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# Effects of set-size and selective spatial attention on motion processing

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## Abstract

In order to investigate the effects of divided attention and selective spatial attention on motion processing, we obtained direction-of-motion thresholds using a stochastic motion display under various attentional manipulations and stimulus durations (100–600 ms). To investigate divided attention, we compared motion thresholds obtained when a single motion stimulus was presented in the visual field (set-size = 1) to those obtained when the motion stimulus was presented amongst three confusable noise distractors (set-size = 4). The magnitude of the observed detriment in performance with an increase in set-size from 1 to 4 could be accounted for by a simple decision model based on signal detection theory, which assumes that attentional resources are not limited in capacity. To investigate selective attention, we compared motion thresholds obtained when a valid pre-cue alerted the subject to the location of the to-be-presented motion stimulus to those obtained when no pre-cue was provided. As expected, the effect of pre-cueing was large when the visual field contained noise distractors, an effect we attribute to ‘noise reduction’ (i.e. the pre-cue allows subjects to exclude irrelevant distractors that would otherwise impair performance). In the single motion stimulus display, we found a significant benefit of pre-cueing only at short durations ( $\leq 150$  ms), a result that can potentially be explained by a ‘time-to-orient’ hypothesis (i.e. the pre-cue improves performance by eliminating the time it takes to orient attention to a peripheral stimulus at its onset, thereby increasing the time spent processing the stimulus). Thus, our results suggest that the visual motion system can analyze several stimuli simultaneously without limitations on sensory processing per se, and that spatial pre-cueing serves to reduce the effects of distractors and perhaps increase the effective processing time of the stimulus. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords:* Motion; Attention; Set-size; Pre-cueing; Directional mechanisms

## 1. Introduction

In the last several decades much has been learned about the influence of spatial attention on visual performance. In general, studies on this topic have focused on the effects of *divided* and *selective* attention. In *divided attention* studies, visual performance is measured under conditions in which subjects must divide their attention across multiple items in a visual display. One typical approach to this issue has been to employ a visual search paradigm, wherein subjects must detect the presence or absence of a ‘target’ stimulus presented

amongst confusable ‘distractors’ (Treisman & Gelade, 1980; Bergen & Julesz, 1983; Wolfe, 1994). The results of such studies demonstrate that reaction time and the number of errors increase as the number of distractors increases, a phenomenon referred to as ‘set-size effect’ (e.g. Estes & Taylor, 1966). Early theories of visual attention interpreted these set-size effects as evidence that attentional resources are subject to capacity limitations (e.g. Broadbent, 1958). According to this *limited capacity* viewpoint, set-size effects occur because increasing the number of visual stimuli to be attended necessarily degrades the quality of processing for each.

An alternative explanation for these set-size effects, which has recently risen to popularity, is based on an *unlimited capacity* viewpoint. Originally described by

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Shaw (1980) to account for the results from visual search, this model proposes that the quality of sensory processing does not decline as the number of items in a visual display increases. However, visual performance worsens with increasing set-size because the presence of distractors increases the probability of an error occurring at the *decision level*. The validity of the unlimited capacity notion has been supported by several studies, which employ decision models based on signal detection theory to quantitatively predict the magnitude of set-size effects for various visual discriminations (e.g. Cohn & Lasley, 1974; Lasley & Cohn, 1981; Davis, Kramer, & Graham, 1983; Shaw, 1984; Pavel, Econopouly, & Landy, 1992; Palmer, Ames, & Lindsey, 1993; Palmer, 1994; Verghese & Nakayama, 1994; Verghese & Stone, 1995; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Monnier & Nagy, 2000; Palmer, Verghese, & Pavel, 2000; Rezec, Bosworth, & Dobkins, 2000).

In *selective spatial attention* studies, visual performance is measured under conditions in which subjects are instructed to direct attention to a stimulus in one region of space while ignoring stimuli in other regions. While many studies have demonstrated that ignored stimuli are not fully processed (e.g. Broadbent, 1958; Hillyard, Hink, Schwent, & Picton, 1973; Rock & Gutman, 1981; Hoffman & MacMillan, 1985; Johnston & Dark, 1985 and see Pashler, 1998 for review), there is far less consensus as to whether selective attention serves to *enhance* the processing of the attended stimulus. One approach to addressing the issue of enhancement has been to employ a *spatial pre-cueing paradigm*, in which subjects' performance when a pre-cue alerts them to the location of a to-be-presented stimulus is compared to their performance when no pre-cue (or an invalid pre-cue) is provided. If performance is better when the stimulus location is validly pre-cued, this is typically taken as evidence for 'perceptual enhancement', the underlying mechanisms of which have been ascribed to the allocation of more attentional resources to the cued stimulus (e.g. Eriksen & Yeh, 1985; Henderson, 1996) and/or a strengthening of the stimulus representation (e.g. Carrasco & Yeshurun, 1998; Lu & Doshier, 1998; Carrasco et al., 2000, see McAdams & Maunsell, 1999; Treue & Maunsell, 1999; Reynolds, Pasternak, & Desimone, 2000 for relevant evidence from single-unit neurophysiological experiments).

Although several studies have investigated the effects of spatial pre-cueing (mostly on letter detection/discrimination tasks), the results have unfortunately been rather mixed; whereas some studies report significant cueing benefits (e.g. Henderson, 1991, 1996; Müller & Humphreys, 1991; Luck, Hillyard, Mouloua, & Hawkins, 1996; Lu & Doshier, 1998; Carrasco et al., 2000), others have been unable to observe such effects (Grindley & Townsend, 1968; Van der Heijden, Schreuder, & Wolters, 1985; Nazir, 1992; Van der

Heijden, 1992; Shiu & Pashler, 1994; Morgan, Ward, & Castet, 1998). As addressed further in Section 4, these discrepancies may be attributable to differences in experimental design across studies. In sum, few studies have unequivocally established the existence of enhanced perception for a cued stimulus.

Recently, the effects of selective spatial attention on *motion processing* have begun to garner much interest, with a key example found in a study by Chaudhuri (1990). He showed that ignoring a moving stimulus in the periphery (by instructing subjects to focus their attention on a letter discrimination task in the center of gaze) significantly diminishes the motion-after-effect resulting from that stimulus (and see Lankheet & Verstraten, 1995; Rees, Frith, & Lavie, 1997 for similar findings). In addition, other psychophysical experiments have demonstrated that instructing subjects to ignore a moving stimulus results in lowered contrast sensitivity (Lu, Liu, & Doshier, 2000, for second-order, but not first-order, motion), and higher directional discrimination thresholds (Buracas, Lee, Koch, Albright, & Croner, 1998) for that stimulus. In line with the substantial body of literature documenting the fate of ignored stimuli (Pashler, 1998), these results indicate that ignored motion stimuli are not fully processed. In addition to the topic of spatial attention, other studies have investigated the effects of *featural* selective attention on motion processing (e.g. where subjects attend to one direction of motion while ignoring another), and have similarly observed differential performance for the attended vs. unattended stimulus (Ball & Sekuler, 1981; Cavanagh, 1992; Lu & Sperling, 1995; Raymond, O'Donnell, & Tipper, 1998; Gray, 2000).

A potential neural substrate for the effects of spatial and featural attention on motion processing has been provided in single-unit neurophysiological recordings in macaques (e.g. Treue & Maunsell, 1996, 1999; Seidemann & Newsome, 1999) and functional magnetic resonance imaging (fMRI) studies in humans (e.g. O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997; Rees et al., 1997; Buchel, Josephs, Rees, Turner, Frith, & Friston, 1998). These neural studies demonstrate reduced activity in the middle temporal area (MT) of extrastriate cortex, a region thought to play a key role in motion perception, when subjects ignore moving stimuli in the visual field.

In order to investigate further the influence of attention on motion processing, we obtained direction-of-motion thresholds from subjects tested under conditions of both divided and selective spatial attention. In our divided attention manipulation, we compared motion thresholds obtained when a single motion stimulus was presented (i.e. set-size 1) to those obtained when that stimulus was presented amongst three confusable noise distractors (i.e. set-size 4). To identify the mechanism underlying the observed set-size effects, rel-

ative performance in the two conditions was compared to predictions from quantitative models of unlimited vs. limited capacity.

In order to investigate the effects of selective attention, we compared motion thresholds obtained when a pre-cue alerted the subject to the location of the to-be-presented motion stimulus to those obtained when no pre-cue was provided. In the single display condition, we entertained two possible explanations for finding benefits of the pre-cue: (1) *perceptual enhancement* (as outlined above); and (2) the pre-cue, by allowing subjects to orient attention to the stimulus location prior to stimulus onset, eliminates the time to orient to that stimulus and thereby increases the effective processing time. This ‘time-to-orient’ hypothesis predicts that the pre-cue should improve performance at short stimulus durations (where thresholds are duration-dependent), but not at longer durations (where thresholds have asymptoted). Finally, comparisons between performance for a single motion stimulus and a cued motion stimulus presented amongst distractors allowed us to address whether uncued distractors interfere with motion performance.

## 2. Methods

### 2.1. Subjects

Nine subjects participated in the main experiment. For six of these subjects, eye fixation was not monitored. Although these were practiced observers and we expect that they maintained adequate fixation, we nonetheless obtained data from three additional subjects while their eye position was monitored. An additional nine subjects were tested in a control experiment, all of whom had their eye position monitored. All subjects were experienced psychophysical observers, yet naive to the purpose of the experiment.

### 2.2. Apparatus

Visual stimuli were generated using a SGT Pepper Graphics board (Number Nine Computer Corporation: 640 by 480 pixel resolution, 60 Hz frame rate) residing in a Pentium-based PC, and were displayed on a Nanao F2-21 video monitor (21” display, 640 × 480 pixels, 60 Hz vertical refresh). A PR-650 SpectraColorimeter (Photoresearch) was used for photometric measurements of our stimuli.

Eye position was monitored using a closed couple device (CCD) infrared camera with variable focus (12.5–75 mm) lens (Model # Fc62, Image Sensor), which was focused on the left eye of the subject. The subjects’ face was lit with an infrared illuminator and an enlarged image of the eye was viewed on a 12”

Monitor (Ultrak) outside the testing room. Before beginning each block of trials, subjects were instructed to fixate a small green square ( $0.35^\circ$ ) in the center of the video display, and the outline of the pupil was drawn on transparency paper that covered the monitor. Using this set-up, saccadic eye movements could easily be detected, and eye drift within  $\pm 2^\circ$  of fixation could be discerned. Subjects were instructed to maintain fixation throughout the experiment and were informed that the experiment would be temporarily interrupted if eye movements or eye drift were detected. Thus, subjects were highly discouraged from breaking fixation, and we never needed to interrupt the experiment.

### 2.3. Stochastic motion stimuli

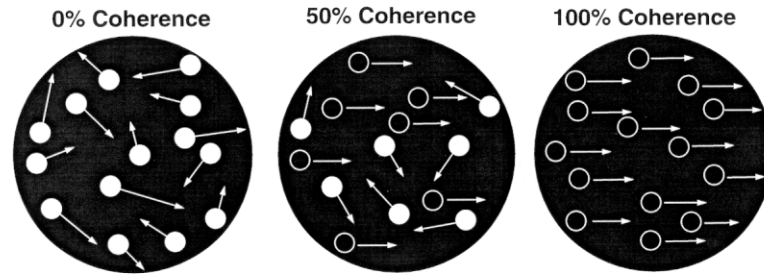
Motion thresholds were obtained using a *stochastic motion stimulus* (after Williams & Sekuler, 1984; Newsome & Paré, 1988). This stimulus consists of a field of white dots presented within a circular aperture, wherein a proportion of dots (i.e. ‘signal’ dots) moves in a coherent direction (‘leftward’ or ‘rightward’) while the others (i.e. ‘noise’ dots) move in a random fashion (Fig. 1A). The signal proportion is varied across trials in order to obtain a *coherent motion threshold* (i.e. the percentage of signal dots required to yield 75% correct directional discrimination). In our display, the motion stimulus consisted of 119 dots (each  $0.12^\circ$  in diameter) presented within an  $8.0^\circ$  diameter aperture (dot density = 2.4 dots/degree<sup>2</sup>). The moving signal dots were displaced  $0.35^\circ$  from one frame to the next, with each frame lasting 50 ms, thus resulting in a dot speed of  $6.9^\circ/s$ . The trajectory for each moving dot lasted two frames (i.e. 100 ms). The dot then reappeared in a random location within the circular aperture and moved coherently for another two frames, and so on. Noise dots were positioned in a random location from frame to frame. The luminance of all dots was 26 cd/m<sup>2</sup>, presented against a black background (0.3 cd/m<sup>2</sup>). This high luminance contrast of the dots ensured that the stimulus would not be confusable with the background.

In order to obtain coherent motion thresholds, seven different levels of coherence were tested, ranging in equal log steps (base 1.58) from 2.5 to 25.2%. These stimuli were presented in random fashion across trials (method of constant stimuli). In order to study the effects of additional ‘noise distractors’ on motion performance, stochastic motion stimuli containing 0% coherence were employed in some conditions (see below).

### 2.4. General procedures

Subjects were tested in a darkened room and viewed the video display binocularly from a chin rest situated 57 cm away. Subjects were instructed to maintain fixa-

### A) Stochastic Motion Stimulus



### B) Experimental Design

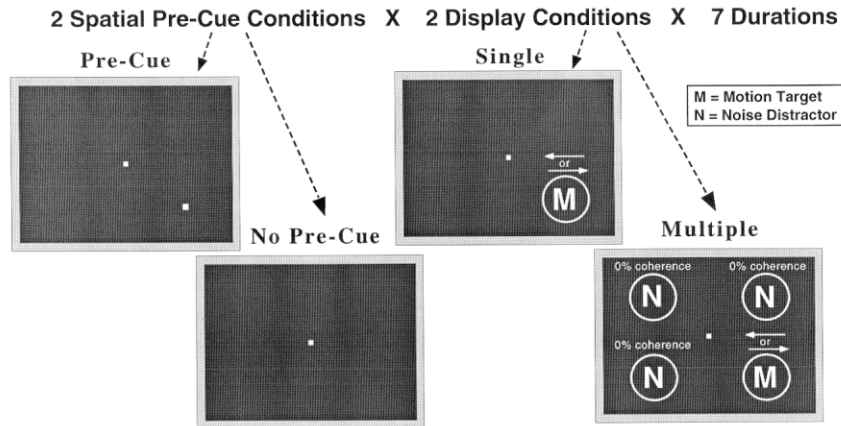


Fig. 1. (A) Stochastic motion stimulus. A proportion of dots (i.e. 'signal' dots) moves in a coherent direction ('leftward' or 'rightward') while the others (i.e. 'noise' dots) move in a random fashion. The signal proportion is varied across trials in order to obtain a *coherent motion threshold* (i.e. the percentage of signal dots required to yield 75% correct directional discrimination); (B) Experimental design: two spatial pre-cueing conditions (pre-cue vs. no pre-cue), two display conditions (single vs. multiple), 7 stimulus durations. See Section 2 for details.

tion on a small green square ( $0.35^\circ$ ) in the center of the monitor for the duration of each trial. Subjects initiated each trial with a key press, 200 ms after which the stochastic motion stimulus appeared (for a fixed duration between 100 and 600 ms) randomly in one of the four quadrants of visual space, centered  $15.4^\circ$  eccentric to fixation (horizontal eccentricity =  $\pm 12.5^\circ$ , vertical eccentricity =  $\pm 9.0^\circ$ ). Subjects reported perceived direction of motion ('leftward' vs. 'rightward') by pressing one of two appropriate keys (2-AFC). Negative feedback was provided for incorrect trials, which consisted of a white circle ( $2.3^\circ$  diameter,  $26 \text{ cd/m}^2$ ) presented  $2.3^\circ$  below the fixation square for 200 ms. Although subjects were not instructed to respond in a speeded fashion, as the emphasis in this study was accuracy, reaction times were obtained for all conditions.

#### 2.5. Experimental design

Data were obtained for 28 different conditions, in a 2 (display types)  $\times$  2 (spatial pre-cueing conditions)  $\times$  7 (stimulus durations) factorial design (Fig. 1B). The two

*display types* were: (1) 'Single Display', the motion stimulus was presented alone in one of the four quadrants of visual space; and (2) 'Multiple Display', the motion stimulus was presented in one visual field quadrant while the three remaining quadrants contained noise distractors (i.e. stochastic motion stimuli containing 0% motion coherence).

The two *pre-cueing conditions* were: (1) 'No Pre-Cue', subjects were uncertain as to which visual quadrant the motion stimulus would appear in. Subjects initiated the trial with a key press, and the stimulus appeared 200 ms later. In the single display condition, the location of the motion stimulus was immediately obvious once it was presented. In the multiple display condition, however, there was uncertainty regarding which stimulus was the motion target and which were the noise distractors, since the motion and noise stimuli were highly confusable; (2) 'Pre-Cue', subjects were alerted to the location of the to-be-presented motion stimulus with a valid pre-cue, consisting of a  $0.23^\circ$  square ( $26 \text{ cd/m}^2$ ) that appeared beforehand in the center of that location (i.e. centered  $15.4^\circ$  eccentric to fixation in one of the four visual field locations). The significance of the pre-cue

was explained to subjects, and they were instructed to use the cue to their benefit. Thus, on trials that contained a pre-cue, subjects knew to first direct their visual attention to the appropriate quadrant of visual space before beginning a trial. When the pre-cue was presented in the multiple display condition, subjects were informed that the three uncued locations of visual space would contain irrelevant information that should be ignored. Subjects initiated the trial with a key press, and 200 ms later the pre-cue disappeared and the stimulus (or stimuli) was presented. Note that the cue overlapped with less than 0.1% of the total area of the 8° diameter stimulus, greatly reducing the possibility of forward masking.

Data were obtained for seven different stimulus durations: 100, 150, 200, 250, 300, 400 and 600 ms. All conditions were tested in separate blocks. In order to minimize order and practice effects, a quarter of the total trials was obtained for each of the 28 conditions, before repeating this cycle three times again. The order of the blocks was randomized and counterbalanced across subjects. The experiment consisted of 21 504 total trials (768 trials per condition), after practice on approximately 400 trials. Subjects typically required a total of 10.5–12 h within 1 week to complete the experiment.

## 2.6. Data analysis

*Coherent motion thresholds:* Psychometric curves were fit to the data using Weibull functions and maximum likelihood analysis (Weibull, 1951; Watson, 1979), with threshold defined as the coherence level yielding 75% correct performance. Each Weibull function, calculated for each condition and for each of the four visual field locations in which the motion stimulus appeared, was comprised of 192 total trials. Because we found no effect of visual field on performance (see Section 3, below), thresholds were averaged across the four locations for each subject. In order to compare performance between conditions, threshold ratios were computed for each subject before averaging across subjects.

*Reaction time data:* Although this was not a speeded reaction time study, we nonetheless analyzed reaction time data. For each subject, a mean reaction time was obtained by averaging reaction time values across the different motion coherence levels within a condition (data collapsed across the four visual field locations). In order to compare performance between conditions, reaction time *differences* were computed for each subject before averaging across subjects. Note that our use of differences, rather than ratios, was motivated by convention (e.g. Eriksen & Yeh, 1985; Gray, 2000).

## 3. Results

### 3.1. Example data

Example data from two subjects are shown in Fig. 2A–B. For both subjects, coherent motion thresholds are plotted as a function of stimulus duration, separately for the single display (*left*) and multiple display (*right*) conditions. Within each plot, data are shown for conditions when subjects received a spatial pre-cue alerting them to the location of the to-be-presented motion stimulus (*filled circles, solid lines*) and when no pre-cue was provided (*open circles, dashed lines*). Because thresholds did not differ significantly as a function of motion stimulus location, in either the single display condition ( $F(3, 24) = 0.93$ ;  $P = \text{NS}$ ) or multiple display condition ( $F(3, 24) = 1.07$ ;  $P = \text{NS}$ ), we averaged data across the four different visual field locations. Thus, each data point represents the geometric mean threshold across location and the error bar denotes the standard error of that mean.

The data from subject CT (Fig. 2A) were obtained without monitoring eye position. Six of our nine subjects were tested in this fashion. Although there is good reason to believe that these subjects adequately maintained fixation throughout the experiment, since the importance of fixation was emphasized repeatedly and our subjects were experienced psychophysical observers, we nonetheless obtained data from three additional subjects while their eye position was being monitored (Section 2). The functions from subject KY (Fig. 2B) were obtained in this manner, and appear quite similar in shape to those of subject CT. For both subjects, motion thresholds decreased significantly with increasing stimulus duration. In the single display condition, the time required to achieve near-asymptotic performance was approximately 200 ms, a result that was observed in all subjects and is in accordance with previous motion studies (e.g. McKee & Watamaniuk, 1994; Watamaniuk, McKee, & Grzywacz, 1995). In the multiple display condition, slightly higher stimulus durations ( $\sim 300$  ms) were required. With regard to cueing benefits, the effect of the pre-cue on motion thresholds was much larger in the multiple display, as compared to the single display, condition.

The results of an ANOVA revealed no significant differences between subjects whose eye position was monitored vs. those whose was not, for threshold data ( $F(1, 7) = 0.86$ ;  $P = 0.38$ ) or reaction times ( $F(1, 7) = 0.19$ ;  $P = 0.67$ ). In addition, no significant interaction of subject group with display type (multiple vs. single display), pre-cueing condition (no pre-cue vs. pre-cue) or stimulus duration was found. For this reason, we have combined data across our nine subjects in our analyses of set-size and pre-cueing effects (below).

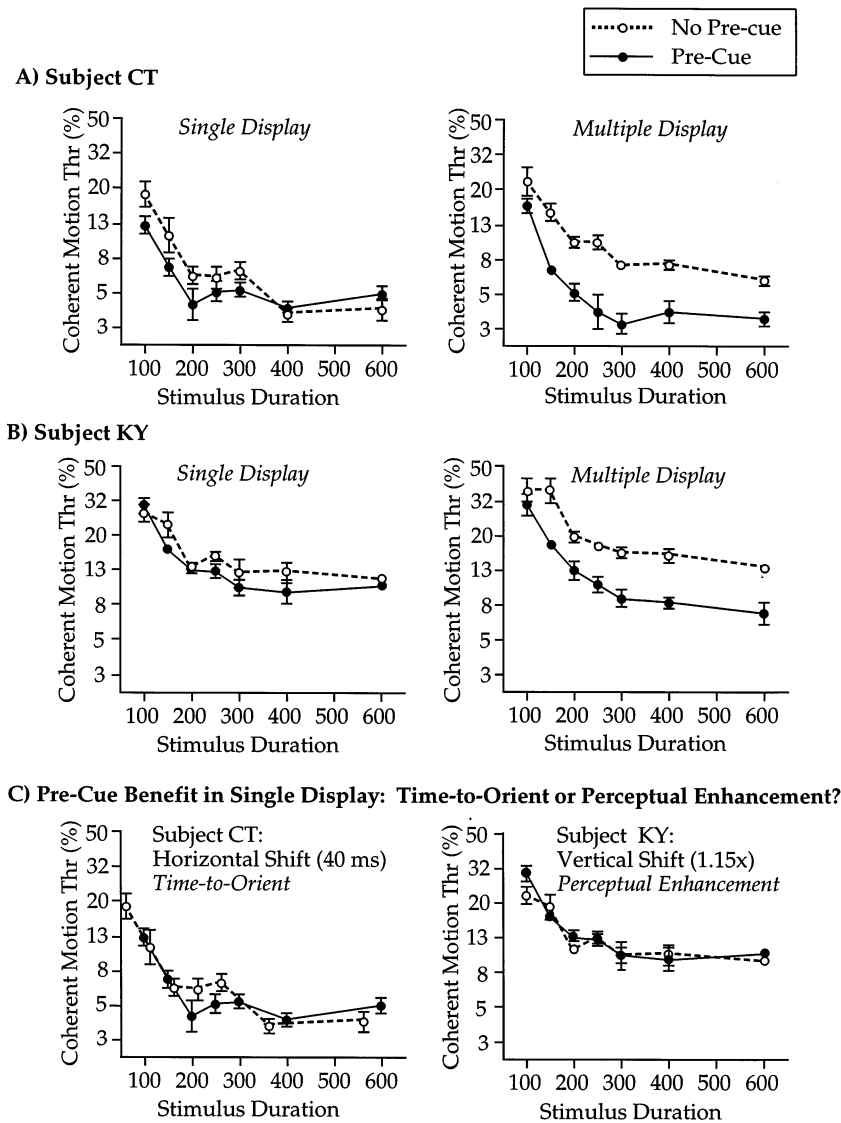


Fig. 2. Example data from two subjects. (A and B): Coherent motion thresholds are plotted as a function of stimulus duration, separately for the single display (left) and multiple display (right) conditions. Within each plot, data are shown for conditions when subjects received a spatial pre-cue alerting them to the location of the to-be-presented motion stimulus (filled circles, solid lines) and when no pre-cue was provided (open circles, dashed lines). Each data point represents the geometric mean threshold obtained by averaging thresholds across the four different visual field locations. Error bars denote standard errors of the means: (A) Subject CT; (B) Subject KY; (C) Threshold vs. duration functions for pre-cue and no pre-cue conditions in the single display can be aligned by a horizontal shift for subject CT (left panel), and by a vertical shift for subject KY (right panel). See text for details.

3.2. Set-size effects

In order to investigate the effects of set-size, we compared thresholds in the no pre-cue, multiple display condition with those from the no pre-cue, single display condition. Our single display condition is equivalent to a set-size of 1, while our multiple display condition is equivalent to a set-size of 4 (i.e. one ‘target’ stimulus containing motion presented simultaneously with three ‘distractor’ stimuli containing noise). For each subject, a *threshold ratio* was obtained by dividing the threshold for set-size 4 by the threshold for set-size 1 (i.e.  $\text{Thr}_{\text{set-size } 4} / \text{Thr}_{\text{set-size } 1}$ ). Group mean threshold ratios and standard errors are plotted as

a function of duration in Fig. 3 (left panel). As expected, threshold ratios were significantly greater than 1.0, indicating better performance for set-size 1 ( $F(1, 8) = 28.25; P < 0.001$ ). Averaged across duration, the group mean threshold ratio was 1.41. For comparison, we have plotted mean reaction time differences (i.e.  $\text{RT}_{\text{set-size } 4} - \text{RT}_{\text{set-size } 1}$ ) in the right panel of Fig. 3. Values greater than zero reflect slower responses for set-size 4. Averaged across durations, reaction times were 53 ms slower for the set-size 4 condition ( $F(1, 8) = 20.13; P < 0.005$ ). Note that, because the set-size effects for threshold data mirror those observed for reaction time data, these findings cannot be explained by a speed-accuracy trade-off.

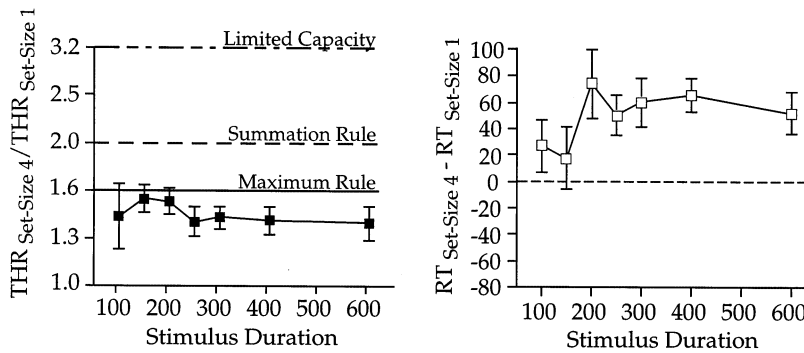


Fig. 3. Set-size effects. *Left panel*: Group mean threshold ratios ( $\text{Thr}_{\text{set-size } 4} / \text{Thr}_{\text{set-size } 1}$ ) are plotted as a function of stimulus duration. Error bars denote standard errors of the means across subjects ( $n = 9$ ). Threshold ratios are greater than 1.0, indicating better performance in the set-size 1 condition. Across all durations, threshold ratios fall close to the predictions for the 'Maximum Rule' (solid line), yet far from the predictions for the 'Summation Rule' (dashed line) and for 'Limited Capacity' (dotted-dashed line). *Right panel*: Mean reaction time differences between set-size 4 and 1 ( $\text{RT}_{\text{set-size } 4} - \text{RT}_{\text{set-size } 1}$ ). Values are greater than zero, indicating longer reaction times for set-size 4.

As discussed in Section 1, these set-size effects indicate that performance on a visual task suffers when, in the face of spatial uncertainty regarding the location of a target, subjects must divide their attention across multiple visual stimuli. Two opposing models have been put forth to explain the impairment in performance that results from increasing set-size. *Unlimited capacity models* posit that the quality of sensory processing is maintained as the number of items in a visual display increases. However, visual performance is worse for larger, as compared to smaller, set-sizes due to the increased probability for errors occurring at the *decision level*. By contrast, *limited capacity models* postulate that set-size effects occur because increasing the number of visual stimuli to be attended necessarily degrades the quality of processing for each.

As described in detail previously (e.g. Mulligan & Shaw, 1980; Shaw, 1980, 1982, 1984; Graham, Kramer, & Yager, 1987; Palmer et al., 1993, 2000; Palmer, 1994, 1995; Verghese & Nakayama, 1994; Verghese & Stone, 1995), these two models yield quantitatively distinct predictions for the effects of set-size on visual thresholds. The theories and equations behind these models, which are based on Signal Detection Theory, are described in detail in Appendix A. In brief, these models assume that an observer's directional decisions ('leftward' or 'rightward') are based on the directional detector (leftward or rightward detector) with the *maximal* response. When there is unlimited capacity, the activity in these detectors is unaffected by increasing set-size, yet performance is expected to decline because the presence of noise distractors increases the overall probability of decision errors. Specifically, this 'maximum rule' model predicts that thresholds should be 1.60 times higher for set-size 4, as compared to set-size 1 ( $\text{Thr}_{\text{set-size } 4} / \text{Thr}_{\text{set-size } 1} = 1.60$ ). Alternatively, a slight variation of the unlimited capacity maximum rule supposes that the activities across detectors with the same direction preferences are summed together before the

maximum rule decision is made. This model, referred to as the 'summation rule', predicts a slightly higher threshold ratio of 2.0. The *limited capacity* model also assumes that a maximum rule decision is employed. However, owing to attentional resources needing to be divided amongst the number of visual stimuli presented, the variance of activity in each detector rises proportionally with increasing set-size.<sup>1</sup> Here, the predicted threshold ratio is 3.20.

Predicted threshold ratios for the different models of attention are presented along with the data in Fig. 3 (*left panel*): *Maximum Rule* (solid line), *Summation Rule* (dashed line) and *Limited Capacity* (dotted-dashed line). Across all durations, statistical analyses revealed that threshold ratios were not significantly different from the predictions for the *Maximum Rule* ( $t(8) < 2.3$ ,  $P = \text{NS}$ ), indicating that this model can adequately account for the observed set-size effects. By contrast, threshold ratios were significantly different from the predictions for *Limited Capacity* (for all durations:  $t(8) > 4.4$ ;  $P < 0.005$ ) and from the *Summation Rule* (for all durations, except 100 ms:  $t(8) > 3.9$ ;  $P < 0.005$ ), indicating that these models do not provide an adequate fit to the data. In sum, these set-size results support the unlimited capacity model of attention, demonstrating that the visual motion system can analyze several stimuli simultaneously without any cost to sensory processing per se.

<sup>1</sup> Note that not all limited-capacity models assume that resources are divided amongst multiple stimuli. Other models of limited-capacity have assumed *serial* processing, predicting that, because only one (of multiple) stimuli can be processed on any given trial, psychometric functions will asymptote far below 100% correct performance (e.g. Davis et al., 1983). Because this effect was not observed in our psychometric functions (or those of other studies that measure thresholds as a function of set-size), we do not entertain this alternative model here.

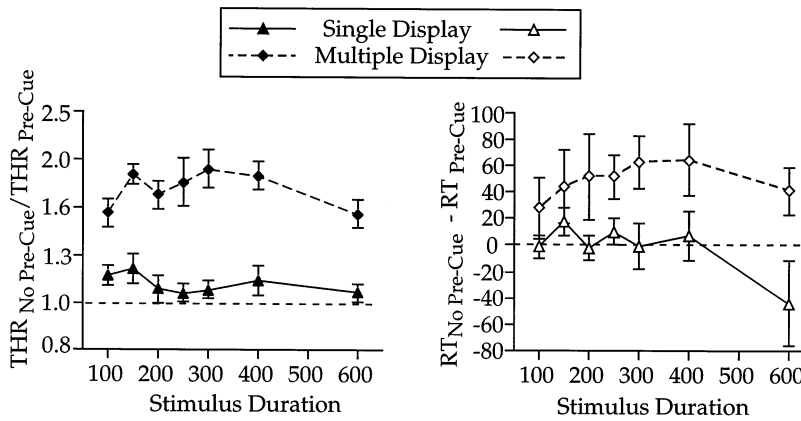


Fig. 4. Spatial pre-cueing effects. *Left panel:* Group mean threshold ratios ( $\text{Thr}_{\text{no pre-cue}}/\text{Thr}_{\text{pre-cue}}$ ) are plotted as a function of stimulus duration. Error bars denote standard errors of the means across subjects ( $n = 9$ ). Data are shown separately for the multiple display (*filled diamonds*) and single display (*filled triangles*) conditions. Ratios greater than 1.0 indicate that the presence of a pre-cue improved motion performance. These data demonstrate a large effect of the pre-cue in the multiple, but not the single, display condition. *Right panel:* Mean reaction time differences between no pre-cue and pre-cue conditions ( $\text{RT}_{\text{no pre-cue}} - \text{RT}_{\text{pre-cue}}$ ). Values greater than zero indicate longer reaction times in the absence of a pre-cue. As for threshold data, the effect of the pre-cue on reaction time is larger in the multiple display (*open diamonds*) as compared to the single display (*open triangles*) condition. Although, in the single display condition, the data appear to indicate that the presence of the pre-cue *increases* reaction times when the stimulus duration is 600 ms (by  $\sim 40$  ms), this effect is not significant.

### 3.3. Pre-cueing effects

In order to investigate the effects of spatial pre-cues on motion processing, thresholds obtained in the no pre-cue condition were divided by those obtained when a pre-cue alerted the subject to the location of the to-be-presented motion stimulus ( $\text{Thr}_{\text{no pre-cue}}/\text{Thr}_{\text{pre-cue}}$ ). Group mean threshold ratios and standard errors are presented in the *left* panel of Fig. 4, separately for the multiple display (*filled diamonds*) and single display (*filled triangles*) conditions. As for the individual data plotted in Fig. 2A–B, these group mean data demonstrate a much larger effect of the pre-cue in the multiple display, as compared to the single display, condition. This difference is supported statistically by a significant interaction between pre-cueing condition and display type ( $F(1, 8) = 91.5$ ;  $P < 0.001$ ). Group mean reaction time differences between no pre-cue and pre-cue conditions ( $\text{RT}_{\text{no pre-cue}} - \text{RT}_{\text{pre-cue}}$ ) are plotted in the *right* panel of Fig. 4, separately for the multiple (*open diamonds*) and single (*open triangles*) display conditions. As for threshold data, the pre-cue had a significantly greater effect on reaction time in the multiple display condition ( $F(1, 8) = 9.2$ ;  $P < 0.025$ ). To investigate the nature of pre-cueing effects further, we turn to a separate discussion of the multiple and single display conditions, below.

*Multiple display:* In the multiple display condition, the presence of the pre-cue lowered thresholds significantly, by a factor of 1.73 across durations ( $F(1, 8) = 118.5$ ,  $P < 0.001$ ). Likewise, the effect of the pre-cue on reaction time was also significant ( $F(1, 8) = 5.6$ ,  $P < 0.05$ ), shortening reaction times, on average, by 49.4 ms. This result is not surprising as the pre-cue pre-

sumably allows subjects to exclude noise distractors that would otherwise impair performance, a phenomenon referred to as ‘noise reduction’ (e.g. Shiu & Pashler, 1994; Carrasco et al., 2000). In theory, noise reduction could occur at either an early stage (sensory level) or a later stage (decision level) of processing, an issue we return to in Section 4.

*Single display:* In the single display condition, we found a very small yet significant effect of the pre-cue ( $F(1, 8) = 8.19$ ,  $P < 0.05$ ). Averaged across all stimulus durations, the presence of the pre-cue lowered thresholds by a factor of 1.09. The effect of the pre-cue on reaction time was also quite small, and here the difference between pre-cue and no pre-cue conditions was not significant ( $F(1, 8) = 0.03$ ,  $P = \text{NS}$ ). Because there were no distractors in this single display condition and the stimulus could not be confused with the background, the importance of finding a cueing benefit here is that the effects cannot be attributed to the exclusion of noise distractors that would otherwise impair performance. Rather, a cueing benefit could be taken as evidence for perceptual enhancement (as described in Section 1).

Before committing to perceptual enhancement, however, we entertain another viable account for pre-cueing benefits based on the notion that switching attention from one location to another takes time (e.g. Tsai, 1983; Eriksen & Yeh, 1985). Specifically, we propose that the benefit of the pre-cue may be to eliminate the time required to orient attention to the peripheral stimulus, without any need to entertain increases in allocation of resources or the effective stimulus strength. According to our ‘time-to-orient’ hypothesis, in the absence of the pre-cue the time spent orienting to the



stimulus would be at the expense of time spent processing the stimulus. In other words, the ‘effective’ duration of the stimulus would be shortened. This should consequently impair performance at short durations, where thresholds are dependent on stimulus duration. At longer durations, where thresholds reach asymptotic levels, the absence of a pre-cue should produce no such impairment in performance. In support of this hypothesis, we found that the effect of the pre-cue on motion thresholds was largest at the two shortest stimulus durations (100 and 150 ms, mean threshold ratio = 1.18), and only at these durations was the effect of the pre-cue significant (100 ms:  $t(8) = 2.55$ ,  $P < 0.05$ ; 150 ms:  $t(8) = 2.40$ ,  $P < 0.05$ ). At longer durations (200–600 ms) the pre-cueing benefit was negligible (mean threshold ratio = 1.04).

In order to investigate further the relative validity of the perceptual enhancement vs. time-to-orient hypotheses, we compared each subject’s ‘threshold vs. duration’ function generated from the pre-cue condition with that generated from the no pre-cue condition. The time-to-orient hypothesis predicts that pre-cue and no pre-cue functions should differ only in the duration that yields asymptotic performance, but that asymptotic performance should be the same for the two. That is, the no pre-cue function should look identical to the pre-cue function, yet simply be displaced horizontally (to the right) by an amount that reflects the time to orient attention to a peripheral motion stimulus. The perceptual enhancement hypothesis, by contrast, predicts that the pre-cue should benefit performance across all stimulus durations, even when thresholds have asymptoted. Here, the no pre-cue function should be displaced vertically (above) the pre-cue function. (And, if the effect is constant across durations, this will result in a contrast vertical displacement when plotted on a log scale.)

Examples of shifted threshold vs. duration functions for the single display condition are shown for two individual subjects in Fig. 2C (i.e. the same subjects plotted in Fig. 2A–B). For subject CT (Fig. 2C, *left* panel) a horizontal shift (of 40 ms) produced a better (although not perfect) alignment of the functions than a vertical shift. This 40 ms shift can be considered the time it took the subject to orient attention to the stimulus in the no pre-cue condition. By contrast, for subject KY (Fig. 2C, *right* panel) a vertical shift (1.15-fold) produced a better alignment, in line with the perceptual enhancement hypothesis. Out of our nine subjects, four exhibited functions that were best aligned with a horizontal shift (mean shift = 21 ms), two exhibited functions that were best aligned with a vertical shift (mean shift = 1.18-fold), and three required no shift to align the functions. Thus, individual differences appear to exist across subjects. In addition, even within a subject, it is possible that pre-cueing effects result from

a combination of orienting time and perceptual enhancement. In sum, while the results from this shifting analysis may not provide conclusive evidence for the time-to-orient hypothesis, they make the important point that finding pre-cueing benefits should not be taken as unequivocal evidence for perceptual enhancement. Especially for experiments that employ short stimulus durations, a time-to-orient explanation should also be considered.

*Effects of cue duration:* In our experiments, the duration of the pre-cue was under the control of the subject, with the pre-cue remaining present on the screen until the subject was ready to begin the trial with a key press<sup>2</sup>. We chose to employ this cueing method to ensure that subjects adequately processed the pre-cue before the stimulus was presented (i.e. that they were ‘ready’ for the stimulus). Because cue duration can affect the magnitude of the cueing benefit (e.g. Eriksen & Collins, 1969; Colegate, Hoffman, & Eriksen, 1973; Müller & Findlay, 1988; Nakayama & Mackeben, 1989), we entertained the possibility that our pre-cueing method may not have been optimal for revealing cueing benefits. In order to investigate this possibility, we obtained data from an additional nine subjects using a pre-cue of various fixed durations. (Eye position in these subjects was monitored.) In these experiments, subjects initiated each trial with a key press, after which the pre-cue was presented for a fixed amount of time and was then replaced by the motion stimulus (stimulus duration = 200 ms). Data were obtained for six pre-cue durations (50, 100, 150, 200, 400 and 1000 ms), presented in separate blocks and interleaved with blocks of trials containing no pre-cue. All other aspects of the stimuli and task were identical to the main experiment.

Resulting threshold ratios ( $\text{Thr}_{\text{no pre-cue}}/\text{Thr}_{\text{pre-cue}}$ ) and reaction time differences ( $\text{RT}_{\text{no pre-cue}} - \text{RT}_{\text{pre-cue}}$ ) are plotted as a function of cue duration in the *left* and *right* panels of Fig. 5, respectively. Note that cue duration in this experiment is equivalent to ‘cue lead-time’, i.e. the length of time between the onset of the pre-cue and the onset of the stimulus. In line with previous findings (e.g. Eriksen & Collins, 1969; Müller & Findlay, 1988; Nakayama & Mackeben, 1989), cueing benefits for threshold performance reached asymptotic levels at a cue lead-time of approximately 200 ms. For reaction time data, however, the effect declined after reaching a peak at 200 ms. Most importantly, the peak benefit of pre-cueing observed in this control experiment (threshold ratio = 1.15) was no larger than that

<sup>2</sup> Because the cue remained present for 200 ms after trial initiation (Section 2), the cue duration was at least 200 ms. Based on a separate study conducted in our laboratory where we directly measured the amount of time subjects waited before initiating a trial, we estimate that the cue duration time was, on average, approximately 550 ms (unpublished data).

observed when using an unfixed pre-cue duration (cf. Fig. 4, *filled triangles*). For this reason, we feel confident that the finding of small pre-cueing effects is reliable and not simply attributable to the temporal characteristics of the pre-cue.

On a final note, it is perhaps important to address the significance of finding no pre-cue effects at cue durations less than 200 ms. This 200 ms duration, we would argue, reflects the time it takes to optimally direct attention to the pre-cue location. Because the pre-cue is extremely small ( $0.23^\circ$ ) and stationary, we believe it acts as an ‘endogenous’ orienting cue, i.e. requiring subjects to rely on their slower (volitional) attentional mechanisms (Müller & Findlay, 1987; Nakayama & Mackeben, 1989). By this account, the endogenous mechanism takes approximately 200 ms to be effective. Although this value might, at first glance, appear to contradict our time-to-orient hypothesis, which estimates orienting time to be on the order of 20 ms (averaged across subjects, see above, and also see Posner et al., 1980; Eriksen & Yeh, 1985; Eriksen et al., 1990), this need not be the case. In contrast to the 200 ms value in the control experiment, which reflects the time to orient to a small (presumably endogenous) cue, the 20 ms value in our time-to-orient analysis reflects the time it takes to orient to a large moving stimulus, which is likely to invoke a faster (automatic) ‘exogenous’ mechanism.

### 3.4. Effects of uncued noise distractors

In order to investigate the degree to which the pre-cue serves to reduce the effects of noise distractors, we divided thresholds obtained in the cued multiple display condition by thresholds obtained in the cued single display condition. If the effect of the pre-cue in the multiple display condition is to eliminate entirely the influence of the three noise distractors, resulting threshold ratios ( $\text{Thr}_{\text{cued, multiple}}/\text{Thr}_{\text{cued, single}}$ ) should be 1.0. That is, the cued multiple display condition should

be equivalent to presenting a single motion target in the visual field. By comparison, if the noise distractors impair performance on the motion task, threshold ratios should be greater than 1.0.

Group mean threshold ratios and standard errors are plotted as a function of stimulus duration in the *left* panel of Fig. 6. Surprisingly, threshold ratios were significantly *less* than 1.0, indicating *better* performance in the multiple display, as compared to the single display, condition ( $F(1, 8) = 28.24$ ;  $P < 0.001$ ). Post hoc comparisons revealed that this effect was only significant at 300 and 400 ms ( $t > 3.60$ ,  $P < 0.01$ ), where the mean threshold ratio was 0.8. Thus, these results suggest that uncued noise distractors presented simultaneously with the motion stimulus facilitate motion processing. [This effect was not mirrored in our reaction time data (Fig. 6, *right* panel), however (mean difference = 1.6 ms slower in the multiple display condition,  $F(6, 42) = 0.76$ ,  $P = \text{NS}$ .)] This could occur if subjects failed to ignore the noise distractors, using them somehow to their benefit. Alternatively, the noise distractors may have served to enhance processing of the motion stimulus at a ‘pre-attentive’ level of sensory processing. We return to these possibilities in Section 4.

## 4. Discussion

The results of these experiments are discussed in several contexts. First, we discuss our set-size effects for motion processing in the context of previous experiments examining set-size effects for other aspects of visual processing. Second, we discuss the literature on pre-cueing effects in single item displays, and evaluate whether benefits observed in previous experiments can be taken as evidence for perceptual enhancement. Finally, we discuss the potential for uncued items in a display to influence performance, and the mechanisms by which this might occur.

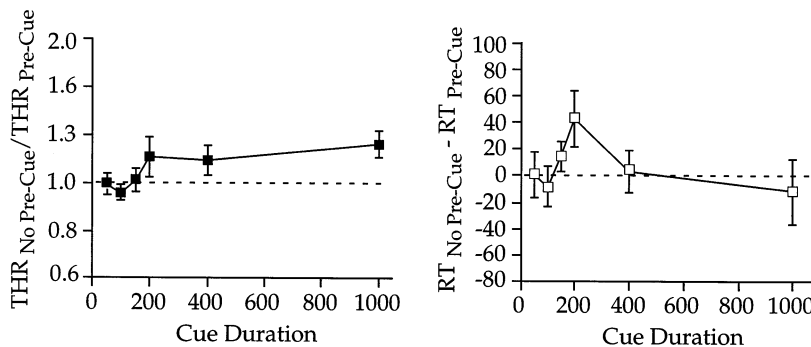


Fig. 5. Effects of cue duration from control experiment. *Left panel*: Group mean threshold ratios ( $\text{Thr}_{\text{no pre-cue}}/\text{Thr}_{\text{pre-cue}}$ ) are plotted as a function of cue duration (in the single display condition, stimulus duration fixed at 200 ms). Error bars denote standard errors of the means across subjects ( $n = 9$ ). The benefit of the pre-cue on performance reaches an asymptote at a cue duration of 200 ms. *Right panel*: For mean reaction time differences ( $\text{RT}_{\text{no pre-cue}} - \text{RT}_{\text{pre-cue}}$ ), the benefit of the pre-cue reaches a peak at a cue duration of 200 ms and falls off at longer durations. See text for discussion.

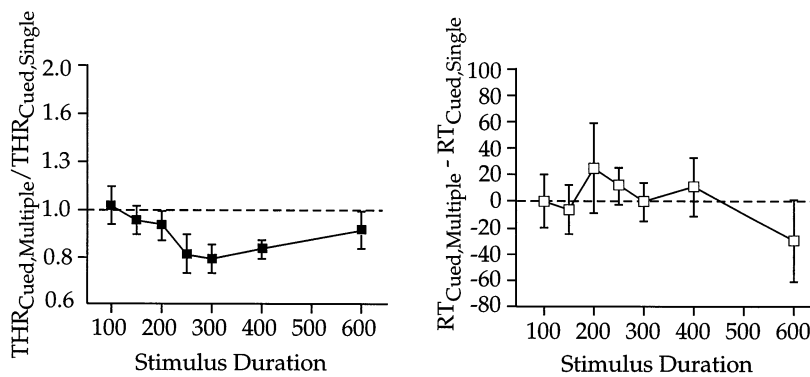


Fig. 6. Effects of uncued noise distractors. *Left panel:* Group mean threshold ratios ( $\text{Thr}_{\text{cued, multiple}} / \text{Thr}_{\text{cued, single}}$ ) are plotted as a function of stimulus duration. Error bars denote standard errors of the means across subjects ( $n = 9$ ). Ratios of 1.0 indicate that the effect of the pre-cue in the multiple display condition is to eliminate entirely the influence of the three noise distractors. Surprisingly, threshold ratios are *less* than 1.0 (particularly at the mid-range of stimulus durations), indicating that the presence of the uncued noise distractors *facilitates* performance on the motion task. *Right panel:* Mean reaction time differences ( $\text{RT}_{\text{cued, multiple}} - \text{RT}_{\text{cued, single}}$ ) reveal no effect of noise distractors on reaction time. See text for discussion.

*Set-size effects:* In our study, we found that set-size effects can be modeled by a simple decision rule (i.e. the ‘maximum rule’) based on signal detection theory (Fig. 3). Here, the quality of sensory processing is maintained as the number of items in the display increases, however, performance declines because the presence of distractors increases the number of errors occurring at the decision level. Thus, contrary to early notions, which proposed that dividing attention across multiple stimuli limits the processing for each (e.g. Broadbent, 1958; Treisman & Gelade, 1980), our results add to the mounting evidence for *unlimited* capacity in visual attention. In previous psychophysical studies employing threshold techniques to explore set-size effects, unlimited capacity has similarly been observed for visual tasks such as: luminance discrimination (Cohn & Lasley, 1974; Lasley & Cohn, 1981; Shaw, 1984; Palmer, 1994), color discrimination (Palmer, 1994; Vergheese & Nakayama, 1994; Monnier & Nagy, 2000), orientation discrimination (Pavel et al., 1992; Palmer et al., 1993; Palmer, 1994; Rezec et al., 2000), size and length discrimination (Palmer, 1994), letter discrimination (Bennett & Jaye, 1995; McLean, Palmer, & Loftus, 1997, but see Shaw, Mulligan, & Stone, 1983; Shaw, 1984 for different results when the task is letter *localization*), as well as contrast detection (Davis et al., 1983; Carrasco et al., 2000). For some higher level tasks (such as line bisection and point separation), however, discrimination may be capacity limited (Palmer, 1994).

Particularly relevant to our study of direction discrimination is an experiment by Vergheese and Stone (1995), which measured speed discrimination thresholds for set-sizes of 1, 2, 4 and 6. In their study, subjects reported which of two temporal intervals contained the faster moving grating (interval duration = 195 ms). The ‘non-target’ interval contained  $n$  gratings presented at a baseline speed, while the ‘target’ interval contained

$n - 1$  gratings moving at the baseline speed and one grating moving either faster or slower than this speed. As in the present study, performance on their task declined with increasing  $n$ , and this could be modeled by a simple decision rule based on the assumption of unlimited capacity. Unlike our study, however, their set-size effects were best accounted for by a *Summation Rule*. This is perhaps not surprising given the authors’ comment that their subjects, in fact, felt as though the discrimination was based on the mean speed in each interval. In any event, both our direction of motion study and the speed discrimination study of Vergheese and Stone suggest that low-level motion processing is not subject to capacity limitations.

There are other situations, however, in which set-size effects cannot be accounted for by a maximum rule based on unlimited capacity. For example, Morgan et al. (1998) found that under some conditions set-size effects for orientation discrimination were much larger than predicted by a maximum rule decision model. Similarly, Vergheese and Nakayama (1994) found set-size effects for orientation and spatial frequency discrimination that were significantly larger than those predicted from the maximum rule. As discussed previously (e.g. Palmer et al., 1993, 2000; Palmer, 1994; Carrasco, Evert, Chang, & Katz, 1995; Geisler & Chou, 1995), such findings do not necessarily reflect capacity limitations. Instead, they may result from the effects of pre-attentive sensory factors (such as ‘crowding’), which covary with set-size.

In fact, our finding of set-size effects that were somewhat *smaller* than predicted by the maximum rule (Fig. 3) may also be attributable to sensory factors. In our case, however, this proposed sensory effect serves to facilitate, not impair, performance. Alternatively, it is possible that the differences between observed and predicted set-size effects in our study arise from errors in

the assumptions of our model (described in Appendix A). For example, our model assumes that detector activity is normally distributed, that signal and noise activity distributions have equal variances, and that directional detectors are unaffected by motion in their non-preferred direction. If these assumptions are in error, this could easily account for set-size predictions that veer slightly from the data (see Palmer et al., 2000 for discussion).

#### *4.1. Pre-cueing benefits: evidence for perceptual enhancement?*

Many previous studies have investigated the effects of spatial pre-cueing subjects to the location of a target stimulus. When the pre-cue is found to improve performance, this is typically taken as evidence for 'perceptual enhancement', i.e. that the pre-cue allows greater allocation of attentional resources or strengthens the stimulus representation. Depending on the particular paradigm employed, however, there are other alternative explanations for pre-cueing benefits. First, if the visual display contains distractors that are confusable with the target, the benefit of the pre-cue can be attributed to 'noise reduction' (see Shiu & Pashler, 1994; Carrasco et al., 2000 for discussion). That is, performance will improve because the pre-cue allows subjects to disregard the distractors, which would otherwise impair performance. It is perhaps important to point out that the notion of noise reduction is logically separable from the issue of whether set-size effects are accounted for by capacity limitations or by decision noise. That is, both models of visual attention predict significant benefits (albeit to differing degrees) of pre-cueing in a display containing a target amongst confusable distractors.

A second alternative account for pre-cueing effects is based on the possibility that subjects lower their criterion in the pre-cue condition, which is likely to occur in studies that employ 'yes/no' detection paradigms or speeded reaction times (e.g. Posner, Snyder, & Davidson, 1980; Müller & Findlay, 1987; Shulman & Posner, 1988). In order to preclude these alternative explanations for pre-cueing effects, for the remainder of this section we discuss only those experiments that employ: (1) a single stimulus in the visual display (i.e. with no confusable distractors); and (2) two-alternative forced-choice methods, which tend not to rely on criterion-based judgments. (For a comprehensive review of the effects of pre-cueing on both accuracy and speeded reaction time, see Doshier & Sperling, 1998 or Pashler, 1998.)

In studies that measure the effects of spatial pre-cueing on visual discrimination performance in single displays, it is generally the case (although not without exception, e.g. Henderson, 1996; Yeshurun & Carrasco,

1999; Carrasco et al., 2000) that pre-cueing benefits are found to be negligible (e.g. Grindley & Townsend, 1968; Van der Heijden et al., 1985; Nazir, 1992; Van der Heijden, 1992; Shiu & Pashler, 1994). However, in studies that employ multiple post-stimulus masks (which appear in each of the potential stimulus locations), the benefits of pre-cueing can be substantially larger (e.g. Henderson, 1991; Shiu & Pashler, 1994, but cf. Morgan et al., 1998). Note that this effect can be accounted for by considering that the presence of multiple masks can create uncertainty about target location, which, in turn, is expected to increase errors at the decisional level (see Shiu & Pashler, 1994 for discussion). Large pre-cueing benefits have also been reported in experiments that employ a valid/invalid cueing paradigm, in which the validity of the pre-cue is varied across trials (e.g. Luck et al., 1996). However, this effect may reflect an impairment for invalidly-cued stimuli, rather than a benefit for validly-cued stimuli. For this reason, it is important to employ neutral cues as well as valid and invalid cues. In such cases, typically only small or negligible benefits of valid cues are observed (e.g. Müller & Findlay, 1988; Pashler, 1998). In sum, the existence of perceptual enhancement has yet to be unequivocally established in the literature (but see Henderson, 1996; Cheal & Gregory, 1997; Yeshurun & Carrasco, 1999 for further discussion).

In our experiments, we found only a small effect of the pre-cue in the single display condition. However, rather than attributing this effect to perceptual enhancement, we argue that this result could potentially be accounted for by our time-to-orient hypothesis, at least in some subjects. Specifically, results from studies measuring reaction times to detect validly vs. invalidly cued stimuli (e.g. Posner et al., 1980; Eriksen & Yeh, 1985; Eriksen, Webb & Fournier, 1990) and the effects of cue lead-time on accuracy in search tasks (e.g. Tsai, 1983; Müller & Findlay, 1988; Nakayama & Mackeben, 1989) indicate that orienting attention to a specified location in the visual field takes time (on the order of 50–150 ms, depending on the stimulus/task). Thus, the pre-cue, by allowing subjects to orient attention to the stimulus location prior to stimulus onset, presumably eliminates this orienting time and thereby increases the 'effective' processing time of the stimulus. This benefit of the pre-cue, however, should only be observed at short durations, where thresholds are dependent on stimulus duration, but not at longer durations, where thresholds have asymptoted. In support of this hypothesis, we found significant effects of the pre-cue only at the two shortest stimulus durations (100 and 150 ms, see Section 3). Although we cannot rule out the possibility that perceptual enhancement occurred as well, the main point of our results is to demonstrate that pre-cueing benefits in single displays should not automatically be interpreted as evidence for increased attentional

resources or strengthened stimulus representation. Especially in studies that employ short stimulus durations, the time-to-orient hypothesis should also be considered.

#### 4.2. Can uncued distractors be perfectly excluded?

One way to measure the efficacy of selective spatial attention is to determine whether ignored (uncued) stimuli affect performance on an attended (cued) stimulus (e.g. Eriksen & Hoffman, 1973; Neisser & Becklen, 1975; Eriksen, Eriksen, & Hoffman, 1986; Yantis & Johnston, 1990; Miller, 1991). Particularly relevant to this question are experiments conducted by Palmer and colleagues (Palmer et al., 1993; Palmer, 1994, 1995). In addition to measuring standard set-size effects (i.e. determining the threshold for detection of a target as a function of the number of distractors in the visual field), these investigators measured thresholds under conditions in which subjects were pre-cued to a subset of locations at which the target stimulus might appear. In these experiments, threshold performance was found to depend on the total number of *potential* target locations (referred to as ‘relevant set-size’) and not on the total number of stimuli in the display (referred to as ‘display set-size’). For example, thresholds obtained for a relevant set-size of 2 (where two locations were pre-cued, yet the total number of stimuli in the field was actually eight) were identical to those obtained for a display set-size of 2. Thus, subjects’ performance in the relevant set-size 2 condition reflected an ability to perfectly exclude information from the six additional distractors in the visual field (and see Morgan et al., 1998 for similar findings).

In our experiments, we found a somewhat curious result in that the presence of uncued noise distractors in the cued multiple condition *improved* performance on the motion task as compared to performance on a cued single motion stimulus (Fig. 6). One possibility for this finding is that, at some pre-attentive sensory level, the processing of a motion stimulus is enhanced by the presence of surrounding noise stimuli. Support for this sensory explanation comes from neurophysiological experiments conducted in macaque area MT (e.g. Allman, Miezin, & McGuinness, 1985; Born & Tootell, 1992). These previous studies showed that the response of an individual MT neuron to preferred motion in its receptive field is often augmented when additional moving stimuli are placed in the surrounding regions of visual space. Although these studies only investigated the effects of *moving* stimuli in the surround, it is also possible that stochastic noise (of the type used in the present experiment) might produce a similar result. It is perhaps important to point out that this sensory hypothesis is not incompatible with the notion of ‘noise reduction’ as an explanation for pre-cueing benefits in the multiple display condition (see Section 3 and Fig.

4). That is, in the cued multiple condition, uncued noise stimuli presumably affect processing of the cued stimulus at an early sensory level, even if the effects of those same noise stimuli are reduced (or eliminated) at the decision level. In a similar vein (and as mentioned earlier in Section 4), this sort of sensory effect could potentially explain why we observed *lower*-than-predicted set-size effects (Fig. 3). Here, increasing set-size in the absence of a pre-cue is expected to hurt performance (based on more chances for errors at the decision level), yet this effect will be counteracted somewhat if noise distractors also serve to enhance sensory processing at an earlier pre-attentive level.

There are at least two other alternative explanations for the effects observed in Fig. 6, which are based on more strategic accounts. First, it is possible that subjects intentionally used the noise distractors as a ‘standard’ by which to compare the motion stimulus. This, in principle, could have yielded better performance in the cued multiple display condition. Second, subjects might have (loosely speaking) tried harder in the cued multiple, as compared to the cued single, condition. While either of these scenarios is possible, both require relatively complicated schemes for why the effects were observed at some (i.e. 300–400 ms), but not all, stimulus durations. For this reason, we tend to find these strategic explanations far less likely than the above-described sensory explanation.

On a final note, the question of whether uncued distractors interfere with performance on the relevant target stimulus is tightly related to another hotly-debated topic in the field of visual attention: to what extent are uncued stimuli actually processed? This question has been difficult to answer for at least two reasons. First, in experiments demonstrating that uncued distractor stimuli interfere with performance on the relevant stimulus, it is possible that such findings simply reflect lapses in subjects’ ability to ignore distracting stimuli. Second, even when uncued stimuli do not interfere with performance, this alone cannot be taken as evidence for incomplete processing since uncued stimuli may be fully processed yet not considered in the decision process (as may be the case in our experiments).

In all likelihood, the extent to which uncued distractor stimuli are processed will depend on how attentionally-demanding the target task is (e.g. Lavie & Tsai, 1994). This suggestion has recently been supported by the results from a human fMRI study showing that activity in area MT elicited by viewing moving stimuli is lower under conditions where subjects concurrently perform a high attentional load, as compared to a low attentional load, linguistic task (Rees et al., 1997). These and previous fMRI results (O’Craven et al., 1997; Buchel et al., 1998) suggest that ignored moving stimuli may not be fully processed, even at relatively early levels in the visual pathway. This is not to say that attentional

manipulations affect the processing of moving stimuli under all conditions, since the results of the present study demonstrate that the quality of motion processing is maintained when subjects must divide their attention across multiple stimuli. As suggested by Pashler (1998), these collective results can easily be reconciled by proposing a ‘controlled parallel’ system of attention, in which multiple items can be processed in parallel in an unimpeded fashion, yet attentional mechanisms can serve as a gate that allows only selected items to be fully processed.

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## Appendix A

In this appendix, we outline the equations for modeling set-size effects, for both unlimited and limited capacity theories of visual attention (see Shaw, 1980; Graham et al., 1987; Palmer et al., 1993, 2000; Verghese & Stone, 1995, for similar derivations). These models, which are based on signal detection theory, assume the following: (1) visual detectors are noisy; (2) the activity in these detectors is normally-distributed; (3) detector activity driven by target and distractor stimuli are statistically independent; and (4) the activity distribution for the target is a shifted version of the distractor distribution. Based on these premises, the observer is assumed to use a ‘maximum rule’ to make decisions. In the case of our experiment, the observer discerns leftward vs. rightward motion by choosing the detector (‘leftward detector’ ( $D_L$ ) or ‘rightward detector’ ( $D_R$ )) that is maximally responsive during the trial. Three variations of this model are described below. The first two (*Maximum Rule* and *Summation Rule*) are based on an assumption of unlimited resource capacity for the task. The third is based on an assumption of limited resources.

### A.1. ‘Maximum rule’ (unlimited capacity)

We describe this model in terms of the activity distributions for ‘signal events’ and ‘noise events’. Both distributions are assumed to be Gaussian with a standard deviation ( $\sigma$ ) of 1. Let  $f(x)$  refer to the probability density function and  $F(x)$  refer to the cumulative distribution of activity observed for a noise event, with  $\mu_n$  representing the mean of that distribution. Let  $f(x-s)$

refer to the probability density function and  $F(x-s)$  refer to the cumulative distribution of activity observed for a signal event, with  $\mu_s$  representing the mean of that distribution (which is shifted some distance ( $s$ ) away from the noise distribution).

These signal and noise distributions are related to activity within directional detectors (i.e.  $D_L$  and  $D_R$ ) as follows: The signal distribution,  $f(x-s)$ , is generated in the following conditions: (1)  $D_L$  presented with leftward motion stimulus; and (2)  $D_R$  presented with rightward motion stimulus. The noise distribution,  $f(x)$ , is generated in the following conditions: (1)  $D_L$  or  $D_R$  presented with the noise stimulus (i.e. 0% coherence); (2)  $D_L$  presented with rightward motion stimulus; and (3)  $D_R$  presented with leftward motion stimulus. Note that the latter two conditions assume that the detectors are insensitive to motion in the direction opposite to their preferred direction, responding in this case as if the stimulus contained only noise. This assumption is generally supported by neurophysiological recordings in area MT, at least for stimuli that are presented near threshold (Thiele, Dobkins, & Albright, 2000).

When the visual field contains one moving stimulus (*set-size 1*), the observer compares the activity between a  $D_L$  and a  $D_R$  representing that location of space, and reports ‘leftward’ if  $D_L$  yields the greater response. The probability of correct direction discrimination in this condition is described as:

$$P_{\text{correct}} = \int_{-\infty}^{+\infty} f(x-s) \times F(x) dx \quad (1)$$

From this equation, we can determine the  $s$  value (reflecting the distance between signal and noise distributions) that yields 75% correct (i.e. threshold performance). This value, referred to as ‘ $s_{75}$ ’, equals 0.9539.

When the visual field contains one motion stimulus along with three noise distractors (*set-size 4*), the observer must compare the activity across *eight* detectors, i.e. a  $D_L$  and a  $D_R$  at each of the four stimulus locations. In this condition, the observer reports ‘leftward’ if any one of the  $D_L$ ’s yields the greatest response. Here, the probability of correct direction discrimination is described as:

$$P_{\text{correct}} = \int_{-\infty}^{+\infty} f(x-s) \times F(x)^7 + 3 \times [f(x) \times F(x-s) \times F(x)^6] dx, \quad (2)$$

and the  $s_{75}$  is 1.527. The  $s_{75}$  values determined from Eq. (1) and Eq. (2) are used to predict set-size effects in the form of threshold ratios. Specifically,  $s_{75}(\text{set-size } 4) / s_{75}(\text{set-size } 1)$  predicts a threshold ratio ( $\text{Thr}_{\text{set-size } 4} / \text{Thr}_{\text{set-size } 1}$ ) of 1.60. Thus, even though the activity distributions for  $D_L$  and  $D_R$  are unaffected as set-size increases, a decrement in performance is predicted based solely on greater errors at the decision level.

### A.2. 'Summation rule' (unlimited capacity)

This model also employs a maximum rule, however, the signals across detectors with the same direction preference are summed together before the decision level (e.g. Verghese & Stone, 1995). Like the *Maximum Rule* (above), this model assumes that the activity distributions within individual detectors are unaffected as set-size increases.

Here, visual performance for set-size 1 is calculated as the difference between the mean signal and noise activity, divided by the standard deviation ( $\sigma$ ) of the distributions:

$$(\mu_s - \mu_n)/\sigma. \quad (3)$$

When set-size is 4, visual performance is calculated as the difference between the *summed* distributions for  $D_L$ 's and the *summed* distributions for  $D_R$ 's, divided by the standard deviation of the summed distributions. Thus, if target motion is leftward, the mean of the summed activity across the four  $D_L$ 's is:  $(1 \times \mu_s) + (3 \times \mu_n)$ , with a standard deviation of  $2\sigma$ . The mean of the summed activity across the four  $D_R$ 's is:  $4 \times \mu_n$ , also with a standard deviation of  $2\sigma$ . In this case, visual performance is described as:

$$[(1 \times \mu_s) + (3 \times \mu_n) - (4 \times \mu_n)]/\sqrt{4} \times \sigma, \quad (4)$$

which reduces to:

$$(\mu_s - \mu_n)/2\sigma. \quad (5)$$

Thus, visual sensitivity is expected to be two times lower for set-size 4, as compared to the set-size 1. In other words, the summation rule predicts a threshold ratio ( $\text{Thr}_{\text{set-size } 4}/\text{Thr}_{\text{set-size } 1}$ ) of 2.0.

### A.3. 'Limited capacity'

This model assumes that attention is capacity limited. As such, the number of internal samples devoted to processing each stimulus is assumed to be inversely proportional to the number of stimuli in the visual field (Verghese & Nakayama, 1994). Accordingly, an increase in set-size from 1 to 4 should result in a quartering of the number of samples per stimulus. This, in turn, is expected to increase the variance of the activity distributions by a factor of 4, and thus the standard deviation by 2. Assuming that the observer still employs a maximum rule, the probability for correct directional discrimination for set-size 4 can be determined from Eq. (2), using  $2\sigma$  as the standard deviation. Under these conditions, the  $s_{75}$  is calculated to be 3.05. As before, set-size 1 performance is calculated using  $\sigma$  as the standard deviation, with the resulting  $s_{75}$  equal to 0.9539 Eq. (1). Thus, the predicted threshold ratio ( $\text{Thr}_{\text{set-size } 4}/\text{Thr}_{\text{set-size } 1}$ ) for limited capacity is 3.20.

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