted about 1 hr.

Observers ran five practice sessions and then 18 experimental sessions. Across sessions, the order of experimental blocks was randomized. The results of the practice sessions were used to set pseudocharacter contrasts in the experimental sessions. In sum, each

observer participated in 23 hr data collection, 4,480 practice trials, and 16,128 experimental trials.

## Observers

The second author and one undergraduate student participated in this experiment. Both observers had normal or corrected-to-normal vision.

## Results

### Psychometric Functions

Thirty-two psychometric functions were measured for each observer (Figure 2), for each of the eight display, two external noise, and two cue-target SOA (precue/simultaneous cue) conditions. A Weibull function

$$P_i = \max - (\max - 0.25) 2^{-\left(\frac{c}{\rho}\right)^\eta}, \quad (1)$$

was fit to each psychometric function (Wichmann & Hill, 2001a) using a maximum likelihood procedure (Hays, 1981). For each psychometric function, the likelihood is defined as a function of the total number of trials  $N_i$ , the number of correct trials  $K_i$ , and the percent correct predicted by Equation (1) in each signal contrast condition,  $i$ :

$$\textit{likelihood} = \prod_{i=1}^7 \frac{N_i!}{K_i!(N_i - K_i)!} P_i^{K_i} (1 - P_i)^{N_i - K_i}. \quad (2)$$

In all, eight different psychometric function models were fit to the data for each observer in each external noise and display condition. Specifically, for each precue/simultaneous cue pair of conditions, we fit one model ( $2\rho 2\eta 2\max$ ) in which all three parameters ( $\rho$ ,  $\eta$ , and  $\max$ ) are free to vary (total number of parameters,  $k=6$ ) to characterize the effect of precuing, three models ( $2\rho 2\eta 1\max$ ,  $2\rho 1\eta 2\max$ , and  $1\rho 2\eta 2\max$ ) in which two of the three parameters are free to vary ( $k=5$ ) between cuing conditions, three models ( $2\rho 1\eta 1\max$ ,  $1\rho 2\eta 1\max$ , and  $1\rho 1\eta 2\max$ ) in which one of the three parameters is free to vary ( $k=4$ ) between cuing conditions, and one model in which all three parameters are the same (no difference due to attention). The optimal fits were selected by nested-model tests based on  $\chi^2$  statistics:

$$\chi^2(df) = 2.0 \times \log\left(\frac{\max \textit{likelihood}_{full}}{\max \textit{likelihood}_{reduced}}\right) \quad (3)$$

where  $df = k_{full} - k_{reduced}$ .

For both observers, the four-parameter  $2\rho 1\eta 1\max$  model provided the optimal fit to the two cuing conditions in the presence of high external noise in all eight display conditions. The quality of fit was statistically equivalent with all the fuller models,  $2\rho 2\eta 1\max$ ,

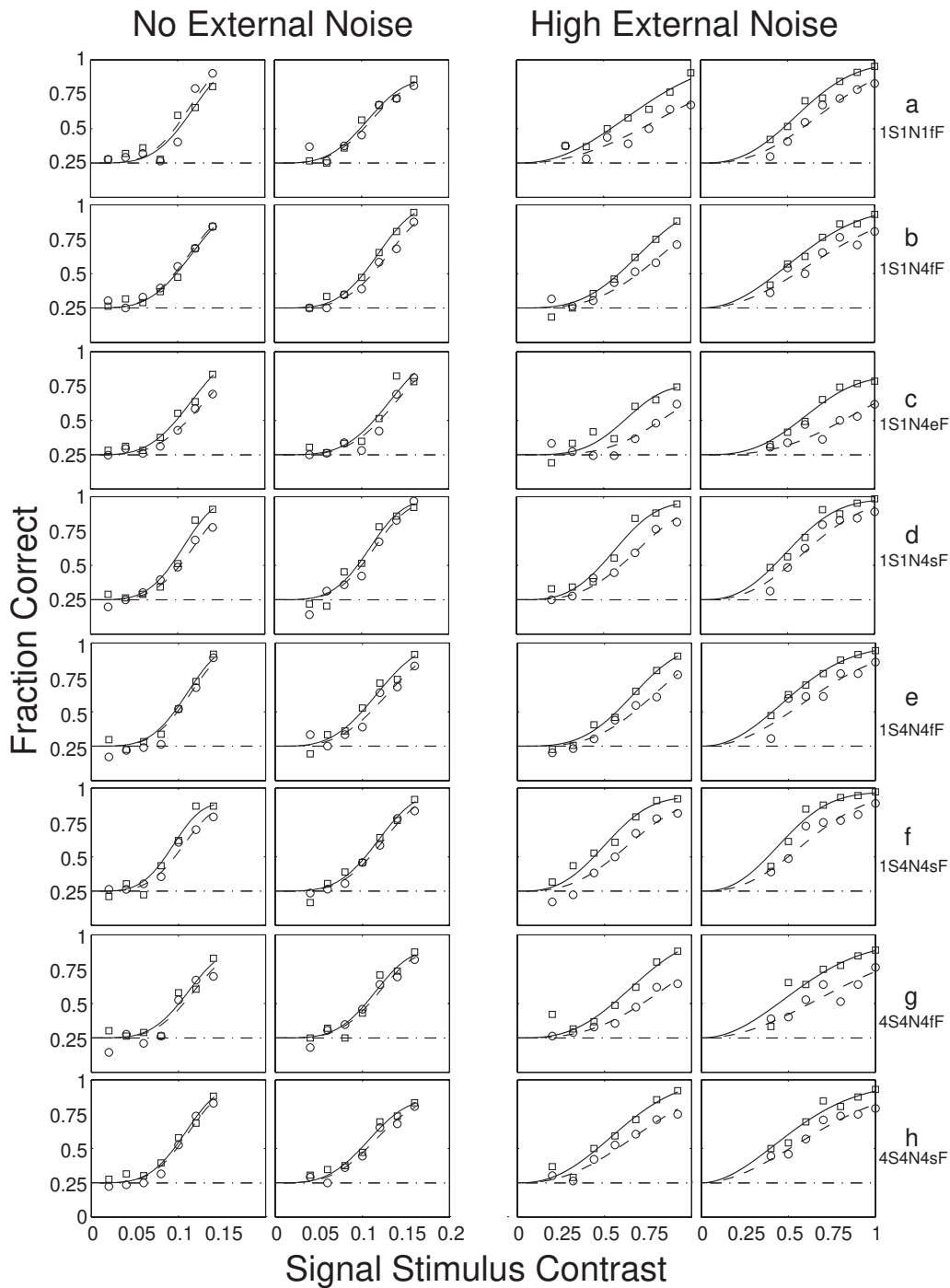


Figure 2. Psychometric functions. Each psychometric function was sampled at seven signal stimulus contrast levels. Seventy-two trials were used to measure every data point. The smooth curves denote the best  $2\rho1\eta1\max$  Weibull fits to the measurements. Solid curves and squares indicate precuing condition; dotted curves and circles, simultaneous condition.

$2\rho1\eta2\max$ , and  $2\rho2\eta2\max$  ( $p > .25$ ). This model is significantly better than the  $1\rho1\eta1\max$  ( $p < .005$ ), which assumes no cuing effect. This documents that, in all the eight display conditions, spatial attention was effective in excluding external noise, and that this difference is well described as a difference in  $\rho$  (the threshold parameter in the Weibull function). The slope ( $\eta$ ) of the psychometric functions are not affected by cuing. In the zero-noise

conditions for both observers, the three-parameter  $1\rho1\eta1\max$  model that assumes no cuing effect cannot be rejected in comparison with all the other more complex models ( $p > .15$ ) in most display conditions. The exceptions are 1S1N4eF, 1S1N4sF, and 1S4N4sF for L.L. and 1S1N4fF and 1S4N4fF for W.C. In all the exceptions, the  $1\rho1\eta1\max$  model was rejected in favor of the  $2\rho1\eta1\max$  model ( $p < .025$ ). The lack of a

consistently significant precuing effect in the noiseless condition suggests that a primary external noise exclusion mechanism underlies the observed spatial attention effects in these experiments. This is consistent with our previous reports (Doshier & Lu, 2000a, 2000b; Lu & Doshier, 2000).

The conclusion that spatial cuing does not change the slope of psychometric functions is also consistent with a number of observations in the literature (Cameron et al., 2002; Doshier & Lu, 2000a, 2000b; Lu & Doshier, 2000). Within the perceptual template model framework (Doshier & Lu, 2000a, 2000b; Lu & Doshier, 1998, 1999a), this result indicates that attention does not alter transduction nonlinearities or multiplicative noise in the observer.

Psychometric functions are plotted in Figure 2, along with the  $2\rho1\eta1\max$  Weibull fits. To keep the presentation in parallel,  $2\rho1\eta1\max$  Weibull functions are plotted in both the high and zero external noise conditions. In general, the  $2\rho1\eta1\max$  model provided good fits to the psychometric functions, with  $r^2=0.95\pm0.04$  for observer L.L. and  $r^2=0.94\pm0.05$  for observer W.C. The parameter  $\max=0.97\pm0.04$ , and  $0.96\pm0.08$  for observer L.L. in the low- and high-noise conditions;  $\max=0.94\pm0.06$ , and  $0.96\pm0.06$  for observer W.C.<sup>4</sup>

## Contrast Thresholds

Contrast threshold at  $p = .625$  was computed from the best-fitting  $2\rho1\eta1\max$  Weibull functions. The results are shown in Figure 3 in log scale. There was a trend for the flashed-frame display conditions to have higher thresholds.

The magnitude of the spatial attention effect was estimated by comparing the threshold contrasts in the pre- and simultaneous cuing conditions. Percent threshold reduction, defined as

$$R = \frac{\text{threshold}_{\text{simul-cuing}} - \text{threshold}_{\text{precuing}}}{\text{threshold}_{\text{simul-cuing}}} \times 100\%, \quad (4)$$

was computed for each of the display and external noise conditions for each observer. The standard deviation of  $R$  was computed by re-sampling the measured psychometric functions (Maloney, 1990; Wichmann & Hill, 2001b).

The values of  $R \pm \sigma$  in all the display conditions are listed in Table 1. In the presence of high external noise, precuing reduced threshold contrast, on average, by about 22% (range, 18%-28%, median = 21%) across all the display conditions. In the absence of external noise, the mean threshold reduction due to precuing is 5% (range, 0% to 9%, median = 6%). Consistent with our earlier results with central cues (Doshier & Lu, 2000a, 2000b; Lu & Doshier, 2000), precuing has a primary effect in high-noise conditions, in which attention serves to overcome the damaging effects of external noise (external noise exclusion). The magnitude of the high-noise effect

appears to differ only modestly over the different condition variants. Also consistent with earlier results, the effects of central cuing in the absence of external noise are negligible in most of the conditions. The few cases of significant precuing effects in “noiseless” displays appeared mostly in conditions with elaborated or flashing frames, which may themselves be sources of external noise.

Although in these conditions of central precuing, attention effects were almost exclusively associated with pure external noise exclusion (Doshier & Lu, 2000b), we would have also expected to observe attention effects due to stimulus enhancement in zero- or low-noise conditions in the case of peripheral precuing (Lu & Doshier, 2000). It may also be the case that some form of stimulus enhancement in zero- or low-noise conditions may occur for central precuing in displays with a larger number of stimulus locations or with crowding (Doshier & Lu, 2000a).

## Contingency Analyses

To assess the possibility that the signal content of the non-cued locations acted as a noise source by contributing to errors, a detailed trial by trial analysis of “cross-talk” between the cued and non-cued locations was computed. This analysis evaluated whether the reported target identity at the cued location depended on the identity of signal in the non-target regions (distractors) by performing contingency analyses on the data from the two display conditions (4S4N4fF and 4S4N4sF) in which four signal Ts were presented. Specifically, for each signal contrast level in each cuing, external noise and display condition, we generated four contingency tables. Each contingency table has four rows and four columns. The four rows represent the four (physical) potential identities of the signal in a given location; the four columns represent the four potential reports. Four locations (and therefore four contingency tables) were considered: the target, the location next to the target (counter-clockwise), the location next to the target (clockwise), and the location that is diagonal to the target. A total of 224 contingency tables were generated for each observer. The contingency analyses were based on  $\chi^2$  statistics:

$$\chi^2(df) = \sum_{i=1}^4 \sum_{j=1}^4 \frac{(M_{ij} - E_{ij})^2}{E_{ij}}, \quad (5)$$

where  $M_{ij}$  is the measured frequency in row  $i$  and column  $j$ ,  $E_{ij} = R_i C_j / n$  the expected frequency in row  $i$  and column  $j$  if the null hypothesis (no contingency) were true.  $R_i$  is the total frequency of responses in row  $i$ ;  $C_j$  is the total frequency of responses in column  $j$ ;  $n$  is the total frequency in the entire table. The degree of freedom for the test is  $df = (\text{rows}-1)(\text{columns}-1) = 9$ .

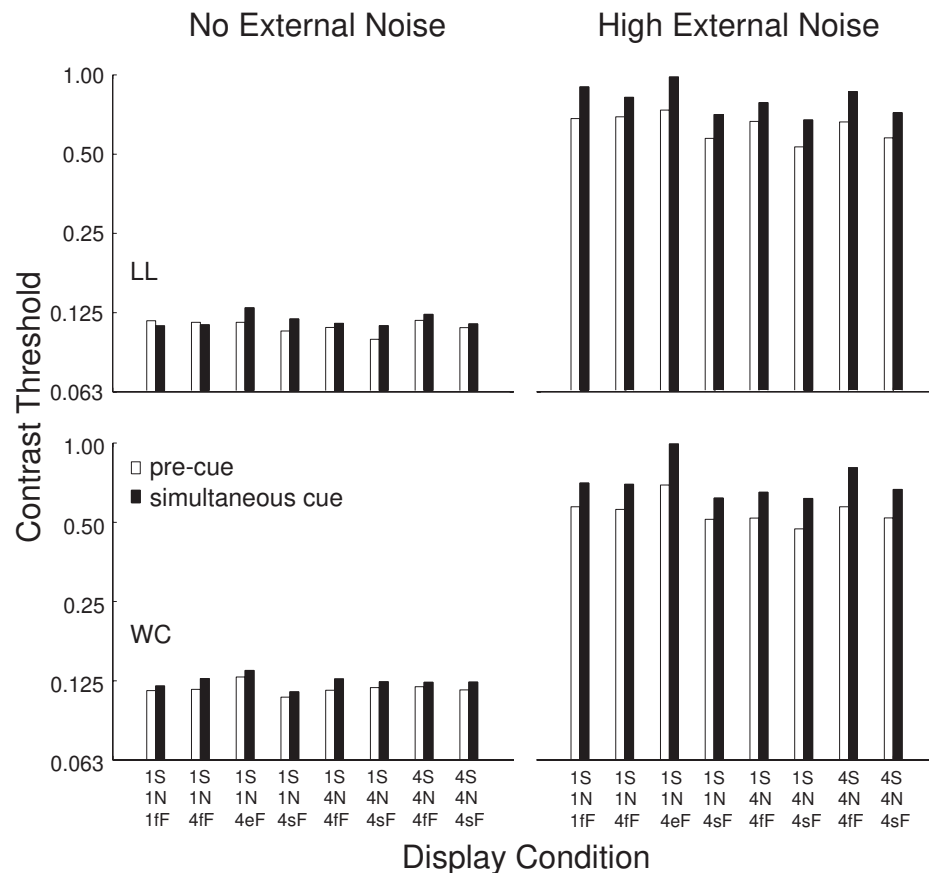


Figure 3. Contrast thresholds at 62.5% correct for each of the eight display conditions in both low and high external noise.

For observer L.L., highly significant contingencies were found between the reported target identity and the identity of the signal stimulus at the target location ( $p < .0001$ ) for the highest three signal contrast levels in the zero-noise condition and the highest four signal contrast levels in the high external noise condition for both display conditions and both types of cuing. Among the 168 contingency tables that measured the relation of the reported target identity and the identity of the stimulus in non-target regions, significant or marginally significant contingencies were found in only four: In 4S4N4fF, at the location clockwise to the target,  $c = 0.10$  precue,  $c = 0.68$  simultaneous cue; in 4S4N4sF, at the location clockwise to the target,  $c = 0.10$  precue,  $c = 0.20$  precue, and  $c = 0.56$  precue. All the other contingencies are insignificant ( $p > .10$ , mostly,  $p > .25$ ). Of the 168 tests, 9 might be expected to be significant by chance. For observer W.C., highly significant contingencies were found between the response and the content of the target location ( $p < .0001$ ) for the highest three signal contrast levels in the zero-noise condition and the highest five signal contrast levels in the high external noise condition for both display conditions and both types of cuing. Among the 168 contingency tables that measured the relation of the response to the stimulus in the non-target regions, significant contingencies were found in only five

of them: In 4S4N4fF, at the location clockwise to the target,  $c = 0.60$  precue; in 4S4N4sF, at the location clockwise to the target,  $c = 0.04$  precue,  $c = 0.40$  precue,  $c = 0.50$  precue; at the location diagonal to the target,  $c = 0.50$  precue. All the other contingencies are insignificant ( $p > .10$ , mostly  $p > .25$ ). Again, of the 168 tests, 8-9 might be expected to be significant by chance.

The systematic, highly significant contingencies between the response and the stimulus in the target region reflect the fact that the observer performed the task at reasonable accuracy when the target contrast was sufficiently high. The few significant contingencies between the response and the content of the non-target regions reflect statistical fluctuations in the contingency tables. We conclude from these analyses that there is no significant “cross-talk” between the target and the non-target regions in either the precuing conditions or the simultaneous cuing conditions. Even simultaneous spatial cuing eliminated target location uncertainty.

## Discussion and Conclusions

In this study, we compared central spatial precuing effects in 16 experimental conditions that varied the amount of external noise, the number of signal stimuli, the number of locations masked by external noise, and



Table 1. Percent Threshold Reduction, *R*

External Noise	Subject	1S1N1f F	1S1N4fF	1S1N4eF	1S1N4sF	1S4N4fF	1S4N4sF	4S4N4fF	4S4N4sF
Zero	L.L.	-5±4	-2±6	11±6	10±4	4±4	11±5	5±5	3±4
	W.C.	4±6	9±3	5±4	5±4	9±4	5±4	4±5	6±6
	Average	0±4	3±3	9±4	7±3	7±3	8±3	4±4	5±4
High	L.L.	24±5	16±4	25±5	19±4	15±4	21±4	23±4	20±5
	W.C.	19±4	20±4	30±5	17±5	20±4	23±5	29±5	22±5
	Average	22±3	18±3	28±4	18±3	18±3	22±3	26±3	21±4

the number and style of frames surrounding potential target locations. We found that, in the presence of high external noise, precuing improved task performance in *all* the display conditions by 18% to 28%. In the absence of external noise, precuing produced only marginal performance improvements in a small number of display conditions for these central precuing conditions. Previously, in conditions comparable to 4S4N4sF in this study, we (Doshier & Lu, 2000a, 2000b; Lu & Doshier, 2000) found a pure external noise exclusion mechanism (attention effects in high-noise conditions only) for spatial attention in central cuing. The current results extend the range of display conditions to which the original theoretical statement applies.

Eight display conditions were studied in this research. In four display conditions (1S1N1fF, 1S1N4fF, 1S1N4eF, and 1S1N4sF), both the signal stimulus and the external noise occurred in only a single spatial location. Because external noise occurs in the target region, spatial attention precueing effects in external noise can reflect only the exclusion of external noise in the target region. In the other four display conditions (1S4N4fF, 1S4N4sF, 4S4N4fF, and 4S4N4sF), the possible signal stimulus occurred in one or four spatial locations but the external noise occurred in all four spatial locations. In these conditions, spatial attention could exclude noise either from the target region, the distractor regions, or both. The magnitude of spatial attention effects, as gauged by contrast threshold reduction, is relatively constant across all the display conditions in the presence of high external noise. Furthermore, there was little or no evidence for “cross-talk” between the non-target regions and the response in either the precued or the simultaneously cued conditions. A parsimonious conclusion is that the simultaneous cue is sufficient to exclude both external noise and signal at the non-target locations. That is, the simultaneous cue was successful in eliminating uncertainty about the target location, allowing the exclusion of both potential signal stimuli and external noise in non-target locations, even in this “unattended” condition. Attention, reflecting the benefit due to central precuing, must reflect the additional benefits of the exclusion of external noise in the target region.

This explanation is fully consistent with previous theoretical claims concerning the pure effect of external noise exclusion in centrally precued attention. The fact that displays with four noise regions produced cuing effects similar to displays with a single noise region in the target location in the current data indicates, as noted previously, that input from the non-target locations is eliminated in both the precued and the simultaneously cued conditions; attention then has its effect over and above this by focusing information input from the target location itself. These results stand in contrast with previous results, such as those by Shiu and Pashler (1994), which found substantial performance differences depending on the number of masked (noisy) locations. In that study, unattended conditions did not use any cue. In such cases, the observers may actually misidentify the target location, or by necessity consider the evidence in all locations in making responses. In such circumstances, the differences between precued and uncued conditions may largely reflect statistical (location) uncertainty effects rather than attention. Given our results, we believe there also should be a contribution of external noise exclusion that was overwhelmed by the uncertainty effect. Henderson (1996) discussed in great detail why Shiu and Pashler might not have observed a significant cuing effect in conditions with a mask only at the target location. In essence, Henderson (1996) postulated that the particular masks used by Shiu and Pashler were not sufficiently effective. Attention has the largest effect of external noise exclusion in the very highest noise conditions. Our finding that attention has a central precueing effect even in displays with a single noise region at the target location (1S1N1fF) is consistent with the finding of Henderson (1996) for single-masked location conditions with peripheral cueing.

Doshier and Lu (2000b) manipulated display size and found that the magnitude of spatial attention effects increased monotonically with display size in the presence of high external noise. In several conditions in this study (e.g., 1S1N1fF), both the target and external noise occurred in only one spatial location. Yet, the magnitude of attention effects was more or less independent of the actual number of target/external noise locations. The

critical manipulation in the current study is that the number of potential locations at which target/external noise could occur was always constant (=4). The presence of other potential locations for the target is critical because if target location is known in advance, attention can be focused on that location with or without a cue. Taken together with [Doshier and Lu \(2000b\)](#), we conclude that the magnitude of spatial attention effects increases with the number of potential target locations.

At the target location, spatial attention excludes external noise by retuning perceptual templates. This retuning could occur in terms of spatial extent, temporal windowing, and/or spatial frequency selectivity of the template. [Yeshurun and Carrasco \(1998\)](#) found that spatial attention improves or impairs visual performance by enhancing spatial resolution. Using broad-band stimuli, [Lu and Doshier \(1999b\)](#) concluded that the perceptual template in precued conditions is better tuned (better matched to the frequency characteristics of the stimulus) than for postcued conditions. Using Gabor targets, [Doshier and Lu \(2000c\)](#) found that external noise exclusion by spatial attention, as manipulated by valid or invalid precues, did not alter the spatial frequency characteristics of the perceptual template, but instead must primarily reflect changes in the spatial or temporal extent of the perceptual template. The exact nature by which spatial attention retunes perceptual templates in space and in time awaits further research.

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## Footnotes

<sup>1</sup>This was based on comparisons of experiments with and without poststimulus masking or with different forms of poststimulus masking. However, because of the large accuracy differences between different masking conditions, such comparisons are hard to interpret. The poststimulus masking procedure is related to the external noise plus attention paradigm ([Lu & Doshier, 1998](#)). In the external noise paradigm, a systematically controlled amount of external noise is combined with the target stimulus. The critical difference between the two procedures is that the external noise plus attention paradigm compares signal contrasts (thresholds) required to produce the same accuracy levels in a range of external noise levels. An additional advantage of performance comparison at threshold is that the threshold regions are the most sensitive (rapidly changing) regions on psychometric functions.

<sup>2</sup>Similar to the multiple-mask situation in [Shiu and Pashler \(1994\)](#), in [Carrasco et al. \(2000\)](#) and [Cameron et al. \(2002\)](#), the observers were uncertain of the target location in the neutral cuing condition when the target is of low contrast (near detection threshold). Even though the authors controlled for this uncertainty confound in relatively high target contrast conditions, most of their targets were of low contrasts. This potential confound in these studies was recently discussed by [Solomon \(2002\)](#).

<sup>3</sup>In our previous research ([Doshier & Lu, 2000a, 2000b; Lu & Doshier, 2000](#)), cue-target SOA of 173 ms was used. Longer cue-target SOAs (~250 ms) were requested by several readers of the original publication. [Lu et al. \(submitted\)](#) investigated the effect of central and peripheral cuing as a function of cue-target SOA. They concluded that SOA = 180 and 250 ms produce qualitatively identical cuing effects, though the magnitude of the cuing effect at SOA = 250 ms is very slightly larger than that of SOA = 180 ms. The results in the current study are consistent with all of our previous results obtained with shorter SOAs (173 ms).

<sup>4</sup>The curves in Figure 2 plot only psychometric functions up to contrast 1.0 in the high-noise condition, whereas an even higher level of contrast might be required to achieve the true asymptotes of the psychometric functions. For example, in the high-noise condition in display condition 4S4N4sF, the max is 1.0 and 0.98 for L.L. and W.C., even though a contrast of 1.0 yields accuracies of only 0.75 for L.L. and 0.80 for W.C. There was one outlier (max = 0.76 & 0.83) in the best-fitting max, which occurred for both observers in the high external noise in display condition 1S1N4eF. This may reflect some crowding effects of the elaborated frames. Max values of .95, corresponding to 0.05 errors, are generally observed for single objects at fovea. Here, the deviation of max from 1.0 reflects lapses of the observer as well as reduced sensitivity in periphery, lack of attention, crowding, etc.

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