Research Article

NOISE EXCLUSION IN SPATIAL ATTENTION

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Abstract—*Precue validity affects the performance of perceptual tasks. These spatial attention effects have been variously attributed to facilitation of processing, capacity allocation, or noise reduction. We used a new attention-plus-external (stimulus)-noise paradigm and model to identify the mechanisms of attention in cue-validity paradigms. A new phenomenon is reported: a large effect of location cue validity in an orientation identification task that specifically occurs when the stimulus is embedded in external (environmental or stimulus) noise. This result identifies the mechanism of the effect as external-noise exclusion, distinguished from stimulus enhancement that manifests itself only in noiseless stimulus environments.*

One of the classic demonstrations of spatial attention without eye movements is a substantial effect on response time, usually to the appearance of a dot of light or stimulus onset, following a cue to attend to a location (Eriksen & Hoffman, 1972; Posner, 1980, 1988; Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980). Responses are faster when the test light appears in the validly cued location, slower when the light is cued invalidly, and intermediate for neutral or uncued trials. Correspondingly, enhanced event-related brain potentials have been observed for validly cued tests (Mangun & Hillyard, 1987). Attentional effects on simple response time have also played a major role in neurophysiological proposals concerning the brain substrates of an attentional system supporting visual orienting (Posner, 1988; Posner & Petersen, 1990). Interestingly, attentional effects of cuing a location have been more difficult to demonstrate for either detection or discrimination accuracy (or sensitivity) (Howarth & Lowe, 1966; Mertens, 1956; Shaw, 1984). Indeed, a number of researchers have suggested that some or perhaps even most of the impact of spatial attention cuing on response time reflects response biases, temporal alerting, or changes in decision structure, rather than improvements in perceptual sensitivity (Palmer, 1995; Shaw, 1984; Sperling, 1984; Sperling & Dosher, 1986; Sperling & Weichselgartner, 1995). This situation naturally raises questions about the functional purpose of spatial attention and the mechanisms by which attention operates.

At the same time, in those cases (among a number of attempts) in which attentional improvements on accuracy (sensitivity) have been reported (e.g., Bashinski & Bacharach, 1980; Downing, 1988; Henderson, 1996; Lyon, 1990; Lu & Dosher, 1998; Shaw, 1984), the conditions that produced them have been actively debated (Cheal, Lyon, & Gottlob, 1994; Henderson, 1996; Shiu & Pashler, 1994). One speculation is that attention may affect sensitivity only in demanding tasks. In one case (Bashinski & Bacharach, 1980), observers were required to detect an 18′-diameter *O* that was displayed at 3.5° eccentricity for 12 to 15 ms, and the observed effect size was equivalent to 17% in two-alternative forced choice (2AFC). In another study (Henderson, 1996), valid location cues yielded about 5% improvements in 2AFC discrimination of a briefly presented and masked 1° *X* or *O* at about 9.5° eccentricity. Finally, in an orientation detection task at 3° eccentricity at threshold contrasts, we (Dosher & Lu, 1997; Lu & Dosher, 1998) observed an attentional shift in threshold of 17%, equivalent to approximately 12% in 2AFC accuracy. In less-demanding tasks, location cuing may have very minor effects on sensitivity (Grindley & Townsend, 1968; Shaw, 1984). Furthermore, certain effects may depend critically on location uncertainty and masking (Henderson, 1991; Shiffrin, 1988; Shiu & Pashler, 1994).

The mechanism for attentional improvements in discrimination has been theorized by various authors to be facilitation of processing (Posner, 1980), capacity allocation (Henderson, 1996), and noise reduction (Shiu & Pashler, 1994). The experiments reported here used a new attention-plus-external-noise paradigm to distinguish mechanisms of attentional improvement (Dosher & Lu, 1997; Lu & Dosher, 1998) in central precuing of attention. This paradigm systematically varies the strength of external (environmental or stimulus) noise added to a perceptual stimulus and compares thresholds at the same criterion levels, which directly reveals the importance of noise exclusion and of processing improvements in the absence of external noise. The perceptual task studied here was inspired by multilocation cuing tasks investigated by a number of researchers (Cheal & Lyon, 1991a, 1991b; Henderson, 1991; Shiu & Pashler, 1994). We present a new phenomenon: the existence of a robust attentional cue-validity effect on discrimination in the presence of high external noise under conditions that lead to very small or nonexistent cuing effects in noiseless conditions. An attentional effect that occurs only in high-noise environments directly reveals a noise-exclusion mechanism. The underlying mechanism of the attentional effect is quantitatively documented using a recently developed model for mechanisms of attention and the external-noise paradigm (see Lu & Dosher, 1998, 1999a).

EXPERIMENT

The main experiment examined the attentional effects of validity of a central precue in an external-noise paradigm (Lu & Dosher, 1998). Observers discriminated among Gabor patches (windowed sine waves) of four different orientations. A central precue pointed to one of four stimulus locations 150 ms prior to the Gabor test stimulus. Although central precues achieve maximum effect at a cue lead time of approximately 300 ms in unpracticed observers, in practiced observers the effect with a cue lead time of 150 ms is essentially indistinguishable from the asymptotic cue effect (Cheal & Lyon, 1991a, Fig. 5b), yet still precludes eye movements. The central precue was replaced during the test stimulus with a report cue indicating the location to be reported. The precue was valid on five eighths (.625) of

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the trials and invalid on three eighths (.375) of the trials, or one eighth (.125) of the trials at each invalid location. The probability ratio of the valid location to any one invalid location was 5:1, a strong manipulation in the context of a four-location display. (Many experiments in cue validity use two stimulus locations and probabilities of .8 and .2, for a ratio of 4:1, or .75 and .25, for a ratio of 3:1.) The dependent measure was the signal contrast required to achieve various threshold levels. Performance following a valid or an invalid central cue was compared in a range of external-noise conditions.

Method

Stimulus and display

The "signals" in the discrimination task were Gabor patterns tilted θ° relative to vertical:

$$l(x, y) = l_0 \left(1.0 + c \sin(2\pi f\,(x\cos\theta + y\sin\theta)) \exp\left(-\frac{x^2 + y^2}{2\sigma^2} \right) \right).$$

There were four values of θ, corresponding to ±22.5° and ±67.5°. Each Gabor was rendered on a 64 × 64-pixel grid and extended 3.57° × 3.57°, with a center frequency of $f = 1.12$ cycles/°, and a standard deviation, σ, of 0.669°. The four Gabor stimuli are shown in Figure 1b. The mean luminance, l_0, was set to 13 cd/m^2. The contrast of the Gabor, c, was determined by the experimental conditions.

External-noise frames (64 × 64 pixels) consisted of 3 × 3 noise elements with contrast levels constructed by sampling from a Gaussian distribution with mean 0 and variance σ^2_{ext} depending on the manipulated level of external noise. To guarantee that the contrast-level distribution was approximately Gaussian, the maximum standard deviation of the external noise was no higher than 33% of the maximum achievable contrast. The eight levels of external noise are illustrated in Figure 1c. Signal frames were sandwiched between noise frames and combined via temporal integration (Lu & Dosher, 1998).

Four Gabor-in-noise stimuli appeared on each trial, one at each corner of a box centered around fixation; the center of each stimulus was at 5.0° of eccentricity (Fig. 1a) at a viewing distance of approximately 62 cm. The precue was an arrow near fixation pointing at one of the four stimulus locations; it appeared 150 ms prior to the signal frame. The report cue consisted of a "caret," presented just slightly more peripherally than the central attention cue; it appeared simultaneously with signal presentation (see timing details, discussed later in this section).

Apparatus

Signal and noise frames were computed on-line and displayed by a Power Macintosh 7300/200 on a Nanao Technology monitor that had a P4 phosphor and a refresh rate of 120 Hz and was driven by the internal video graphics controller and a version of the Video Toolbox (Pelli & Zhang, 1991). A special circuit combined two output channels to produce 6,144 distinct gray levels (12.6 bits). The minimum luminance of the monitor (all pixels at minimum gray level) was 0.6 cd/m^2, the maximum luminance (all pixels at maximum gray level) was 28 cd/m^2, and the assigned background was 13 cd/m^2. The monitor was calibrated to linearize the luminance range.

Design

There were eight external-noise contrast levels ($\sigma_{ext} = 0$, .02, .04, .08, .12, .16, .25, and .33). Nine signal contrast (c) levels, selected for each observer based on practice data to span a psychometric function, were tested for each external-noise level. The orientations of the Gabor stimuli appearing on each trial were chosen independently; they all were of the same contrast. On each trial, all noise frames were independent samples with the same contrast (variance). Conditions were intermixed randomly. There were 576 trials per session, of which five eighths were validly cued and three eighths were invalidly cued. For valid trials, the precue matched the report cue; for invalid trials, the report cue randomly identified one of the three uncued locations. Observers participated in a minimum of five practice sessions, followed by seven experimental sessions.

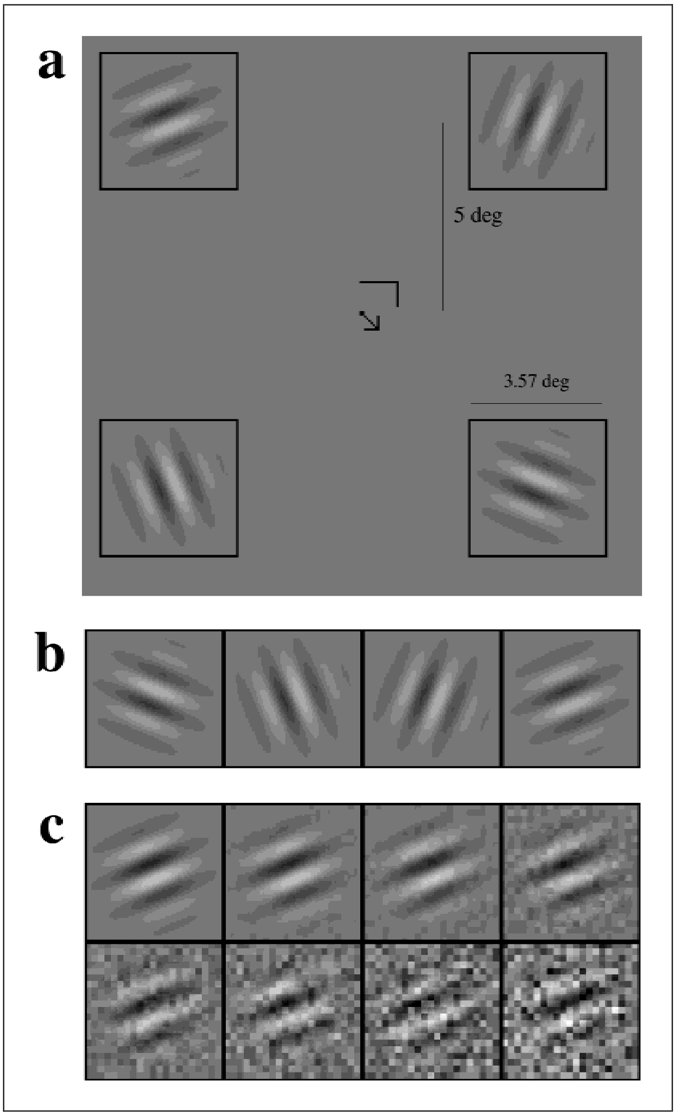

Fig. 1. Sample displays and illustrations of stimuli. A sample layout of an invalidly cued trial is shown in (a). The precue (→) cued attention to one of four stimulus locations, and the "caret" (¬) cued the location to be reported. The precue appeared 150 ms prior to, and the report cue appeared simultaneously with, the first signal frame. The orientations of the four Gabor patches were chosen randomly with replacement; the four possible orientations are shown in (b). An illustration of Gabor patches embedded in the eight levels of broadband, random Gaussian external noise is shown in (c). High external noise requires higher signal contrasts of the Gabor to achieve accurate identification.

Procedure

Each trial began with a fixation point initiated by a key press. The central precue replaced the fixation point after 675 ms. The sequence of noise (N) and signal (S) frames (NSNSN, 16.7 ms, or two frame refreshes each) occurred in each of the four locations. The stimulus onset asynchrony between the onset of the precue and the onset of the first signal frame was 150 ms. The report cue replaced the central cue simultaneously with the appearance of the second signal frame. The observer entered the identity of the Gabor in the report-cue location on the keyboard (“d,” “f,” “j,” and “k,” respectively, for top tilted far to the left, near to the left, near to the right, and far to the right). Auditory feedback, a beep, was provided after a correct response. Observers were instructed to maintain fixation throughout the trial.

Observers

Observers were 4 students naive to the purposes of the experiment. They were paid for participating. All had normal or corrected-to-normal vision.

Results

Cuing effects on psychometric functions

Sixteen 9-point psychometric functions—percentage correct in orientation identification versus contrast of the Gabors—were measured for each of the 4 observers. Figure 2 shows psychometric functions for the zero-external-noise and the highest-external-noise conditions. The smooth curves are Weibull functions (percentage correct = max

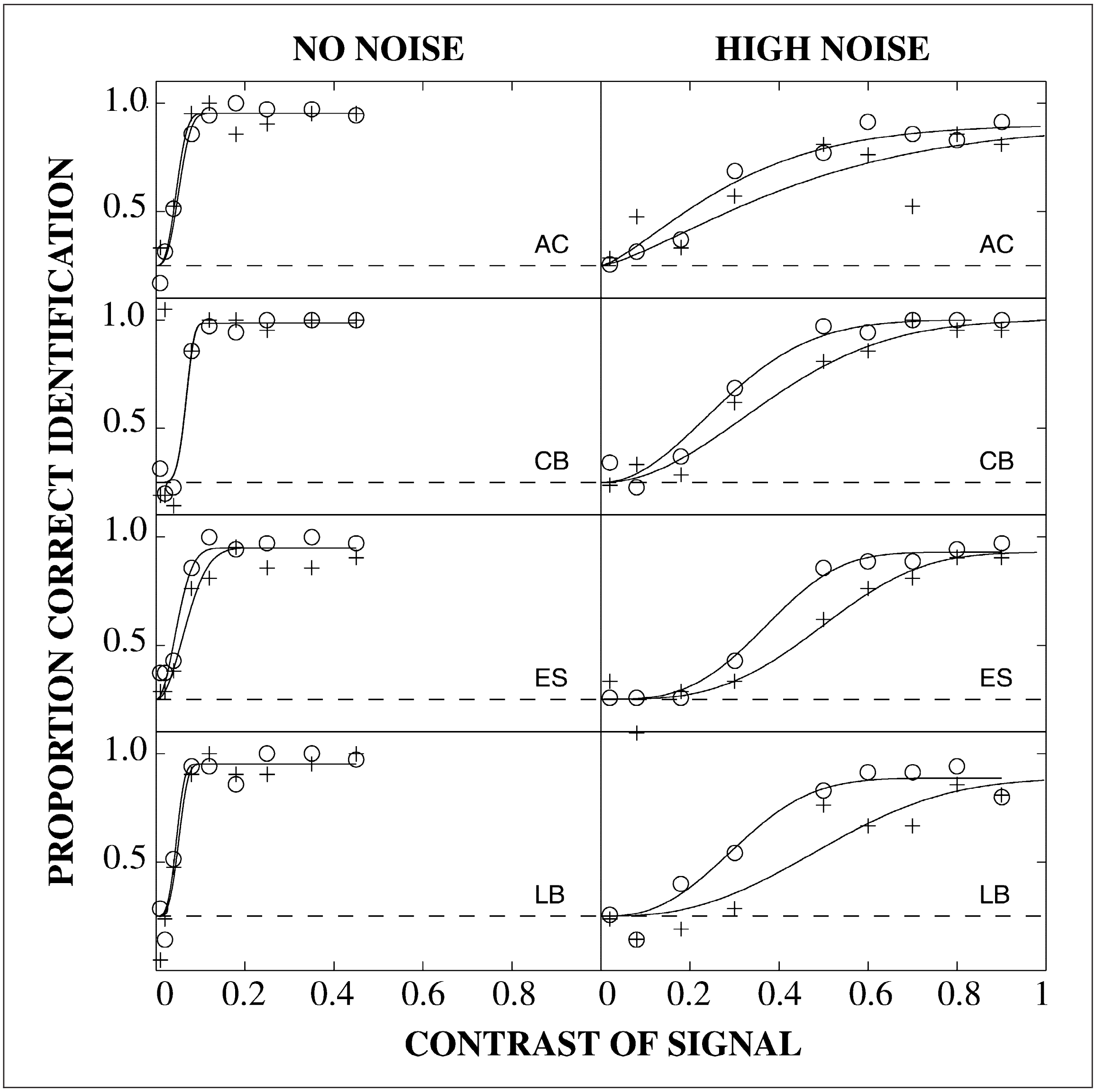

Fig. 2. Psychometric functions (percentage correct versus contrast of the signal Gabor) showing the attentional effect of location cuing without external noise (left) and at the highest level (.33) of external noise (right). Results are shown separately for each of the 4 observers. Circles are for data from validly cued trials, and plus signs are for data from invalidly cued trials. The dashed lines reflect the accuracy associated with guessing, or 25% correct. Smooth curves are Weibull functions fitted by maximum likelihood methods.

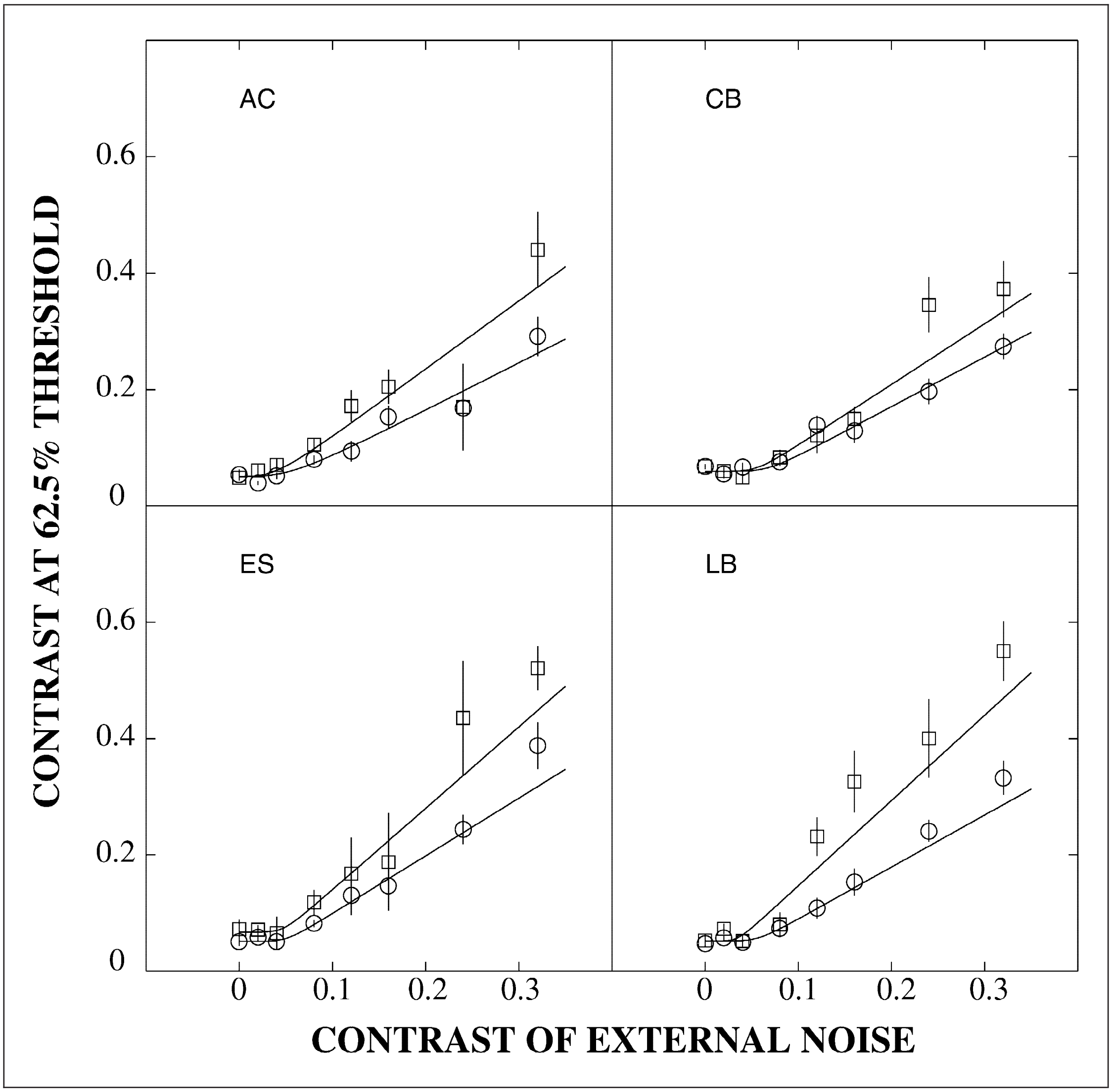

Fig. 3. Signal contrasts required to achieve a 62.5% (d' of 1.24) accuracy threshold as a function of external-noise level for validly cued trials (circles) and invalidly cued trials (squares). Results are shown separately for each of the 4 observers.

$- 0.5 \times 2^{\left(\frac{c}{\alpha}\right)^{\eta}}$ fitted by maximum likelihood methods to the psychometric functions. In the absence of external noise, spatial attention (cue validity) had little or no impact on discrimination accuracy ($p >$ .10, except for observer E.S., by nested model tests on the Weibull). In the presence of high external noise, cue validity had a systematic and substantial impact on discrimination accuracy ($p < .01$ by nested tests on the Weibull).[1]

The increasing effects of spatially cued attention in increasing noise are best shown in contrast-threshold-versus-external-noise functions. Threshold signal contrasts at three performance levels, 50%, 62.5%, and 75%, corresponding to d's of 0.84, 1.24, and 1.68 (Macmillan & Creelman, 1991), were computed from the psychometric functions using the Weibull as an interpolation function.[2] The same pattern of data held for all three threshold levels. Figure 3 shows data for the 62.5% threshold. Cuing of spatial attention reduced the signal contrast necessary to achieve threshold in high external Gaussian stimulus noise, while having modest (observer E.S.) or no impact on contrast threshold in the absence of external noise, the typical condi-

1. Four additional observers performed an experiment consisting only of the zero- and highest-noise conditions, but including a neutral-cue condition (+ instead of →) as well as the valid and invalid cues. The neutral cues yielded accuracies intermediate between those for valid and invalid cues; otherwise the results were similar. This result suggests that the attentional effect in high external noise reflects both costs and benefits relative to neutral performance.

2. Standard deviations of each threshold were calculated using a resampling procedure assuming that each point on a psychometric function was distributed binomially around the observed probability correct. Twenty-five theoretically generated resamplings of each psychometric function were fit with the Weibull, and the standard deviations of the resulting 25 sets of threshold values estimate the variability in the measured thresholds (Maloney, 1990).

tion under which spatial attention effects are measured (Bashinski & Bacharach, 1980; Henderson, 1996; Posner, 1980). With high external noise, there was a substantial and increasing role of attention as measured by the difference between valid and invalid cues. Valid cuing reduced threshold by an average of 24.5% at the maximum external-noise level.

These empirical results directly indicate that the mechanism of spatial attention in this paradigm is the exclusion of external noise. External-noise exclusion is mediated by the retuning of perceptual filters to eliminate some portions of the Gaussian pixel noise in the stimulus. These effects were quantified and statistically evaluated within a model of the observer.

Perceptual-template model and fits

A perceptual-template model (PTM; Dosher & Lu, 1998, 1999b; Lu & Dosher, 1998, 1999a) provides a quantification of the magnitude of the effects due to spatially cued attention, and also documents that perceptual-template retuning yields the pattern of data seen in Figure 3. Based on the fundamental principles of signal and limiting noise, the discrimination sensitivity in the task, d', depends on signal contrast power and the equivalent contrast power of various limiting noises, including external noise (N_{ext}) and internal additive noise (N_a) and internal multiplicative noise (N_m). The PTM model (Fig. 4a) derives signature patterns for two distinct mechanisms of attention: (a) S*timulus enhancement*, in which attention "turns up the gain" on a cued stimulus location, is equivalent to the reduction of internal additive noise by a multiplier A_a, and is characterized by a threshold difference due to attention at low but not high levels of external noise (Fig. 4b). (b) *External-noise exclusion*, in which attention reduces the external-noise power by multiplier A_f through perceptual-template filter sharpening at the cued stimulus location, is characterized by threshold differences at high but not low external noise (Fig. 4c). Values of A_f and A_a less than 1 refer to a reduction relative to the invalid condition, and a value of 1 indicates no difference. A summary of the model equations appears in the appendix (see also Dosher & Lu, 1999b; Lu & Dosher, 1998, 1999a).[3]

Previous treatments of the PTM model (Dosher & Lu, 1997, 1999b; Lu & Dosher, 1998) also considered the possibility of a third mechanism, multiplicative noise reduction, in which internal noise that is proportional to the stimulus contrast is reduced in attended locations. Multiplicative noise, along with transduction nonlinearities, models processes of nonlinear gain control. Measurement of contrast thresholds at three criterion levels (50%, 62.5%, 75%) provide specific tests for changes in nonlinear transduction and in multiplicative noise (see Dosher & Lu, 1999b, for details). Changes in nonlinear transduction and multiplicative noise due to attentional state were ruled out in the current data, as in previous data sets using the external-noise methods. We omit a full treatment of multiplicative-noise-reduction signatures for brevity.

3. The model form considered here and in our previous work (Lu & Dosher, 1998, 1999a) places additive internal noise after multiplicative noise and nonlinear transduction. We (Dosher & Lu, 1999b) showed that additive internal noise before the template, or after the template but prior to multiplicative noise, can be rewritten in this form. If the limiting additive noise occurs before the perceptual template, this predicts a strict coupling of stimulus enhancement and external-noise exclusion. The current data that exhibit external-noise exclusion without stimulus enhancement rule out substantial additive internal noise prior to the template. See Dosher and Lu (1999b) for an extended discussion of alternative model forms.

Full sets of PTM model fits were performed on data from individual observers (see the appendix). Parameter estimates of the best-fitting model are in Table 1. For all 4 observers, external-noise exclusion via perceptual-template sharpening, estimated by A_f, was the primary mechanism of attention. The attentional multipliers (*A*s) provide a quantification of the size of the attention effect. The attentional filter multipliers A_f ranged from 0.610 to 0.817, corresponding to attentional filtering of between 30% and 60% of the contrast power of external noise. A pure case of external-noise exclusion such as this predicts exactly the observed pattern of no attentional effect in the absence of noise, and an increasing effect in high external noise. For 1 of the 4 observers (E.S.), the best model ($p < .001$) also included A_a—a reduction in internal additive noise corresponding to stimulus enhancement.

GENERAL DISCUSSION

The attentional mechanisms of external-noise exclusion and stimulus enhancement are related, respectively, to the concepts of noise reduction and facilitation in previous behavioral literature on location cuing in single and multielement displays (Cheal & Gregory, 1997; Henderson, 1991; LaBerge & Brown, 1989; Mangun & Hillyard, 1987; Posner, 1980; Shiu & Pashler, 1994). The dominant view has been that location cuing produces behavioral benefits by facilitating sensory processing (Bashinski & Bacharach, 1980; Cheal et al., 1994; Mangun & Hillyard, 1987; Posner, 1980). An alternative view emphasizes the role of attention in noise reduction (Henderson, 1991; Shiu & Pashler, 1994). A number of authors have argued that location cuing may result in both facilitation and inhibition, possibly related to noise exclusion (Cheal & Gregory, 1997; Henderson, 1991). For example, Cheal and Gregory (1997) stated that "attention can both facilitate responses to attended objects and inhibit responses to other objects" (p. 69).

Several forms of spatial cuing of attention are generally distinguished theoretically and experimentally. For example, central and peripheral precuing are thought to reflect different orienting processes. Orthogonally, manipulations of the timing of a single cue (Cheal & Lyon, 1989, 1991a) are distinguished from manipulations of cue validity (Chastain & Cheal, 1997; Posner, 1980, 1988; Posner et al., 1978) that may involve misdirection of attention. The current study evaluated the effects of cue validity, or of misdirection in the case of invalid trails, following a central cue of attention in multielement (four-location) displays.

Several factors have been shown to be relevant to the size and occurrence of location-cuing effects in both temporal precuing and studies of cue validity. A number of reported location-cuing effects on identification or discrimination performance were critically dependent on the presence of poststimulus masks as a form of visual noise (Cheal & Lyon, 1989, 1991a, 1991b; Shiu & Pashler, 1994). These previous evaluations, however, compared performance for otherwise identical masked and unmasked displays that differed substantially in difficulty. In contrast, the current study equated difficulty in conditions with varying amounts of external noise by considering performance at comparable threshold levels. Similarly, Shiu and Pashler (1994) demonstrated that attentional cuing in cue-validity paradigms with masks may in large part reflect uncertainty in the report location (but see Cheal et al., 1994; Henderson, 1996, for exceptions). In our identification paradigm, the report cue always determines which location is to

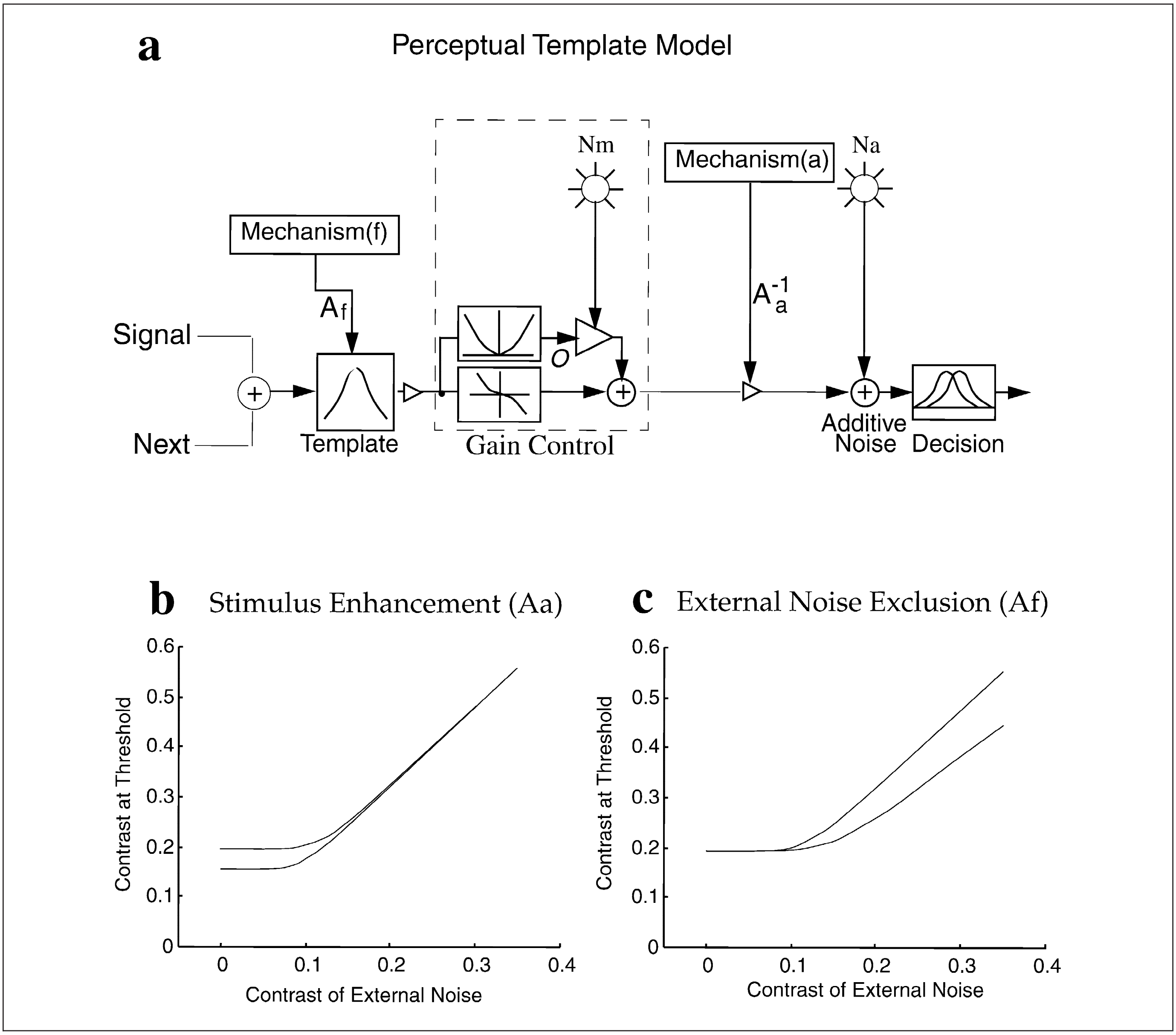

Fig. 4. A perceptual-template model (PTM) and signature data patterns for two attentional mechanisms (see the appendix). The observer model of the PTM (a) includes a perceptual template or filter tuned to the target stimulus, a contrast gain-control mechanism (including nonlinearities and multiplicative internal noise), and additive internal noise; the input combines signal plus external noise. Processing inefficiencies are captured by a level of internal noise that would produce an equivalent performance loss. Two mechanisms of attention are quantified by A_f, for perceptual-template sharpening, and A_a, for reduction of additive internal noise that is equivalent to stimulus enhancement. Stimulus enhancement (A_a) improves performance at low or zero external noise (b). External-noise exclusion (A_f) improves performance only in high external noise, where there is noise to be excluded (c).

be reported, thus eliminating location-based structural or decision uncertainty in an ideal observer. Decision uncertainty refers to performance losses due to incorporating additional information samples in the decision in an unlimited-capacity observer (Shaw, 1984; Sperling & Dosher, 1986). If the observer is not ideal, or is resource limited, then there will be additional effects of attention on performance. These attentional effects might reflect limitations in either perception or the transfer of information from perception to memory, and any such limitations, if they occur, are more relevant in multielement displays with many stimuli than in those with few stimuli (Dosher & Lu, 1999a).

The experiments reported here investigated the attentional effects of central-cue validity in multielement displays. They provide the first clear parametric demonstration at the behavioral level of external-noise exclusion due to spatial attention. In perceptual-system models, external-noise exclusion is associated with the sharpening of perceptual templates to exclude irrelevant external noise. Changes in the perceptual template refer to changes in filter tuning at the level of the

Table 1. *Fits of the perceptual-template model (PTM)*

	Observer			
Parameter	A.C.	C.B.	E.S.	L.B.
A_a	—	—	0.423	—
A_f	0.704	0.817	0.708	0.610
N_m	0.4500	0.4957	0.5153	0.5444
$N_a^{\dagger}$	0.6021	0.1872	0.0769	0.0231
β	3.338	3.635	2.706	2.624
γ	2.395	3.028	3.227	3.234
r^2	.9202	.9474	.9779	.9500
F_f	20.53**	11.09**	44.46**	47.76**
F_a	2.82	0.00	18.90**	1.97
F_g	11.20**	40.86**	122.76**	35.27**

Note. $F_f(1, 43)$ is the test for significant improvement due to external-noise-exclusion parameter $A_f < 1.0$; $F_a(1, 42)$ is the test for significant improvement due to internal-additive-noise-reduction parameter $A_a < 1.0$ added to A_f; $F_g(1, 41)$ is the test for significant improvement for a nonlinearity parameter $\gamma \neq 1.0$ in a full model.
†$N_a \times 10^{-3}$. N_m and N_a scale very differently because of their different roles in the PTM equations.
**$p < .01$.

whole observer. These may correspond to retuning sets of perceptual channels or changing the set of channels entering into the decision (see Dosher & Lu, 1999b).

The noise-exclusion mechanism may be related to previously reported location-cuing effects that occur only with masked stimuli (Cheal & Lyon, 1989, 1991a, 1991b; Shiu & Pashler, 1994), although the interpretation of the previous results was complicated by uncontrolled variations in task difficulty and the results have been interpreted in terms of both noise exclusion and facilitation. Attentional benefits of location cuing that are restricted to high-noise conditions in an external-noise paradigm provide *prima facie* evidence of external-noise exclusion as an isolable attention mechanism. Similar results also obtain for central temporal precuing (precue vs. simultaneous report cue; Lu & Dosher, 1999b). The result may be related to a recent demonstration of attentional change in spatial resolution (Yeshurun & Carrasco, 1998). At the cellular level, our result appears consistent with attentionally mediated changes in responsiveness in the presence of competing stimuli in V4 and other early visual areas (Kastner, De Weered, Desimone, & Ungerleider, 1998; Maunsell & Hochstein, 1991; Moran & Desimone, 1985).

The spatial attention mechanism that excludes external noise is separable from the spatial attention effects observed in the absence of external noise in other visual tasks. Several previous investigations of spatial attention using the external-noise paradigm (Dosher & Lu, 1997; Lu & Dosher, 1998; Lu, Liu, & Dosher, 2000) have been shown to reflect stimulus enhancement, yielding attentional effects restricted to zero- or low-noise conditions (Fig. 4b). Stimulus enhancement appears to be more likely to occur under conditions of peripheral precuing than of central precuing (Lu & Dosher, 1999b).

The current data, which demonstrate a pure case of attentional effects in high external noise, together with the previous data that demonstrated attentional effects restricted to conditions of very low external noise (Dosher & Lu, 1997; Lu & Dosher, 1998), provide key evidence for the existence of two separable and identifiable mechanisms of attention, external-noise exclusion and stimulus enhancement. These two patterns are associated with separate attention mechanisms in the attention-plus-external-noise paradigm and the PTM model (Fig. 4). The two mechanisms occur together in peripheral temporal precuing of location (Lu & Dosher, 1999b) and in perceptual learning (Dosher & Lu, 1999b).

The existence of behavioral signatures for attentional mechanisms in terms of overall accuracy of performance both suggests the functional goal of attention and provides a taxonomy of mechanisms of attention at the behavioral level. Further work is necessary to specify the full range of conditions that give rise to the two attentional mechanisms and their respective signatures.

Acknowledgments—This work was supported by Air Force Office of Scientific Research, Life Science Directorate, Visual Information Processing Program. We wish to thank Marissa Carrasco, MaryLou Cheal, and John Palmer for helpful comments.

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(RECEIVED 2/17/99; ACCEPTED 8/31/99)

APPENDIX

The perceptual-template model (PTM; Dosher & Lu, 1997; Lu & Dosher, 1998, 1999a) describes the fundamental signal and noise properties of the observer in terms of d', an unbiased measure of performance accuracy:

$$d' = \frac{(\beta c)^{\gamma}}{\sqrt{N_{\mathrm{ext}}^{2\gamma} + N_{\mathrm{m}}^{2}((\beta c)^{2\gamma} + N_{\mathrm{ext}}^{2\gamma}) + N_{\mathrm{a}}^{2}}}$$

The experimenter controls the contrast of the signal stimulus c and the contrast of the external noise, N_{ext}. Internal-noise sources N_{a} (additive) and N_{m} (multiplicative) limit performance, reflecting internal processing inefficiencies. Additive noise is independent of stimulus contrast; multiplicative noise depends on stimulus contrast. The value of β scales signal strength; γ estimates nonlinearities in the early visual system. Solving for threshold contrast c_{τ} as a function of external-noise power N_{ext}, and adding attentional multipliers, yields

$$c_{\tau} = \frac{1}{\beta}\left[\frac{(1 + N_{\mathrm{m}}^{2})(A_{\mathrm{f}}N_{\mathrm{ext}})^{2\gamma} + (A_{\mathrm{a}}N_{\mathrm{a}})^{2}}{1/d'^{2} - N_{\mathrm{m}}^{2}}\right]^{\frac{1}{2\gamma}}$$

This equation specifies the form of the contrast-threshold-to-external-noise functions for a selected performance level d'.

The PTM equations were fit to threshold contrasts for 50%, 62.5%, and 75% correct (d's of 0.84, 1.24, and 1.68) for valid- and invalid-cue conditions at each of the eight levels of external noise. Consideration of three thresholds provides strong constraints on estimation (Dosher & Lu, 1998, 1999b; Lu & Dosher, 1999a). The squared error of log contrast thresholds ($\sum(\log c_{\tau}^{\mathrm{model}} - \log c_{\tau})^{2}$) (approximating weighted least squares and hence a maximum likelihood solution) was minimized using Matlab minimization tools. Model fits were performed including zero, any one, or both of the attentional parameters A_{f} (external-noise exclusion) and A_{a} (stimulus enhancement). Modulations in A_{m} (multiplicative noise reduction) were also considered. Standard nested models significance tests were performed.