

# Temporal tuning characteristics of the perceptual template and endogenous cuing of spatial attention <sup>☆</sup>

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## Abstract

External noise presented in temporal contiguity with a target impairs perceptual performance, reflecting the temporal tuning of the perceptual template. Deriving the temporal characteristics of the perceptual template, however, requires an observer model that segregates the impact of non-linearities and intrinsic inefficiencies of the observer in order to account for the impact of external noise in various temporal configurations. In Experiment 1, we showed that the perceptual template model successfully accounts for temporal masking functions in foveal Gabor orientation identification masked by external noise with a wide range of temporal configurations, and estimates the temporal characteristics of the perceptual template. In Experiment 2, we extended the paradigm and the model to compare the temporal tuning characteristics of the perceptual template in central pre- and simultaneous cuing of endogenous spatial attention in a Gabor orientation identification task in visual periphery. We found that endogenous spatial attention excludes external noise by both sharpening the temporal window of the perceptual template and (mostly) reducing the impact of external noise uniformly across the entire temporal window.

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## 1. Introduction

It has been demonstrated consistently at multiple levels of brain processing that spatial attention excludes unwanted information: at the neuronal level by monkey single cell recording (Desimone & Duncan, 1995; Hanny, Maunsell, & Schiller, 1988; Luck, Chelazzi, Hilliard, & Desimone, 1997; Moran & Desimone, 1985; Reynolds, Chelazzi, & Desimone, 1999; Spitzer, Desimone, & Moran, 1988; Treue & Maunsell, 1996), at the neural population level by functional imaging (Kastner, De Weerd, Desimone, & Ungerleider, 1998), and at the overall behavioral level by human psychophysics (Doshier & Lu, 2000c; Enns & Di Lollo, 1997; Lu, Lesmes, & Doshier, 2002; Smith, 2000). At the behavioral level, we

recently concluded that a major role of spatial attention is to exclude external noise in the target region (Doshier & Lu, 2000c; Lu et al., 2002), although attention can also increase the gain on the target stimulus, especially in peripheral cuing conditions (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lu & Doshier, 2000).

What is the functional nature of external noise exclusion in spatial attention? We investigate this question by extending the external noise plus attention paradigm (Lu & Doshier, 1998). In the original paradigm, effects of spatial attention are measured as a joint function of spatial cuing and the *amount* of white Gaussian external noise added to the signal stimuli. We identify mechanisms of attention by characterizing changes of the *magnitude* of various observer inefficiencies and the impact of external noise through the perceptual template model (PTM; Doshier & Lu, 2000c; Lu & Doshier, 1998). In this study, we investigated the nature of external noise exclusion in the time domain. Performance in an orientation identification task was measured over a wide range of configurations of the timing of the external noise in

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relation to the signal stimulus, first in fovea without any spatial attention manipulation, and then in periphery with two levels of temporal cuing of endogenous spatial attention. In both experiments, threshold versus external noise configuration functions were well modeled by the PTM. We found that cuing of endogenous spatial attention excludes external noise by both sharpening the temporal window of the perceptual template and (mostly) reducing the impact of external noise uniformly across the entire temporal window.

### 1.1. Endogenous and exogenous attention systems

It has been proposed that two different attention systems could be engaged in orienting spatial attention, depending on the location of the cue in relation to that of the target stimulus (Briand & Klein, 1987; Ladavas, 1993; Posner, 1980; Posner & Cohen, 1984; Rafal, Calabresi, Brennan, & Sciolto, 1989; Rafal, Henik, & Smith, 1991). Central or symbolic cues, which contain information about the target location but are themselves neutrally positioned in space, e.g., in the geometric center of all the possible target locations, are said to activate the *endogenous* attention system. Peripheral cues, independent of whether they contain information about the target location but are themselves positioned near the target(s), are said to activate the *exogenous* attention system. Several functional differences between the two attention systems have been observed: 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; Hopfinger & Mangun, 2001; Mueller & Rabbitt, 1989), and different inhibition of return (Posner & Cohen, 1984; Rafal et al., 1989), as well as possibly different neural substrates (Ladavas, 1993; Rafal et al., 1991). In a previous application of the external noise plus attention paradigm, we compared the mechanisms of visual spatial attention invoked by visual central and peripheral cues in a temporal pre-cuing paradigm (Lu & Doshier, 2000). We found that both central and peripheral pre-cuing excluded external noise at the target location, and peripheral pre-cuing also enhanced the stimulus in the absence of external noise. In the current study, we are primarily interested in the nature of external noise exclusion by spatial attention. We restrict our investigation to the endogenous attention system using central cuing.

### 1.2. Visual masking by external noise

Spatially overlapping external noise presented in temporal contiguity with a brief target stimulus often “masks” the target and reduces human performance (Breitmeyer, 1984). Traditionally, effects of visual masking by external noise have been measured with

brief masks at various stimulus onset asynchronies (SOA) in relation to the onset of the target. In both forward (mask proceeds target) and backward (mask follows target) masking, the performance versus target–mask SOA curves (“masking functions”) have been classified into two categories (Breitmeyer, 1984): (1) type A, in which the impact of masking decreases as a function of the temporal separation between the target and the mask (absolute value of target–mask SOA), and (2) type B, in which the impact of masking is a non-monotonic function of the temporal separation between the target and the mask. In type B situations, the maximum impact of masking on performance usually occurs in middle duration SOA’s (often 80 ms). For example, the masking function is sometimes U-shaped in backward masking (Alpern, 1953; Breitmeyer & Ogmen, 2000; Francis, 2003; Scheerer & Bongartz, 1973; Spencer & Shuntich, 1970).

A large number of studies suggest that the difference between these two types of masking function patterns might be related to the overall strength of masking (e.g., Hellige, Walsh, Lawrence, & Prasse, 1979; Kolers, 1962; Spencer & Shuntich, 1970; Turvey, 1973). External noise that covers the entire target and is presented close in time with a target (SOA < 200 ms) is “integrated” as part of the target representation in the early stages of visual processing, due to the limited temporal resolution of the visual system (e.g., Block, 1885, De Lange, 1954; Georgeson, 1987; Gorea & Tyler, 1986; Kelly, 1961; Koenderink & Van Doorn, 1980; Kulikowski & Tolhurst, 1973; Robson, 1966; Watson, Ahumada, & Farrell, 1986). When integration occurs, human performance suffers from the resulting noisy representation of the target—a phenomenon often referred to as “integration masking” (Breitmeyer, 1984; Enns & Di Lollo, 2000; Kahneman, 1968; Scheerer, 1973; Turvey, 1973). With very strong masks (energy in the mask divided by energy in the target  $\gg 1.0$ ), the shape of the masking SOA function is often approximately symmetric around zero SOA, and there is generally no effect of masking when the target and the mask are separately by more than 100 ms (Breitmeyer, 1984; Hellige et al., 1979; Kahneman, 1968; Kolers, 1962; Spencer & Shuntich, 1970; Turvey, 1973). In this study, we have restricted the experimental conditions to the classical regime of “integration masking” with very strong masks—the masks were made of the highest achievable contrast of the display system and were of much higher root-mean-square (RMS) energy than that of the targets. In addition, the masks covered the entire target region in space and were all presented within about 135 ms of the target onset. Under these conditions, the masking function is expected to be approximately symmetric around zero target–mask SOA. This allowed us to use temporal configurations of external noise that are symmetrically placed around the target stimuli and therefore reduce the necessary exper-

imental conditions while satisfying other objectives in the experimental design. Another added advantage of using symmetrically-placed masks is to discourage so-called “off-channel looking” (Patterson, 1976), i.e., adaptive shifting of the center of the temporal window to match the signal-to-noise ratio profile in the stimuli.

### 1.3. Characterizing the perceptual temporal window with external noise

In 1940, H. Fletcher (Fletcher, 1940) introduced the concept of “a critical band”, i.e., the masking of a tone by a broad-band noise is mainly determined by those frequencies close to the frequency of the tone. Fletcher hypothesized that the threshold for detecting a pure tone embedded in external noise with constant spectrum energy (constant energy per unit bandwidth) would remain constant as the bandwidth of the noise narrows around the frequency of the pure tone from a very wide bandwidth to the critical band. Narrowing the bandwidth of the external noise within the critical band, however, would reduce the threshold because all the noise energy within the critical band contributes to masking, and making the noise bandwidth narrower than the critical band reduces the amount of noise energy in the critical band and therefore masking.

Whereas the concept of critical band has been widely confirmed and accepted in audition (see Scharf & Buus, 1986 for a review), Fletcher’s method has also been extended to and widely used in vision research to estimate the spatial frequency tuning (Anderson & Burr, 1985; Daugman, 1984; Henning, Hertz, & Hinton, 1981; Legge, 1978; Legge & Foley, 1980; Lu & Doshier, 2001; Solomon & Pelli, 1994; Stromeyer & Julesz, 1972; Wilson, MacFarlane, & Phillips, 1983), orientation tuning (Campbell & Kulikowski, 1966; Daugman, 1984; Phillips & Wilson, 1984), and temporal frequency tuning (Anderson & Burr, 1985; Hess & Snowden, 1992; Lehky, 1985; Wilson, 1980) of visual channels.

In this study, we applied Fletcher’s method to estimate the characteristics of the perceptual template in the time domain. Two important modifications were made. First, we studied a large number of temporal configurations of external noise, with both “basic” configurations and their combinations (see Section 2.1.4). The result is a rich data set that provided very strong internal crosschecks for any interpretation of the data. Second, we estimated the temporal window of the perceptual template with an observer model that fully accounted for the entire data set.

### 1.4. The perceptual template model

In visual masking, the impact of external noise on human performance depends on the temporal contiguity of the target and the noise, reflecting the temporal

window of the perceptual template. However, quantitative estimates of the temporal window of the perceptual template require an observer model that segregates the impact of the temporal window from intrinsic observer non-linearities and inefficiencies.

The perceptual template model (PTM) was developed as an observer model to account for human performance in detecting or discriminating signals embedded in white external noise (Doshier & Lu, 1999; Lu & Doshier, 1998, 1999b). It is an elaborated version of the simple linear amplifier model (LAM), which consists of a linear amplification stage, an additive internal noise source, and a decision stage (Ahumada & Watson, 1985; Burgess, Wagner, Jennings, & Barlow, 1981; Nagaraja, 1964; Pelli, 1981). Compared to the LAM, the PTM has two additional components: a non-linear transducer function and a multiplicative noise whose amplitude depends on the energy in the input (Fig. 1a). The elaboration was necessary to “fix” a few well-known deviations of the behavior of LAM from human performance (Burgess & Colborne, 1988; Eckstein, Ahumada, & Watson, 1997; Lu & Doshier, 1999b; Pelli, 1985).

In this study, we show that an extended perceptual template model successfully accounts for masking functions measured with a wide range of temporal configurations of external noise. In addition, the model generates a quantitative estimate of the temporal characteristics of the perceptual template. This is first demonstrated in estimating the temporal tuning characteristics of the perceptual template in a foveal Gabor orientation identification task. The same procedure is then used to compare the temporal tuning characteristics of the perceptual template in pre- and simultaneous cuing of endogenous spatial attention in a Gabor orientation identification task in visual periphery.

## 2. Experiment 1: temporal window of the perceptual template in fovea

In this experiment, we measured temporal masking functions for a Gabor orientation identification task in the fovea over a wide range of external noise temporal configurations, consisting of four basic configurations and their combinations. The aim was to develop the basic experimental paradigm, and to extend and test the PTM model in the time domain. We showed that the perceptual template model successfully accounted for all the data. We estimated the temporal characteristics of the perceptual template using the model.

### 2.1. Methods

#### 2.1.1. Apparatus

The experiment was conducted on a Macintosh Power G4 computer running a version of Psychtoolbox

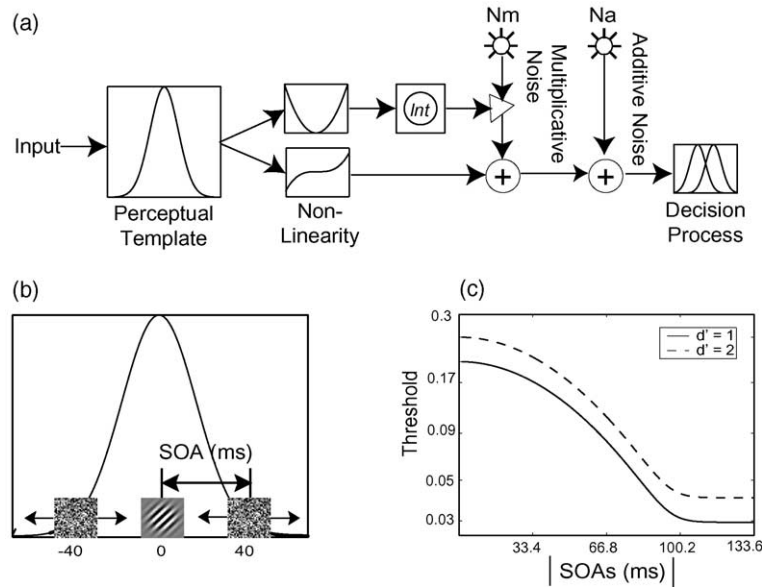


Fig. 1. (a) A noisy perceptual template model (PTM) with five components: a perceptual template, non-linear transducer function, a multiplicative internal noise source with proportional constant  $N_m$ , an additive internal noise source with mean 0 and standard deviation  $N_a$ , and a decision process. The triangle denotes an amplifier which multiplies its two inputs to produce an output. (b) An example of a temporal window of the perceptual template and an illustration of an experimental procedure in which the target is presented in the middle of the temporal window and two “fixed” masks are presented symmetrically around the target at varying target–mask onset asynchronies (SOA’s). (c) Threshold versus the absolute value of the SOA (TVS) functions for a perceptual template model with a temporal window and the procedure depicted in (b). The TVS functions are shown at two performance criterion levels ( $d' = 1$  and  $d' = 2$ ).

(Brainard, 1997; Pelli, 1997). All visual stimuli were shown on a Nanao monitor (FlexScan 6600) with a P4 phosphor and a refresh rate of 120 Hz. A special circuit (Pelli & Zhang, 1991) combined two 8-bit output channels of the video card and divided the full luminance range of the monitor (1–53 cd/m<sup>2</sup>) into 6144 distinct gray levels (12.6 bits). The display system was gamma corrected using a psychophysical procedure (Li, Lu, Xu, Jin, & Zhou, 2003). All displays were viewed binocularly with natural pupil at a viewing distance of approximately 72 cm in a dimly lighted room. Observers were instructed to maintain fixation throughout the experiment. A chinrest was used to help observers maintain their head positions.

### 2.1.2. Participants

One naïve observer (CC) and the second author participated in this experiment. Both observers had corrected-to-normal vision.

### 2.1.3. Stimuli

The “signal” stimuli were Gaussian-windowed ( $\sigma = 0.57^\circ$ ) sinusoidal gratings (“Gabor”; center frequency  $f = 1.64$  c/d), oriented  $\theta = \pm \frac{\pi}{4}$  ( $\pm 45^\circ$ ) from vertical. The luminance profile of the Gabors is described by the following equation:

$$L(x, y) = L_0 \left\{ 1.0 + c \sin[2\pi f(x \cos \theta + y \sin \theta)] \times \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \right\} \quad (1)$$

where the background luminance  $L_0$  was set in the middle of the dynamic range of the display ( $L_{\min} = 1$  cd/m<sup>2</sup>;  $L_{\max} = 53$  cd/m<sup>2</sup>); the contrast of the Gabor,  $c$ , was randomly chosen from a set of contrasts determined from pilot data to span a wide range of performance levels in each external noise condition for each observer. The Gabors were rendered on a  $64 \times 64$  pixel grid, extending  $2.78 \times 2.78^\circ$  of visual angle.

External noise images ( $2.78 \times 2.78^\circ$ ) were constructed using 2 by 2 pixel elements ( $0.087 \times 0.087^\circ$ ). The contrast of each element was drawn independently from a Gaussian distribution with mean 0 and standard deviation 0.33. Because the maximum achievable contrast is  $\pm 1.0$ , a sample with standard deviation of 0.33 conforms reasonably well to a Gaussian distribution. In a given trial, all external noise images were made of elements with jointly independent, identically distributed contrasts.

All signal and noise frames were centered at fixation.

### 2.1.4. Design

Eleven stimulus configurations were tested (Fig. 2). Each configuration consisted of a sequence of 17 frames, with one signal image in the middle of the sequence and external noise images in some of the other frames. To describe the stimulus configurations, we denote the sequence position of the signal frame as 0, the sequence positions before the signal as  $-8$  to  $-1$ , and those after the signal frames as  $1$ – $8$ . In the noiseless condition

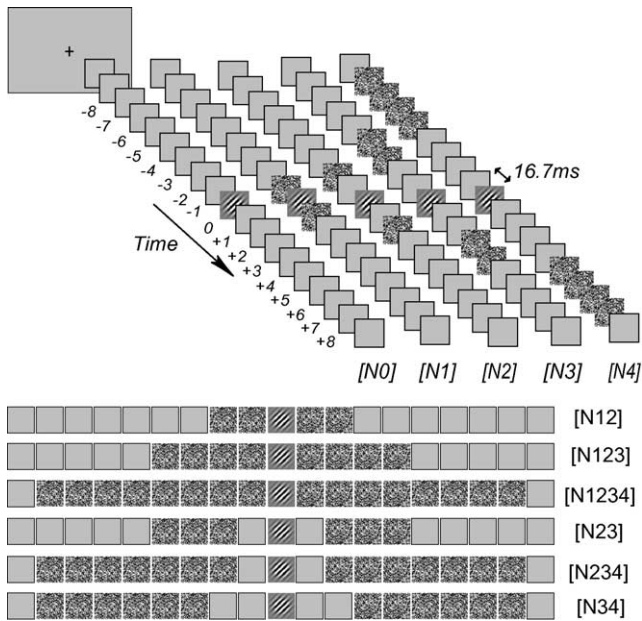


Fig. 2. Signal and external noise temporal configurations used in Experiment 1. The zero noise [N0] and the four non-overlapping basic configurations, [N1], [N2], [N3], and [N4], are shown on the top. Six additional mixtures of the basic temporal configurations ([N12], [N123], [N1234], [N23], [N234] and [N34]) are shown on the bottom. A total of eleven different external noise temporal configurations was used in this study.

([N0]), all the frames in the sequence except the signal frame were blank. In the four basic noise configurations conditions, external noise images occupied symmetric sequence positions centered on the signal frame:  $\pm 1$  ([N1]),  $\pm 2$  ([N2]),  $\pm 34$  ([N3]), and  $\pm 5678$  ([N4]).<sup>1</sup> The other six noise configurations, [N12], [N123], [N1234], [N23], [N234], and [N34], were constructed by combining the four basic configurations. For example, [N12] had external noise images in sequence positions  $\pm 1$  ([N1]) and  $\pm 2$  ([N2]).

The symmetric placement of the noise images around the signal frame can only assess joint effects of both forward and backward masking. As discussed in Section 1.1, the literature suggests that the masking functions would be approximately symmetric around the target onset. More complex patterns of temporal masking (e.g., sequential blanking effects; difference between forward and backward masking; see (Breitmeyer, 1984)) can be studied in a design with a greater variety of noise configurations. For our purposes, these eleven stimulus configurations provided sufficient constraints and tests of the PTM model—the noiseless and the four basic stimulus configurations are sufficient to specify all the parameters of the PTM (see Section 2.2.2); the six

combinations of the basic configurations provided crosschecks of model predictions.

The method of constant stimuli (Woodworth & Schlosberg, 1954) was used to measure psychometric functions in all the noise configurations. Each psychometric function was sampled at seven Gabor contrast levels, specified for each observer based on results from practice trials. The 11 (configuration)  $\times$  7 (contrast)  $\times$  2 (Gabor orientation) = 154 conditions were mixed in random order with equal number of trials in each experimental session. The observers ran two practice sessions of 1540 trials each before five experimental sessions (a total of 7700 trials). An experimental session lasted about 60 min.

### 2.1.5. Procedure

Observer pressed any key to initiate a trial when ready. A fixation-cross appeared immediately in the center of the screen and stayed on for 500 ms. The screen then turned blank for 83.3 ms, followed by the 17 frame ( $16.7 \times 17 = 283.9$  ms) stimulus sequence and another blank frame that lasted till response. The onset of the signal frame was always 250 ms after the disappearance of the fixation cross. The observer, asked to identify the orientation of the Gabor, entered his/her response on the keyboard: “a,” “s,” or “d” for Gabors tilted to the left from top, and “j,” “k,” or “l” for Gabors tilted to the right from top. Because the experiment was conducted in a dark room, three buttons for each response were used for observer’s convenience. Auditory feedback, one beep for a correct response and two beeps for an incorrect one, followed each response entry.

## 2.2. Results

### 2.2.1. Threshold patterns

For each observer, percent correct ( $P$ ) was computed at each of the seven Gabor contrast levels for the eleven stimulus configurations for each participant (Fig. 3). The data were organized as 11 psychometric functions, one for each stimulus configuration. To estimate threshold contrasts in each noise condition, Weibull functions

$$P(c) = [0.5 + (\max - 0.5)(1 - 2^{-(c/\alpha)^n})] \times 100\% \quad (2)$$

were first fit to the psychometric functions (Wichmann & Hill, 2001). The fits were excellent: the mean and standard error of  $r^2$  were 0.97 and 0.02 for CC, and 0.95 and 0.03 for SJ. The smooth curves in Fig. 3 represent the predictions of the best fitting Weibull functions.

Threshold contrasts at three performance levels (65%, 75% and 85% correct; corresponding to  $d'$  values of 0.7706, 1.3490, and 2.0729 in 2AFC identification) were calculated from the best fitting Weibull functions. Measurements of thresholds at three different performance criterion levels across a range of external noise

<sup>1</sup> More frames of external noise images were used in configurations with longer target-mask SOAs to “compensate” for reduced masking effects at longer SOAs.

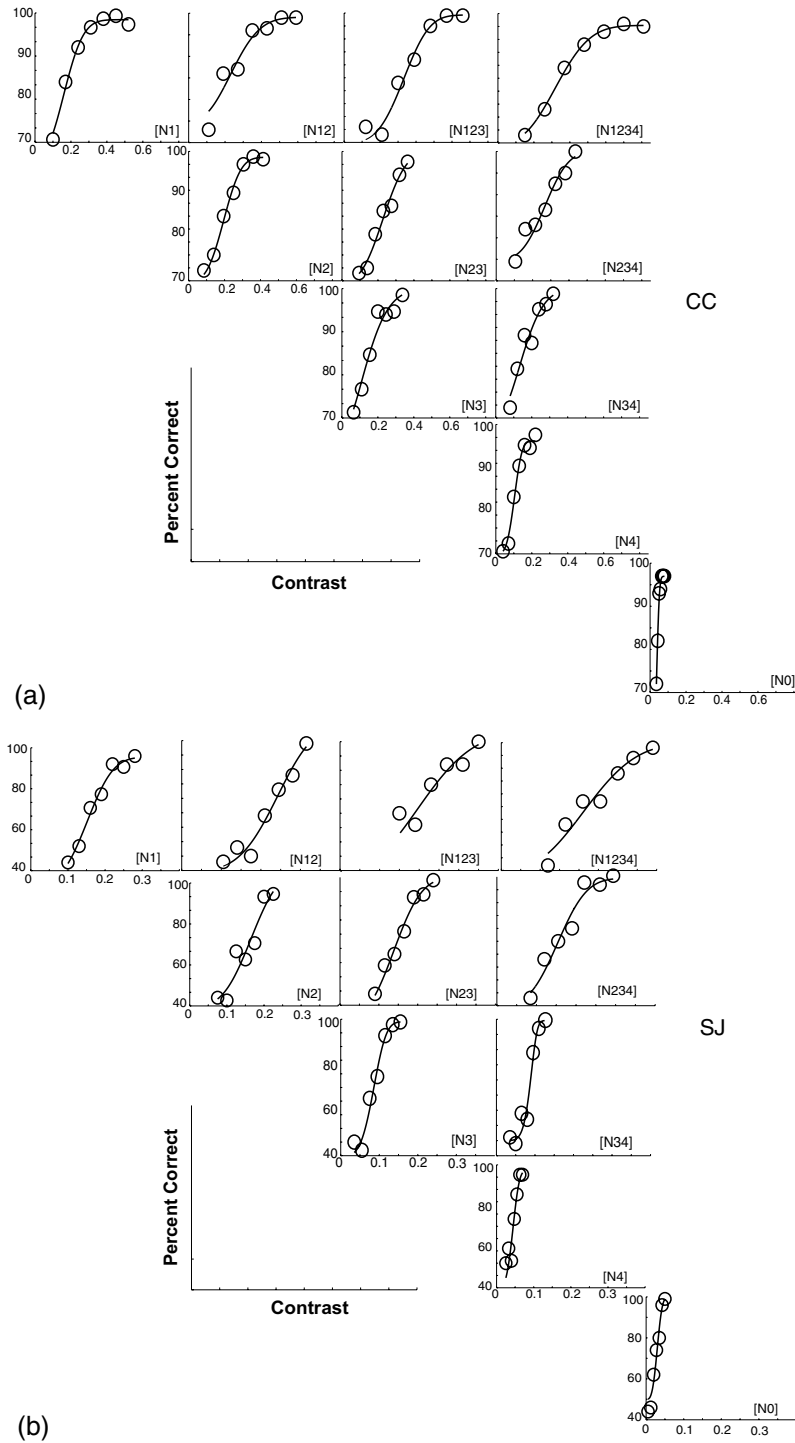


Fig. 3. Results of Experiment 1: Psychometric functions (percent correct identification versus Gabor signal contrast) for observers CC (a) and SJ (b). Eleven psychometric functions are shown for each observer, corresponding to and labeled by the eleven temporal configurations of the external noise used in the experiment. Both measurements (circles) and the best fitting Weibull functions (smooth curves) are plotted.

conditions provide very strong constraints on observer models (Lu & Doshier, 2002a). Thresholds at 75% correct for each observer and their average are plotted in Fig. 4a. In order to illustrate the relationship between the thresholds in different external noise configurations,

we used the following convention in plotting: First, thresholds from the four basic noise configurations ([N1], [N2], [N3] and [N4]) and the no noise condition ([N0]) are connected with solid lines; second, the series of thresholds with the same starting basic configuration

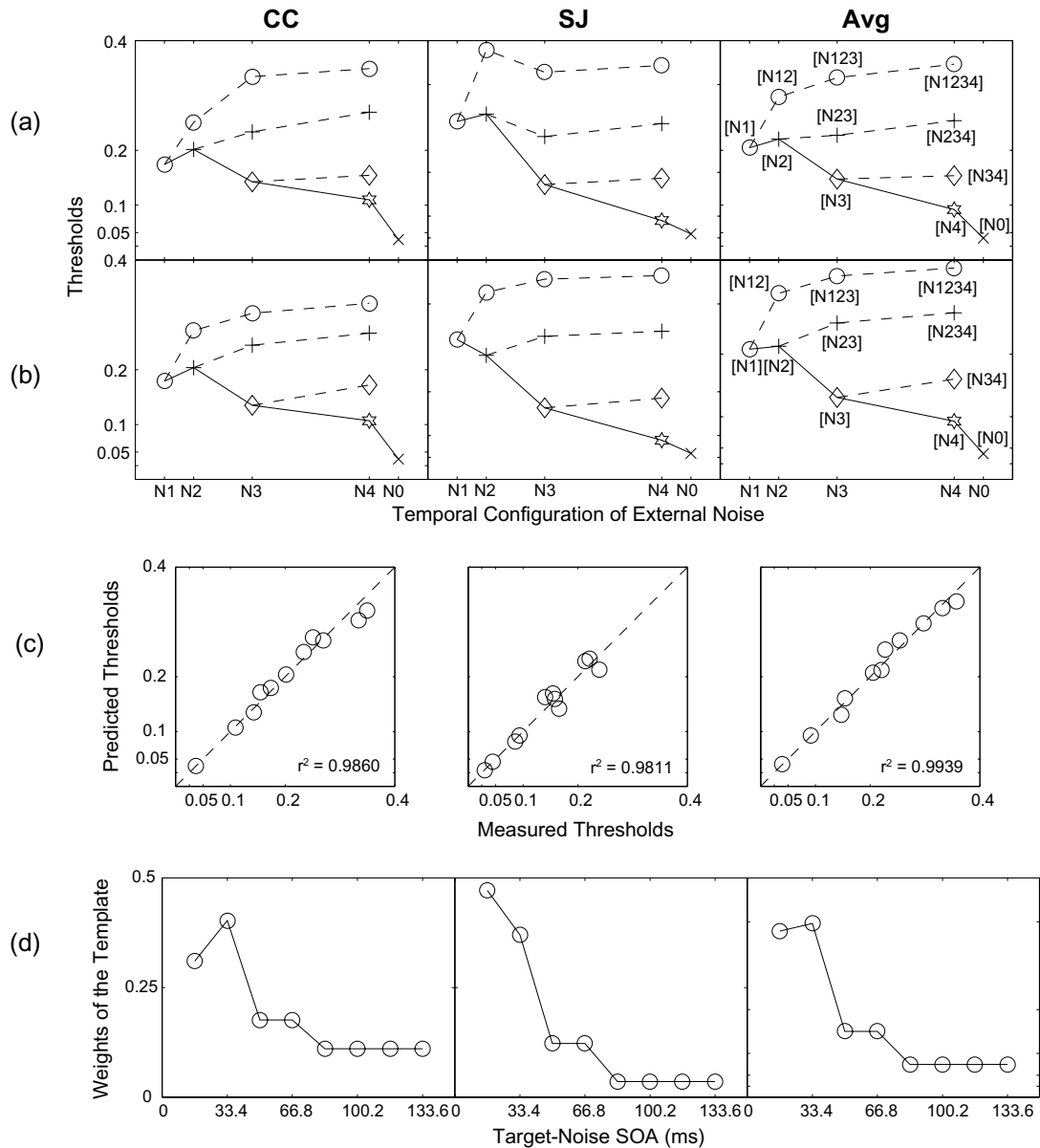


Fig. 4. Results of Experiment 1: (a) Measured Gabor contrast thresholds at 75% correct for the eleven external noise temporal configurations. (b) Predicted thresholds at 75% correct from the best fitting PTM. (c) Predicted versus measured thresholds at 75% correct with  $r^2$  shown in the figure. (d) Derived temporal characteristics of the perceptual templates from the best fitting PTM.

(e.g., [N1], [N12], [N123], and [N1234] all start from [N1]; [N2], [N23], and [N234] all start from [N2]) are connected with dotted lines.

Two qualitative observations can be made from Fig. 4a: (1) The effect of external noise diminished as a function of the temporal gap between the signal and external noise (solid curve)—threshold elevation from [N0] is greatest at [N1] and [N2]; the elevation reduces quite a bit at [N4]. (2) Thresholds increased as more external noise frames were added to each basic external noise configuration (dotted curves), e.g., higher thresholds for [N1234] than [N123] than [N12] than [N1].

### 2.2.2. Temporal window of the perceptual template

Whereas the threshold pattern in the basic external noise configurations (solid curves in Fig. 4a) provides a qualitative glimpse of the temporal window of the perceptual template. We fitted an elaborated PTM model to the thresholds estimated from the fitted Weibull functions to derive the quantitative weights of the temporal window at each SOA. In the “original” PTM (Fig. 1a; Lu & Doshier, 1999b), contrast threshold is expressed as a function of external noise

$$c = \frac{1}{\beta} \left[ \frac{(1 + N_m^2)N_{ext}^{2\gamma} + N_a^2}{1/d^2 - N_m^2} \right]^{1/(2\gamma)} \quad (3)$$

with four parameters: internal additive noise  $N_a$ , proportional constant for multiplicative noise  $N_m$ , relative gain of the perceptual template to signal stimuli,  $\beta$ , and the exponent of the non-linear transducer  $\gamma$ . To model the temporal properties of the perceptual template, we introduced three independent weights of the perceptual temporal window for the three basic external noise configurations,  $W_1$  for [N1],  $W_2$  for [N2], and  $W_3$  for [N3]. Designating the number of external noise image frames in the  $i$ th basic stimulus temporal configuration as  $F_i$ ,  $i = 1, 2, 3$ , and 4, we have:  $F_1 = 2$ ,  $F_2 = 2$ ,  $F_3 = 4$ , and  $F_4 = 8$ . Because the total gain of the perceptual template to external noise is normalized to 1.0 in the PTM (Lu & Doshier, 1999b)

$$\sum_{i=1}^4 F_i W_i^2 = 1.0 \quad (4)$$

we can calculate  $W_4$  from the other three weights.

For external noise images with variance  $\sigma_i^2$  in each basic temporal configuration  $i$ , the total variance of external noise in a given temporal configuration is

$$N_{\text{ext}}^2 = \sum F_i (W_i \sigma_i)^2 \quad (5)$$

where  $\sum$  runs over all the basic temporal configurations participating in this stimulus sequence.

Substituting Eq. (6) into Eq. (4), we have

$$c = \frac{1}{\beta} \left[ \frac{(1 + N_m^2) [\sum F_i (W_i \sigma_i)^2]^\gamma + N_a^2}{1/d^2 - N_m^2} \right]^{1/(2\gamma)} \quad (6)$$

The functional relationship between contrast threshold and the temporal configuration of the external noise is plotted in Fig. 1c for a given external noise frame placed at various SOA's from the target (Fig. 1b).

In this study, a total of eleven stimulus temporal configurations based on four basic configurations were used; and  $\sigma_i = 0.33$  was constant. The PTM had seven free parameters:  $N_a$ ,  $N_m$ ,  $\beta$ ,  $\gamma$ ,  $W_1$ ,  $W_2$ , and  $W_3$ . There were 33 data points for each observer (11 configurations  $\times$  3 performance levels). Even though the parameters of the PTM can be fully determined by the data from the four basic stimulus configurations, the mixture configurations provided strong constraints and tests of the model.

A least-square minimization procedure based on *fmins* in Matlab 5.3 (Mathworks, 1998) was used to estimate the best fitting PTM model parameters for each observer. First, we computed  $\log(c^{\text{theory}})$  from the PTM model with an initial set of parameters for each external

noise configuration at three performance criteria (65%, 75% and 85% correct). Second, we calculated the squared difference between the theoretical prediction and the observed log thresholds  $\text{sqdiff} = [\log(c^{\text{theory}}) - \log(c)]^2$ . Third, we summed all the  $\text{sqdiff}$ 's to form the least-square  $L$ . Finally, *fmins* was used to adjust the model parameters to find the minimum  $L$  based on a gradient descending method.

The goodness of model fit was assessed using the  $r^2$  statistic

$$r^2 = 1.0 - \frac{\sum [\log(c^{\text{theory}}) - \log(c)]^2}{\sum [\log(c^{\text{theory}}) - \text{mean} \log(c)]^2} \quad (7)$$

where  $\sum$  and  $\text{mean}()$  run over all the noise configurations and three difference performance levels.

The PTM provided an excellent account of the data. The  $r^2$ -values for the best fitting model are 0.986 for CC, 0.981 for SJ, and 0.994 for the average of the two observers. The parameters of the best fitting models are listed in Table 1. The theoretical predictions of the best fitting model are plotted in the second row of Fig. 4b. To facilitate visual comparisons of the model predictions to the data, scatter plots of the predicted versus observed thresholds are also shown in Fig. 4c.

The best fitting temporal weights of the four basic external noise configurations are plotted in Fig. 4d. In these panels, we converted the unit of the abscissa to milliseconds in order to calculate the half-width of the perceptual temporal window at half maximum-height,  $\Gamma$ , via linear interpolation.  $\Gamma = 51$ , 58, and 60 ms for CC, SJ, and AVG.

### 3. Experiment 2: temporal window of the perceptual template: effects of cueing

We extended the basic experimental paradigm and the elaborated PTM model developed in Experiment 1 to investigate effects of central cueing of spatial attention on the temporal window of the perceptual template. Several changes were made. First, we changed the task from 2AFC orientation identification to 4AFC orientation identification. Second, we moved the stimuli from the fovea to the periphery and simultaneously presented stimuli in eight fixed and marked spatial locations. Several studies have shown that the magnitude of cueing effects increases with the number of potential targets in the display (Doshier & Lu, 2000a; Shiu & Pashler, 1994).

Table 1  
Parameters of the best fitting PTM (Experiment 1)

	$N_m$	$N_a$	$\beta$	$\gamma$	$W_1$	$W_2$	$W_3$	$W_4$	$r^2$
SJ	0.1994	0.0030	4.878	2.843	0.4855	0.4302	0.1752	0.0671	0.9811
CC	0.2181	0.0069	3.647	2.319	0.3937	0.4490	0.2100	0.1175	0.9600
AVG	0.2192	0.0049	4.1775	2.5258	0.4352	0.4450	0.2740	0.0970	0.9939



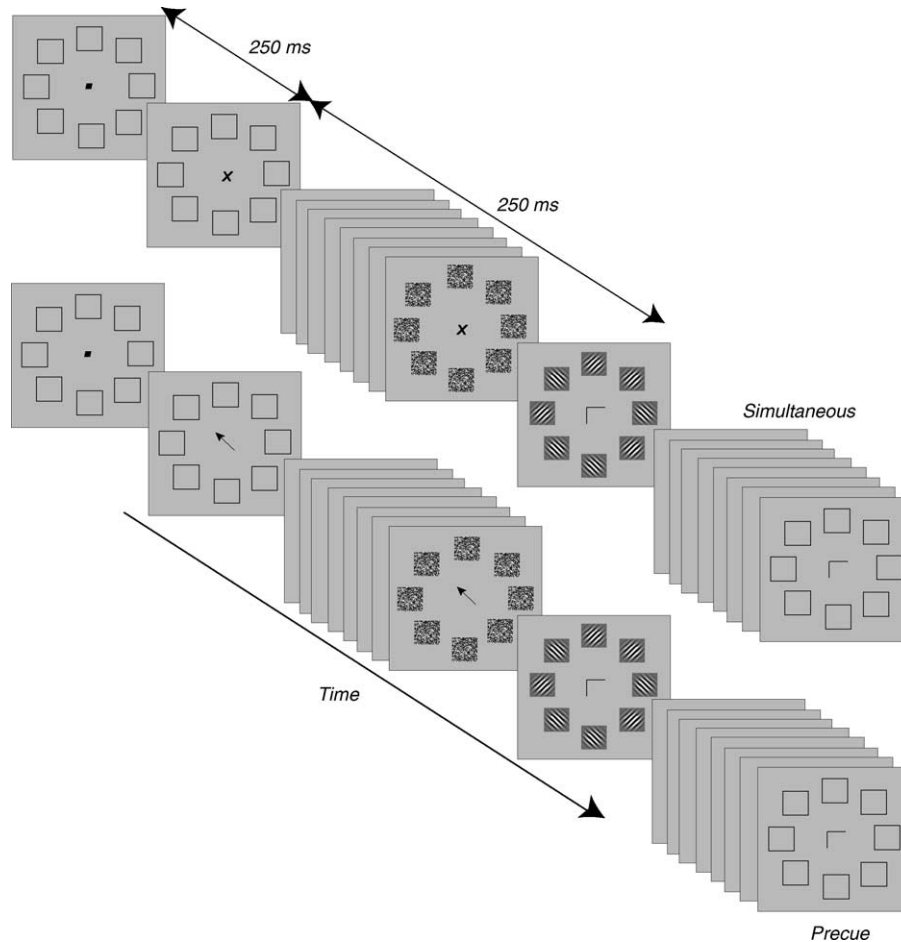


Fig. 5. Experiment 2: display sequences in the simultaneous and the pre-cueing conditions.

Third, we added a cuing manipulation—observers were cued to the target location with either a pre-cue that occurred 250 ms before the onset of the signal stimuli or a simultaneous cue that occurred simultaneously with the signal stimuli. Both types of cues occurred in the center of the display.

### 3.1. Methods

The methods are the same as those in Experiment 1 except where it is noted.

#### 3.1.1. Participants

Two naïve observers, CL and MO, and the second-author (SJ) participated in this experiment. They all had corrected-to-normal vision. SJ ran this experiment after finishing Experiment 1.

#### 3.1.2. Stimuli and display

Four Gabor patterns, tilted  $\pm 22.5^\circ$  and  $\pm 67.5^\circ$  from the vertical, served as the signal stimuli. All the other parameters of the Gabors and noise images were identical to those used in Experiment 1 (Section 2.1.2).

Sequences of signal and external noise images occurred in temporal synchrony in eight marked  $2.78 \times 2.78^\circ$  spatial regions (Fig. 5) arranged on a circle centered on the fixation with equal distances between adjacent regions. The distance from the fixation to the center of each region was  $5.85^\circ$ . The centers of the Gabors aligned with those of the eight spatial regions.

#### 3.1.3. Design

Eleven stimulus temporal configurations, same as those described in Section 2.1.4, were tested. In each trial, one single stimulus temporal configuration was used in all the eight spatial regions, with Gabors of the same contrast but randomly chosen orientations and external noise images with independently sampled pixel contrasts in different spatial regions. One of two types of cues, a pre-cue that occurred 250 ms prior to the onset of the Gabors or a simultaneous cue that occurred with the Gabors, was used to direct the observer to the target spatial region. The contrasts of the Gabors were determined for each observer and type of trial from practice sessions to adequately sample seven levels of the psychometric functions in each condition. There were a

total of 2 (cue type) × 11 (external noise configuration) × 7 (Gabor contrast) × 4 (Gabor orientation) = 616 conditions, all mixed in random order in each experimental session. Each observer ran 10 sessions of 616 trials each after 2 practice sessions. A session lasted approximately an hour.

3.1.4. Procedure

The procedure was almost identical to that of Experiment 1 except spatial cuing was involved (Fig. 5). Initiated by a key press, each trial began with a fixation dot in the center of the display and eight outlined squares marking the eight stimulus regions. The fixation dot stayed for 250 ms. In a pre-cue trial, an arrow pointing to one of the eight locations, i.e., the target location, was presented at the center of the display. 250 ms later, the array of Gabors appeared. At the onset of the Gabor, the arrow became a caret pointing to the target location and stayed on till response. In a simultaneous cue trial, a cross instead of an arrow appeared 250 ms prior to the onset of the Gabor. The cross became a caret pointing to the target location at the onset of the Gabor stimuli and stayed on till response. The timing of the transient changes in the center of the display (fixation-arrow-caret; fixation-cross-caret) was matched in the two cuing conditions to equate temporal warning of the Gabor onset. The short cue-target SOA in the pre-cuing condition eliminated potential saccadic eye movements to the target region (Hallett, 1986, Chap. 10). The observer entered the identity of the Gabor orientation in the report-cue location on the keyboard (“s,” “f,” “j,” and “l” respectively, for the tilted far to the left, near to the left, near to the right, and far to the right from top). Auditory feedback was identical to that of Experiment 1. The observer was asked to maintain fixation throughout the experiment.

3.2. Results

3.2.1. Threshold patterns

A total of 22 psychometric functions were obtained from each observer (Fig. 6). Similar to Experiment 1, Weibull functions were fitted to the psychometric functions. We constrained the slope of the Weibull functions,  $\eta$ , to be the same in fitting each pair of psychometric functions for a given external noise temporal configuration in the two cuing conditions. A  $\chi^2$  test compared the log maximum likelihood ratio of the constrained and the full, unconstrained model ( $df = 1$ ). In 30 out of 33 comparisons, the constrained fits were not significantly worse than the unconstrained fits ( $p > 0.10$ ). The two fits were marginally different in one comparison and significantly different in two comparisons. This is consistent with the specified  $p$ -value of the test as well as several reports in the literature that documented no

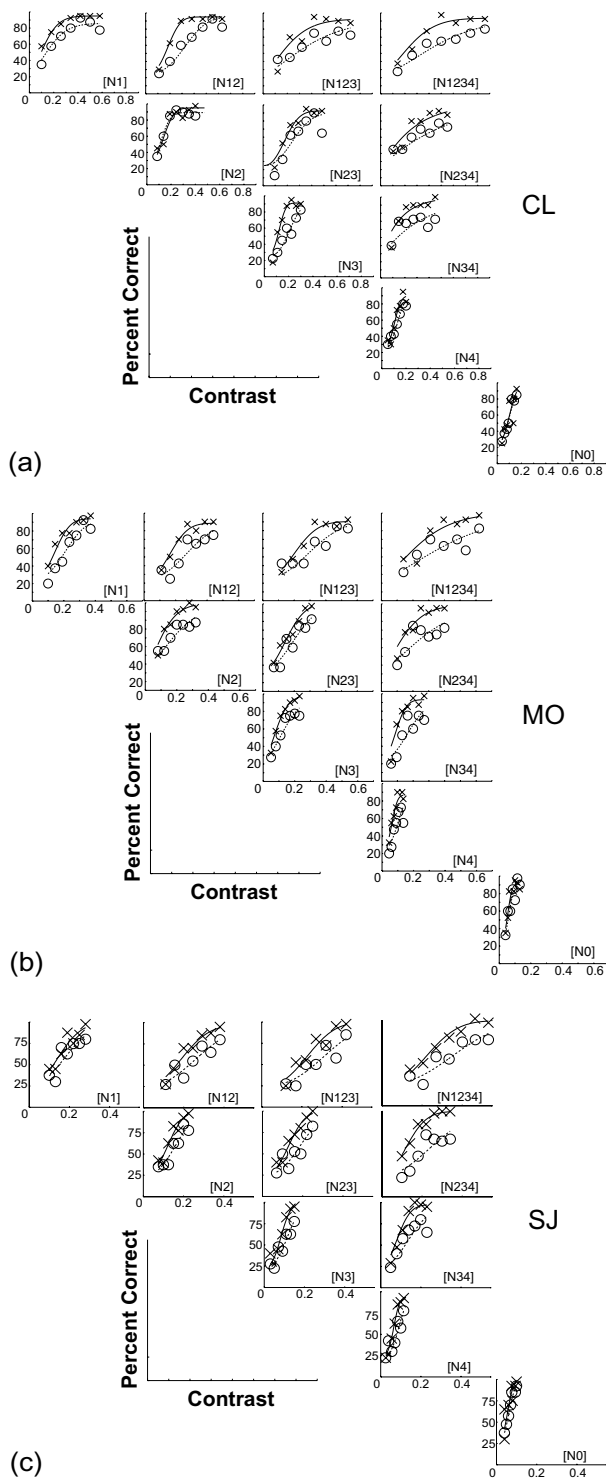


Fig. 6. Results of Experiment 2: psychometric functions for observers CL (a), MO (b), and SJ (c). Twenty-two psychometric functions are shown for each observer, two (pre- and simultaneous cuing) for each of the eleven temporal configurations of the external noise used in the experiment. Both measurements and the best fitting Weibull functions (smooth curves) are plotted. Crosses and solid curves: pre-cuing; Circles and dotted curves: simultaneous cuing.

significant effect of cuing on the slope of psychometric functions (Cameron, Tai, & Carrasco, 2002; Doshier &

Lu, 2000c; Lu & Doshier, 2000). We used the results from the constrained fits for further analysis.

The quality of the Weibull fits was reasonable: the mean and standard error of  $r^2$  were 0.89 and 0.07 for CL, 0.89 and 0.05 for MO, and 0.91 and 0.03 for SJ. The smooth curves in Fig. 6 represent the predictions of the best fitting Weibull functions.

Threshold contrasts at three performance levels (50%, 62.5% and 75% correct, corresponding to  $d$ 's of 0.84, 1.24, and 1.68 in 4 AFC identification) were calculated from the best fitting Weibull functions. Measurements of thresholds at three different performance criterion levels provide very strong constraints on observer models and mechanisms of attention (Doshier & Lu,

1999; Lu & Doshier, 2002b). Thresholds at 75% correct for each observer and their average are plotted in Fig. 7a. The same convention from Experiment 1 was used in plotting the thresholds: First, thresholds from the four basic noise configurations ([N1], [N2], [N3] and [N4]) and the no noise condition ([N0]) are connected with solid lines; second, series of thresholds with the same starting basic configuration are connected with dotted lines. Pre-cuing and simultaneous cuing conditions were plotted with different colors.

Within each cuing condition, the qualitative relationship between thresholds is very similar to that of Experiment 1: (1) The effect of external noise diminished as a function of the temporal gap between the signal and

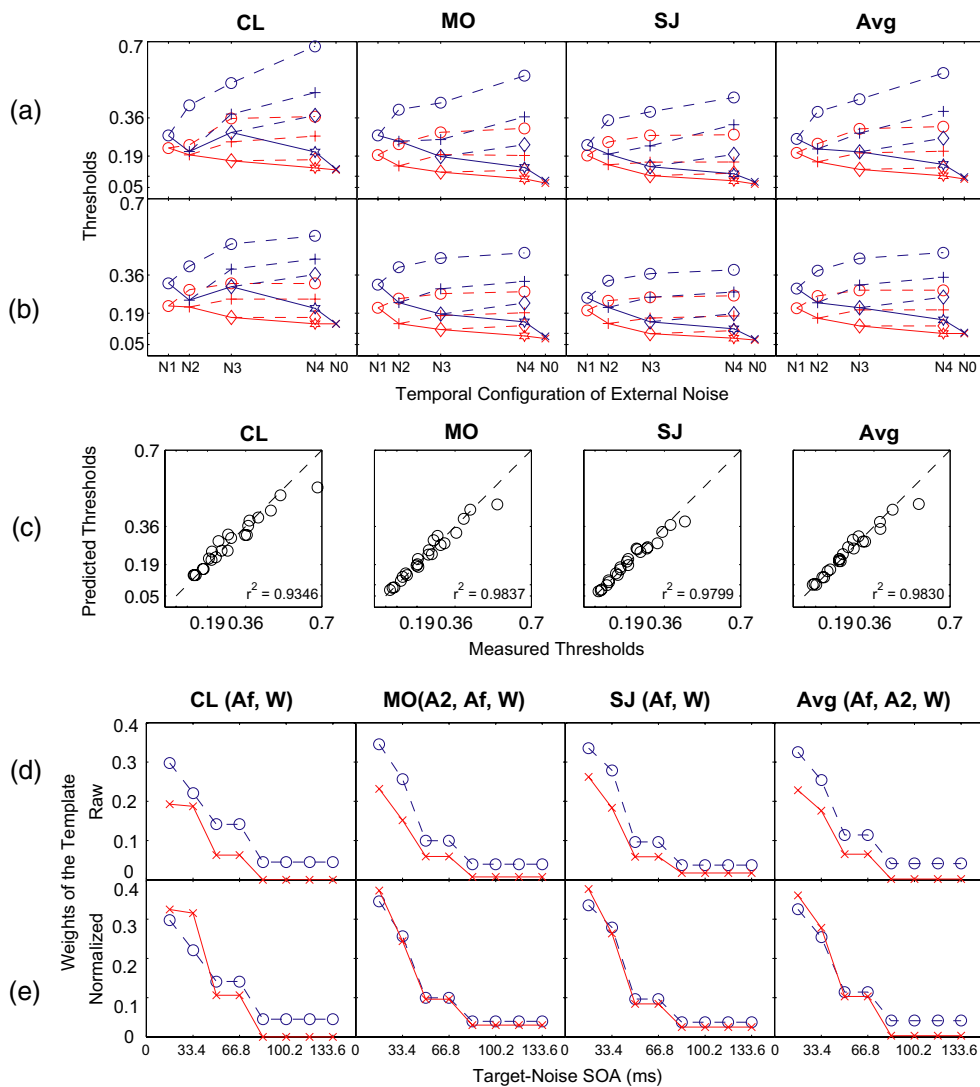


Fig. 7. Results of Experiment 2: (a) Measured Gabor contrast thresholds at 75% correct for the eleven external noise temporal configurations (red: pre-cuing; blue: simultaneous cuing). (b) Predicted thresholds at 75% correct from the best fitting PTM. (c) Predicted versus measured thresholds at 75% correct with  $r^2$  shown in the figure. (d) Derived temporal characteristics of the perceptual templates from the best fitting PTM. Circles and dotted curves: simultaneous cuing; crosses and solid curves: pre-cuing. (e) Normalized temporal windows in the pre- and simultaneous cuing conditions: “the total area under each curve” is 1.0. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

external noise (solid curve)—threshold elevation from [N0] is greatest at [N1] and [N2]; the elevation reduces quite a bit at [N4]. (2) Thresholds increased as more external noise frames were added to each basic external noise configuration (dotted curves), e.g., threshold for [N1234] > threshold for [N123] > threshold for [N12] > threshold for [N1]. Between the two cuing conditions, the magnitude of the cuing effect, defined as percent threshold reduction in the pre-cuing condition relative to that of the simultaneous cuing condition, increased with the magnitude of the threshold in the simultaneous cuing condition (Fig. 8)—attention was more effective in higher external noise. In addition, consistent with our previous publications (Doshier & Lu, 2000c; Lu & Doshier, 2000; Lu et al., 2002), there was essentially no cuing effect for two observers and only modest (13%) cuing effect for one observer in the zero noise condition. Taken together, these results are consistent with an external noise exclusion mechanism of attention (Doshier & Lu, 2000c; Lu & Doshier, 1998).

### 3.2.2. Comparing temporal windows in the two cuing conditions

We estimated and compared the temporal windows in the two cuing conditions by fitting the PTM to the threshold data (2 cuing conditions  $\times$  11 external noise configurations  $\times$  3 performance levels). For the simultaneous cuing condition, Eq. (7) is used to compute the threshold as a function of stimulus configurations. The corresponding PTM consisted of seven free parameters:

internal additive noise  $N_a$ , multiplicative noise  $N_m$ , relative gain of the signal stimuli  $\beta$ , the exponent of the non-linear transducer  $\gamma$ , and three independent weights of the perceptual temporal window for the three basic external noise configurations, here denoted as  $W_{1s}$ ,  $W_{2s}$ , and  $W_{3s}$ . We modeled the potential mechanisms of attention in the pre-cuing condition as “modifiers” acting on the parameters of the PTM in the simultaneous condition:

- (1)  $A_a$ , applied on  $N_a$ , reduces the internal additive noise to  $A_a N_a$ . It reflects the internal additive noise reduction (or, equivalently, stimulus enhancement) mechanism of attention. We use the term “stimulus enhancement” instead of “signal enhancement” because attention increases the gain to both the signal and the external noise in the input. Stimulus enhancement is only effective when the masking energy is low: in the absence of external noise or at long target–mask SOA’s.
- (2) Sharpening of the temporal window of the perceptual template. We introduced a new set of temporal weights,  $W_{1a}$ ,  $W_{2a}$ ,  $W_{3a}$ , and  $W_{4a}$ , with  $\sum_{i=1}^4 F_i W_{ia}^2 = 1.0$ . It reflects a mechanism of attention that changes the shape but not the magnitude of the perceptual temporal window. We label this mechanism “external noise exclusion I”. The mechanism improves performance in intermediate target–mask SOA’s.
- (3)  $A_f$ , applied on the temporal weights, reduces the temporal weights to  $A_f W_{1s}$ ,  $A_f W_{2s}$ , and so on. This

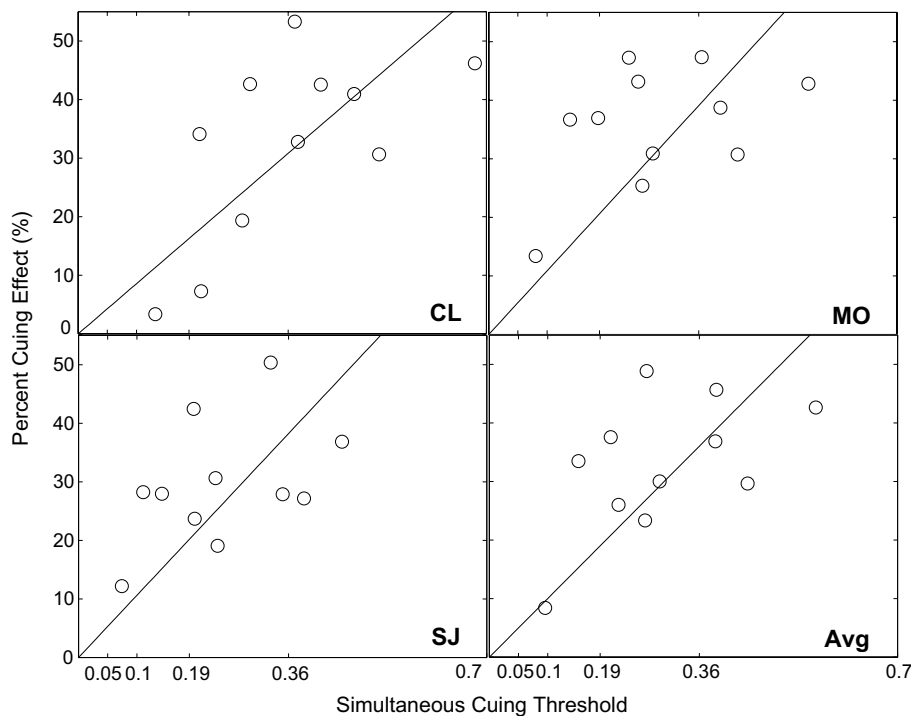


Fig. 8. Magnitude of the cuing effect (percent threshold reduction in each temporal configuration) as a function of the threshold in the simultaneous cuing condition.

corresponds to a uniform reduction of the gain of the perceptual temporal window to the external noise across time. Excluding external noise in dimensions other than time, this mechanism changes the magnitude but not the shape of the perceptual temporal window. We label this mechanism “external noise exclusion II”. The mechanism improves performance when the masking energy is high, i.e., at short target–mask SOA’s.

- (4)  $A_m$ , applied on  $N_m$ , reduces the proportional constant of multiplicative internal noise to  $N_m$ . It reflects the internal multiplicative noise reduction (or, equivalently, contrast-gain control change) mechanism of attention. This mechanism improves performance over the entire temporal range of masking.

We can summarize the effect of all the four attention mechanisms in one single equation by applying all the modifiers simultaneously on Eq. (7)

$$c = \frac{1}{\beta} \left[ \frac{(1 + (A_m N_m)^2) \left[ \sum F_i (A_f W_{ia} \sigma_i)^2 \right]^\gamma + (A_a N_a)^2}{1/d'^2 - (A_m N_m)^2} \right]^{1/(2\gamma)} \quad (8)$$

The signature performance patterns for each of the four attention mechanisms are illustrated in Fig. 9.

A full combination of these four different mechanisms of attention resulted in sixteen models, ranging from no cuing effects on any of the model parameters to applications of all the mechanisms. Because we have never found significant multiplicative noise reduction in very similar paradigms in our previous research (Doshier & Lu, 2000b, 2000c; Lu & Doshier, 1998, 2000), we first tested and confirmed that there was no significant multiplicative noise reduction in the current data set ( $p > 0.25$ ). We focused our subsequent model testing on the eight models resulting from combinations of the other three mechanisms of attention: Stimulus enhancement ( $A_a$ ), external noise exclusion I ( $W_a$ ’s), and external noise exclusion II ( $A_f$ ).

An  $F$ -test was used to statistically compare nested models. Designating the more saturated model as “full”, and the less saturated model as “reduced”, the  $F$  statistic is defined

$$F(df_1, df_2) = \frac{(r_{full}^2 - r_{reduced}^2)/df_1}{(1 - r_{full}^2)/df_2} \quad (9)$$

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

After eliminating multiplicative noise reduction, the fullest model assumed the union of three attention modifiers: 1  $A_a$ , 1  $A_f$ , and 3  $W_a$ ’s, with a total of 12 parameters. For observer MO and AVG, this fullest model is superior to all its reduced models ( $p < 0.025$ ).

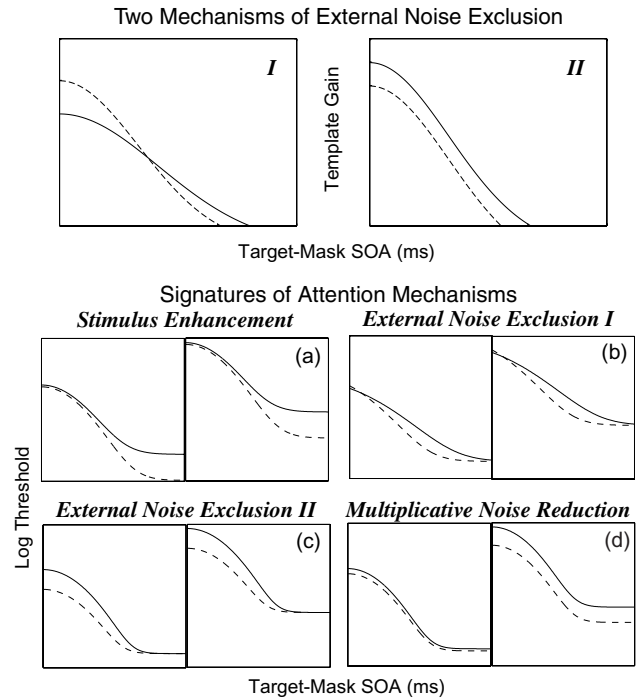


Fig. 9. Upper panels: two mechanisms of external noise exclusion. Solid curves: the gain of the perceptual template in the simultaneous cuing condition. Dotted curves: the gain of the perceptual template in the pre-cuing condition. Lower panels: performance signature of four different attention mechanisms at two performance levels (solid curves: simultaneous cuing; dotted curves: pre-cuing). (a) Stimulus enhancement: attention is only effective when the effective masking energy is low: at long target–mask SOA’s. (b) External noise exclusion I—attention sharpens the tuning of the temporal window without changing the total gain of the temporal window: Attention improves performance in intermediate target–mask SOA’s. (c) External noise exclusion II—attention reduces the gain of the temporal window uniformly across the entire window without changing the shape of the temporal window: attention improves performance when the effective masking energy is high, i.e., at short target–mask SOA’s. (d) Internal multiplicative noise reduction: attention improves performance over the entire temporal range of masking. The magnitude of attention effect is constant across different  $d'$  levels in (a)–(c), while it increases with  $d'$  in (d).

For the other two observers, CL and SJ, the fullest model is statistically equivalent ( $p > 0.25$ ) to a reduced model with only  $A_f$  and  $W_a$ ’s as attention modifiers, but superior to all the other reduced models ( $p < 0.0025$ ). In turn, this two- mechanism model is superior to all its reduced models ( $p < 0.0025$ ). We conclude that three attention mechanisms, stimulus enhancement and both forms of exclusion of external noise, operated to improve observers’ performance in this experiment. The best fitting PTM parameters are listed in Table 2. The predictions of the best fitting PTM are plotted in Fig. 7b. The model provides a very good account of the data, as illustrated in the scatter plot (measured versus predicted thresholds) in Fig. 7c.

We plotted the best fitting temporal weights ( $W_s$ ’s and  $W_a$ ’s) of the perceptual template window in Fig. 7d. In

order to illustrate the full impact of cuing on perceptual temporal windows, we plot  $A_f W_a$  in Fig. 7e. As in Fig. 6, we converted the units of the abscissa in these panels to milliseconds in order to calculate the half-width of the perceptual temporal window at half-height,  $T$ .  $T_s = 60, 50, 58,$  and  $60$  ms for CL, MO, SJ, and AVG. In comparison,  $T_a = 58, 45, 58,$  and  $50$  ms for CL, MO, SJ, and AVG. On average, cuing of spatial attention reduced the width of the temporal window by 16%.

For the average observer, the most reduced model (no attention effect) accounted for 0.8068 of the total variance; the best fitting model accounted for 0.9830 of the total variance. In the best fitting model, there were three attention mechanisms: stimulus enhancement, external noise exclusion I, and external noise exclusion II. Invoked alone, each of these three mechanisms accounted for 0.8518, 0.9701, and 0.8715 of the total variance. Of the total variance accounted for by attention mechanisms in the best fitting model ( $0.9830 - 0.8068 = 0.1762$ ), external noise exclusion II accounted for most of the variance ( $(0.9719 - 0.8068) / (0.9830 - 0.8068) \times 100\% = 92.7\%$ ). Stimulus enhancement and external noise exclusion I only accounted for about 7.7% of the attention effects.

#### 4. Discussion

In this study, we adopted Fletcher's method to the time domain to derive the temporal window of the perceptual template, first in fovea without any attention manipulation and then in periphery with two levels of cuing of endogenous spatial attention. A large number of basic and combined temporal configurations of the external noise were used to constrain and to test the perceptual template model as well as the temporal window of the perceptual template. We found that, with strong masks and short target-mask SOA's, the perceptual template model accounted for a very rich data set, and cuing of spatial attention excludes external noise by both sharpening the shape and reducing the gain of the temporal window of the perceptual template.

The primary goal of this research was to investigate the effects of cuing of endogenous spatial attention on the temporal window of the perceptual template—how spatial attention excludes external noise presented at different SOA's from the target. For these purposes, we restricted the study to stimulus conditions that usually produced relatively simple visual masking functions (Breitmeyer, 1984). We showed that the PTM model with a relatively simple temporal window of integration provided a good account of the data. Accounting for the details of visual masking in general would require further extension of the PTM framework to include more detailed temporal processing of the signal and noise. We believe a combination of the PTM with some of the current visual masking models that are based on the temporal dynamics of vision at a more abstract level of visual representation (Francis, 2003) might be a potentially fruitful research direction.

Many studies in the literature have documented reduction of decision uncertainty as a very important function of spatial attention (Burr, Verghese, Morrone, & Baldassi, 2003; Eckstein, Shimozaki, & Abbey, 2002; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Palmer, Ames, & Lindsey, 1993; Shaw, 1984; Shiu & Pashler, 1994; Sperling & Doshier, 1986). For example, in some cuing studies, the observers were only explicitly informed of the target location in the valid trials but not in the invalid trials. In invalid trials, there is "statistical uncertainty" in the decision process—information from the non-target locations (distractor or noise) may participate in the decision processes. In valid trials, the probability that a distractor was mistaken for a target was greatly reduced by cuing. Therefore, the benefits of valid cuing may have only reflected a reduction of the uncertainty effect in the decision process rather than changes in the quality or processing of the target stimulus. In this and several of our previous studies, we focused on mechanisms of attention using paradigms that eliminate "structural decision uncertainty": we precisely marked all the potential target regions consistently prior to each trial, and explicitly cued the observers of the target region in all the conditions before response. For

Table 2  
Parameters of the best fitting PTM (Experiment 2)

	$N_m$	$N_a$	$\beta$	$\gamma$	$A_a$	$A_f$	$W_1$	$W_2$	$W_3$	$W_4$	$r^2$
CL	0.4594	0.1331	3.7267	1.6493	1.0	1.0	0.4212	0.3132	0.2821	0.1277	0.9346
					1.0	0.5935	0.2726	0.2648	0.1261	0.0050	
MO	0.3911	0.0581	3.6706	1.7855	1.0	1.0	0.4888	0.3626	0.1995	0.1118	0.9837
					0.8023	0.6214	0.3277	0.2147	0.1192	0.0592	
SJ	0.2393	0.0465	3.6893	1.8813	1.0	1.0	0.4742	0.3948	0.1929	0.1058	0.9800
					1.0	0.6958	0.3707	0.2592	0.1175	0.0495	
AVG	0.4402	0.0665	3.8197	1.9257	1.0	1.0	0.4599	0.3593	0.2289	0.1166	0.9830
					0.9333	0.6332	0.3230	0.2488	0.1308	0.0050	

an ideal observer with no functional capacity limitation (Palmer et al., 1993), this procedure eliminates *structural uncertainty*. However, cuing cannot eliminate capacity limitations in the observer (Doshier & Lu, 2000d). Thus, once structure uncertainty is eliminated, any observed performance variation due to cuing of spatial attention reflects some form of capacity limitations of the human observers. The fact that we did not observe any cuing effect in the zero noise condition for two out of three observers and only a modest cuing effect for one observer in Experiment 2 shows that structural uncertainty was successfully eliminated in both the pre- and simultaneous cuing conditions.

Lu et al. (2002) compared central spatial pre-cuing effects in sixteen conditions that varied the amount of external noise, the number of signal stimuli, the number of locations masked by external noise, and the number and style of frame surrounding potential target locations. They concluded that simultaneous cuing successfully eliminated uncertainty about the target location—it excluded from decision both the external noise and signal in the non-target locations. And the advantages of pre-cuing therefore reflected additional benefits of the exclusion of external noise in the target region, a limited capacity attentive process that only occurs in the target region.

In order to characterize the functional nature of external noise exclusion by spatial attention, we extended the external noise plus attention paradigm (Lu & Doshier, 1998) in several new studies (Doshier, Liu, Blair, & Lu, 2003; Doshier & Lu, 2000d; Jeon, Lu, & Doshier, 2003; Lu & Doshier, submitted; Lu & Doshier, 1999a). Instead of manipulating the magnitude of the external noise, we manipulated the characteristics of the external noise. We measured effects of spatial attention as a joint function of spatial cuing and the characteristics (e.g., filtering in spatial frequency, windowing in space, or distribution in time) of the external noise added to the signal stimuli. In the spatial frequency domain, we (Doshier & Lu, 2000d; Lu & Doshier, 1999a) found that spatial attention excludes external noise uniformly across spatial frequencies without changing the tuning characteristics of the perceptual template, a result also obtained by Talgar, Pelli, and Carrasco (in press). In the orientation domain, Baldassi and Verghese (2003) found that cuing of spatial location did not change the orientation tuning of the perceptual mechanism. In the space domain, Doshier et al. (2003) found that endogenous spatial attention mostly excluded external noise uniformly in space without affecting the spatial profile of the perceptual template in the target region. In this study, we found that spatial attention both sharpens the shape and reduces the gain of the temporal window of the perceptual template, with most of the variance accounted by the uniform reduction of the gain of the perceptual template across time. In summary, all these

studies found that cuing of spatial attention excludes external noise primarily by reducing the gain of the perceptual template to external noise uniformly, without major re-tuning of the perceptual template in the investigated stimulus feature dimension.

In this and several previous studies, we found that cuing of endogenous spatial attention is very effective in reducing contrast thresholds in the presence of high external noise, it does not however significantly reduce thresholds in the presence of no or low external noise (Doshier & Lu, 2000c, 2000d; Lu & Doshier, 2000; Lu et al., 2002). The pattern of results suggests that endogenous attention does not change the gain to the signal stimulus.

How can endogenous spatial attention uniformly reduce the gain to external noise in each of the investigated dimensions without affecting the gain to the signal stimulus? We suggest that this is possible because of the different internal representations of the signal and external noise in the visual system. In all the studies cited above that investigated effects of attention on the perceptual template, the tuning characteristics of one single dimension was investigated. Whereas the signal stimuli in most studies are represented by the activity of a few visual channels, the external noise activates many more channels, including channels representing characteristics of the external noise not under the explicit manipulation in a given study. Excluding external noise in those channels could reduce the impact of external noise without affecting the tuning characteristics of the perceptual template under investigation.

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