Spatial Attention: Different Mechanisms for Central and Peripheral Temporal Precues?

Zhong-Lin Lu
University of Southern California

Barbara Anne Dosher
University of California, Irvine

The external noise paradigm (Z.-L. Lu & B. A. Dosher, 1998) was applied to investigate mechanisms of spatial attention in location precuing. Observers were precued or simultaneously cued to identify 1 of 4 pseudocharacters embedded in various amounts of external noise. The cues were either central or peripheral. Both central and peripheral precuing significantly reduced threshold in the presence of high external noise (16% and 17.5%). Only peripheral precuing significantly reduced threshold in the presence of low, or no, external noise (11%). A perceptual template model identified different mechanisms of attention for central and peripheral precuing, external noise exclusion for central precuing, and a combination of external noise exclusion and stimulus enhancement (or equivalently, internal additive noise reduction) for peripheral cuing.

In a high workload environment, a human operator might need to monitor a large number of information sources simultaneously. Whereas this might be accomplished by saccades, the eye movement system is limited by the relatively long time (about 200 ms) each saccade takes (Hallett, 1986). On the other hand, the existence of a faster spatial attention system was proposed about a century ago (Helmholtz, 1866/1911; Wundt, 1902), selecting regions of the visual field for further processing without eye movements. This view has been established by the more recent literature (e.g., Beck & Ambler, 1973; Cohn & Lasley, 1974; Hoffman & Nelson, 1981; Posner, Snyder, & Davidson, 1980; Sperling & Melchner, 1978; Wolford & Morrison, 1980). However, the mechanisms of spatial attention (how spatial attention improves human performance) remain one of the central questions in cognitive psychology. In this article, we investigate the mechanisms of spatial attention involved in one particular phenomenon: a precuing advantage in multiple-element displays.

Background

Precuing Advantage

Many studies in the literature have demonstrated that precuing, that is, informing the observer about the target location before

stimulus onset in multiple-element displays, may improve the observer's performance both in terms of accuracy (e.g., Cheal & Lyon, 1991; Henderson, 1991; Lyon, 1990) and in terms of response time (e.g., Egly & Homa, 1991; Eriksen & Hoffman, 1972; Henderson & Macquistan, 1993). In a typical task (e.g., Henderson, 1991), a target stimulus appears briefly in only one of eight possible locations, all of which are masked by high-contrast patterns immediately after target presentation. For example, in Henderson (1991), 100-ms peripheral temporal precuing of the target location improved two alternative forced choice accuracy by approximately 10%.

Central Versus Peripheral Cuing

Precues are normally classified as central or peripheral, depending on the spatial location of the cue relative to that of the target stimulus. Central precues point to the target location but are located in the geometric center of all the possible target locations, whereas peripheral precues are located near the target location. There is evidence that central and peripheral cues may activate two different spatial attention systems: an *exogenous* system and an *endogenous* system (Briand & Klein, 1987; Posner, 1980; Posner & Cohen, 1984). Several functional differences exist between the two systems: reflexive versus voluntary (Jonides & Yantis, 1988; Nakayama & Mackeben, 1989), large versus small cuing effects (Henderson, 1991; Jonides, 1981), faster versus slower action (Cheal & Lyon, 1991; Muller & Rabbitt, 1989), and differences in inhibition of return (Posner & Cohen, 1984). In this article, we directly compare the mechanisms of attention in central and peripheral temporal precuing.

Temporal Precuing Versus Cue Validity

A temporal precuing experiment studies performance differences as a function of cue-target stimulus onset asynchrony (SOA; e.g., Cheal & Lyon, 1991; Lyon, 1990). A highly related yet different manipulation involves cue validity: A precue is always

presented at a given cue-target SOA while the validity of the precue is manipulated. In some cases, a simultaneous or delayed report cue[1] indicates to the observer the target location (Cheal & Gregory, 1997; Dosher & Lu, 2000a, 2000b; Downing, 1988; Henderson, 1991, 1996; Posner, 1980; Shiu & Pashler, 1994). Intrinsically, these two types of experiments may reflect different attention mechanisms because cue validity experiments involve providing the participant with misleading information, whereas temporal precuing experiments do not. In this study, we concentrated on temporal precuing effects. Cue validity effects are studied in another article (Dosher & Lu, 2000b).

Poststimulus Masking Versus External Noise

In temporal precuing experiments using accuracy as the dependent measure, poststimulus masks were often used to keep the overall accuracy level in the experiment below ceiling when target stimuli were of high contrast (Cheal & Lyon, 1992; Henderson, 1996; Lyon, 1990; Shiu & Pashler, 1994). Some authors (e.g., Cheal & Lyon, 1992) even identified poststimulus masking as a critical condition for precuing advantages 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. On the surface, the poststimulus masking procedure is very similar to the external noise plus attention paradigm (Lu & Dosher, 1998; see below for a description) used in the current studies. 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.

Mechanisms of the Precuing Advantage

Various mechanisms of spatial attention have been proposed to account for spatial precuing effects in multiple-element displays. The earliest and possibly still the most popular proposal is that spatial precuing facilitates perceptual processing at the cued location (Cheal, Lyon, & Gottlob, 1994; Corbetta, Miezin, Shulman, & Petersen, 1993; Mangun, Hillyard, & Luck, 1993; Posner, Nissen, & Ogden, 1978). If this were true, spatial precuing would enhance performance in discrimination tasks in the absence of poststimulus masking, a phenomenon that has been debated (Henderson, 1996; Klein & Hansen, 1990; Shiu & Pashler, 1994).

Another widely held view is that perceptual processing is resource limited; spatial precuing allocates the limited capacity (Broadbent, 1957, 1971; Henderson, 1996; Henderson & Macquistan, 1993). Other proposed mechanisms for precuing advantages include elimination of interference from masks or stimulus information in other nontarget locations (Shiu & Pashler, 1994), suppression of masking at the cued location (Enns & Di Lollo, 1997), and both facilitation of responses to attended objects and inhibition of responses to other objects (Cheal & Gregory, 1997).

To summarize, the mechanism of the temporal precuing advantage is still actively debated (Henderson, 1996). Additional testable hypotheses of the proposed mechanisms would be useful in explicating the important functions of attention in these paradigms.

Overview

In this article, we offer a theoretical framework in which a number of attention mechanisms manifest unique signature performance patterns, as well as an external noise plus attention paradigm (Lu & Dosher, 1998) that generates critical test data. With the identical procedure and the same observers, we compare mechanisms of attention in central and peripheral temporal precuing by using a task inspired by Lyon (1990). The pattern of performance enables us to identify the mechanism of attentional improvement under the investigated conditions.

Theoretical Framework and the Empirical Paradigm

In this section, we briefly introduce our theoretical framework and empirical paradigm: the perceptual template model (PTM) and the external noise plus attention paradigm (see Dosher & Lu, 1999, 2000a; Lu & Dosher, 1998, 1999b, for more details). In an external noise plus attention paradigm, we studied human performance in a perceptual task in systematically controlled external noise under different attention conditions. Modeling the human perceptual system with a PTM (Figure 1), we generated signature performance patterns for three different mechanisms of attention (Figure 2; Lu & Dosher, 1998) and derived characteristic data patterns to distinguish mechanism mixtures based on measurements at multiple criterion levels (Figure 3; Dosher & Lu, 1999, 2000a).

PTM

Limited by various sources of noise in the perceptual processes (e.g., intrinsic stimulus variability, receptor sampling errors, randomness of neural responses, and loss of information during neural transmission), human perceptual processes exhibit certain inefficiencies. At an overall system level, these inefficiencies can be characterized by using observer models with *equivalent* internal noise—random internal noise necessary to produce the degree of inefficiency exhibited by the perceptual system (Ahumada & Watson, 1985; Barlow, 1956; Burgess, Wagner, Jennings, & Barlow, 1981; Lu & Dosher, 1999b; Nagaraja, 1964; Pelli, 1981). The amount of equivalent internal noise is normally estimated by systematically manipulating the amount of *external* noise added to the signal stimulus and observing how threshold—signal stimulus energy required for an observer to maintain a given performance level—depends on the amount of external noise (see Lu & Dosher, 1999b, for a review). Although the equivalent noise approach does not distinguish between various sources of observer inefficiency, it does allow us to quantify the overall efficiency of the perceptual system and to compare the efficiency of the perceptual system in

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[1] Many experiments in the literature use single stimuli and no report cue. The neutral and invalid trials in these experiments suffer from statistical uncertainty loss (see General Discussion). Thus, performance difference between valid and invalid (or neutral) trials may reflect both "attention" effects and stimulus uncertainty losses.
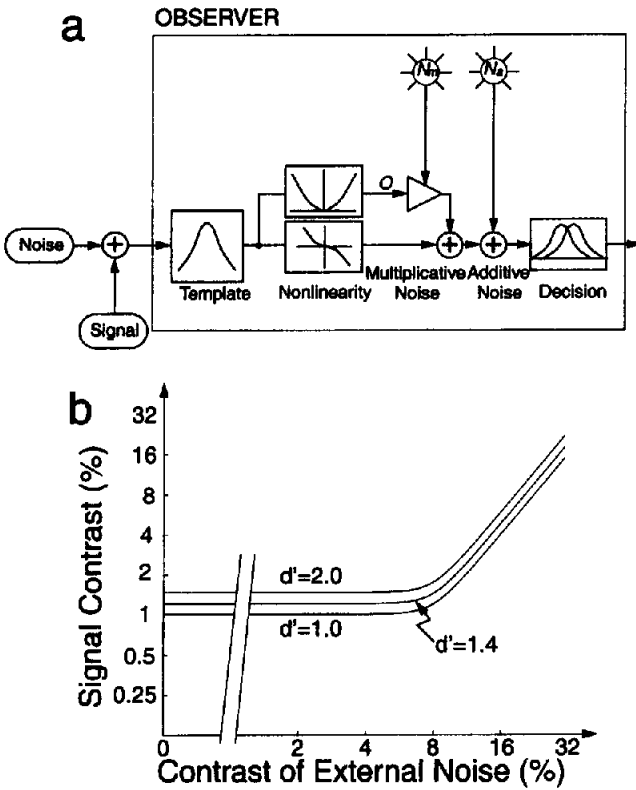
a OBSERVER

b

Figure 1. Panel a: A noisy perceptual template model with five major components: (a) a perceptual template; (b) nonlinear transducer function; (c) a multiplicative internal noise source, N_m; (d) an additive internal noise source, N_a; and (e) a decision process. The triangle denotes an amplifier, which multiplies its two inputs to produce an output. Panel b: Simulated threshold versus external noise contrast functions for a perceptual template model with $N_m = 0.2$, $N_a = 0.0039$, $\beta = 4.0$, and $\gamma = 2.0$, at three criterion performance levels ($d' = 1.0$, 1.4, and 2.0.)

different perceptual tasks (Burgess et al., 1981; Parish & Sperling, 1991; Pelli, 1981, 1990).

The external noise paradigm and noisy observer models have a long history in visual psychophysics extending over the past half century (see Burgess, Shaw, & Lubin, 1999, for a review). The PTM model improves and extends many similar models in the literature (Ahumada & Watson, 1985; Barlow, 1956; Burgess et al., 1981; Nagaraja, 1964; Pelli, 1981). The PTM (Lu & Dosher, 1998, 1999b) is an observer model with five components (Figure 1): (a) A perceptual template (e.g., a spatial frequency filter) with selective tuning. We assume, without losing generality, that the template passes the signal stimulus with gain β and the external noise with gain 1.0. (b) A nonlinear transducer function that raises its input to the γ power (Foley, 1994; Foley & Legge, 1981). (c) A multiplicative internal noise with a Gaussian distribution. The mean of the multiplicative noise is 0; the standard deviation is proportional (with a coefficient of N_m) to the total energy in the stimulus. Multiplicative noise is the basis for Weber-law behavior. (d) An independent additive internal noise with a Gaussian distribution. The mean of the additive noise is 0; the standard deviation is N_a. Additive internal noise is the basis for absolute sensory threshold. (e) A decision process that, depending on the task, could

reflect either detection or discrimination and could take the form of either N-alternative forced choice or "yes"/"no" with confidence rating (for details of these models, see MacMillan & Creelman, 1991).

In a PTM, signal discriminability, d', is determined by the strength of the signal, S, and the standard deviation of the noise, σ_N, at the decision stage:

$$d' = S/\sigma_N, \tag{1}$$

where

$$S = (\beta c)^\gamma \tag{2}$$

is the strength of the signal (with contrast c) after the template and the nonlinear transducer; the total variance of the noise, σ_N^2 is the sum of the variance of all three (external [ext], multiplicative, and additive) noise sources.[2]

$$\sigma_N^2 = \sigma_{ext}^{2\gamma} + \sigma_m^2 + \sigma_a^2 = N_{ext}^{2\gamma} + N_m^2[N_{ext}^{2\gamma} + (\beta c)^{2\gamma}] + N_a^2. \tag{3}$$

Combining Equations 1, 2, and 3:

$$d' = \frac{S}{\sigma_N} = \frac{(\beta c)^\gamma}{\sqrt{N_{ext}^{2\gamma} + N_m^2[(\beta c)^{2\gamma} + N_{ext}^{2\gamma}] + N_a^2}}. \tag{4}$$

Thus, for a given performance criterion (i.e., a fixed d'), we can solve Equation 4 to express the threshold contrast c_τ as a function of N_{ext}:

$$c_\tau = \frac{1}{\beta}\left[\frac{(1 + N_m^2)N_{ext}^{2\gamma} + N_a^2}{1/d'^2 - N_m^2}\right]^{[1/(2\gamma)]}. \tag{5}$$

Figure 1b plots threshold versus external noise contrast (TVC) functions in log–log form at three performance levels ($d' = 1$, 1.41, and 2) for a PTM model with parameters $\beta = 4.0$, $N_m = 0.2$, $N_a = 0.0039$, and $\gamma = 2.0$. Such graphs possess a characteristic shape: (a) When $N_{ext} \ll N_a$, $\log(c_\tau)$ is essentially independent of N_{ext} because internal additive noise N_a dominates. (b) When $N_{ext} \gg N_a$, $\log(c_\tau)$ increases as a linear function of $\log(N_{ext})$ because external noise dominates. (c) When $N_{ext} \approx N_a$, there is a smooth transition from the additive noise dominant region to the external noise dominant region.

Signature Patterns for Three Attention Mechanisms

In a PTM model, attention improves performance in only three different ways: stimulus enhancement, external noise exclusion, and internal noise reduction. Stimulus enhancement (Lu & Dosher, 1998; Lu, Liu, & Dosher, 2000) is modeled by multiplying N_a by a factor of $A_a < 1.0$ in the attended condition. Stimulus enhancement and internal additive noise reduction might, in theory, be distinguished biologically but cannot be distinguished on the basis of performance measures. External noise exclusion (Dosher & Lu, 2000a, 2000b; Lu & Dosher,

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[2] Several approximations were made in deriving the total amount of variance. For a discussion of the relationship between the analytical PTM presented here and the stochastic PTM model, see Dosher & Lu (2000a).
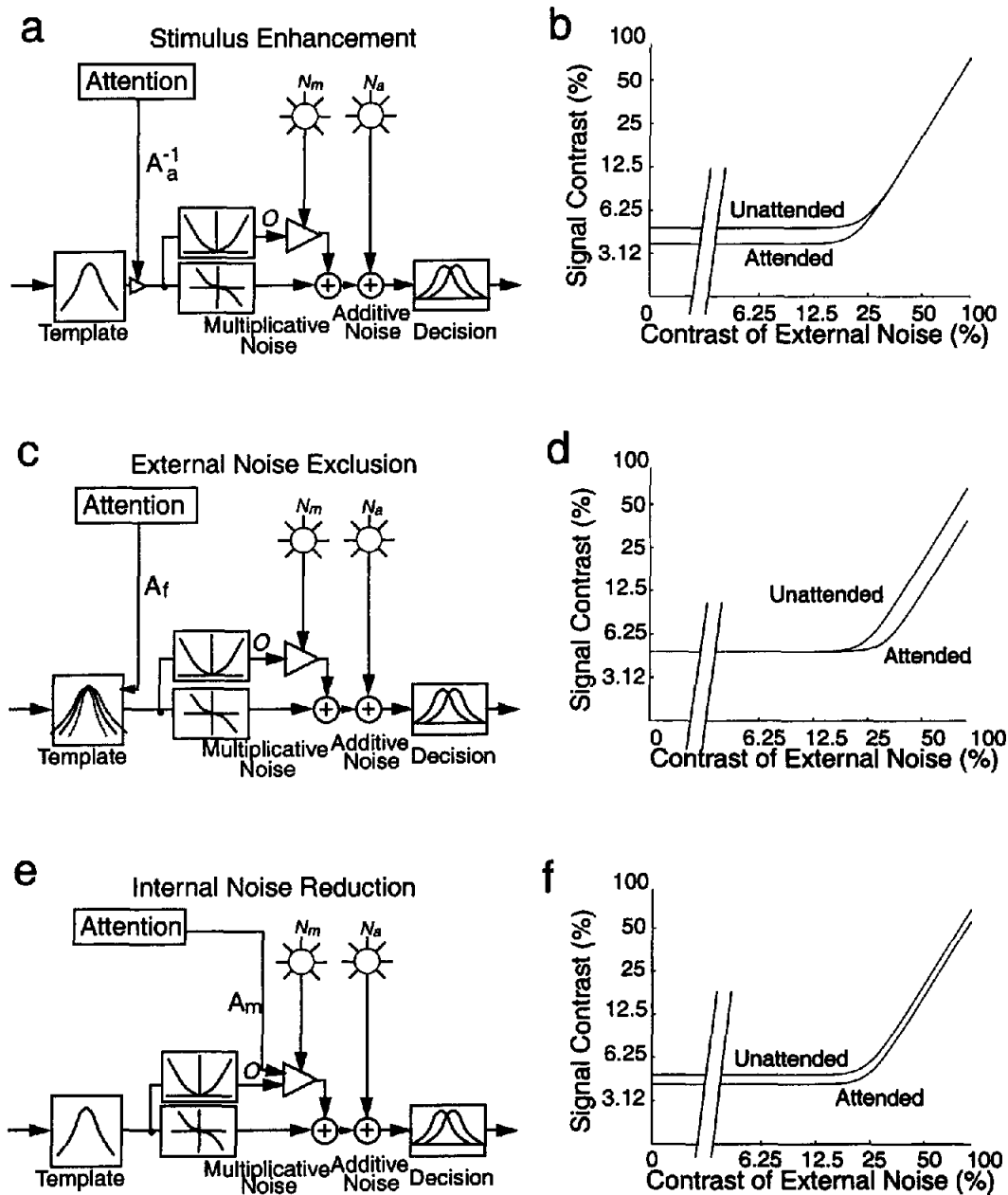
Figure 2. Signature performance patterns for three mechanisms of attention within the framework of a perceptual template model (PTM). Panel a: A PTM in which attention operates by way of stimulus enhancement. Panel b: Signature performance pattern for attention mechanism in Panel a. The threshold versus external noise contrast (TVC) functions in the attended and unattended conditions split at low external noise levels. They overlap with each other at high external noise levels. Stimulus enhancement can improve performance only when the external noise level is low. Panel c: A PTM in which attention operates by way of external noise exclusion. Panel d: Signature performance pattern for attention mechanism in Panel c. For this pair of TVC functions, attention modulates performance only at high levels of external noise. Panel e: A PTM in which attention operates by way of internal multiplicative noise reduction. Panel f: Signature performance pattern for attention mechanism in Panel e. Attention affects performance at all levels of external noise, but increasingly so as external noise increases.

2000), a consequence of better tuning of the perceptual template, is modeled by multiplying N_{ext} by a factor $A_f < 1.0$ in the attended condition. Internal multiplicative noise reduction, a

change of the contrast gain control properties of the system, is modeled by multiplying N_m by a factor $A_m < 1.0$ in the attended condition. To summarize, in the attended condition, the contrast

threshold at a given performance level (corresponding to a fixed d') could potentially be affected by all three mechanisms and is modeled as

$$c_\tau = \frac{1}{\beta}\left[\frac{(1 + (A_m N_m)^2)(A_f N_{ext})^{2\gamma} + (A_a N_a)^2}{1/d'^2 - (A_m N_m)^2}\right]^{[1/(2\gamma)]}. \quad (6)$$

Setting each of the individual As to be less than 1.0, while leaving the other two As at 1.0, generates signature performance patterns for each of the individual attention mechanisms (Figure 2): Stimulus enhancement (or equivalently, internal additive noise reduction) only improves performance at low external noise levels (Figures 2a and 2b), external noise exclusion only improves performance at high external noise levels (Figures 2c and 2d), and internal multiplicative noise reduction improves performance at all levels of external noise (Figures 2e and 2f). The mechanism of stimulus enhancement is related to earlier proposals of perceptual facilitation, whereas the mechanism of external noise exclusion is related to proposals of mask suppression.

Distinguish Mechanism Mixtures

In certain simple situations, a direct comparison of the measured TVC functions and the signature patterns of the PTM model identifies the underlying mechanism of attention (Lu & Dosher, 1998). In other situations (e.g., observing performance improvement over the entire range of external noise), it is critical to distinguish mechanism mixtures (e.g., a combination of stimulus enhancement and external noise exclusion versus multiplicative noise reduction). A simple solution to this problem is suggested by examining Equation 6: The magnitude of threshold reduction (measured in terms of threshold ratio in the attended and unattended conditions) due to stimulus enhancement (A_a) or external noise exclusion (A_f) does not depend on d', whereas the magnitude of threshold reduction due to multiplicative noise reduction (A_m) does depend critically on d'. This is illustrated in Figure 3. Thus, measuring TVC functions at more than two criterion performance levels allows us to compare the magnitude of threshold reduction at different d' levels to resolve the individual contribution of each mechanism in an apparent mixture situation (see Dosher & Lu, 1999, 2000a).

Choice of Experimental Parameters

The spatial attention task we chose to investigate in this study was inspired by the work of Lyon (1990), who demonstrated large temporal precuing advantages (sensitivity improvements indexed by d') in a pseudocharacter (rotated T) identification task in multiple-element displays. In every trial of Lyon's experiment, four pseudocharacters were simultaneously presented at four corners of a square centered around the fixation point for a very brief period, followed by high-contrast masks. Observers were cued (with a dot near the target location) to identify the pseudocharacter at only one location. Lyon found that varying the onset of the cue from 100 ms prior to the onset of the pseudocharacters to 100 ms after the onset causes a drop of d' from about 2.5 to about 0.5.

Lyon's (1990) results demonstrated a condition that produces a sizable temporal precuing advantage. On the other hand, the mechanisms of attention underlying the temporal precuing advantage remain debated. To investigate the mechanisms, we applied the
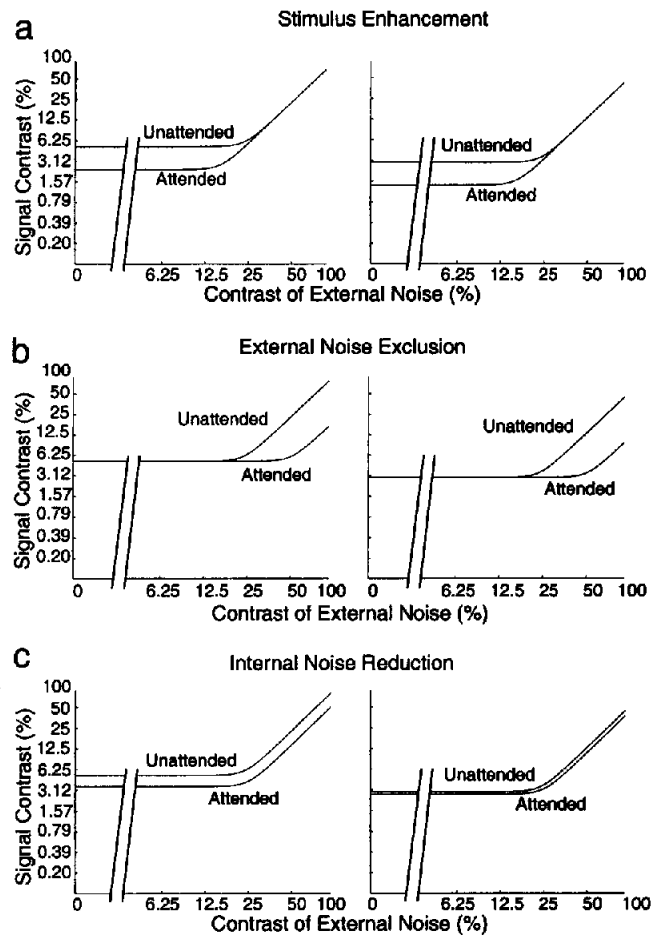

Figure 3. Dependence of the size of the attention effect on performance criteria (following Dosher & Lu, 2000a). The panels in the left column plot threshold versus external noise contrast (TVC) functions at $d' = 0.75$. The panels in the right column plot TVC functions at $d' = 1.25$ for the same perceptual template model under the same influence of attention. In (a) stimulus enhancement and (b) external noise exclusion, the size of the attention effect is a constant (in a log scale) across the two performance levels. In (c) multiplicative noise reduction, the size of the attention effect is a highly accelerated increasing function of criterion level (d').

external noise paradigm and the PTM framework to the basic task used by Lyon under both central and peripheral temporal precuing conditions. Our choice of the specific experimental parameters was based on existing parametric studies of the precuing advantage in the literature. We briefly discuss these factors in turn.

Number of Possible Target Locations

Others have shown that the size of the precuing advantage increases with the number of possible target locations (Chastain & Cheal, 1997; Dosher & Lu, 2000a; Grindley & Townsend, 1968; Lu & Dosher, 2000; Shiu & Pashler, 1994). Typically, one, two, four, or eight possible target locations are used. However, increasing possible target locations to eight might have introduced sensory crowding effects (Dosher & Lu, 2000a; Lu & Dosher, 2000;

Palmer, 1994). We chose to use four possible target locations in this study.

Target Type

Cheal, Lyon, and Hubbard (1991) and Cheal and Lyon (1992) concluded that the size of the precuing advantage varies in a complex way with target type; the difficulty of task, as gauged by the overall accuracy, could not explain the different magnitude of the temporal precuing advantage over target types. This is consistent with Palmer (1994) who found that, whereas the set-size effects in simple visual search tasks can be fully accounted for by statistical uncertainty effects, the much larger set-size effects in complex visual search tasks can only be explained by a significant loss in perceptual coding in addition to statistical uncertainty effects. The dependence on target type suggests different demands on attentional resources for different perceptual processes. We chose as our task pseudocharacter (rotated T) discrimination, which has been shown to produce large precuing effects (Cheal et al., 1991; Lyon, 1990).

Cue-Target SOA

The dependence of the temporal precuing advantage on cue-target SOAs has been investigated extensively (e.g., Cheal & Lyon, 1991; Cheal et al., 1991; Lyon, 1990). Peripheral precuing is thought to require only about 100-ms cue-target SOA to reach its maximum effect. Central precuing is thought to require approximately 300 ms to achieve its maximum effect in unpracticed observers; in practiced observers, the effect of central precuing at 150-ms SOA is very close to the maximum effect (Cheal & Lyon, 1991). Because our observers were all well practiced at the two particular SOA conditions (see Method section), we chose a cue-target SOA of 150 ms in the precuing conditions. Our choice of the particular SOA reflects our effort to ensure large temporal precuing advantages in both central and peripheral cuing conditions and to avoid saccadic eye movements to the target locations.

Experiment 1: Central Precuing With External Noise

In this experiment, we chose a task very similar to Lyon (1990) to investigate the mechanisms of attention involved in central precuing advantage. Central cuing was used to isolate the contributions from the endogenous (vs. exogenous) attention system (Briand & Klein, 1987; Posner, 1980; Posner & Cohen, 1984). Each of the four spatial locations contained a T in one of four possible orientations, simultaneously presented on the computer screen for a brief period of time. Observers were either precued or simultaneously cued with an arrow in the center of the display to identify the orientation of the T-like pseudocharacter at one of the locations. The pseudocharacters were embedded in systematically varying amount of external noise. The method of constant stimuli was used to measure psychometric functions for pseudocharacter identification for each external noise level in both precuing and simultaneous cuing conditions. Threshold contrasts at three performance criterion levels were calculated for each of the external noise and cuing conditions. PTMs with various combinations of attention mechanisms were fit to the TVC curves at the three criterion performance levels (Dosher & Lu, 1999) to identify the

attention mechanism underlying central or endogenous precue advantage.

Method

Observers

Three undergraduate students—AC, SM, and VL—and 2 graduate students—AT and QL—all from the University of Southern California, participated in this experiment. AC, AT, SM, and VL were paid for their participation, and QL volunteered. All observers had normal or corrected-to-normal vision. Each observer performed five practice sessions (2,880 trials) before the experimental sessions.

Stimuli

Display apparatus. All stimuli were presented on a Nanao Technology FlexScan-6600 monitor with a P4 phosphor and a refresh rate of 120 frames/s. The display was driven by the internal graphics card in a 7500/100 Power Macintosh, controlled in real time with a program based on a C++ version of Video Toolbox Library (Frederickson, 1996; Pelli & Zhang, 1991). A special circuit (Pelli & Zhang, 1991) combined two 8-bit output channels of the video card to produce 6,144 distinct gray levels (12.6 bits). A psychophysical procedure (Lu & Sperling, 1999) was used to compute the gamma correction for the monitor. The background luminance was set at 27 cd/m^2, with a dynamic range from 1 cd/m^2 to 53 cd/m^2. All displays were viewed binocularly with natural pupil at a viewing distance of approximately 72 cm in a dimly lighted room.

Pseudocharacters, fixation cross, and visual cues. Four T-like pseudocharacters were created by using 1.15° × 0.14° line segments that were darker than the background. First, crosses were made of two intersecting line segments, one horizontal and the other vertical. Then, four pseudocharacters, each like a rotated letter T, were made by removing each one of the four arms of the crosses. The fixation cross was made of two 0.23° × 0.05° black line segments. Four arrows, pointing to each of the four stimulus locations, were also made of black line segments. These arrows, always occurring in the center of the display, cued the observers to the reporting location. Only one cue appeared in each trial.

External noise. External noise frames (3.3° × 3.3°) were made of 3 × 3 pixel patches (0.14° × 0.14°) with random contrast levels. The contrasts of the pixels in each noise frame were drawn randomly from a single Gaussian distribution with mean 0 and a certain standard deviation. To conform to the Gaussian distribution, the maximum standard deviation of external noise was kept below 0.33 of maximum achievable contrast.

Spatial layout. Four pseudocharacters were always shown on each trial. Each of them occurred in the center of a 3.3° × 3.3° square (Figure 4). The locations of the squares were clearly marked in each trial by four black frames with the same size as the squares. The centers of the squares were displaced from the center of the display by ±4.14° both vertically and horizontally, equivalent to 5.85° eccentricity.

Design

Cue manipulation. Cues with two different temporal relations to the stimulus frame were used: a precue with a cue-target SOA of 150 ms, and a simultaneous cue[3] with a cue-target SOA of −33 ms.

External noise manipulation. Eight external noise levels were used in each cue condition. The contrast of the random pixels in external noise frames corresponding to a given external noise level was drawn from a

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[3] Because temporal summation was used to present signal and noise frames, we call this cue with SOA = −33 ms the simultaneous cue because it coincided with the second set of signal frames.
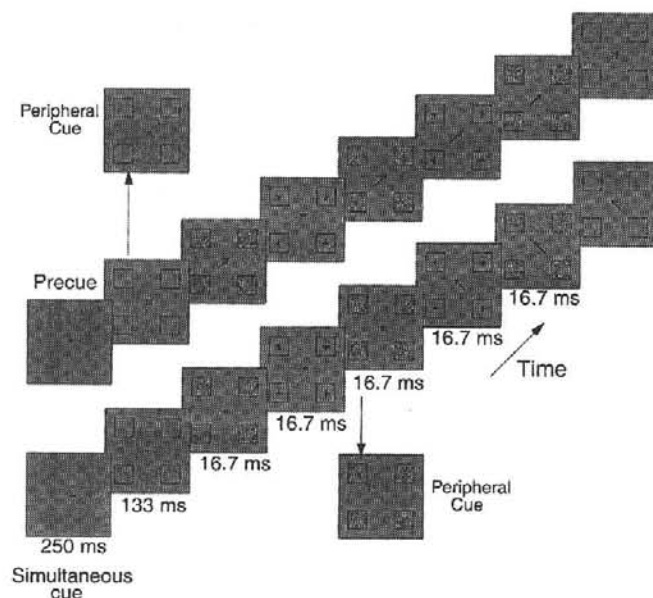
Figure 4. Procedure for Experiment 1. Following a key press, a fixation cross was presented immediately for 250 ms. Another display with four black square outlines then came on for 133 ms. In a precue trial, an arrow pointing to one of the four locations came on simultaneously with the four squares and stayed on throughout the entire display sequence. In a simultaneous cue trial, the arrow cue did not appear until the presentation of the second set of target stimulus frames. Following the four-square display, five frames of 16.7 ms each were shown at each of the four spatial locations in the following sequence: an external noise frame, a target pseudocharacter frame, another external noise frame, a repetition of the target pseudocharacter frame, and an external noise frame. In the simultaneous cue condition, the cue came on simultaneously with the second signal frame. All the noise frames contained independent samples from the same Gaussian distribution. The contrast of the pseudocharacters is also always the same at the four spatial locations. The observer was asked to identify the pseudocharacter at the cued location in each trial. Auditory feedback was provided after each response. In peripheral cuing (Experiment 2), the temporal sequence is identical to that of Experiment 1. Only the spatial location of the cue is changed from the center of the display to the periphery (near the target location). This is illustrated with the two inserted examples.

Gaussian distribution with mean 0 and one of eight standard deviations: 0, 0.02, 0.04, 0.08, 0.12, 0.16, 0.24, and 0.32. In a given trial, all the noise frames had the same level of external noise.

Contrast of pseudocharacters. Performance at nine pseudocharacter contrast levels was measured for each external noise level in each cue condition. The contrast levels were selected according to each observer's performance in the practice sessions to span a psychometric function. In a given trial, all of the four pseudocharacters had the same contrast.

Procedure

Stimulus presentation. The procedure and representative conditions of Experiment 1 are illustrated in Figure 4. The observer pressed a key to initialize a trial when ready. A fixation cross was presented immediately for 250 ms. Another display with four black square outlines then came on for 133 ms. The four squares always occurred in the same spatial locations and framed the subsequent stimuli. In a precue trial, an arrow pointing to one of the four locations was presented at the center of the display with the four squares and stayed on until the end of the trial. In a simultaneous cue

trial, the arrow cue appeared during the target stimulus sequence and stayed on until the end of the trial. The fixation cross occupied the central part of the display prior to the cue. Following the four-square display, five blocks of two refreshes each (16.7 ms) were shown at each of the four spatial locations in the following sequence: an external noise block, a target pseudocharacter block, another external noise block, a repetition of the target pseudocharacter, and an external noise block. Instead of direct summation of signal and noise in each frame of presentation, temporal summation was used to guarantee linearity in the summation process. In the simultaneous cue condition, the cue came on simultaneously with the second target block. All of the noise blocks contained independent samples of the same Gaussian distribution. Thus, the total duration from the onset of the precue to the offset of the last signal frame was limited to 208 ms to avoid voluntary saccades to the target location (Hallett, 1986).

Response and feedback. Observers were required to identify the orientation of the pseudocharacter at the cued location by pressing one of four keys. A beep was given immediately following every correct response.[4]

Experimental sessions. Observers ran 5 practice sessions with only four external noise levels (0.0, 0.08, 0.16, and 0.32) and then 10 experimental sessions. Each 1-hr session consisted of 576 trials: 4 trials for each of the 2 (cue type) × 8 (external noise levels) × 9 (pseudocharacter contrast levels) conditions. All 144 types of experimental conditions were intermixed within each session. Each observer participated in 15 hr of data collection in Experiment 1, 2,880 practice trials, and 5,760 experimental trials.

Results

Collapsing over the four spatial locations, percentages of correct responses were tabulated for each observer, each cue condition, each magnitude of external noise, and each pseudocharacter contrast level. For each observer, 16 psychometric functions resulted, each containing 40 trials at every pseudocharacter contrast level. Figure 5 plots psychometric functions for each observer at only the low and the highest external noise levels for both the precuing and the simultaneous cuing conditions. These data are representative of the remaining conditions. At each external noise level, the proportion of correct response generally increases with increasing pseudocharacter contrast. At low external noise levels, performance in the precuing and the simultaneous cuing conditions was very similar, that is, the psychometric functions in the left column of Figure 5 overlap. It is only in high external noise levels that performance in the precuing condition is much better than that in the simultaneous cuing condition, that is, the psychometric functions in the precuing conditions are above the psychometric functions in the simultaneous conditions at the same external noise level. This is

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[4] For observers AT, QL, and SM, one beep was given for a correct response in the simultaneous cue condition; two beeps were given for a correct response in the precue condition. The following scoring system was used to encourage the observers to pay attention to the cues: five points for each correct response in the precue condition; one for each correct response in the simultaneous cue condition; zero for an incorrect response. Observers were informed of their score on each trial via auditory feedback. The accumulative score was also presented to the observer in the end of each experimental session. Referees of an earlier version of this article suggested this feedback system might have introduced a "vigilance" confound in the design. In running subsequent observers AC and VL in this experiment and all the observers in Experiment 2, only one beep was given immediately following each correct response, independent of the cue type. These two different feedback conditions did not introduce any apparent difference in the results (see below).
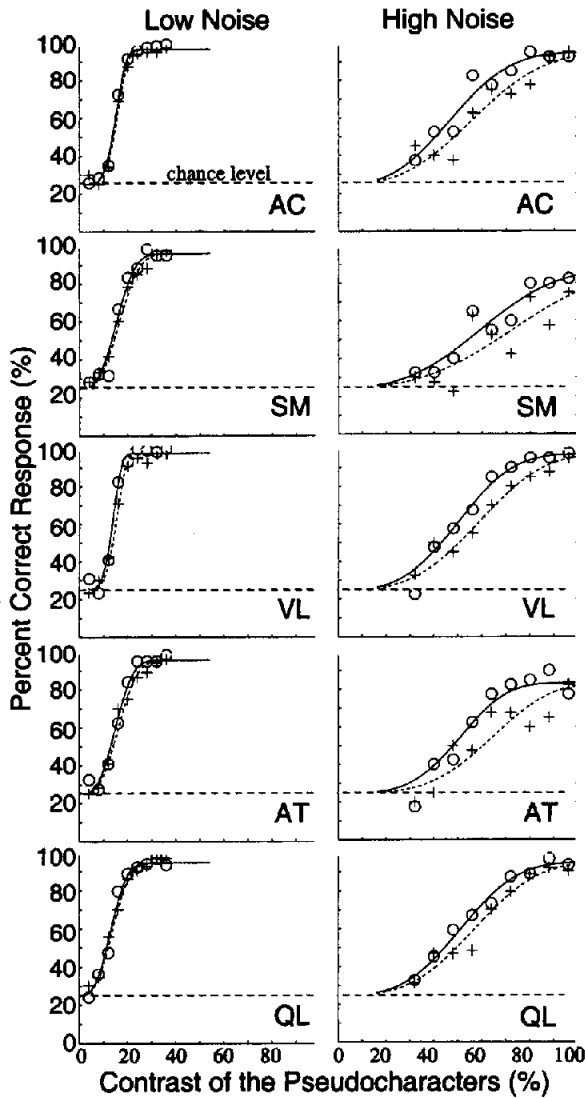
Figure 5. Psychometric functions for the 5 observers in Experiment 1 in the low noise and the highest noise conditions are shown for both simultaneous cuing and precuing. A total of 16 psychometric functions were measured for each participant: 2 precuing and simultaneous cuing conditions × 8 external noise levels. Only a subset of representative psychometric functions is shown. Smooth curves are best Weibull fits to the data. Circles and solid curves denote the precuing condition. Crosses and dotted curves denote the simultaneous cuing condition. In the low external noise condition, the two psychometric functions overlap substantially. In the high noise condition, the pair of psychometric functions in each panel differ significantly. The psychometric functions in the low noise condition are the average of those in the lowest three external noise conditions.

consistent with Lyon (1990), who observed a large precuing advantage in the presence of high contrast masks.

To quantify the difference between the precuing and the simultaneous cuing conditions, Weibull functions,[5]

$$\text{Percent correct} = 0.25 + (\text{max} - 0.25) \times (1 - 2^{-(c/\alpha)^\eta}), \quad (7)$$

were fit to the psychometric functions by using a maximum-likelihood ratio procedure (Hays, 1981), where c is the contrast

of the pseudocharacters and max, α, and η are fitted parameters, assuming that minimum performance is at the chance guessing level (25%). Each pair of psychometric functions, consisting of one from the precuing condition and the other from the simultaneous cuing condition at a given external noise level for an observer, was fit jointly by constraining the Weibull functions to have the same max and the same nonlinear coefficient η.[6]

The quality of the Weibull fits is high for all the observers. The mean and the standard deviation of r^2 between the theoretical and the measured psychometric functions are 0.9757 and 0.0252, 0.9629 and 0.0404, 0.9794 and 0.0191, 0.9656 and 0.0442, and 0.9755 and 0.0258 for participants AC, SM, VL, AT, and QL, respectively.

Threshold contrasts were calculated from the Weibull fit in each experimental condition at three performance levels: $p = 50\%$, 62.5%, and 75% correct:
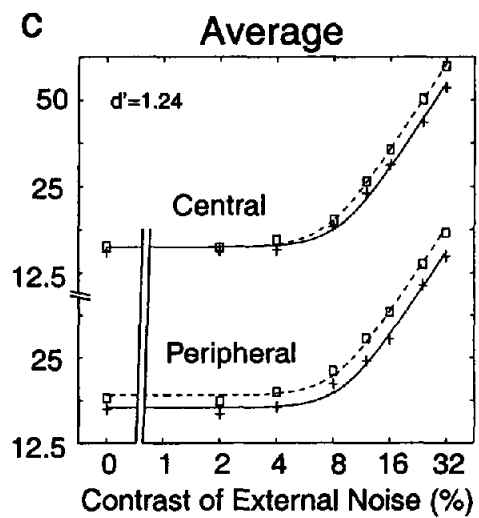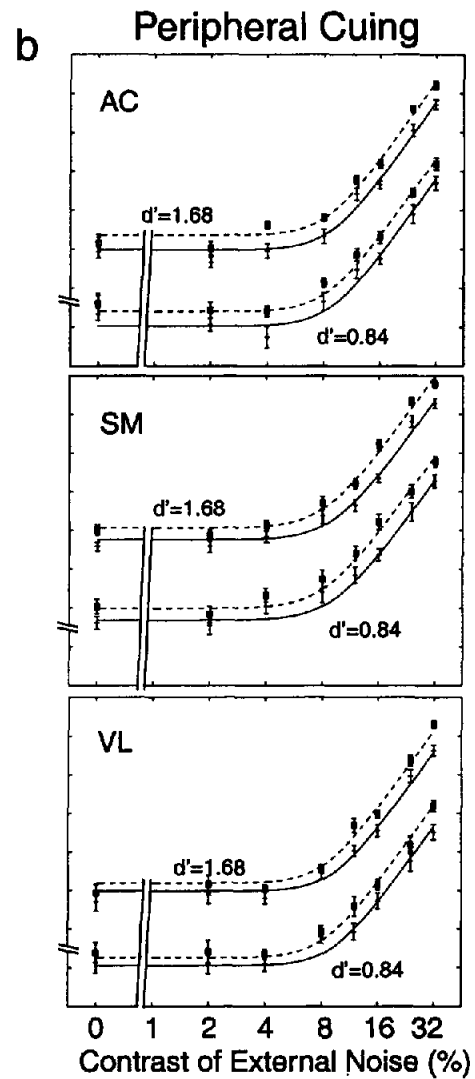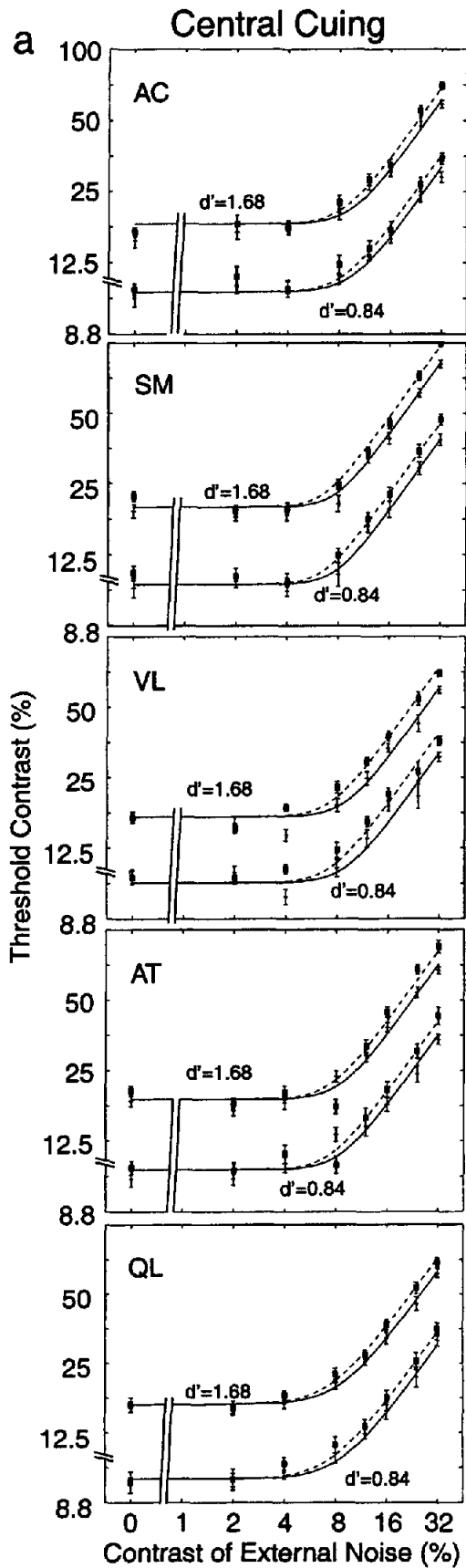
$$\tau_p = \alpha \left[-\log\left(1 - \frac{p - 0.25}{\text{max} - 0.25} \right) / \log(2.0) \right]^{1/\eta}. \quad (8)$$

Figure 6a plots the log threshold pseudocharacter contrast as a function of the log external noise contrast for both precuing and simultaneous cuing conditions for each observer at each of two performance criteria ($d' = 0.84$ and 1.68). Error bars were estimated with a resampling procedure (Maloney, 1990): 64 resampled psychometric functions were generated by sampling a binomial distribution at each pseudocharacter contrast level with p equal to the measured proportion of correct responses and N equal to the total number of trials. Weibull functions were fit to each of the resampled psychometric functions by using the procedure described above. The standard deviations of the resulting 64 estimates provide an estimate of the variability in each of the three threshold pseudo-character contrasts. The error bars in Figure 6 indicate one standard deviation.

The TVC functions in Figure 6a all share the same properties: Whereas the threshold is virtually identical in the precuing and simultaneous cuing conditions in the low external noise region, the threshold in the precuing condition is lower than that in the

a Central Cuing

b Peripheral Cuing

c Average

simultaneous cuing condition in the high external noise region. This pattern of results clearly suggests that external noise exclusion was the mechanism for the precuing advantage (Figures 2c and 2d). The size of the precuing advantage at high levels of external noise is quite substantial. It appears modest in Figure 6a because of the use of the log scale for threshold contrast. At the highest noise level, the threshold with precued spatial attention represents a 17%, 19%, 15%, 21%, and 11% reduction for observers AC, SM, VL, AT, and QL, respectively. The data are summarized in Figure 6c, which plots the average TVC functions at d' = 1.24 performance level (derived by averaging the contrast threshold at d' = 1.24 in each condition across all the participants).

Another remarkable feature of the data shown in Figure 6a is that, for each observer, the TVC functions at two widely separated d' levels are all parallel to each other on the log scale. Comparing this feature with the theoretical predictions in Figure 3 suggests that multiplicative noise reduction was not involved in the observed central precuing advantage.

Modeling

To quantitatively characterize the attention mechanisms involved in the precuing advantage, we fit the PTM model (Equation 6) with various combinations of attention mechanisms to the external noise contrast. If there were no precuing effects, we would set A_m, A_a, and A_f to 1.0 in both the precuing and the simultaneous cuing conditions. A lattice of models was generated by setting different combinations of As free to vary in the precuing condition. A total of eight models were fit and compared: (a) one model with combinations of all As; (b) three models with combinations of pairs of As; (c) three models with single As; and (d) one model that sets all the As to 1.0.

Programs using a gradient descent method based on Matlab 5.3 (1999) were used to find the best fitting parameters for each of the eight models. The best fitting model minimized the least squares difference between the log of the measured threshold contrast and the log of the predicted threshold. As seen in Figure 6a, the log approximately equates the standard error over a large range of contrast thresholds. Minimizing the difference in log values approximates weighted least squares, which is equivalent to the maximum-likelihood solution for continuous data. The goodness of fit is gauged by the r^2 statistic:

$$r^2 = 1.0 - \frac{\Sigma[\log(c_r^{\text{theory}}) - \log(c_r)]^2}{\Sigma[\log(c_r) - \text{mean}(\log(c_r)]^2}, \quad (9)$$

where Σ and mean () operate over all the attention and external noise conditions at all three performance levels for a particular observer in an experiment.

Of the eight models, some are reduced models (proper subsets) of the others. An F test for nested models was used to compare these models:

$$F(df_1, df_2) = \frac{(r_{\text{full}}^2 - r_{\text{reduced}}^2)/df_1}{(1 - r_{\text{full}}^2)/df_2}, \quad (10)$$

where $df_1 = k_{\text{full}} - k_{\text{reduced}}$, and $df_2 = N - k_{\text{full}}$. The ks are the number of parameters in each model, and N is the number of predicted data points.

Our statistical procedure identified the best model as the one with five free parameters in which attention affects only A_f. This five-parameter model was superior to the four-parameter model with no precuing effects ($A_a = A_m = A_f = 1.0$), $F(1, 43) = 15.94$, 12.63, 47.94, 46.13, 29.31, all $ps < .001$, for participants AC, AT, QL, SM, and VL, respectively. No six- or seven-parameter model statistically improved the quality of fit (all $ps > .15$). On the other hand, dropping either A_m or A_a or both from the full model with all three attention mechanisms does not significantly decrease r^2 ($p > .15$); but dropping A_f significantly decreases r^2 ($p < .05$). This is true for all 5 individual observers, confirming our qualitative conclusions based on the data pattern. From this, we conclude that an external noise exclusion attentional mechanism best accounts for our data on central precuing. The parameters of the best fitting model are listed in Table 1. Similar statistics resulted from fitting the average TVC functions shown in Figure 6c.

Experiment 2: Peripheral Precuing With External Noise

In this experiment, we investigated the mechanisms of attention involved in the peripheral precuing advantage. One major purpose of this experiment was to distinguish the contribution of the exogenous (vs. endogenous) attention system (Briand & Klein, 1987; Posner, 1980; Posner & Cohen, 1984). To facilitate the comparison of peripheral and central precuing, we used the same experimental procedure of Experiment 1 in this experiment. Only the form of cuing varied—central cues were replaced by cues in periphery. Three of the 5 observers from Experiment 1 participated in this experiment.

Method

Except where it is noted, the method is the same as that used in Experiment 1.

Figure 6. (opposite). Threshold versus external noise functions (TVC). Panel a: TVC functions for each individual participant from Experiment 1 (central cuing) at two performance levels (d' = 0.84 and 1.68). Panel b: TVC functions for each individual participant from Experiment 2 (peripheral cuing) at two performance levels (d' = 0.84 and 1.68). Panel c: Average TVC functions at d' = 1.24 across all the observers in Experiment 1 (central cuing) and Experiment 2 (peripheral cuing). Smooth curves are best fitting perceptual template model (PTM) predictions. The crosses and solid curves denote data and model predictions for the precuing condition. The squares and dotted curves denote data and model predictions for the simultaneous cuing condition. Error bars in Panels a and b are generated with a resampling method. A PTM with a single external noise exclusion mechanism of attention best fits all the data in Panel a. A PTM with a combination of external noise exclusion and stimulus enhancement mechanisms of attention best fits all the data in Panel b.

Table 1
Best Fitting Perceptual Template Model Parameters (Experiment 1)

Observer	A_a	A_f	N_m	N_a	β	γ	r^2
AC	1.0	0.8872	0.0000	0.0041	1.664	2.224	0.9811
SM	1.0	0.8448	0.0000	0.0075	1.300	1.800	0.9902
VL	1.0	0.8190	0.0000	0.0023	1.534	2.328	0.9723
AT	1.0	0.8729	0.0000	0.0052	1.455	2.026	0.9745
QL	1.0	0.8738	0.0000	0.0106	0.7109	1.752	0.9932

Note. A_a = factor by which internal additive noise is reduced by stimulus enhancement; A_f = factor by which external noise is reduced by retuning of perceptual template (external noise exclusion); N_m = coefficient by which the standard deviation of the multiplicative internal noise is proportional to the energy in the input stimulus; N_a = standard deviation of the internal additive noise; β = the gain of the perceptual template for the signal stimulus (assuming that it passes the external noise with gain 1.0); γ = the exponent of the nonlinear transducer function; r^2 = a statistical measure of goodness of fit.

Observers

Three undergraduate students—AC, SM, and VL—all from the University of Southern California, participated in this experiment after finishing Experiment 1. They were paid for their participation. Each observer performed two practice sessions (1,152 trials) before the experimental sessions.

Stimuli

Four "caret" (L) cues, with corners pointing to each of the four stimulus locations, were made of black line segments (Figure 4). The corner of the caret (L) cues were 0.18° vertically and 0.18° horizontally away from the corner of the marking frame of the cued location. In a given trial, one of these cues, occurring next to the inner corner of the frame outlining one of the four spatial locations, cued the observer to the reporting location. Only one cue appeared in each trial.

Procedure

Stimulus presentation. The procedure and representative conditions of Experiment 2 are also illustrated in Figure 4. It is exactly analogous to that of Experiment 1.

Experimental sessions. Following their participation in Experiment 1, observers ran 2 practice sessions with only four external noise levels (0.0, 0.08, 0.16, and 0.32) and then 10 experimental sessions. Each session consisted of 576 trials: 4 trials for each of the 2 (cue type) × 8 (external noise levels) × 9 (pseudocharacter contrast levels) conditions. All 144 types of experimental conditions were intermixed within each session. Each observer participated in 12 hr of data collection. This corresponded to 5,760 experimental trials per observer.

Results

As in Experiment 1, data were collapsed across the four spatial locations, and percentages of correct responses were tabulated for each observer, each cue condition, each magnitude of external noise, and each pseudocharacter contrast level. For each observer, 16 psychometric functions resulted, each containing 40 trials at every pseudocharacter contrast level. Figure 7 plots psychometric functions for each observer at only low and the highest external noise levels for both the precuing and the simultaneous cuing conditions. At each external noise level, the proportion of correct response generally increases with increasing pseudocharacter contrast. Unlike the results from Experiment 1, performance in the precuing condition is better than that in the simultaneous

cuing conditions throughout the external noise levels (Figure 7); that is, psychometric functions in the precuing conditions are shifted to the left of those in the simultaneous cuing condition.

The same procedure from Experiment 1 was followed to fit Weibull functions to the psychometric functions, to calculate
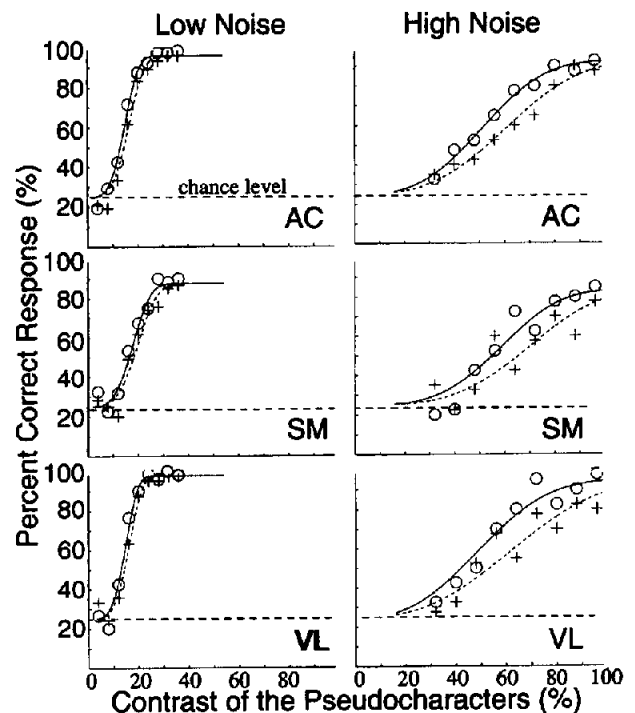
Figure 7. Psychometric functions for the 3 participants in Experiment 2 in the low noise and the highest noise conditions for both simultaneous cuing and precuing. A total of 16 psychometric functions were measured for each participant: 2 precuing and simultaneous cuing conditions × 8 external noise levels. Only a subset of representative psychometric functions is shown. Smooth curves are best Weibull fits to the data. Circles and solid curves denote the precuing condition. Crosses and dotted curves denote the simultaneous cuing condition. In both low and high external noise conditions, the pair of psychometric functions in each panel differ significantly. The psychometric functions in the low noise condition are the average of those in the lowest three external noise conditions.

threshold pseudocharacter contrasts at three performance levels: $p = 50\%, 62.5\%$, and 75% correct, and to estimate error bars for each threshold contrast.

The quality of the Weibull fits was high for all the observers. The mean and the standard deviation of r^2 between the theoretical and the measured psychometric functions were .9777 and .0198, .9255 and .0636, and .9796 and .0161 for observers AC, SM, and VL, respectively.

Figure 6b plots the log threshold pseudocharacter contrast as a function of the log external noise contrast for both precuing and simultaneous cuing conditions for each observer at each of the three performance criteria with error bars estimated from the resampling procedure. The data are summarized in Figure 6c, which plots the average TVC functions at $d' = 1.24$ performance level (derived by averaging the contrast threshold at $d' = 1.24$ in each condition across all the observers).

The TVC functions in Figure 6b all share the same properties: Threshold at each external noise level in the precuing condition is lower than that in the simultaneous cuing condition at all external noise and performance levels. This pattern of results suggests a different mechanism of attention from that found in Experiment 1: A mixture of external noise exclusion and stimulus enhancement appears to be the mechanism for the precuing advantage with peripheral cues. The remarkable parallelism of all the TVC functions for each observer at three widely separated d' levels suggests that a mixture of external noise exclusion and stimulus enhancement is the mechanism for peripheral precuing advantage (see Figure 3), rather than internal multiplicative noise reduction alone or in combination with either or both of the external noise exclusion and stimulus enhancement. The parallelism of TVC functions (in the log) is a strong, systematic property of the data, easily handled by the PTM model, which requires an explanation by any theoretical approach to the data.

The size of the precue advantage is quite substantial at all the external noise levels. Averaged across the lowest three external noise levels, the threshold with precued spatial attention represents a 13%, 11%, and 9% threshold reduction for observers AC, SM, and VL. At the highest noise level, the threshold in the precue condition represents a 16%, 16%, and 21% reduction for observers AC, SM, and VL, respectively. In Experiment 1, the geometric mean threshold reduction in the precue condition at the highest noise level across all the 5 observers is 16.2%; the geometric mean for AC, SM, and VL is 16.9%. Here, the geometric mean is 17.5%. So, peripheral and central cuing produced essentially the same effect in the high external noise region.

Modeling

To distinguish various mixtures of attention mechanisms involved in the precue advantage in peripheral cuing, the same procedure from Experiment 1 was used to compare different model fits with the threshold data. Our statistical procedure identified the best model as the one with six free parameters in which attention affects both A_a and A_f—a mixture of stimulus enhancement and external noise exclusion. This six-parameter model is superior to the four-parameter model with no precuing effects ($A_a = A_m = A_f = 1.0$), $F(2, 42) = 30.63, 45.37, 38.37$, all $ps < .001$, for observers AC, SM, and VL. It is also superior to either five-parameter model with stimulus enhancement only ($A_m = A_f = 1.0$), $F(1, 42) = 34.97, 61.97, 59.34$, all $ps < .001$, for observers AC, SM, and VL, or with external noise exclusion only ($A_a = A_m = 1.0$), $F(1, 42) = 16.02, 13.36, 7.69, p < .01$, for observers AC, SM, and VL. On the other hand, eliminating A_m from the full model with all three mechanisms of attention does not significantly decrease r^2 (all $ps > .25$); but eliminating either A_f ($p < .001$ for all 3 observers) or A_a ($p < .025$ for AC, SM, and VL) or both ($p < .001$ for all 3 observers) significantly decreases r^2. Similar statistical results were obtained for the average TVC functions in Figure 6c. Thus, we conclude that a combination of stimulus enhancement and external noise exclusion mechanisms of attention operate in the peripheral cue condition. The parameters of the best fitting model are listed in Table 2.

The geometric mean of A_fs across observers AC, SM, and VL from Table 2 is .8233. In comparison, the geometric mean of A_fs across participants AC, SM, and VL in Table 1 is 0.8499. Thus, peripheral cuing might have some very slight effects in the high noise conditions than what exists in central cuing. However, the difference is not very large. On the other hand, peripheral cuing does introduce a significant precue advantage in the low noise conditions, which did not exist with central cuing.

General Discussion and Conclusions

In this study, we applied the external noise plus attention paradigm to investigate the mechanisms of attention involved in central and peripheral precuing advantages. We found, in Experiment 1, that central precuing at 150-ms SOA (vs. simultaneous cuing at −33-ms SOA) significantly improved performance (reduced threshold by an average of 16%) only in the presence of high external noise, not in low levels of external noise. In contrast, in Experiment 2, peripheral precuing at 150-ms SOA (vs. simul-

Table 2

Best Fitting Perceptual Template Model Parameters (Experiment 2)

Participant	A_a	A_f	N_m	N_a	β	γ	r^2
AC	0.7628	0.8368	0.0000	0.0054	1.492	2.094	0.9833
SM	0.8221	0.8049	0.0000	0.0094	1.203	1.866	0.9865
VL	0.8575	0.8284	0.0000	0.0046	1.565	2.154	0.9889

Note. A_a = factor by which internal additive noise is reduced by stimulus enhancement; A_f = factor by which external noise is reduced by retuning of perceptual template (external noise exclusion); N_m = coefficient by which the standard deviation of the multiplicative internal noise is proportional to the energy in the input stimulus; N_a = standard deviation of the internal additive noise; β = the gain of the perceptual template for the signal stimulus (assuming that it passes the external noise with gain 1.0); γ = the exponent of the nonlinear transducer function; r^2 = a statistical measure of goodness of fit.

taneous cuing at −33-ms SOA) significantly improved performance in the presence of high external noise (reduced threshold by an average of 17.5%) as well as in low levels of external noise (reduced threshold by an average of 11%). Quantitative PTM model fits found that, under the specific conditions investigated, central precuing improves performance by way of external noise exclusion associated with better tuning of the perceptual template at the precued locations; peripheral precuing improves performance by way of a combination of stimulus enhancement (or equivalently, internal additive noise reduction) and external noise exclusion.

Identifying the Mechanisms

Our results in the presence of high external noise are largely consistent with previous findings in the literature (e.g., Cheal & Lyon, 1991; Lyon, 1990). For example, Lyon found systematic d' changes as he varied the SOA between the cue and the pseudo-character targets in the presence of highly effective poststimulus mask. In fact, Cheal and Lyon (1992) stated that the presence of a poststimulus mask was a necessary condition for the existence of precue advantage. Because delayed masking is a form of noise, these results are plausibly related to our results on external noise exclusion. On the other hand, the external noise plus attention paradigm and the related theoretical framework enabled us, for the first time, to robustly identify the mechanisms of attention involved in central and peripheral precuing advantages in this task.

Enns and Di Lollo (1997) suggested that suppression of masking was the mechanism for the precuing advantage. If we assume that high contrast masking has effects similar to those of high external noise, our conclusion in central precuing is consistent with theirs. In peripheral cuing, we observed some effects due to stimulus enhancement in addition to external noise exclusion.

The PTM provides a general framework within which we could quantify the effects of various attention manipulations. On the other hand, the qualitative interpretation of the data patterns does not depend on the details of the PTM modeling, that is, any observer model would associate threshold reduction in the absence of external noise with stimulus enhancement and threshold reduction in high external noise with external noise exclusion.

Studying a concurrent location-cued orientation discrimination task at two locations, Lu and Dosher (1998) concluded that stimulus enhancement underlies performance improvement at the attended location. Two factors are important in comparing Lu and Dosher (1998) and the current results: (a) Lu and Dosher (1998) used combined central and peripheral cuing; (b) Lu and Dosher (1998) studied only two possible target locations. According to the current result, the first factor seems to suggest that both stimulus enhancement and external noise exclusion might be operative in Lu and Dosher (1998). However, we also know that external noise exclusion tends to manifest itself only when the number of possible target locations in the display is high (Cheal & Gregory, 1997; Dosher & Lu, 2000a; Lu & Dosher, 2000). When there are only two possible target locations, the external noise exclusion mechanism may not be effective at all under certain display conditions (Dosher & Lu, 2000a; Lu & Dosher, 2000). Thus, the results from the current study are consistent with Lu and Dosher (1998).

The PTM is an observer model at the overall perceptual system level. A mechanism of external noise exclusion identified by the

PTM is associated with the sharpening of perceptual templates to exclude irrelevant external noise. Changes in the perceptual template refer to changes in any or all of the spatial extent, temporal tuning, or spatial frequency characteristics at the whole observer level. The exact nature of external noise exclusion is under further investigation (Lu & Dosher, 1999a).

Statistical Uncertainty Effect Versus Capacity Limitation

In multiple-element displays, an ideal observer exhibits poorer performance in conditions where the target location is unknown than in conditions where the target location is known. This performance loss of an ideal observer is referred to as a *statistical uncertainty effect*. Statistical uncertainty reflects information loss and decision limits of the observer, not changes of perceptual sensitivity or limits of information-processing capacity of the ideal observer. Statistical uncertainty effects must be considered before drawing any conclusions about attention effects (Palmer, Ames, & Lindsey, 1993; Shaw, 1984; Sperling & Dosher, 1986).

To eliminate statistical uncertainty effects, we followed the practice of Cheal and colleagues (e.g., Cheal & Lyon, 1992; Cheal et al., 1994; Lyon, 1990) by explicitly cuing the target location in all the cue-target SOA conditions. For an ideal observer with no capacity limitation (Palmer et al., 1993), this procedure eliminates statistical uncertainty. However, cuing cannot eliminate capacity limitations in the observer. Thus, any observed performance variation due to cue-target SOA changes in our temporal precuing paradigm reflects some form of capacity limitations of the human observers.

On the other hand, no simple limited capacity theory can account for all of our data. In the central cuing condition, we observed only a precuing advantage in the presence of high contrast external noise; in the peripheral cuing condition, we observed a smaller precuing advantage in low levels of external noise than in high levels of external noise. A simple limited capacity model such as the sample size model (Kinchla, 1980; Lindsay, Taylor, & Forbes, 1968; Palmer, 1994; Shaw, 1980) would predict precuing advantages of the same magnitude (in terms of threshold ratio between the precuing and the simultaneous cuing conditions). This prediction is clearly falsified by the data in this study. The observed interaction between the size of the temporal precuing advantage and external noise level suggests a particular capacity limitation: an inability of the observer to exclude external noise simultaneously at multiple locations.

Reduction of Interference From Other Locations

Chastain and Cheal (1997) investigated the effect of distractor identity on observers' performance in a cue-target SOA experiment. They found that the accuracy in target identification increased when a large number of distractors were identical to the target. This suggested that the observers processed information from the distractor locations in spite of instructions to process information at only target locations. On the other hand, without an explicit model, the effect of distractor identity on performance is difficult to interpret. We chose a design in which 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 pseudocharacter at the cued location and that at the uncued

locations). Thus, in identifying the target, any *cross-talk* from the locations containing distractors was uncorrelated and treated as random noise.

The fact that the precue advantage occurs only in high external noise in central cuing suggests that a simple reduction of interference from other locations cannot be the only mechanism for the location precue advantage. If a simple reduction of interference from locations were the mechanism for the spatial precuing advantage, one would predict some precuing advantage over the entire range of external noise levels, because at threshold the signal-to-noise ratio, or difficulty, is the same across all the external noise conditions. This is not what we observed in central cuing.

Facilitation

Henderson (1996) reported a modest cue validity (5% accuracy difference in two alternative forced-choice) in a paradigm in which both the target and the masking pattern appear in only one of eight locations in a given trial. In the invalid trials, if we assume that the high-intensity mask served as postcue, then there would be no spatial uncertainty about target location. Stressing that the displays had no competing locations, Henderson cited his results as supporting evidence for facilitation as the mechanism of precue advantage. However, because high contrast pattern poststimulus masks (a form of high external noise) were used in the experiment, we reinterpret his results as supporting external noise exclusion in the current theoretical framework.

Our results show that stimulus enhancement (facilitation of information acquisition at the precued location) is only significant in the peripheral cuing condition, whereas external noise exclusion is the primary mechanism for the precuing advantage in both central and peripheral cuing. Identifying stimulus enhancement (or facilitation) has not been possible previously because poststimulus masking has always been used in controlling task difficulty.

Exogenous Versus Endogenous Attention

Perhaps the most striking conclusion from the current study is that central and peripheral cuing activate different attention mechanisms. It has been proposed that two functionally separate attention systems, an exogenous system and an endogenous system, are involved in central and peripheral cuing tasks (Briand & Klein, 1987; Posner, 1980; Posner & Cohen, 1984). In spatial precuing, the major observed differences between the two systems are the size (Henderson, 1991; Jonides, 1981) and time course (Cheal & Lyon, 1991; Muller & Rabbitt, 1989) of cuing effects. Despite their importance, the nature of these observed differences are quantitative rather than qualitative. A stronger difference in mechanism between the two attention systems is suggested by our results: external noise exclusion for the endogenous system and external noise exclusion plus stimulus enhancement for the exogenous system. Although this view is generally consistent with the broad literature, our results may have been a consequence of the particular experimental design. The generality of our results awaits further testing.

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