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Attention mechanisms for multi-location first- and second-order motion perception

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Abstract

We applied the external noise plus attention paradigm to study attention mechanisms involved in *concurrent* first-order and second-order motion perception at two spatial locations. Cued to attend to one of the locations, the observer was instructed to independently judge direction of motion of either first-order (Experiment 1) or second-order (Experiment 2) motion stimuli at both locations in every trial. Across trials, systematically controlled amounts of external noise were added to the motion displays. We measured motion threshold at three performance criteria in every attention × external noise condition. We find that observers could, without any loss, simultaneously compute first-order motion direction at two widely separated spatial locations across a broad range of external noise conditions. However, considerable loss occurred at the unattended location in processing second-order motion direction at two separated spatial locations. We conclude that, under the conditions investigated in the current study, (1) in first-order motion perception, the visual system could simultaneously process motion direction at two widely separated locations without any capacity limitation; (2) in second-order motion perception, attending to a spatial location enhances stimulus contrast at that location by a factor of about 1.37 (or equivalently, reduces the internal additive noise by a factor of about 0.73). © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Simultaneous computation of visual motion at multiple locations is crucial for tasks such as motion parallax (Helmholtz, 1911), kinetic depth effects (Wallach & O'Connell, 1953), structure from motion (Ullman, 1979), and control of locomotion (Gibson, 1950, 1958). Recently, it has been proposed that visual motion perception is served by three parallel, independent computational systems (Lu & Sperling, 1995a, 1996, 1999a; Sperling & Lu, 1998): a first-order system, a second-order system and a third-order system, each computing motion from some particular properties of moving objects (see Section 1.1 for a brief review). Given its importance, it is natural to ask questions concerning simultaneous motion processing at multiple spatial locations in the proposed systems: Is it possible? What are the limitations? How is each system limited? The questions can be rephrased in the language of spatial attention: Can we attend to motion at several locations simultaneously? What are the attention mechanisms involved in multi-location motion perception?

In this study, we are primarily concerned with attention mechanisms involved in concurrent processing of first-order or second-order motion at multiple locations. Empirically, we study attention limitations in two-location first-order and second-order motion processing across a broad range of external noise conditions. The external noise manipulation enables us to identify the attention mechanisms underlying the observed attentional phenomena. We start with a brief review of the literature, distinguishing types of motion perception (Section 1.1) and of prior studies in motion and attention (Section 1.2); We then consider the theo-

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retical development relating the external noise paradigm, and corresponding mechanisms of attention (Section 2).

1.1. Three systems theory of motion perception

Recent psychophysical results have led to a three-system functional architecture of human visual motion perception (Lu & Sperling, 1995a, 1996, 1999a; Sperling & Lu, 1998). The first-order system extracts motion from moving luminance modulation using a primitive motion-energy (or equivalently, Reichardt detector) algorithm (Reichardt, 1957; Watson & Ahumada, 1983; van Santen & Sperling, 1984; Adelson & Bergen, 1985). The second-order system (Cavanagh & Mather, 1989; Chubb & Sperling, 1989) can extract motion from moving stimuli in which the expected luminance is the same everywhere but some features (i.e. contrast, orientation, and/or spatial frequency) deviate from the background. It employs a texture-grabber (spatiotemporal linear filtering plus fullwave rectification, see Chubb & Sperling, 1989) to compute the amount of features prior to a primitive motion energy algorithm (Werkhoven, Sperling & Chubb, 1993; Lu & Sperling, 1995a, 1999a; Sperling & Lu, 1998). The third-order system detects movement of feature salience, that is, changes in location of areas marked as 'salient' (Lu & Sperling, 1995b; Blaser, Sperling & Lu, 1999). It computes motion from a dynamic salience map, i.e. the locations of the salient features as a function of time.

1.2. Attention and motion perception

Attention affects motion perception in many different ways. In this section, we briefly review the literature in three subsections: Section 1.2.1, attention in third-order motion perception; Section 1.2.2, attention effects at multiple locations; and Section 1.2.3, other attention effects on motion perception. Section 1.2.3 is only indirectly relevant for the current study. It is included for completeness.

1.2.1. Attention in third-order motion perception

Much has been learned about attention mechanisms involved in third-order motion processing (Cavanagh, 1992; Lu & Sperling, 1995b; Ho, 1998; Blaser et al., 1999). Cavanagh (1992) suggested that certain third-order motion is based on active attentional tracking of the relevant stimulus features. Lu and Sperling (1995b) demonstrated that the dynamic salience map, from which third-order motion is computed, is jointly determined by top-down attentional processes and by automatic bottom-up processes. Blaser et al. (1999) measured the *equivalent* amplification of the magnitude of a stimulus feature when the feature is attended in third-order motion. Their study suggests that attention enhances the salience of the attended feature.

Given that third-order motion is intrinsically susceptible to attention and given the current active research on that topic, we restrict our discussion in this article to the effect of attention on first- and second-order motion perception at multiple locations.

1.2.2. Attention effects on multi-location first- or second-order motion

Dosher, Landy and Sperling (1989) found that, while the output of first-order motion detectors is the primary input for kinetic depth effects, second-order motion could only support limited, non-robust kinetic depth effects with low spatial resolution (see also Landy, Dosher, Sperling & Perkins, 1991). They hypothesized that this reflected limits on the ability to evaluate second-order motion simultaneously at multiple locations. Studying motion segmentation (finding the patch with a different motion direction) at multiple spatial locations, these authors (Dosher et al., 1989) found that, while the observers could simultaneously attend to first-order motion at seven different spatial locations, they could at most simultaneously attend to second-order motion at two separated spatial locations.

Using a visual search paradigm, Horowitz and Treisman (1994) concluded that short-range (or first-order, in our terminology) motion at multiple locations is computed in parallel; long-range (or second-order, in our terminology) motion at multiple locations is computed in serial. Consistent with this point of view, Verghese and Stone (1995) found that the set-size effect (threshold increases as a function of the number of distractors) in searching for a windowed (first-order) luminance sinewave grating that moves faster than the distractors can be completely accounted for by a stimulus uncertainty effect (Shaw, 1978; Palmer, Ames & Lindsey, 1993), implying that there exists no-capacity limitation in processing first-order motion at multiple locations (Shaw, 1980).

The studies reviewed above all utilized compound visual search paradigms (Sperling & Dosher, 1986), involving some intrinsic structural stimulus uncertainty effects (Shaw, 1980; Sperling & Dosher, 1986; Palmer et al., 1993). Interpretation of results from the compound tasks requires mathematical modeling of structural uncertainty. Therefore it is somewhat more difficult to draw definitive conclusions from those studies. In contrast, concurrent tasks in which each task has its own response may eliminate structural uncertainty.

Using a concurrent dual task paradigm, Ho (1998) found that observers could not simultaneously judge motion direction from two second-order motion stimuli, one at fovea, the other at peripheral vision, though they could perform a rapid serial visual presentation (RSVP) letter identification task at fovea and a second-order motion direction discrimination task in periphery simultaneously. She also found that observers can not simultaneously attend to a peripheral third-order motion direction discrimination and a foveal RSVP letter identification task.

1.2.3. Other attention effects on motion perception

Many other attention effects on motion perception have been observed. For example, it is well known that attention can modulate the perceptual dominance in ambiguous motion displays (von Gruenau, Bertone & Pakneshan, 1998) and even selectively switch on-and-off motion aftereffects from competing motion directions (Chaudhuri, 1990; Shulman, 1993; Lankheet & Verstraten, 1995). In a dual task paradigm involving a linguistic task and a movement task, Rees, Frith and Lavie (1997) showed that the processing load in a linguistic task affected both the motion-related activity level in cortical area V5 as recorded from fMRI and the magnitude of motion after-effect produced by the moving stimulus. Sekuler and Ball (1977), Ball and Sekuler (1980) found that both the threshold and the response time for detecting a moving target is significantly reduced if the direction of movement was known to the observer ahead of the time. Ball and Sekuler (1980) concluded that, in detecting moving targets, observer can only monitor a single motion mechanism which is tuned to the mean of the expected directions, despite the existence of motion mechanisms tuned to various directions in the visual system[1]. While these and many other attention effects on single location motion perception are very interesting, we chose to investigate the mechanisms of attention involved in multi-location first-order and second-order motion perception.

1.3. Mechanisms of attention

Lu and Dosher (1998a) proposed a formal perceptual template model (PTM) and an external noise plus attention paradigm to test attention mechanisms. Focusing on fundamental signal and noise relations in perceptual processes, the PTM model generates mathematical predictions for three different attention mechanisms: (1) *stimulus enhancement or internal additive noise reduction* — attending enhances the strength of the attended stimulus or reduces internal additive noise — is characterized by a threshold difference between attentional conditions at low, but not high levels of external noise; (2) *external noise exclusion* — attention differentially excludes external noise — is characterized by threshold divergence between attentional conditions at high, but not low levels of external noise; and (3) *internal multiplicative noise reduction* — attending reduces multiplicative internal noise — is characterized by threshold divergence between attentional conditions at both low and high levels of external noise. Procedures have also been developed to distinguish mixtures of mechanisms (Dosher & Lu, 1998, 1999a; Lu & Dosher, 1999).

In this article, we first briefly describe a noisy perceptual template model (PTM) of a human observer. We then introduce the external noise plus attention paradigm and summarize mathematical predictions for the performance of the model under each of the three attention mechanisms. Finally, we apply the general paradigm to study attention mechanisms in location-cued first-order and second-order motion direction identification tasks at multi-locations. Thus, empirically, we extend previous research on attentional limitations in first- and second-order motion perception to high external noise conditions; Theoretically, we classify the mechanism of attention involved in processing multi-location first-order and second-order motion using the PTM model.

[1] On the other hand, it is not clear that the computation involved in motion detection is the same as motion direction discrimination (Ball, Sekuler & Machamar, 1983), the task investigated in the current study.

2. The external noise plus attention paradigm

In this section, we briefly describe the PTM, the external noise method used to characterize the parameters of a PTM, and the signature performance patterns of the PTM under three different attention mechanisms. The relevant mathematical details may be found in Appendix A.

2.1. The perceptual template model (PTM)

A model of the human observer is necessary in order to make precise mathematical predictions on the effect of various attention mechanisms on human performance. At the overall system level, the PTM (Lu & Dosher, 1998a, 1999) has been demonstrated to be capable of characterizing human behavior in signal detection and identification. Elaborating the notion of *equivalent* internal noise (Barlow, 1956; Nagaraja, 1964; Burgess, Wagner, Jennings & Barlow, 1981; Pelli, 1981; Ahumada & Watson, 1985), a PTM (Fig. 1a) consists of five components: (1) a perceptual template; (2) a nonlinear transducer function, $\|\cdot\|^{\gamma}$; (3) an independent multiplicative Gaussian internal noise with mean 0 and variance proportional (with a factor of N_{mul}^2) to the total energy in the stimulus after the nonlinear transducer stage; (4) an independent additive Gaussian internal noise source with mean 0 and variance N_{add}^2; and (5) a decision process, which, depending on the particular task, predicts human performance based on the distributions of the signal and the noise at its input.

2.2. The equivalent input noise method

A PTM can be completely specified using 'the equivalent input noise' method originally developed in electrical engineering to characterize noisy amplifiers (North, 1942; Friis, 1944; Mumford & Schelbe, 1968). The method systematically manipulates the amount of *external* noise added to the signal stimulus and observes how threshold — signal stimulus energy required for an observer to maintain a given performance level — depends on the amount of external noise (Barlow, 1956; Nagaraja, 1964; Burgess et al., 1981; Pelli, 1981; Ahumada & Watson, 1985). Typically, a TVC (log Threshold c_τ versus log external noise Contrast N_{ext}) function (Blakemore & Campbell, 1969) is obtained. Fig. 1b plots sample TVC functions arising from the PTM model at three performance criterion levels ($d' = 1, 1.41, 2.0$). The set of curves have the following properties: (1) When the external noise N_{ext} is very small, threshold signal contrast c_τ does not vary with the amount of external noise. (2) When the external noise N_{ext} is very large, $\log(c_\tau)$ increases as a linear function of log external noise. (3) There is a smooth transition when external noise is comparable to internal noise.

Application of a PTM model to a particular perceptual task normally involves measuring threshold versus external noise functions and then fitting the data with the theoretical predictions. In fact, Lu and Dosher (1999) showed that a complete specification of the PTM model requires measuring a single TVC function at three different d' levels[2].

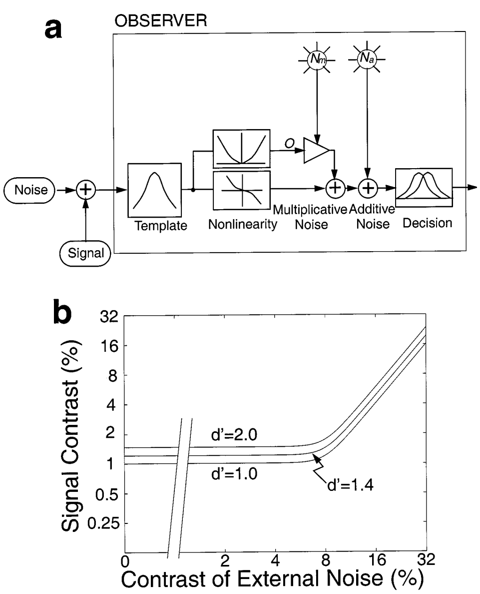

Fig. 1. (a) A noisy perceptual template model with five major components: (1) a perceptual template; (2) non-linear transducer function; (3) a multiplicative internal noise source, N_{mul}; (4) an additive internal noise source, N_{add}; and (5) a decision process. The triangle denotes an amplifier which multiplies its two inputs to produce an output. (b) Threshold versus external noise function for a particular perceptual template model ($N_{mul} = 0.2$, $N_{add} = 0.0039$, $\beta = 4.0$, $\gamma = 2.0$) at three d' levels ($d' = 1.0, 1.4, 2.0$).

2.3. Signature patterns for attention mechanisms

Within the framework of a PTM model, attention may have impacts in three different ways: (1) Stimulus enhancement — stimulus (both signal and external noise) strength at the attended location is multiplied by an amplification factor greater than 1. This is mathematically equivalent to reducing internal additive noise by a factor $A_a < 1.0$ (Lu & Dosher, 1998a). (2) External noise exclusion — a narrowing of the template matching filter would differentially exclude some amount of external noise. This is modeled by multiplying the amount of external noise at attended locations by a factor $A_f < 1.0$. (3) Internal noise reduction — while internal additive noise reduction is equivalent to stimulus enhancement, multiplicative internal noise reduction can be characterized by reducing N_{mul} by a factor $A_m < 1.0$.

Fig. 2 depicts the attention mechanisms and their signature effects on TVC functions for a sample PTM model. Stimulus enhancement (or equivalent internal additive noise reduction) reduces contrast threshold only at low external noise levels at attended locations (Fig. 2a and b). External noise exclusion reduces contrast threshold only at high external noise levels (Fig. 2c and d). Multiplicative internal noise reduction has effects over the whole range of external noise levels (Fig. 2e and f).

In applying the external noise plus attention paradigm, TVC functions are measured at both attended and unattended locations. In simple cases, direct comparison of the measured TVC functions and the signature patterns will reveal the attention mechanism in operation. In cases where the measured TVC functions don't match one of the signature patterns, measurement of TVC functions at multiple performance criteria may resolve mixtures of attention mechanisms (Dosher & Lu, 1999a,b; Lu & Dosher, 1999). We apply the external noise plus attention paradigm in the next section.

3. General methods

A concurrent paradigm was used to study attention mechanisms in first- and second-order motion. In this paradigm, stimuli are independently varied at each of two spatial locations and the observer was required to make an independent response for both locations.

[2] Fewer than three may suffice in certain situations with strong inter-condition constraints (see also Dosher & Lu, 1999a,b).

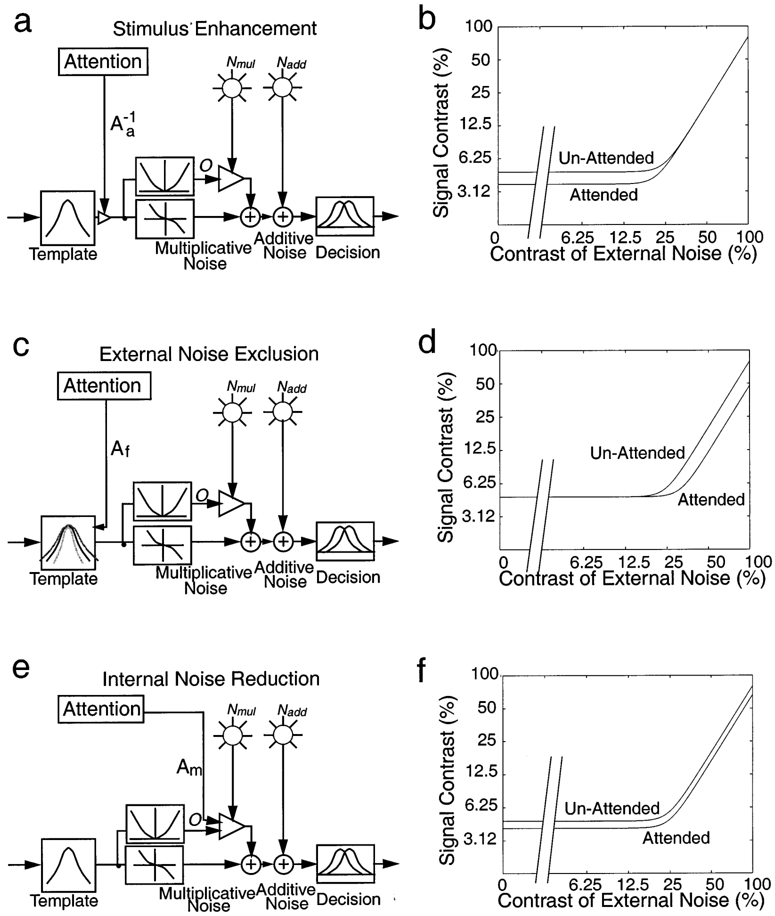

Fig. 2. Three possible attention mechanisms and the performance of the noisy perceptual template model under each of the three possible mechanisms. (a) A PTM model in which attention operates via stimulus enhancement. (b) Prediction of performance of the model in (a): signal threshold of the PTM model versus external noise contrast. These curves split at low external noise levels, and they overlap with each other at high external noise levels. Stimulus enhancement can only improve performance in low external noise levels. (c) A PTM model in which attention operates via external noise exclusion. (d) Prediction of performance of the model in (d). The signature feature of these curves is that attention only modulates performance at high levels of external noise. (e) A PTM model in which attention operates via internal multiplicative noise reduction. (f) Prediction of performance of the model in (g). Attention affects performance at all levels of external noise, but increasingly so (in log units) as external noise increases.

Statistical uncertainty issues in the decision process are avoided in concurrent paradigms compared to compound paradigms in which only one detection response is required in a trial involving multiple locations (Shaw, 1980; Sperling & Dosher, 1986; Palmer et al., 1993; Dosher & Sperling, 1998). In the two experiments reported in this article, the display always consisted of two motion stimuli, one above and the other below fixation. Observers were cued on each trial to attend to the location above or below fixation. The cue on each trial was selected randomly from the two possibilities. The motion stimulus was a (first-order in Experiment 1 and second-order in Experiment 2) sinewave modulation moving either to the left or to the right. Varying amounts of random external noise — from 0 to moderately high contrast — was added to the basic motion displays. The threshold signal contrast for each subject in performing the motion direction discrimination task was determined for all combinations of attention and external noise conditions.

Both experiments used the following methods except where noted.

3.1. Basic motion stimuli with external noise

A visual stimulus can be specified by a function $L(x, y, t)$ that defines the luminance of each point in space (x, y) as a function of time t. For displays with a fixed background luminance L_0, a point contrast function, $C(x, y, t) = (L(x, y, t) - L_0)/L_0$, is usually used to describe the stimuli because most visual tasks depend only on the local contrast $C(x, y, t)$, not on L_0.

In both of the experiments reported here, $C(x, y, t)$is composed of a moving modulator $M(fx + \gamma\omega t)$ and a stationary texture carrier $T(x, y)$, such that $C(x, y, t) = M(fx + \gamma\omega t)T(x, y)$, where $\gamma = \pm 1$ determines motion direction (left or right); $T(x, y) = 1$ for the first-order motion stimuli; $T(x, y) = +1$ or -1 with equal probability for the second-order motion stimuli.

The modulator in first-order motion displays is defined as:

$$M_1(fx + \gamma\omega t) = m_1 \sin[2\pi(fx + \gamma\omega t) + \theta_1] \quad (1)$$

with m_1 as the modulation depth and θ_1 as the initial phase.

The second-order modulator is defined as:

$$M_2(fx + \gamma\omega t) = 0.5 + m_2 \sin[2\pi(fx + \gamma\omega t) + \theta_2] \quad (2)$$

with m_2 as the modulation depth and θ_2 as the initial phase. The term 0.5 in Eq. (2) is very important — it ensures that, after fullwave rectification, second-order stimuli with modulation m_2 (<0.5) will have a fundamental sinewave component at spatial frequency f and temporal frequency ω.

All the first- and second-order motion stimuli have the same spatial frequency f at 0.55 cyc/deg and the same temporal frequency $\omega = 7.5$ Hz. The carrier textures are all defined in a $5.1 \times 4.4°$ region with each texture element subtending $0.092 \times 0.092°$. The motion stimuli were temporally sampled at every 90° phase shift such that one full cycle of a motion display consists of four distinctive frames. To remove any positional cues, one cycle plus one extra frame (five frames total) were always shown in a given trial such that the first and the last frames were identical.

Gaussian distributed external noise with mean 0 and certain experimenter controlled variance was added to the basic motion displays: For a given frame of the display, the motion stimulus and the external noise occupied alternating rows (width = 0.092°). Across frames, a given row in the display alternated between external noise and motion stimulus. To guarantee that the external noise confirmed to the Gaussian distribution, the maximum standard deviation of the noise was 33% or less of the maximum achievable contrast.

3.2. Apparatus

All stimuli were present on a Nanao Technology FlexScan 6600 monitor with a P4 phosphor and a refresh rate of 120 Hz, driven by the internal video graphics card in a PowerPC Macintosh 7500/100 computer. The displays and data collection were controlled in real time by programs using a C++ version of Video Toolbox (Pelli & Zhang, 1991; Fredericksen, 1996). To gain fine control of luminance levels, a special circuit (Pelli & Zhang, 1991) was used to combine two eight-bit output channels of the video card to produce 6144 distinct gray levels (12.6 bits).

A psychophysical procedure was used to generate a linear lookup table that evenly divided the entire dynamic range of the monitor (from 1 cd/m^2 to 53 cd/m^2) into 256 levels (Lu & Sperling, 1999b). Linear interpolation was used to obtain finer gray level scales when it is necessary. The background luminance was set at 27 cd/m^2.

All displays were viewed binocularly with natural pupil at a viewing distance of approximately 70 cm in a dimly lighted room.

3.3. Design

Each experiment consisted of ten sessions, each made of 448 trials and lasting about 0.5 h. In a given trial, two (noisy) motion displays, one above and another below the fixation point, were shown to the observer. The observer was instructed by a cue to either attend to the display above or below the fixation point with a cue lead time of 83 ms. While the motion display lasted 167 ms, the total duration of the display measured from the beginning of the cue to the end of the motion display was 250 ms. This design was chosen to avoid saccadic eye-movements to the attended location (Hallett, 1986). The two basic motion displays in a trial were both of first-order in Experiment 1, and of second-order in Experiment 2. Moreover, the modulation depths of the motion stimuli and the variance of the external noise in the two motion displays were always the same, though the motion directions of the stimuli in the two displays were chosen randomly and independently. The observer was required to report the motion direction of the attended display and then the unattended display by pressing certain keys on the computer keyboard. A beep followed immediately after each correct response. Subjects were told that a correct response at the attended location was worth 10 points while a correct response at the unattended location was only worth 1 point. A typical trial sequence is depicted in Fig. 3.

In each session, two attention conditions (attend to the display above or below the fixation point), and eight different external noise rms contrasts (0, 0.02, 0.04, 0.08, 0.12, 0.16, 0.25, and 0.33), were intermixed. The method of constant stimuli (Woodworth, 1938) was used to measure psychometric functions for each attention condition and each external noise level. Every psychometric function was sampled at seven signal contrast levels. Eight trials were obtained at each signal contrast level on every psychometric function per session. The signal contrasts were pre-determined through pilot studies.

Each observer first participated in five training sessions in which only four external noise levels were used. We concentrated on the stabilized performance. After the training phase, data from the next ten sessions were combined to generate 16 psychometric functions, one at each attention condition and each external noise contrast level.

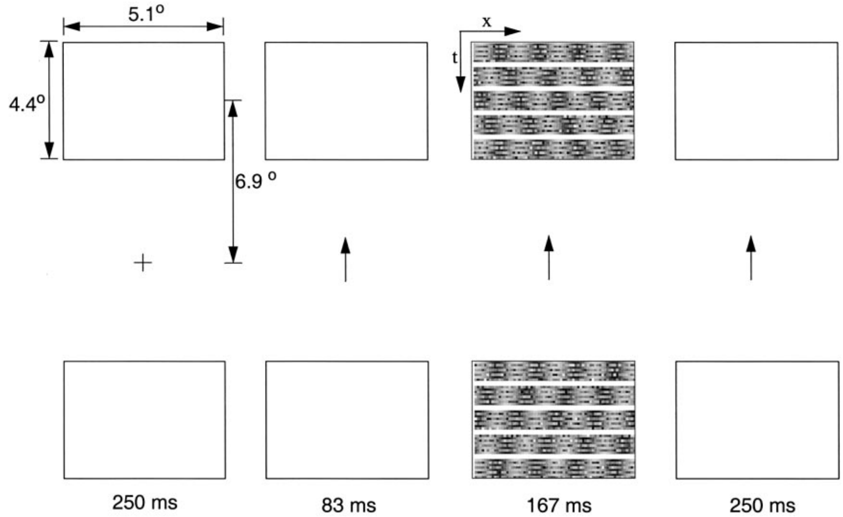

Fig. 3. Experimental procedure for first-order motion. Following a subject key press, a fixation display appears for 0.25 s. The fixation display includes two square-frames each displaced 6.9° above or below the central fixation cross. Then an attention cue replaces the fixation dot, instructing the observer to attend to the top (or the bottom) display. The cue appears 83 ms prior to the stimulus. The stimulus includes five frames of first-order motion stimulus embedded in external noise in alternating rows. All noise samples in each trial are independent samples with the same variance (contrast), as do the signal frames. Each frame appears for 33.3 ms, so the total time from the beginning of the attention cue to the end of the signal frame is only 250 ms; this precludes an eye movement to the attended location. After the stimulus sequence, a 250 ms response cue instructing the subject to report the motion direction at the attended location first, then the unattended location. The trial ends with auditory feedback for both top and bottom responses.

3.4. Observers

Three observers, all with normal or corrected-to-normal vision, served in the experiments. Two were naive to the purposes of the experiment, the third is the second author of this paper.

3.5. Data analysis procedures

For each observer in each experiment, data were analyzed in two steps: (1) extract contrast thresholds at three criterion performance levels from the maximum likelihood fitting Weibull functions for each of the 16 psychometric functions; and (2) fit the PTM model with various combinations of attention mechanisms to the threshold data and statistically compare the model fits.

3.5.1. Calculating contrast thresholds

For every subject and external noise condition in an experiment, we combined data from attending to the top and attending to the bottom to form 'attended' and 'unattended' categories. We then tabulated percent correct in motion direction discrimination at seven contrast levels for each attention × external noise condition. A Weibull function:

$$\text{Percent correct} = 1.0 - 0.5 \times 2^{-(c/\alpha)^{\eta}} \quad (3)$$

was fit to each of the 16 psychometric functions for each observer using a maximum likelihood procedure (Hays, 1981). Finally, we computed threshold signal contrast at three performance levels: 65, 75 and 85% correct identification, corresponding to d' of 0.77, 1.35 and 2.07.

The standard deviation of each threshold was estimated using a re-sampling procedure (Maloney, 1990). The procedure assumes that, at a given signal contrast for every attention and external noise condition, the number of correct responses has a binomial distribution with a single event probability p, best approximated by the measured percent correct in the condition, and an N equal to the number of trials in the condition. We constructed a 'theoretically re-sampled' psychometric function for each attention × external noise condition by generating the number of correct responses at each of the seven contrast levels from the assumed binomial distributions. Repeating this process 25 times, we generated 25 theoretically re-sampled psychometric functions in every attention × external noise condition. Maximum likelihood Weibull fits were performed on each of the 25 'theoretical' psychometric functions. Twenty-five thresholds were computed from the best Weibull fits at each of the three criterion levels (65, 75 and 85% correct). A standard deviation for the threshold at each criterion level was then estimated from the 25 samples. Standard deviations yields error bars on the estimated-threshold.

3.5.2. PTM model fits

To quantify the magnitude of the attention effects and to characterize the attention mechanisms involved, we fit PTM models (Eq. (A4)) with various possible combinations of attention mechanisms to the threshold data. First, we set $A_m = 1.0$, $A_a = 1.0$, and $A_f = 1.0$ for the unattended condition. Then, eight models, each with a unique combination of A_m, A_a and A_f as free-varying parameters for the attended condition in addition to the 'common' free parameters of the two attention conditions (N_{add}, N_{mul}, β and γ), were fit to the data of each individual observer and compared. (If a particular A does not occur in a condition, it is automatically set to 1.0, equal to the unattended conditions.) (1) Multiplicative noise reduction ($A_m < 1.0$), stimulus enhancement ($A_a < 1.0$) and external noise reduction ($A_f < 1.0$); (2) multiplicative noise reduction ($A_m < 1.0$) and stimulus enhancement ($A_a < 1.0$); (3) stimulus enhancement ($A_a < 1.0$) and external noise exclusion ($A_f < 1.0$); (4) multiplicative noise reduction ($A_m < 1.0$) and external noise exclusion ($A_f < 1.0$); (5) multiplicative noise reduction ($A_m < 1.0$); (6) stimulus enhancement ($A_a < 1.0$); (7) external noise reduction ($A_f < 1.0$); (8) no attention effects ($A_a = A_m = A_f = 1.0$). Wherever it is appropriate, an F-test for nested models was used to compare and select models.

The fitting procedure was implemented in Matlab. It was applied to data sets with thresholds at three performance levels in each of the two attention and eight external noise conditions. For a given PTM model with a particular set of A_m, A_a and A_f as parameters for the attended condition, the procedure consists of: (1) setting parameters, N_{mul}, N_{add}, β, γ and the particular combination of A_1, A_2 and A_f, using Eq. (A4) to compute $\log(c_\tau^{theory})$ from the PTM model with guessed parameter values for each attention and external noise condition; (2) computing the squared difference between the log threshold prediction from the model and the observed $\text{sqdiff} = (\log(c_\tau^{theory}) - \log(c_\tau))^2$ for each attention and external noise condition at each performance level; (3) computing L: summation of sqdiff from all the attention and external noise conditions at all three performance levels; (4) using a gradient descending method to adjust all the parameters to find the minimum of L;[3] and (5) after obtaining the least square L, computing the r^2 statistic to evaluate the goodness of the model fit:

$$r^2 = 1.0 - \frac{\sum[\log(c_\tau^{theory}) - \log(c_\tau)]^2}{\sum[\log(c_\tau) - \text{mean}(\log(c_\tau))]^2} \quad (4)$$

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

An F-statistic can be computed for each pair of nested models:

$$F(df_1, df_2) = \frac{(r^2_{full} - r^2_{reduced})/df_1}{(1 - r^2_{full})/df_2} \quad (5)$$

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. Non-nested models with the same number of parameters were compared directly using their r^2 values.

4. Experiments

4.1. Experiment 1. Concurrent first-order motion direction judgment at two spatial locations

In this experiment, two first-order motion displays with identical stimulus modulation depth, identical external noise variance, but independently chosen motion directions were shown simultaneously in each trial to the observer at two separated spatial locations: one 6.9° above fixation and the other 6.9° below fixation.[4] The observer was cued 83 ms prior to the beginning of the motion displays to pay attention either to the location above or below fixation and to make independent judgments of motion direction first at the attended and then the unattended locations (Fig. 3).

Psychometric functions for each of the eight external noise levels were tabulated for both attended and unattended conditions. Threshold contrasts for each joint attention and external noise condition at three performance levels, 65, 75 and 85% correct, were computed from Weibull fits to the psychometric functions. Threshold signal contrasts at three performance levels were necessary in discriminating PTM models (Dosher & Lu, 1999a,b; Lu & Dosher, 1999). Because of the similarity in the appearance of the thresholds at the three performance levels, Fig. 4 shows only thresholds at 75% correct as a function of the rms external noise contrast in both attended and unattended conditions. Each panel of the figure corresponds to an observer. Error bars are estimated standard deviations of each threshold value from the resampling method.

Adding external noise clearly had significant effects on observers' performance: averaged across attention conditions, the threshold increased from 0.65, 0.55 and 0.88% at 0 external noise to 2.9, 1.3 and 2.9% at maximum external noise for observers CS, QL and SM,

[3] The log approximately equates the standard error over large ranges in contrast thresholds, corresponding to weighted least squares, an equivalent to the maximum likelihood solution for continuous data. In the current data set, this assumption is true.

[4] The two stimulus regions were separated by at least 9°, far greater than distances that were known to produce significant interactions between two motion patches.

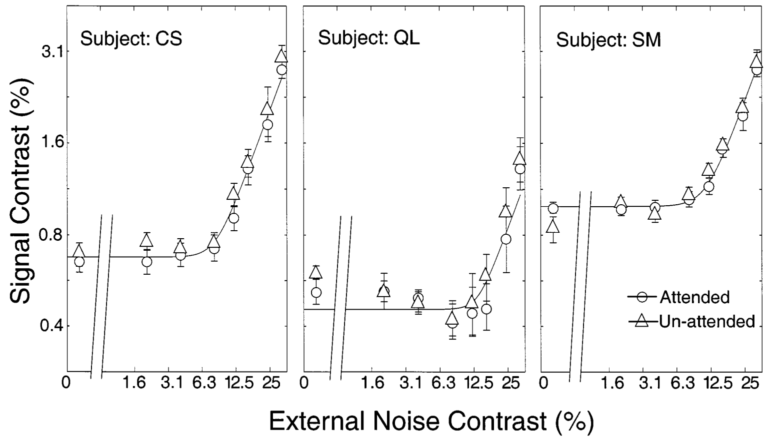

Fig. 4. Threshold contrast (rms contrast of the Gabor) versus external noise level (rms contrast of the Gaussian random noise) for three subjects each in two different attention conditions (Experiment 1: first-order motion). The curves are generated from the best fit PTM model without any attention effects.

respectively.[5] On the other hand, attention instructions had very small effects on observers' performance — the two signal threshold contrast versus external noise functions for the attended and the unattended conditions for each observer were virtually identical within the variability of the estimates of the thresholds. These effects are quantified using the PTM model.

PTM models with all possible single mechanisms and mixtures of the three attention mechanisms were fit to the threshold data at three performance levels for each observer. For all three observers, the simple PTM model without any attention modulation ($A_m = 1.0$, $A_a = 1.0$ and $A_f = 1.0$ in both attended and unattended conditions) fit the data well ($P > 0.10$ in comparison with any of the other PTM models with $A < 1.0$ in the attended condition). In other words, we found no attention effects in concurrent first-order motion direction judgment at two spatial locations. The best fitting parameters are listed in Table 1 and the corresponding PTM model predictions are plotted in Fig. 4 along with the data.

4.2. Experiment 2. Concurrent second-order motion direction judgment at two spatial locations

Two second-order motion displays with identical texture-contrast modulation depth, identical external noise variance, but independently chosen motion directions were shown simultaneously in each trial to the observer at two separated spatial locations: one 6.9° above fixation and the other 6.9° below fixation. The observer was cued 83 ms prior to the beginning of the motion displays to pay attention either to the location above or below fixation and to give answers to the motion direction first at the attended then the unattended location (Fig. 5).

The data analysis procedure was identical to that of Experiment 1. Threshold texture-contrast modulation for each attention × external noise condition at three performance levels, 65, 75 and 85% correct, were computed from Weibull fits to the psychometric functions. Because the same data pattern was observed across three criterion levels, only thresholds at 75% correct were shown as TVC functions in Fig. 6. Error bars are estimated standard deviations of each threshold computed using the resampling method (Maloney, 1990).

Adding external noise clearly had significant effects on observers, performance: averaged across attention conditions, the threshold increased from 25, 24 and 27% at 0 external noise to 32, 33 and 33% at the maximum external noise for observers CS, QL and SM, respectively. Attention instructions had relatively large effects when the external noise was low and small to no effects when the external noise was high. The pattern is consistent with a stimulus enhancement mechanism of attention.

For each observer, PTM models with all possible single and mixtures of the three attention mechanisms were fit to the threshold data at all at three criterion levels. The PTM model with only A_a as the free parameter in the attended condition best fit the data:

Table 1
Parameter estimates first-order motion

Subject	N_{mul}	N_{add}	β	γ	r^2
CS	0.2817	0.001524	14.72	2.620	0.9771
QL	0.4403	0.001343	36.50	3.351	0.8647
SM	0.0000	0.006429	13.26	2.316	0.9628

[5] We have rarely observed any dipper-shaped TVC functions in our applications of the external noise method. We believe that the dipper-shaped TVC function in the middle panel of Fig. 4 (data for observer QL) was due to random fluctuation.

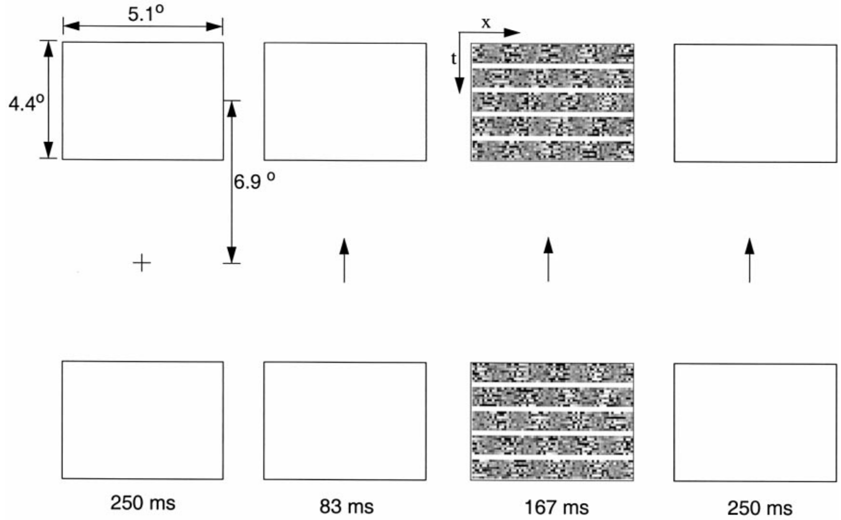

Fig. 5. Experimental procedure for second-order motion. Following a subject key press, a fixation display appears for 0.25 s. The fixation display includes two square-frames each displaced 6.9° above or below the central fixation cross. Then an attention cue replaces the fixation dot, instructing the observer to attend to the top (or the bottom) display. The cue appears 83 ms prior to the stimulus. The stimulus includes five frames of second-order motion stimulus embedded in external noise in alternating rows. All noise samples in each trial are independent samples with the same variance (contrast), as do the signal frames. Each frame appears for 33.3 ms, so the total time from the beginning of the attention cue to the end of the signal frame is only 250 ms; this precludes an eye movement to the attended location. After the stimulus sequence, a 250 ms response cue instructing the subject to report the motion direction at the attended location first, then the unattended location. The trial ends with auditory feedback for both top and bottom responses.

$P < 0.0005$ in comparison with the null, no-attention effect model in which $A_a = A_f = A_m = 1.0$ in the attended condition (For CS, QL and SM, $F(1, 42) = 45.80$, 44.15, 54.71, respectively) $P > 0.10$ for all the more saturated models: models with mixed attention mechanisms of A_a and A_m ($F(1, 42) = 0.0$, 0.0, 0.0) A_a and A_f ($F(1, 42) = 2.302$, 0.6992), and A_a, A_m and A_f ($F(2, 41) = 1.178$, 0.3413). In addition, the PTM model with a single A_a has higher r^2 ($r^2 = 0.9307$, 0.9294, 0.9206) than the PTM models with A_f ($r^2 = 0.8843$, 0.8605, 0.8399) or A_m alone ($r^2 = 0.8573$, 0.8569, 0.8559), or a mixture of A_f and A_m ($r^2 = 0.8969$, 0.8927, 0.8697). We conclude that stimulus enhancement is the attention mechanism in concurrent second-order motion direction judgment at two spatial locations. The best fitting parameters are listed in Table 2 and the corresponding PTM model predictions are plotted in Fig. 6 along with the data.

From Table 2, in second-order motion, attending to a location reduces internal additive noise at that location to about 73% of that at the unattended location. This is mathematically equivalent to enhancing stimulus at the attended location by a factor of $1/0.73 = 1.37$ (Lu & Dosher, 1998a,b). Given that, in the second-order motion system, the high internal additive noise is the true limiting factor in observer performance, such an attention mechanism could be extremely important and effective.

5. Summary and discussion

In this study, we found that observers could, without any loss, simultaneously compute first-order motion direction at two widely separated spatial locations across a wide range of external noise levels. Whereas our result at 0 external noise level is consistent with the previous literature (Dosher et al., 1989; Landy et al., 1991; Horowitz & Treisman, 1994; Verghese & Stone, 1995), we have also extended the result into high external noise regions which may be a more realistic sample of the normal visual environment. We also found that, even though it is possible for observers to extract second-order motion direction at two widely separated spatial locations, considerable loss occurs at the unattended location. This result is also consistent with the other studies in the literature (Dosher et al., 1989; Landy et al., 1991; Horowitz & Treisman, 1994; Ho, 1998). What is novel in the current study is that the external noise plus attention paradigm allowed us to identify the attention mechanism involved in multi-location second-order motion processing as stimulus enhancement, distinctively different from external noise exclusion, usually resulting from better tuning of the template at the attended locations.

We found in the current study that, in second-order motion perception, attending to a spatial location enhances stimulus contrast at that location by a factor of about 1.37 relative to the unattended location. To compare the magnitude of this effect with other empirical and theoretical attention effects in the literature, we first have to cast our results in terms of attended versus equal attention conditions. Assuming that equal attention is in the middle of the attended and the unattended condi-

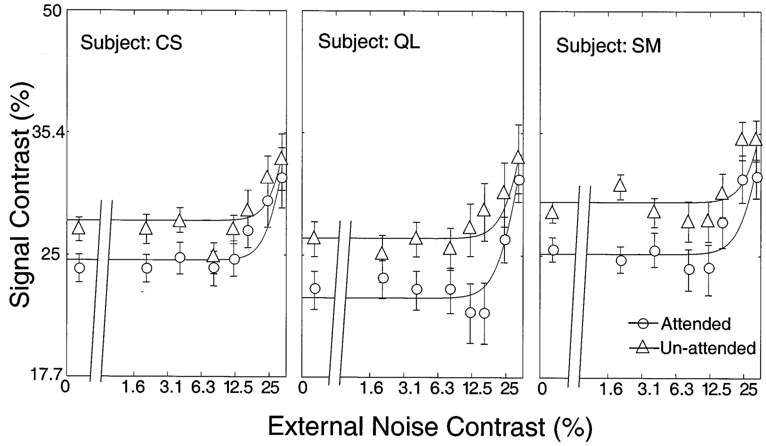

Fig. 6. Threshold contrast (rms contrast of the Gabor) versus external noise level (rms contrast of the Gaussian random noise) for three subjects each in two different attention conditions (Experiment 2: second-order motion). The curves are generated from the best fit PTM model with stimulus enhancement. Attention affected threshold contrast only at low external noise levels. For higher levels of external noise, attention conditions did not affect threshold contrast values at all. Fitting PTM model to the data suggests that attention operates via enhancing signal by about 1.37 at attended locations.

tions, the magnitude of the attention effect (attended versus equal attention) is about 18%. Suppose a fixed amount of capacity is shared between the locations (Broadbent, 1957; Lindsay, Taylor & Forbes, 1968; Broadbent, 1971) or equivalently, perception is based on sampling the input information some fixed number of times (the sample size model, Lindsay et al., 1968; Kinchla, 1980; Shaw, 1980), one would predict that the magnitude of the attention effect should be 41% because the fixed number of samples (or capacity) has to be distributed at two locations in the equal attention condition which will reduce the signal to noise ratio by a factor of $\sqrt{2}$ in comparison to allocating the full capacity to the attended location in the attended condition. Relative to a maximum effect size of 41%, the magnitude of the observed attention effect in second-order motion is 18%, somewhat under half of the maximum effect size under the sample size model. Palmer (1994) found that for simple search tasks, the set-size effect can be fully accounted for by stimulus uncertainty. (Stimulus uncertainty is not relevant to the current experiments because they utilize concurrent tasks). For complex search tasks, he found that an additional 10% to 28% ‘perceptual coding’ effect was involved in producing the larger set-size effects. Our 18% attentional effect is comparable to the additional perceptual coding effects estimated by Palmer (1994) for more complex search tasks. On the other hand, one should be cautious about the conclusions drawn from calculations based on this extreme version of a capacity model. The full tradeoff assumptions of, for example, the sample size version of the capacity model have only been observed for fully incompatible tasks such as simultaneously searching for digits among letters and letters among digits in two display regions (Sperling & Melchner, 1978), whereas searching for a digit among letters in two display regions yielded less extreme losses. It seems to be more realistic to assume that only partial capacity competition occurs between multiple locations in situations like ours where the tasks are compatible.

The stimulus enhancement mechanism has also been found to be operative in a concurrent Gabor orientation discrimination task at two widely separated spatial locations (Lu & Dosher, 1998a,b). One natural question is: Can we generalize our conclusions to other attention tasks? The answer to this question is both theoretical and empirical. Applying the external noise plus attention paradigm to a different set of attentional manipulations in which the observer is either pre-cued or simultaneously cued to a form discrimination at one of four spatial locations, attention exclusively affects performance at high levels of external noise, reflecting a mechanism of external noise exclusion (Lu & Dosher, 1998b, 1999; Dosher & Lu, 1999b). In a perceptual learning experiment, coupled improvements in threshold contrast at both high and low levels of external noise were found following many days of practice (Dosher & Lu, 1998, 1999a) reflecting a mixture of external noise filtering and internal additive noise reduction. Manifestation of a particular attention mechanism is neither trivial nor obligatory. Further research is under way to explicate the circumstances under which various attention mechanisms operate.

Observers could simultaneously attend to first-order (but not second-order) motion computations with no (or very little) loss at two widely separated spatial regions in a broad range of external noise conditions. This result is consistent with earlier observations that the set size effect in searching for a first-order moving target that moves faster than the distractors could be

Table 2
Parameter estimates second-order motion

Subject	A_a	N_{mul}	N_{add}	β	γ	r^2
CS	0.7523	0.0000	0.04634	1.2170	2.5374	0.9307
QL	0.7302	0.0000	0.04701	1.2025	2.3382	0.9294
SM	0.7189	0.0000	0.07745	1.2572	2.2474	0.9206

fully accounted for by uncertainty effects in the decision process (Verghese & Stone, 1995). This observation provides important theoretical constrains for higher level perceptual and cognitive processes that depend on low level motion information from multiple spatial locations. Only the first-order motion system is capable of providing primary input to higher level mechanisms requiring motion analysis at several locations, even though the second-order motion system may be important in certain other perceptual processes (Wilson, Ferrera & Yo, 1992). On the other hand, our current comparisons of first-order and second-order motion processing at multiple locations, like most such comparisons in the literature, are based on equating stimulus characteristics, e.g. the same modulator spatial frequency, the same temporal frequency, and the same retinal eccentricity. In such cases, the nominal stimulus is matched but the processing load on the perceptual system is not. It is well known in the motion literature that the spatial resolution of the first- and second-order motion systems are very different at the same eccentricity (Solomon & Sperling, 1995). We speculate that if we knew how to match the two kinds of stimuli in terms of the perceptual demand, first-order and second-order motion processing at multiple locations might produce the same attention effects. Further investigation of more demanding first-order tasks might reveal an attentional benefit similar to that documented here for second-order motion stimuli.

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Appendix A

The perceptual template model (PTM)

In this appendix, we outline a mathematical description of the PTM model and its signature performance patterns for the three mechanisms of attention. To simplify the mathematical description, we chose to use only the expectations of the random variables and ignore certain cross products. At the meantime, we also used one particular form of the PTM model with a late additive internal noise and a single transducer nonlinearity. The consequences of these choices and simplifications have been previously discussed (Dosher & Lu, 1999a,b; Lu & Dosher, 1999). There is good reason to believe that the errors introduced by these simplifications are very small compared to the range of effects in typical data (Dosher & Lu, 1999a; Lu & Dosher, 1999).

A.1. Theoretical TVC functions from a PTM model

In general, a signal can be expressed as a function of space and time: $S(x, y, t) = cS_0(x, y, t)$, where c is stimulus contrast and S_0 is rescaled such that $\iiint S_0^2(x, y, t)\,dx\,dy\,dt = 1.0$. The contrast of random external noise used in these experiments can be expressed as: $N(x, y, t) = N_{ext}G(x, y, t)$ where the value of $G(x, y, t)$ at a particular spatio-temporal point (x, y, t) is drawn from a Gaussian distribution with mean 0 and S.D. of 1.0. For a template matching function $T(x, y, t)$, matching the template to a signal-valued stimulus yields the output: $T_S = \iiint T(x, y, t)\,S(x, y, t)\,dx\,dy\,dt = c\iiint T(x, y, t)\,dx\,dy\,dt$; The output of template matching operation to the external noise is: $T_N = \iiint T(x, y, t)\,N(x, y, t)\,dx\,dy\,dt = N_{ext}\iiint T(x, y, t)\,G(x, y, t)\,dx\,dy\,dt$. For a fixed template and a fixed signal stimulus, $T_{S_0} = \iiint T(x, y, t)S_0(x, y, t)\,dx\,dy\,dt$ is a constant; $T_G = \iiint T(x, y, t)G(x, y, t)\,dx\,dy\,dt$ is a Gaussian random variable with mean 0 and a fixed standard deviation σ_{T_G}. Because mathematically, T_S and T_N can only be known up to a constant, without losing any generality, we set σ_{T_G} to 1.0. Thus, after template matching, $T_N = N_{ext}G(0, 1)$, $T_S = \beta c$, where $\beta = T_{S_0}/\sigma_{T_G}$.

The stimulus (signal plus external noise) is then passed through the nonlinearity $\|\cdot\|^{\gamma}$. At the decision stage, the distance between signal and noise is: $(\beta c)^{\gamma}$, the total variance of the noise is the sum of the variance of all the noise sources: the external noise $N_{ext}^{2\gamma}$, the multiplicative noise[6] $N_{mul}^2((\beta c)^{2\gamma} + N_{ext}^{2\gamma})$, and the addi-

[6] Multiplicative noise is in proportion to the signal and external noise power; this form eliminates cross products. Lu and Dosher (1999) showed that, consistent with the elimination of the cross product in the multiplicative noise, ratio of thresholds in the same external noise condition between two performance levels is a constant across all the external noise levels.

tive internal noise N_{add}^2. Thus, signal discriminability, d', is determined by the signal to noise ratio:

$$d' = \frac{(\beta c)^\gamma}{\sqrt{N_{ext}^{2\gamma} + N_{mul}^2((\beta c)^{2\gamma} + N_{ext}^{2\gamma}) + N_{add}^2}} \tag{A1}$$

For a given fixed d' (corresponding to a fixed criterion performance level), one can solve Eq. (A1) for the threshold contrast c_τ as a function of external noise level N_{ext}:

$$c_\tau = \frac{1}{\beta}\left[\frac{(1 + N_{mul}^2)N_{ext}^{2\gamma} + N_{add}^2}{1/d'^2 - N_{mul}^2}\right]^{1/2\gamma} \tag{A2}$$

A.2. Signature patterns for attention mechanisms

Within the framework of a PTM model, attention could have impacts in three different ways: (1) stimulus enhancement, modeled by reducing internal additive noise by a factor $A_a < 1.0$. (2) External noise exclusion, modeled by multiplying the amount of external noise at attended locations by a factor $A_f < 1.0$. (3) Internal multiplicative noise reduction, characterized by reducing N_{mul} by a factor $A_m < 1.0$.

The effect of all possible single and/or mixture mechanisms is summarized in one single equation by combining the effects of A_a, A_f and A_m:

$$c_\tau = \frac{1}{\beta}\left[\frac{(1 + (A_m N_{mul})^2)(A_f N_{ext})^{2\gamma} + (A_a N_{add})^2}{1/d'^2 - (A_m N_{mul})^2}\right]^{1/2\gamma} \tag{A3}$$

In log form:

$$\log(c_\tau) = \frac{1}{2\gamma}\log[(1 + (A_m N_{mul})^2(A_f N_{ext})^{2\gamma} + (A_a N_{add})^2] - \frac{1}{2\gamma}\log[1/d'^2 - (A_m N_{mul})^2] - \log\beta \tag{A4}$$

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