

## Characterizing visual performance fields: effects of transient covert attention, spatial frequency, eccentricity, task and set size\*

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**Abstract**—We investigated whether transient covert attention would differentially affect ‘performance fields’ (shape depicted by percent correct performance at particular locations in the visual field) for orientation discrimination, detection and localization tasks, while manipulating a number of visual factors. We found that although attention improved overall performance, it did not affect performance fields. Two patterns were observed regardless of the presence of a local post-mask, the stimulus orientation, or the task. A horizontal–vertical anisotropy (HVA) became more pronounced as spatial frequency, eccentricity and set size increased. A vertical meridian asymmetry (VMA) became more pronounced as spatial frequency and eccentricity increased. We conclude that performance fields are determined by visual, rather than by transient attentional, constraints.

*Keywords:* Transient covert attention; discrimination; detection; localization; set size; performance fields; spatial frequency; eccentricity.

### INTRODUCTION

Performance across the visual field is not always homogeneous at equal eccentricities. Studies have reported a *horizontal–vertical anisotropy* (HVA) — better performance on the horizontal than vertical meridian (e.g. Rovamo and Virsu, 1979; Rijdsdijk *et al.* 1980; Carrasco *et al.*, 1995), as well as a *vertical asymmetry* (VA) — better performance in the lower than upper visual field (e.g. Edgar and Smith, 1990; Previc, 1990; Rubin *et al.*, 1996; Gordon *et al.*, 1997). These *performance fields*

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\*Results of Experiments 1, 2 and 3 were part of studies reported at ARVO (Carrasco and Penpeci-Talgar, 1999; Penpeci-Talgar, Lee and Carrasco, 2000; Cameron, Tai and Carrasco, 2000, respectively).

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may reflect ecological constraints; typically there is more relevant visual information across the horizontal than the vertical dimension.

Covert attention can be allocated to a given location either voluntarily according to goals ('sustained attention') or involuntarily, in a reflexive manner ('transient attention') to a stimulus that appears in the visual field. These sustained and transient components of attention have been characterized by several authors (e.g. Nakayama and Mackeben, 1989; Cheal and Lyon, 1991). Recently, an HVA reported in a letter identification task (Mackeben, 1999) and a VA reported in a Snellen acuity task (in 50% of the observers tested; Altpeter *et al.*, 2000) have been attributed to effects of sustained attention (e.g. Nakayama and Mackeben, 1989). Likewise, the VA reported in search tasks has been attributed to higher attentional resolution in the lower visual field (He *et al.*, 1996). However, a more parsimonious explanation — that performance may be determined by visual constraints — has not been ruled out. Furthermore, our previous studies have reported that performance fields (shape depicted by percent correct at particular locations in the visual field) were similar for both attentional and control conditions. This was the case in acuity tasks (Yeshurun and Carrasco, 1999) and in feature and conjunction searches (Carrasco *et al.*, 1995, 1998a, b), which are considered to involve different degrees of attentional participation. This discrepancy regarding the nature of the performance fields prompted our systematic characterization of the effects of visual and attentional factors on performance fields.

This is the first study to investigate whether covert attention differentially affects performance fields while systematically manipulating several visual factors — spatial frequency, stimulus orientation, presence or absence of a local post-mask, target eccentricity and set size — in discrimination, detection and localization tasks. We manipulated covert attention via a stimulus-driven peripheral precue, which is presented at a location directly adjacent to the relevant location, and compared its effects with a neutral precue. Several findings have led to the conclusion that peripheral cues capture attention in an 'automatic' manner (Posner, 1980; Jonides, 1981; Posner and Cohen, 1984; Müller and Rabbitt, 1989; Nakayama and Mackeben, 1989; Cheal and Lyon, 1991), for instance: (a) Peripheral cues result in faster reaction times than central cues; (b) performance directed by relevant central cues can be impaired by irrelevant peripheral cues; (c) performance at peripherally cued locations is facilitated even when observers are instructed to ignore the peripheral non-informative cues. The maximum attentional benefit of the peripheral precue is transient and occurs at about 100 ms (e.g. Nakayama and Mackeben, 1989; Cheal and Lyon, 1991). We have previously characterized the effects of transient covert attention by comparing the effects of peripheral and neutral precues on visual search (Carrasco and Yeshurun, 1998), acuity (Yeshurun and Carrasco, 1999), texture segmentation (Yeshurun and Carrasco, 1998, 2000), and contrast sensitivity (Carrasco *et al.*, 2000) tasks.

## EXPERIMENT 1 — SPATIAL FREQUENCY AND LOCAL POST-MASK

Carrasco *et al.* (2000) have reported that in an orientation discrimination task, covert attention improves contrast sensitivity when a Gabor patch (a sinusoidal grating embedded in a Gaussian window) is presented at one of 8 possible locations, regardless of its spatial frequency and the presence of a local post-mask. In that study, the attentional effect was assessed by the signal contrast necessary to perform at 82% correct under ‘peripheral’ and ‘neutral’ precue conditions. However, as is typically the case, performance level was assessed by averaging percent correct across all possible locations. To evaluate whether attention affects the shape of the performance fields, here we systematically examined performance fields under peripheral and neutral precue conditions. Given that the HVA becomes more pronounced as spatial frequency increases (Rijsdijk *et al.*, 1980), we hypothesized that, for both cueing conditions, both the HVA and the VA would be exacerbated as the spatial frequency of the Gabor target increased. In addition, because performance in an orientation discrimination task was highly similar regardless of the presence a local post-mask (Carrasco *et al.*, 2000), we hypothesized that performance fields would not differ as a function of mask presence.

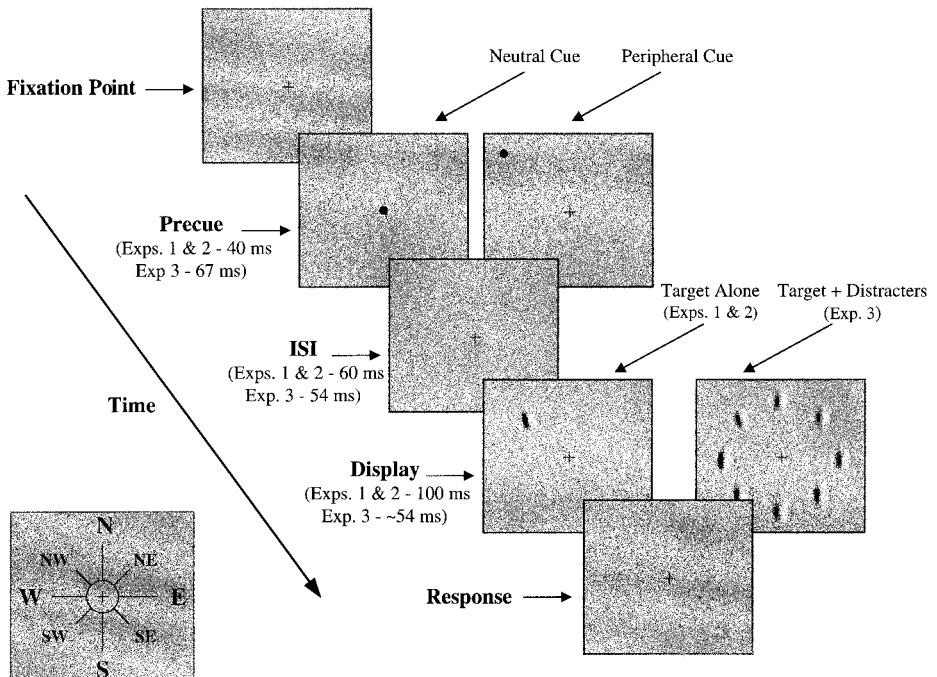
### Method

*Observers.* There were 6 observers (3 graduate students, 2 undergraduate students and 1 postdoctoral fellow from NYU); 2 of the observers were trained psychophysical observers, and 4 were not trained and were naïve to the purpose of the experiment. All had normal or corrected-to-normal vision.

*Apparatus.* Gabor stimuli were displayed on a gamma-corrected computer monitor (Pelli and Zhang, 1991) in a dark room. A video attenuator drove only the green gun of the color monitor.

*Stimuli and Design.* The stimuli were created on a Power Macintosh 7500/100 computer using MATLAB 5.2 and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Background luminance was set to the middle of the monitor’s range, about 16 cd/m<sup>2</sup>. All Gabor patches subtended 1.5° of visual angle, were vertically or horizontally oriented and had a center spatial frequency of 0.5, 1, 2, 4, 8 or 10 cpd. On each trial, the target appeared with equal probability at one of 8 equally spaced locations, on an imaginary circle, at 3.2° eccentricity (Fig. 1). Half of the blocks contained *peripheral* trials — a small black precue (subtending a radius of 0.25° of visual angle) that appeared 2° beyond the target’s center indicated the target location. The cue was 100% valid in terms of location, but conveyed no information about the correct response. The remaining blocks contained *neutral* trials — the precue appeared at the center of the display indicating that the target was equally likely to appear at any of the 8 locations. Both the peripheral and the neutral precues signaled the timing of the stimulus onset. A small black fixation square (0.2 × 0.2°) was present at the center of the screen throughout the trial, except when the neutral precue appeared.

**Procedure.** Observers viewed the display binocularly. They were instructed to fixate on the fixation point throughout the trial and to report the target orientation. On each trial the cue appeared for 40 ms, and after an ISI of 60 ms (i.e. an SOA of 100 ms) the stimulus was presented for 100 ms. The interval between the cue onset and the stimulus offset was brief enough to prevent goal or target directed eye movements, as about 250 ms are needed for a saccade to occur (Mayfrank *et al.*, 1987). In Phase A, a local post-mask appeared at the target location for 200 ms; in Phase B, no mask appeared. Contrast thresholds at 82% correct for each frequency were measured for each block of 75 trials using the QUEST sequential estimation procedure (Watson and Pelli, 1983); the average contrast of the Gabor stimuli was equal at all 8 locations. Each observer performed 10 practice and 60 experimental blocks (total = 4500 experimental trials). Observers responded by pressing a key to indicate the stimulus orientation. The following trial appeared immediately after observers responded. Feedback was given after each trial; a high-frequency tone indicated a correct response and a low-frequency tone signaled an incorrect response.

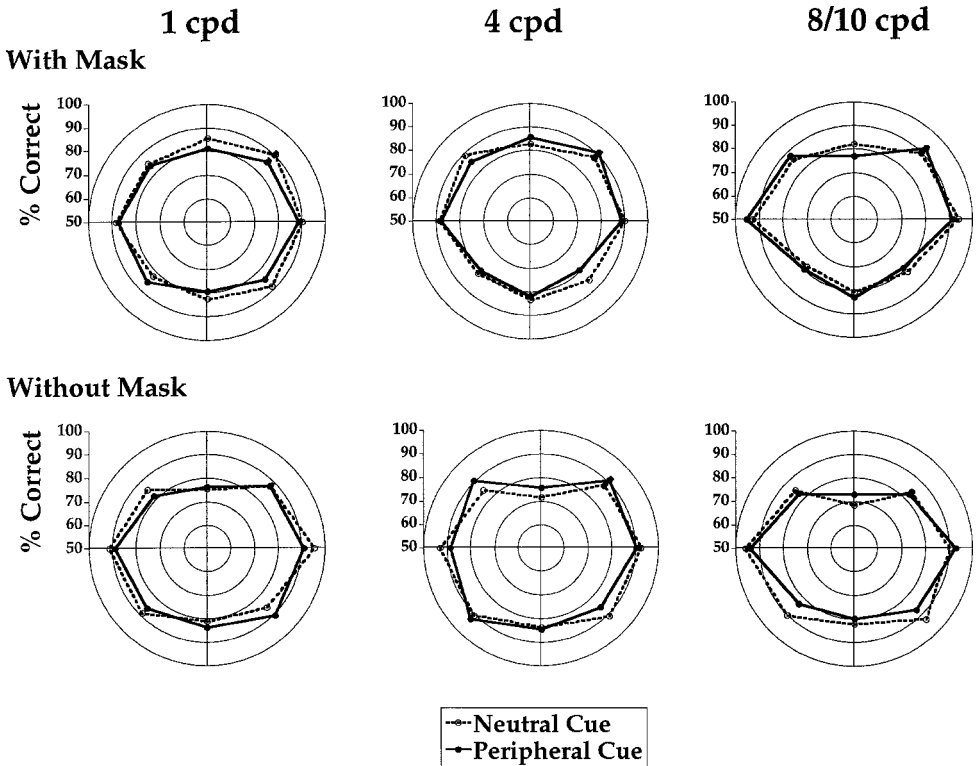


**Figure 1.** A schematic representation of a trial sequence. On half the blocks, the target was preceded by a peripheral cue (a circle appearing just beyond the target) and on the other half of the blocks it was preceded by a neutral cue (a circle in the center of the display). The target (Exps. 1–3) was equally likely to appear in one of eight iso-eccentric and equi-spaced locations. In Phase A of Exp. 1 a local mask was presented following the target. In of Exp. 3, for set size 4, the distracters appeared at alternating locations (N, S, E and W or NW, NE, SW and SE); for set size 8 distracters appeared at all remaining locations. We use the compass to refer to specific locations in the display.

## Results

Figure 2 illustrates performance fields for Phases A and B. We averaged the data for individual observers (in this and the next two experiments) given that observers' data resulted in similar 'performance fields'. A repeated-measures ANOVA (2 precue types  $\times$  6 spatial frequencies  $\times$  8 locations) was conducted for each Phase. All effects and Newman–Keuls planned comparisons reported here were significant at  $p < 0.05$ . Overall, performance fields were consistent in both phases. For both

### Discrimination (with and without mask)



**Figure 2.** Performance fields (polar plots of accuracy as a function of location) for sampled spatial frequencies (low, intermediate and high — 8 cpd for mask condition and 10 cpd for no-mask condition) used in Exp. 1. The data are an average of the 6 observers. The upper panel depicts the results from the local post-mask condition (Phase A), and the lower panel the no-mask condition (Phase B). Plot origins represent chance performance (50%) and the outer limits (100%) correct response. There were approximately 188 trials per data point. Note that, by definition, overall performance was similar for both precue conditions because the staircase procedure ensured that for both conditions observers performed at 82% correct. In addition, there was no systematic effect of cueing condition on location. [Solid line = peripheral precue; dashed line = neutral precue for all figures; error bars correspond to the average  $\pm 1$  s.e. for each condition.]

precue types, a horizontal–vertical asymmetry (HVA) was present — performance was better at the East (E) and West (W) locations than at the North (N) and South (S) locations — and became more pronounced as spatial frequency increased in Phase A. In addition, in Phase B a vertical meridian asymmetry (VMA) — performance was better at the S than at the N locations — became more pronounced with increasing spatial frequencies. Precueing the target location improved overall performance: The stimulus contrast necessary to attain the same performance level was significantly lower in the peripheral than the neutral cue conditions. However, the attentional manipulation did not alter the shape of the performance fields. In short, the performance fields were determined by visual constraints.

## EXPERIMENT 2 — SPATIAL FREQUENCY AND ECCENTRICITY

In this experiment we explored whether the effect of frequency on performance fields would interact with target eccentricity. Given that contrast sensitivity drops with increasing eccentricity (e.g. DeValois and DeValois, 1988), we hypothesized that as target eccentricity increased both the HVA and the VMA would emerge at lower spatial frequencies. In addition, we used slightly tilted rather than vertical and horizontal Gabor stimuli to investigate whether the performance fields would be affected by stimulus orientation, and to test the generality of the finding that attention did not affect the shape of the performance field (Experiment 1).

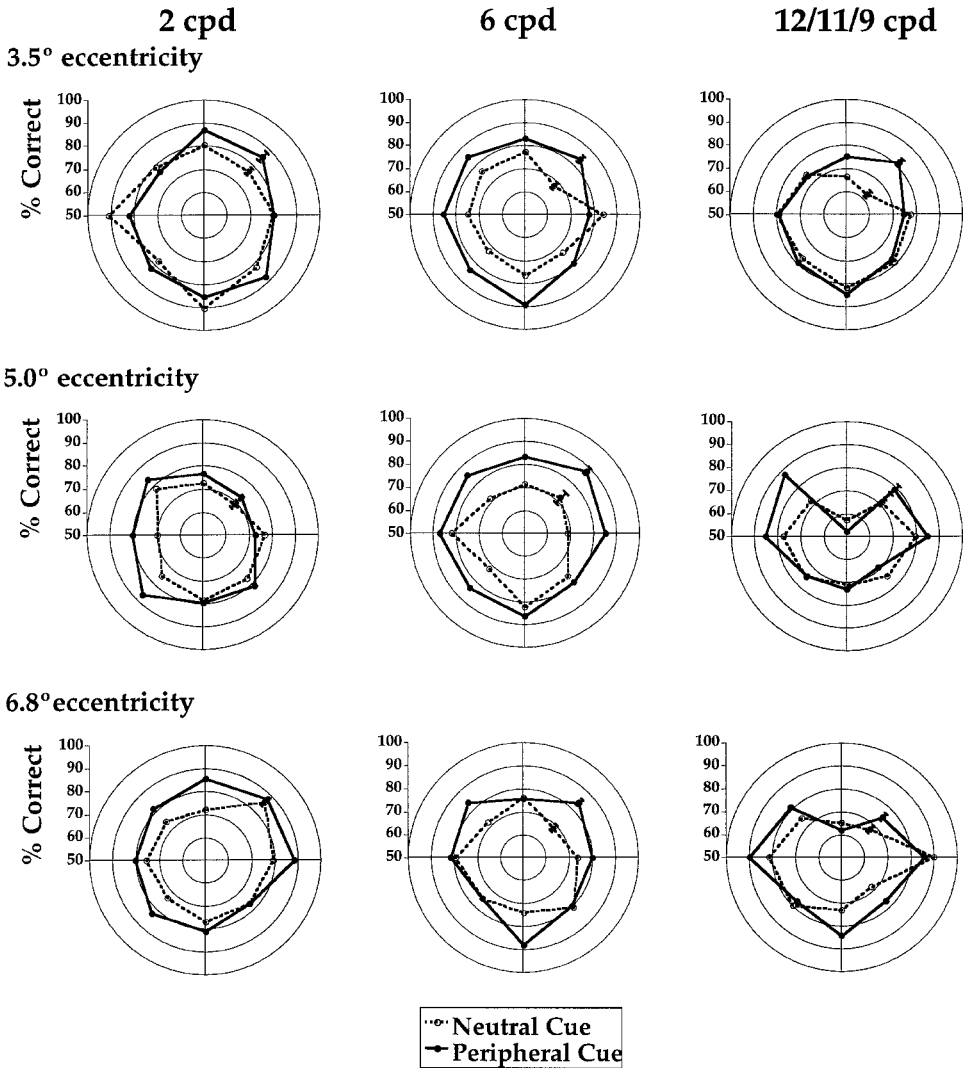
### *Method*

Two of the 4 observers had participated in Experiment 1, and 3 of these 4 observers were naïve. The methods were the same as in Experiment 1, except for the following: (a) The stimuli were tilted ( $\pm 2^\circ$ ) Gabor patches, which appeared at 3.5, 5 or 6.8° eccentricity; (b) Observers were asked to report the Gabor's orientation (right vs. left); (c) Target contrast was adjusted for each observer to yield performance of about 80% correct for each frequency (0.5, 1, 2, 4, 6, 8, 9, 10, 11 and 12 cpd) before performing the experimental trials; (d) Each observer performed 12 000 experimental trials (400 per 10 spatial frequencies at 3 eccentricities).

### *Results*

A repeated-measures ANOVA (2 precue types  $\times$  10 spatial frequencies  $\times$  8 locations) was conducted for each eccentricity. Figure 3 shows that performance fields evolved from being isotropic to showing both the HVA and VMA as spatial frequency increased at all eccentricities. That is, at the low frequencies, performance was relatively homogeneous across the visual field, but as frequency increased the visual field inhomogeneity became more pronounced at each eccentricity, as illustrated by the increasing HVA and the VMA asymmetries. The HVA was significant at 5° and 6.8° eccentricity and became more pronounced as spatial frequency increased. Moreover, as eccentricity increased, the HVA became more pronounced at

## Discrimination (eccentricity)



**Figure 3.** Performance fields (polar plots of accuracy as a function of location) for sampled spatial frequencies (low, intermediate and high) used in Exp. 2. The highest spatial frequencies at which observers could perform this task were: 12 cpd for 3.5°, 11 cpd for 5° and 9 cpd for 6.8°. The data are an average of the 4 observers. The upper panel illustrates the nearest eccentricity, the middle panel the intermediate eccentricity and the lower panel the farthest eccentricity. Plot origins represent chance performance (50%) and the outer limits (100%) correct response. There were approximately 113 trials per data point. Note that there was no systematic effect of cueing condition on location. [Solid line = peripheral precue; dashed line = neutral precue for all figures; error bars correspond to the average  $\pm 1$  s.e. for each condition.]

lower frequencies: 10 cpd at 5° eccentricity and 9 cpd at 6.8° eccentricity. The VMA followed the same pattern: it became more pronounced at 12 cpd at 3.5° eccentricity, 10 cpd at 5° eccentricity and 9 cpd at 6.8° eccentricity. Precueing improved performance, but did not interact with location. (A subsidiary reaction time (RT) analysis revealed no significant main effect of cue type and no significant interaction of cue and location.) These results indicate that, as in the previous experiment, the performance fields were constrained by visual factors.

### EXPERIMENT 3 — SPATIAL FREQUENCY, SET SIZE AND TASK

To characterize further the performance fields, we investigated whether set size and task (discrimination, detection and localization) would affect their shape. Manipulating set size allowed us to test the following specific hypotheses: (a) Given that as set size increases, the signal-to-noise ratio decreases (e.g. Eckstein, 1998), we hypothesized that the HVA would become more pronounced as set size increased; (b) Because the stronger the distracter representation, the more their presence would interfere with target processing, we predicted that distracters at salient locations would hurt performance (e.g. targets on the vertical meridian would be further impaired by distracters appearing on the horizontal meridian); (c) Because precueing the target location would enhance its signal (Carrasco *et al.*, 2000), we also predicted that precueing would make the target more resilient to the competitive effect of distracters, thus reducing the HVA.

#### *Method*

Four observers participated in each task: The same 2 trained observers participated in all 3 tasks; 2 other observers participated in each task (5 out of these 6 observers were naïve). The methods were the same as in Experiment 2, except for the following: (a) No green-gun video-attenuator was used; (b) The Gabor patches, subtending 2 deg of visual angle, were vertical or tilted ( $\pm 15^\circ$ ) right or left at 0.5, 1, 2, 4, 8 and 12 cpd; (c) The tilted target appeared by itself or simultaneously with 1, 3 or 7 vertical distracters at 4.5° eccentricity (Fig. 1); (d) Each observer performed 14400 experimental trials per task (300 per 2 precue types, 6 spatial frequencies, and 4 set sizes).<sup>1</sup>

In the discrimination task, a tilted target was presented in all trials, and observers were asked to report its orientation (right vs. left). In the detection task, half of the trials contained a tilted target, and regardless of its orientation observers had to report whether the target was present or absent. In the localization task, observers pressed a button on a numeric keypad corresponding to the target location.

#### *Results*

A repeated-measures ANOVA (2 precue types  $\times$  6 spatial frequencies  $\times$  8 locations  $\times$  4 set sizes) was conducted for each task (except that, as mentioned above, in the



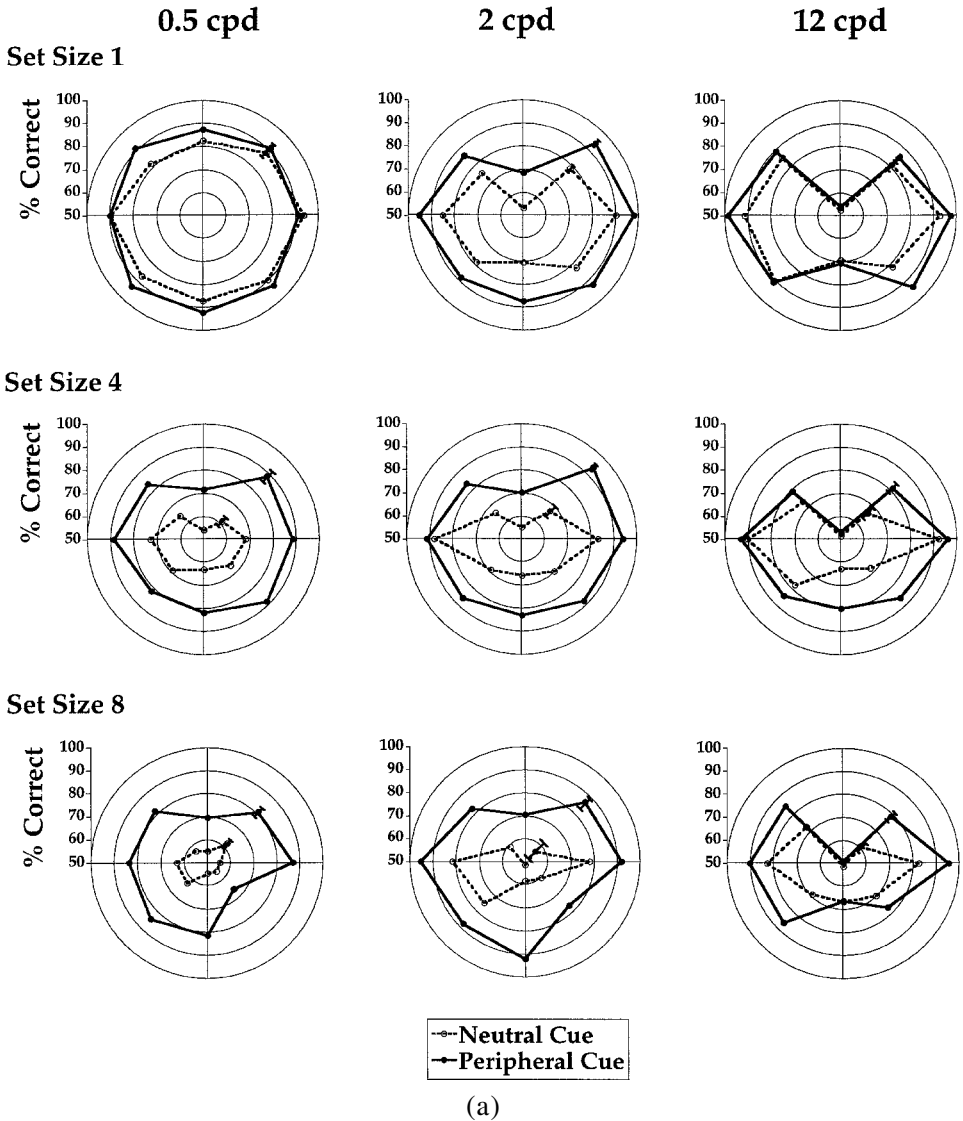
localization task precue was not a factor). Only the neutral blocks were conducted; the peripheral blocks were not conducted because observers could have based their target location response on the cue rather than on the target). Figure 4 illustrates that the precue improved performance but did not interact with location. The HVA emerged in all three tasks; it became more pronounced as frequency and set size increased for discrimination and as either frequency or set size increased for both detection and localization. These results show that both the number of distracters and their location affect performance. The VMA was present in all three tasks (except for one observer in the localization task). It became more pronounced as frequency increased, but, consistent with Rijdsdijk *et al.*'s (1980) findings, in detection the VMA disappeared at 12 cpd — performance was almost as poor at the S as at the N location.

## DISCUSSION

Our results showed significant main effects of precueing and location, but no significant interaction between these two variables; performance fields were not systematically affected by a peripheral precue. A notable characteristic of the performance fields reported here is the nearly ubiquitous poor performance at the North (N) location relative to the others. This was the case for all 12 observers that participated in this study. (The only exception to this pattern was one observer who showed poor performance in the detection and discrimination tasks at the N location but did not show it in the localization task, Exp. 3.) This characteristic was primarily responsible for both the HVA and the VMA. The HVA became more pronounced as spatial frequency, eccentricity and set size increased, and the VMA became more pronounced as spatial frequency (except for localization) and eccentricity increased. This pattern was the same regardless of stimulus orientation and whether a local post-mask was used. In addition, no significant differences emerged in any experiment: (a) Among the 4 other locations (NE, NW, SE and SW); (b) between the upper (NW, N and NE) and lower (SW, S and SE) locations, notwithstanding the VMA; (c) between the right (NE, E and SE) and left (NW, W and SW) locations. Performance fields are also the same when observers perform a discrimination task, either monocularly or binocularly, with Gabor stimuli tilted about the horizontal axis (unpublished data from our lab)<sup>2</sup>.

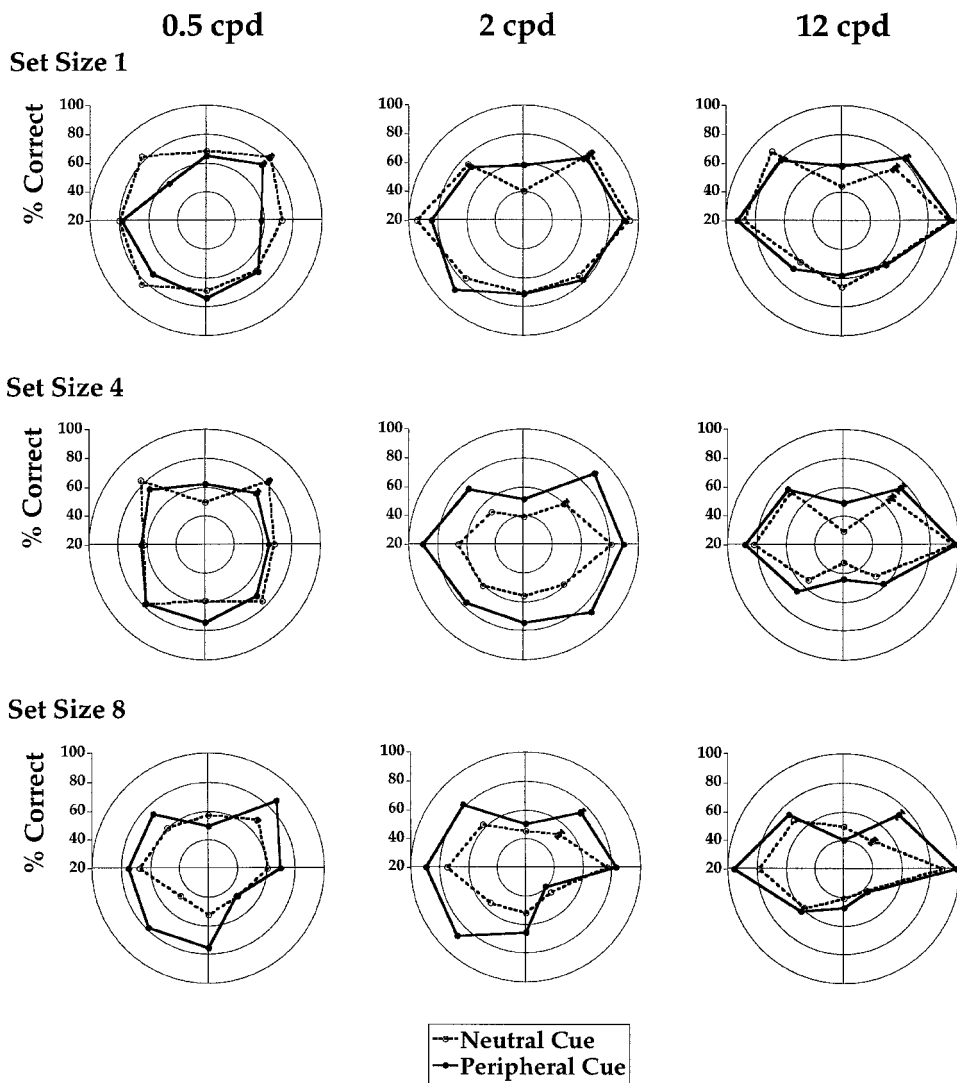
The HVA is consistent with previous psychophysical studies (e.g. Rovamo and Virsu, 1979; Rijdsdijk *et al.*, 1980; Regan and Beverley, 1983; Kröse and Julesz, 1989; Nazir, 1992; Carrasco and Frieder, 1997; Mackeben, 1999; Yeshurun and Carrasco, 1999). Anatomical and physiological research in macaque monkeys provide a possible neural correlate: A lower density of ganglion cells (Perry and Cowey, 1985; Curcio and Allen, 1990) and a faster decline of cone density with increasing distance from the fovea (Curcio *et al.*, 1987) along the vertical than horizontal meridian. Moreover, evidence of such an HVA exists in the LGN

## Discrimination (set size)



**Figure 4.** Performance fields (polar plots of accuracy as a function of location) for sampled spatial frequencies and set sizes (low, intermediate and high) used in Exp. 3 for (a) discrimination, (b) detection, and (c) localization tasks. The data are an average of the 4 observers in each task. The upper panel illustrates set size 1 (target alone), the middle panel set size 4 and the lower panel set size 8. Note that plot origins differ by task: (a) discrimination = 50%; (b) detection = 20% (target-present trials only); (c) localization = 0%, and the outer limits represent 100% correct performance. There were approximately 150 trials per data point ( $\pm 1\%$ ). Note that there was no systematic effect of cueing condition on location. [Solid line = peripheral precue; dashed line = neutral precue for all figures; error bars correspond to the average  $\pm 1$  s.e. for each condition.]

## Detection (set size)



(b)

Figure 4. (Continued).

(Connolly and Van Essen, 1984) and V1 (Van Essen *et al.*, 1984; Tootell *et al.*, 1988).

The VMA is also consistent with an advantage of the lower visual field in a variety of psychophysical tasks (Rijsdijk *et al.* 1980; Edgar and Smith, 1990; Previc, 1990; Nazir, 1992; Rubin *et al.*, 1996). Indeed, it would be interesting to assess whether these reported hemifield asymmetries are due mainly to the poor performance at the

## Localization (set size)

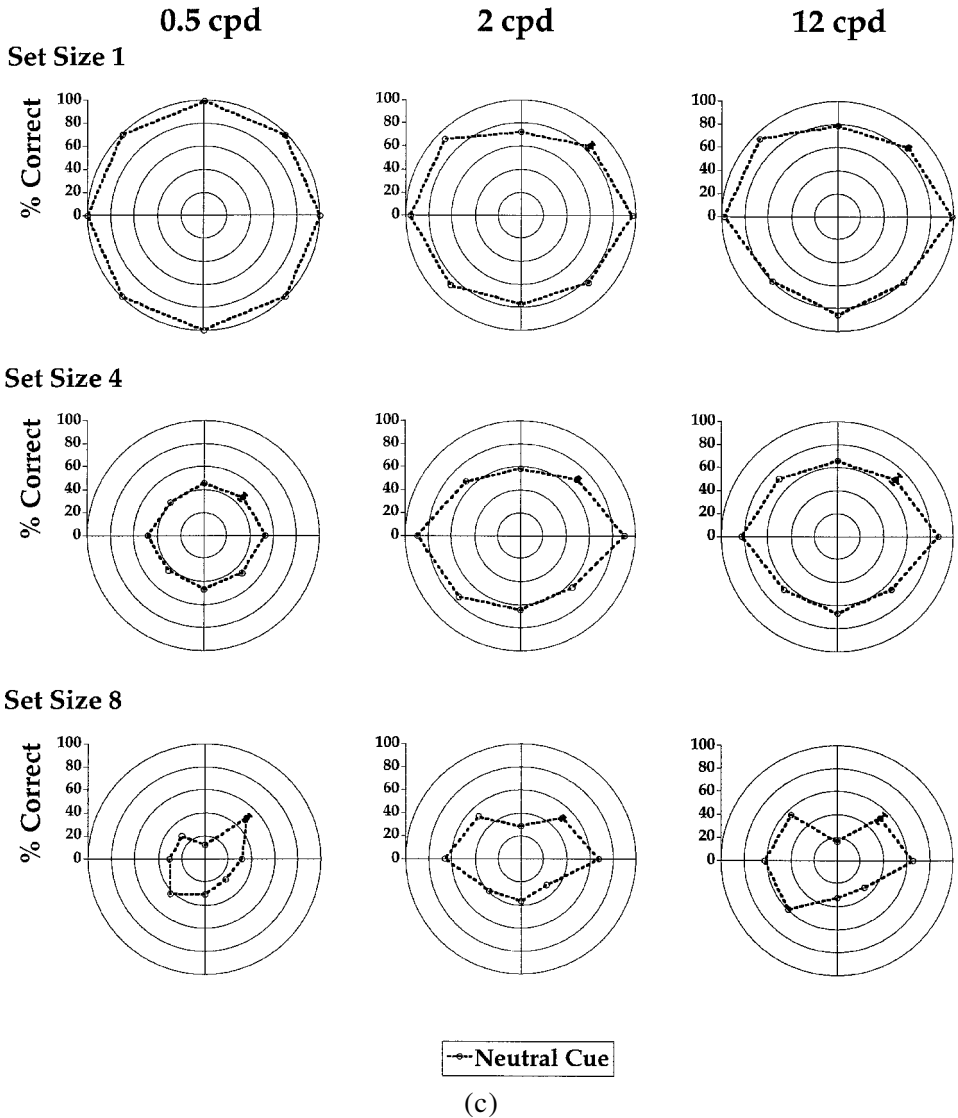


Figure 4. (Continued).

North location. Possible neural correlates for the VMA include the greater cone and ganglion cell densities in the lower than upper visual field (Perry and Cowey, 1985), and the fact that slightly more area is devoted to the inferior than superior visual field in the LGN (Connolly and Van Essen, 1984) and V1 (Van Essen *et al.*, 1984; Tootell *et al.*, 1988).

To summarize, by systematically manipulating both transient attention and visual factors, we found that the attentional effect did not vary as a function of location.<sup>3</sup> That is, the attentional manipulation did not affect the shape of the performance fields. As has been established in visual search (Carrasco *et al.*, 1995, 1998b; Geisler and Chou, 1995; Vergheze and Nakayama, 1994; Carrasco and Frieder, 1997), before invoking an attentional explanation it is important to rule out the more parsimonious explanation that performance is determined by visual constraints. When we compared performance fields in conditions that did or did not invoke transient attention, there was no difference in the pattern of performance. We conclude, thus, that performance fields are determined by visual, not transient covert attentional, constraints. Whereas some have attributed performance fields to sustained attention (He *et al.*, 1996; Mackeben, 1999; Altpeter *et al.*, 2000), our study indicates that first visual constraints need to be ruled out *experimentally*.

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### NOTES

1. There were 7200 trials for the localization task. (Only the neutral precue was used since precueing target location resulted in perfect performance. In addition, observers could have based their target location response on the cue rather than on the target.)
2. We repeated the present experiments under fully light-adapted conditions to rule out a rod basis for the reported performance asymmetries. We obtained the same performance fields (unpublished data).
3. Note that when performance was very high for the E & W locations, attention could not have further improved performance.

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