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Covert attention affects the psychometric function of contrast sensitivity

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Abstract

We examined the effect of transient covert attention on the psychometric function for contrast sensitivity in an orientation discrimination task when the target was presented alone in the absence of distracters and visual masks. Transient covert attention decreased both the threshold (consistent with a contrast gain mechanism) and, less consistently, the slope of the psychometric function. We assessed performance at 8 equidistant locations (4.5° eccentricity) and found that threshold and slope depended on target location—both were higher on the vertical than the horizontal meridian, particularly directly above fixation. All effects were robust across a range of spatial frequencies, and the visual field asymmetries increased with spatial frequency. Notwithstanding the dependence of the psychometric function on target location, attention improved performance to a similar extent across the visual field.

Given that, in this study, we excluded all sources of external noise, and that we showed experimentally that spatial uncertainty cannot explain the present results, we conclude that the observed attentional benefit is consistent with signal enhancement.

Keywords: Transient covert attention; Discrimination; Spatial frequency; Performance fields; Asymmetry

1. Introduction

The aim of this study was fourfold: (1) To investigate the effect of covert attention on the psychometric function of contrast sensitivity over a wide range of spatial frequencies when targets were presented alone; (2) to assess the mechanisms by which attention can affect performance; (3) to characterize the psychometric function across the visual field; and (4) to explore whether the effect of attention on the psychometric function interacted with stimulus location in the visual field.

1.1. Attention improves performance

Covert spatial attention allows us to grant priority in processing of visual information at a particular location, without eye movements to that location (Posner, 1980). It is one mechanism by which the visual system can overcome the overload of information present in the visual scene. Many psychophysical studies have now shown that covert attention (hereafter referred to simply as "attention") affects early visual processing, such as contrast sensitivity (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lee, Itti, Koch, & Braun, 1999; Lee, Koch, & Braun, 1997; Lu & Dosher, 1998, 2000) and spatial resolution (Talgar & Carrasco, in press; Tsal & Shalev, 1996; Yeshurun & Carrasco, 1998, 1999, 2000). Attention also improves observers' performance on hyperacuity (Morgan, Ward, & Castet, 1998; Shiu & Pashler, 1995; Yeshurun & Carrasco, 1999), visual search (Carrasco & McElree, 2001; Carrasco & Yeshurun, 1998; Yantis & Jonides, 1984), and orientation detection, discrimination and localization (Baldassi & Burr, 2000; Cameron, Tai, & Carrasco, 2000; Carrasco et al., 2000; Morgan et al., 1998) tasks. In addition, attention enhances the motion (Chaudhuri, 1990; Lankheet & Verstraten, 1995) and tilt (e.g., Spivey & Spirn, 2000) after effects.

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The notion that attention affects early visual processing is also supported by neurophysiological studies. Single unit recordings in awake behaving macaque monkeys have shown that attention can increase the response of neurons as early as V1 (e.g., Gilbert, Ito, Kapadia, & Westheimer, 2000; Ito & Gilbert, 1999; Motter, 1993; Reynolds, Pasternak, & Desimone, 2000; Roelfsema, Lamme, & Spekreijse, 1998). A debate exists over whether these modulations are a result of response gain—increase in overall response of neurons (e.g., Reynolds et al., 2000) or contrast gain—shift in the neuronal response to lower contrast stimuli (e.g., McAdams & Maunsell, 1999; Treue, 2000). Functional magnetic resonance imaging studies in humans have also revealed a modulation of activity due to attention in many regions in visual cortex, including V1 (e.g., Brefczynski & DeYoe, 1999; Kastner, De Weerd, Desimone, & Ungerleider, 1998, 1999; Ress, Backus, & Heeger, 2000; Somers, Dale, Seiffert, & Tootell, 1999).

Attention can be allocated to a given location either voluntarily, according to goals ("sustained attention") or involuntarily, in a reflexive manner, to a stimulus that appears suddenly in the visual field ("transient attention"). Several authors have characterized these sustained and transient components of attention (e.g., Cheal & Lyon, 1991; Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Yantis, 1996). Studies assessing the effect of attention on visual processing have manipulated attention in a conceptually-driven way by using either instructions or central precues ("sustained attention") or in a stimulus-driven way by using peripheral precues ("transient attention"). The effect of attention on contrast threshold has been well documented (e.g., Carrasco et al., 2000; Foley & Schwartz, 1998; Lee et al., 1999, 1997; Lu & Dosher, 1998, 2000; Solomon, Lavie, & Morgan, 1997). These studies have employed an array of methods for manipulating attention. For instance, Lu and Dosher (1998) used a central precue, Foley and Schwartz (1998) used a precue that is not easily classified because of the location at which it appeared (mid-way between fixation point and target), Lee et al. (1999, 1997) used a concurrent task (i.e. observers perform two tasks simultaneously), [1] and Carrasco et al. (2000) used a peripheral precue. The transient component of attention is considered to operate at an earlier stage of visual processing than the sustained component (e.g., Nakayama & Mackeben, 1989). Given that we are interested in the effect of attention on performance across the psychometric function, and on early visual processing, in the present study we manipulated transient attention.

A previous study has reported that transient attention increases contrast sensitivity across the contrast sensitivity function when the target is presented alone in the absence of any distracting information (Carrasco et al., 2000). Like most psychophysical studies on attention, that study examined either threshold or supra-threshold judgements (e.g., Lee et al., 1999, 1997; Lu & Dosher, 1998; Solomon et al., 1997). Very few studies have examined the relative effect of attention across a range of performance levels, from sub-to supra-threshold. In the studies in which performance level was manipulated, distracters were always presented simultaneously with the target, which were low spatial frequency Gabor patches of about 1 cpd, or pseudo-characters (Dosher & Lu, 2000, 2001; Lu & Dosher, 2000). To our knowledge, no study has examined the relative effect of attention across the psychometric function when targets are presented alone.

Attention could affect the psychometric function of contrast sensitivity in a number of ways (see Fig. 1). For instance: (a) It could simply shift the curve to the left with no effect on the slope. (b) It could increase or decrease the slope of the function without shifting the curve. (c) It could both shift the curve and change the slope. A leftward shift in the psychometric function reflects a decrease in threshold that indicates that the observer needs less contrast to perform the task when attention is directed to the target location. The slope, on the other hand, reflects the system's dynamic range for contrast. A steeper slope indicates a more restricted dynamic range.

Our primary goal in this study was to characterize the effect of attention across the psychometric function of contrast sensitivity. Because the visual system's sensitivity to contrast is subserved by several parallel "channels" which are limited in the range of spatial frequencies and orientations they process (e.g., DeValois & DeValois, 1988), we tested a range of spatial frequencies. This is the first study to measure the effect of attention on the psychometric function across the contrast sensitivity function when the target is presented alone.

1.2. Mechanisms of attention

Several mechanisms have been proposed to account for improvements in performance with attention—signal enhancement (e.g., Carrasco et al., 2000; Lu & Dosher, 1998), distracter exclusion (e.g., Dosher & Lu, 2000), and uncertainty reduction (e.g., Eckstein, 1998; Palmer, 1994). The way in which attention is manipulated may affect the mechanism of attention involved. Lu and Dosher (2000) compared central and peripheral precues and found stimulus enhancement (increase in the sensory representation) only when peripheral precues were used. Moreover, they showed that a peripheral precue

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[1] Note that concurrent tasks are complex and it is difficult to isolate the source of an observed processing deficit (McElree & Carrasco, 1999; Pashler, 1998; Sperling & Dosher, 1986).

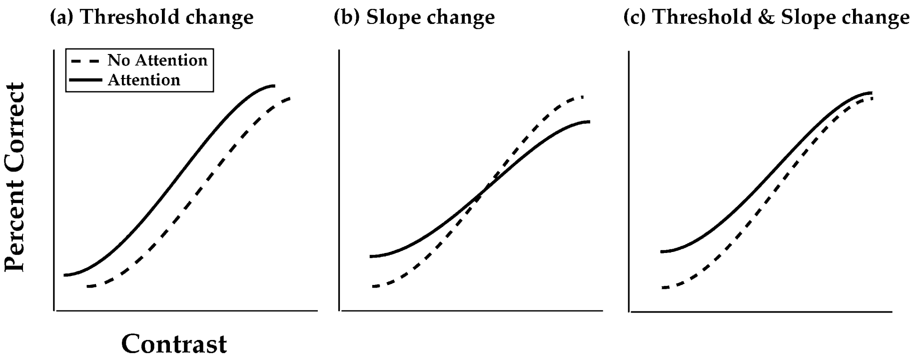

Fig. 1. Possible effects of attention on the psychometric function. (a) A pure shift in the psychometric function, to the left. This reflects a decrease in threshold without a concomitant change in slope. (b) A pure decrease in the slope of the psychometric function with no concomitant shift. The shallower slope in the attentional condition reflects an increase in the range of contrasts over which the system is sensitive. (c) Both a shift of the curve to the left and a decrease in the slope of the psychometric function.

affected performance across a range of external noise levels whereas central precues did so only at high levels of noise. The authors suggest that at high noise levels attention enhances the signal and reduces the effect of external noise, but at low noise levels there is only signal enhancement. We hypothesized that signal enhancement would be responsible for improved performance across the psychometric function when targets were presented alone, a low noise condition.

To explore the effects of attention due to signal enhancement, it is necessary to ensure that an attentional benefit occurs under conditions that exclude all variables predicted by the external noise reduction model to be responsible for the attentional effect. Presenting a suprathreshold target alone, without distracters and local or multiple masks, and eliminating spatial uncertainty, has allowed us to conclude that the effects of transient attention on contrast sensitivity (Carrasco et al., 2000) and spatial resolution (Carrasco, Williams, & Yeshurun, 2001b) reflect signal enhancement.

One issue to consider when targets are presented alone at contrast levels below discrimination threshold, is that of spatial uncertainty. According to noise-limited models, performance decreases as uncertainty and distracters increase, because the noise they introduce can be confused with the target signal (e.g., Eckstein, 1998; Foley & Schwartz, 1998; Palmer, 1994). Both uncertainty reduction and signal enhancement models predict that spatial precueing would lower the threshold and make the psychometric function shallower (as shown in Fig. 1(c)). Uncertainty models (e.g., Eckstein, 1998; Palmer, Verghese, & Pavel, 2000) predict that the precueing benefit would be more pronounced when observers' overall performance is low because the uncertainty of target location produces a more noticeable degradation at low than at high performance levels (Pelli, 1985). Likewise, according to signal enhancement models of attention (e.g., Carrasco et al., 2000; Lu & Dosher, 1998), increasing the signal would result in a larger signal-to-noise ratio for low contrast signals. In two control experiments we assessed the extent to which uncertainty could account for the observed precue effect. We measured performance on a fine discrimination task that required higher contrast stimuli (thus reducing uncertainty) and we assessed uncertainty directly by performing a localization task. The second goal of this study was to assess the mechanisms underlying changes in the psychometric function of contrast sensitivity due to attention.

1.3. Performance depends on visual field location

We have recently reported that performance on an orientation discrimination task depends on the location of the target in the visual field (Carrasco, Talgar, & Cameron, 2001a). Performance fields (percent correct as a function of location in the visual field) show a characteristic pattern: performance is better (at a range of eccentricities and set sizes) on the horizontal than the vertical meridian and it is the worst when the target is presented directly above fixation (denoted "north" or "N" location). These measurements were made when overall performance was at threshold, defined as approximately 80% correct on an orientation detection, discrimination or localization task. Overall, these asymmetries become more pronounced as spatial frequency, eccentricity and the number of distracters increase. These patterns of performance were observed in all three tasks and under several conditions (e.g., different stimulus orientations, monocular and binocular viewing conditions). A third goal of the present study was to establish how these performance fields vary as a function of contrast. To investigate this question we manipulated target contrast to measure overall performance (averaged across all eight locations examined previously) from chance to asymptote and assessed performance at each location (Fig. 2). We expected uniform

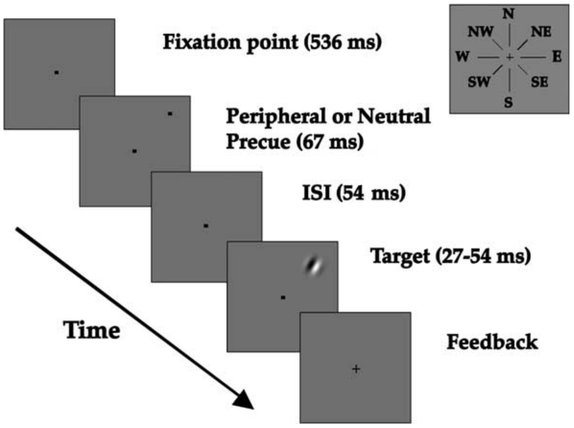

Fig. 2. A schematic representation of a typical trial. Each trial began with a cross in the center of the screen that the observers were instructed to fixate. The fixation was followed by a precue (small black square). In the neutral condition the precue appeared at the center of the screen; in the peripheral condition, it appeared just beyond the location of the target (1.3° from target center). The peripheral precue was 100% valid in terms of location. Observers received visual feedback after each trial, and error rate at the end of each block of trials. Targets appeared randomly at one of eight locations. We used the compass (shown in the upper right of the figure) to refer to specific locations in the display.

performance across the visual field at chance and asymptotic levels, and that the asymmetries would be apparent within the dynamic range of the psychometric function.

1.4. Interaction of attention and visual field location

It has been argued that attention improves performance differentially across the visual field. For example, better performance in the lower than the upper half of the visual field in search and tracking tasks has been attributed to higher attentional resolution (He, Cavanagh, & Intrilligator, 1996). Recently, better performance on the horizontal than the vertical meridian in a letter identification task (Mackeben, 1999) and better performance in the upper than the lower visual field in a Snellen acuity task (in 50% of the observers tested; Altpeter, Mackeben, & Trauzettel-Klosinski, 2000) have been attributed to effects of sustained attention. Our previous studies (Carrasco et al., 2001a; Talgar & Carrasco, in press), however, did not support these conclusions. We found that attention improved overall performance and that this effect did not interact with target location. That is, we found no evidence that attention systematically improves performance more at particular regions in the visual field for threshold tasks. Our fourth goal in the present study was to address whether transient covert attention affects performance fields differentially across the psychometric function.

2. Experiment

In short, in this study we examined the effect of transient attention on the psychometric function of contrast sensitivity for targets presented alone, as well as the underlying performance fields, at a range of spatial frequencies. To assess the effect of transient attention in any given task it is necessary to compare performance when the target follows a peripheral precue and a neutral precue. In this study, we assessed the effect of attention by comparing the stimulus contrast necessary for observers to perform an orientation discrimination task under neutral and peripheral precue conditions (Carrasco et al., 2000, 2001a; Nachmias, 1967) at performance levels ranging from chance to asymptote. Because the peripheral precue always indicated target location and appeared equally often adjacent to a Gabor of either orientation, it did not associate a higher probability with one of the responses and observers could not rely on its presence to respond correctly (e.g., Carrasco et al., 2000, 2001a,b; Carrasco & Yeshurun, 1998; Yeshurun & Carrasco, 1998, 1999, 2000).

Several authors have used a central–neutral cue to indicate the target onset without conveying information regarding the target location (e.g., Carrasco et al., 2000, 2001a,b; Jonides, 1981; Nakayama & Mackeben, 1989; Yeshurun & Carrasco, 1998). It has been suggested that this central–neutral cue may reduce the degree of attention spread, by attracting attention to its location, away from the peripheral locations where the target is presented (e.g., Pashler, 1998). We have ruled out the possibility that the attentional benefits we have found could be due to a narrowing of attention caused by the central-neutral cue. In an acuity task, we used a spread-neutral cue designed to spread attention throughout the display and found that the performance difference between the peripheral precue and the spread-neutral cue was at least as pronounced as the difference between the peripheral cue and the central-neutral cue (Carrasco et al., 2001b). Similarly in texture segmentation, we have found pronounced attentional effects when comparing performance with a peripheral precue and a neutral cue designed to spread attention across the display (Talgar & Carrasco, in press; Yeshurun & Carrasco, 1998, 2000).

3. Methods

3.1. Observers

Three observers participated in this study. Two were authors (LC and JT) who were trained psychophysical observers, and one was an undergraduate research assistant (JH) who was untrained and naïve to the purposes of the experiment. All observers had corrected-to-normal visual acuity.

3.2. Stimuli and design

Stimuli were generated using HIPS (Landy, Cohen, & Sperling, 1984) and presented in Vscope^{TM} (Enns & Rensink, 1992) on a Macintosh G3 computer with a 20 in. gamma-corrected color monitor. The refresh rate of the monitor was 13.4 ms and the mean luminance was 47 cd/m^2. Observers sat in a dark room with their head stabilized by a chin rest. Viewing was binocular at 114 cm. Observers performed an orientation discrimination task with visual feedback. The target was a 2° Gabor patch (cosine-wave grating in a Gaussian vignette) of one of 4 spatial frequencies (1, 2, 4, or 8 cpd). The target was tilted 15° clockwise or counterclockwise and was present on every trial. The task of the observer was to report (with a key-press) whether the target was tilted to the left or right of vertical. The target was presented randomly at one of eight equally spaced locations on an imaginary circle of 4.5° eccentricity (see Fig. 2). Targets were preceded by either a neutral or peripheral precue (a $0.13^\circ \times 0.13^\circ$ black square). In the neutral precue condition, the precue replaced the fixation (an “x” with the same extent as the precue) in the center of the screen so that it indicated the time at which the upcoming target would appear, but not its location. In the peripheral precue condition, the precue was presented at 5.8° eccentricity, 1.3° beyond the center of the upcoming target so that it indicated both the time and the location at which the upcoming target would appear.

3.3. Procedure

On each trial, a fixation cross appeared at the center of the computer monitor for 536 ms. The fixation was followed by a precue which remained present for 67 ms. There was a 54 ms interval between the precue and the target. No mask followed the stimulus display. The stimulus onset asynchrony (SOA) of 121 ms was deliberately chosen to maximize the peripheral precueing effect (Cheal & Lyon, 1991; Jonides, 1981; Nakayama & Mackeben, 1989). In addition, given that it takes about 250 ms for a target directed saccade to be initiated (e.g., Carpenter, 1988; Mayfrank, Kimmig, & Fischer, 1987) this SOA eliminated the possibility of saccadic eye movements to the target.

3.3.1. Baseline performance

We first established the contrasts required to measure the full extent of the psychometric function (six or seven levels of contrast from chance to asymptote) under the neutral precue condition, for each observer, at each spatial frequency. Stimulus duration ranged from 27–54 ms which is well within the integration time of the visual system (see Table 1).

3.3.2. Experimental Trials

We used the method of constant stimuli to measure performance on the orientation discrimination task described above as a function of target contrast in neutral and peripheral precue conditions. Each observer completed 400 experimental trials for each of the two precue

Table 1
Stimulus parameters, threshold, slope and chi-square values of the fits and significance levels (nested hypothesis test) for each subject in each spatial frequency condition

	LC				JH				JT			
	1 cpd*	2 cpd	4 cpd	8 cpd	1 cpd*	2 cpd	4 cpd	8 cpd	1 cpd*	2 cpd	4 cpd	8 cpd
Stimulus Parameters												
Contrast (%)	3–8	1–6	1–6	5–10, 12	4–10	2–7	2–7	6–12	3–8	1–6	1–6	3–8, 10
Duration (ms)	27	40	54	54	27	40	54	54	27	40	54	54
Neutral												
Threshold (alpha)	5.99	3.82	3.76	9.03	7.45	4.37	4.47	9.65	5.51	3.60	3.47	7.60
Slope (beta)	3.92	3.71	3.40	3.83	2.45	3.22	3.22	3.74	3.24	2.58	2.59	4.09
Chi-square	2.73	10.35	22.60	34.15	10.96	42.80	27.50	14.80	20.48	44.47	19.40	19.91
Peripheral												
Threshold (alpha)	5.70	3.48	3.29	8.05	6.65	3.82	3.57	8.85	5.06	3.03	3.18	7.32
Slope (beta)	3.46	3.41	2.66	3.77	2.25	2.35	2.46	3.40	2.85	2.18	2.03	3.64
Chi-square	17.27	13.76	6.90	19.22	20.87	54.00	23.10	11.50	18.44	12.68	12.40	13.68
Precue Effect												
Threshold (p<)	0.052	0.001	0.001	0.001	0.001	0.003	0.001	0.001	0.003	0.001	0.286	0.111
Slope (p<)	0.216	0.043	0.011	0.841	0.393	0.001	0.003	0.332	0.162	0.07	0.009	0.229

* 1 cpd = 57 cm viewing distance.

conditions at each of six or seven contrast levels for all four spatial frequencies. The spatial frequency conditions were blocked, as we did not want to introduce spatial frequency uncertainty. The precue types and contrast levels were both randomized within each spatial frequency condition. For each spatial frequency, observers completed 5 experimental sessions (lasting about 1 h) of 10 blocks of 96 or 112 trials (six or seven levels of contrast, respectively); there were eight practice trials at the beginning of each session.

4. Results

4.1. Effect of attention on the psychometric function

Fig. 3 (a-l) shows the psychometric functions (percent correct as a function of contrast) in neutral and peripheral precue conditions for each of the three individual observers at the four spatial frequencies tested. As expected, performance increased as a function of target contrast in both neutral and peripheral precue conditions for all spatial frequencies. The data shown here were fit with separate Quick functions (Quick, 1974) [2] with the only constraints being that chance and asymptote were 50% and 100% respectively. Threshold (α) was taken at 82%. To determine whether there was a change in threshold (α) and a change in slope (β) of the psychometric functions under the peripheral precue condition, we used a nested hypothesis test (Mood, Graybill, & Boes, 1974). We calculated the chi-square value for three conditions: (1) neutral and peripheral precue conditions fit with a single function (i.e. α and β fixed), (2) precue conditions fit with β fixed but α free to vary, and (3) precue conditions fit with both α and β free to vary. In order to assess whether thresholds were different in the neutral and peripheral precue conditions, we compared the chi-square values of condition (1) α and β fixed to (2) α free, β fixed (see Hoel, Port, & Stone, 1971). In order to assess whether there was a slope difference we compared the chi-square values of condition (2) α free, β fixed to (3) α and β free.

We made the above comparisons for each observer in each spatial frequency condition, which resulted in a total of 24 comparisons. Given that such repeated testing increases the chance of a significant effect, we applied a Bonferroni correction (the corrected chi-square value needed for a comparison to be statistically significant; see Neter & Wasserman, 1974). We chose the 0.05 significance level and divided it by the number of comparisons (24)—this yielded a significance level of 0.002.

It is clear that performance was typically higher in the peripheral than in the neutral precue condition. [3] Table 1 shows threshold, slope, and chi-square values (measure of the goodness of fit, see Hoel et al., 1971), as well as the statistical comparisons for each observer in each spatial frequency condition. In general, thresholds were lower in the peripheral precue condition (leftward shift in the psychometric function). There were three exceptions (LC 1 cpd and JT 4 & 8 cpd). Two other conditions (JH 2 cpd, JT 1 cpd) just missed the criterion specified by the Bonferroni correction; they would have been significant if considered independently.

In all but one condition (JH 2 cpd) there was no significant decrease in slope in the peripheral precue condition. There was, however, a trend towards more shallow slopes in the peripheral precue condition (e.g., all observers at 4 cpd). Again, these comparisons would have been significant if considered independently.

4.1.1. Subsidiary analyses

4.1.1.1. Reaction time. We examined reaction time as a secondary measure of performance (data not shown). We found that in both neutral and peripheral precue conditions observers almost always responded faster as contrast increased, and reaction times were always faster in the peripheral than in the neutral precue condition across all spatial frequencies. These results indicate that there was no speed accuracy tradeoff.

4.1.1.2. Bias. Although the 2-alternative forced choice procedure that we employed is thought to discourage response bias, we examined observers' responses to ensure that a bias did not confound our results. We computed a chi-square value on frequency of response (tilted left vs. right) for each condition (for each observer at each SF and contrast). We found a significant bias only at the lowest contrast tested. At the lowest contrast, 20% of the comparisons revealed a bias (80% of those cases were a bias to report "tilted to the left" in the peripheral precue condition). Note that the lowest contrast contributed less weight to the Quick fits of the psychometric functions than the contrasts within the dynamic range. The lack of consistent bias throughout the bulk of our data indicates that bias did not confound our results.

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[2] We also fit the data with a cumulative Gaussian function. The fits were indistinguishable from the Quick fits.

[3] We were unable to obtain an effect of precue at 1 cpd because there were too few cycles present in the stimulus. To remedy this problem, we decreased the viewing distance by half (to 57 cm) to double the number of cycles in the 1 cpd stimulus. Therefore, in the 1 cpd condition, both the size (4°) and the eccentricity (9°) were double the other spatial frequency stimuli.

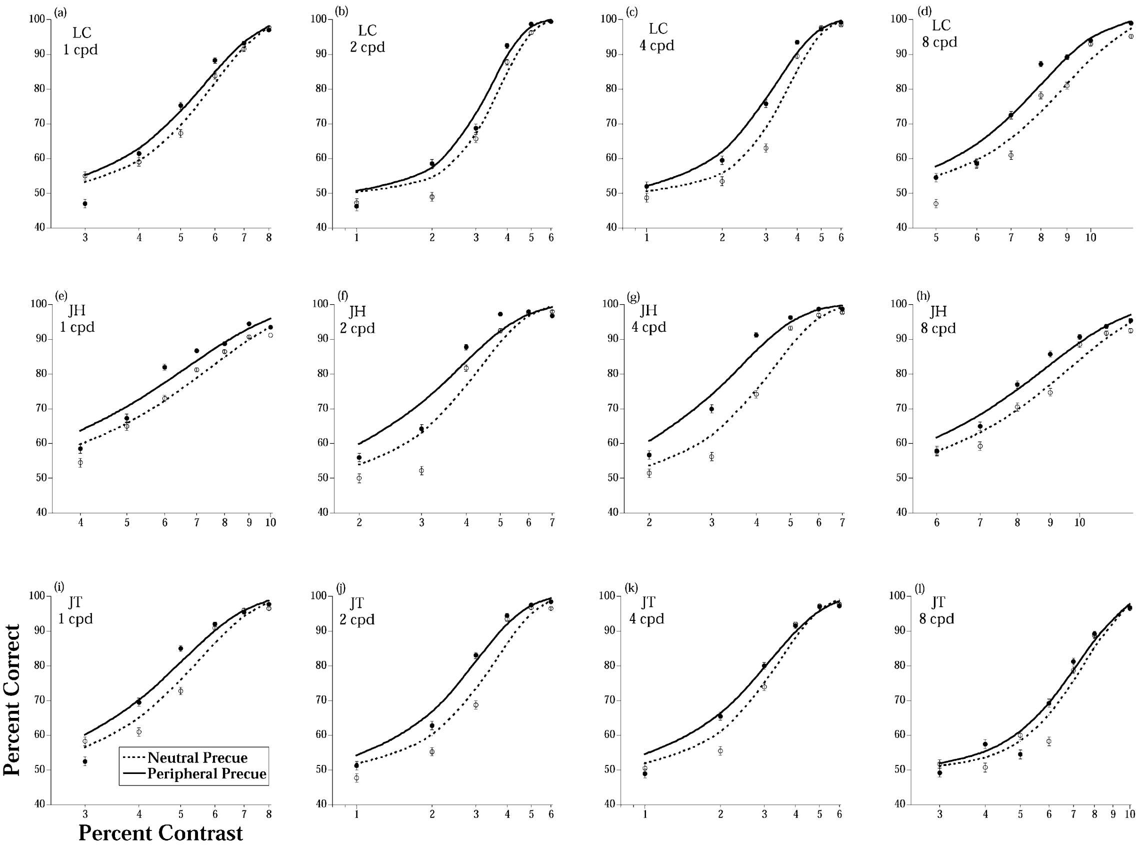

Fig. 3. Psychometric functions (percent correct as a function of target contrast) for each of the four spatial frequency conditions (1–8 cpd) for all three observers. Neutral precue condition is represented with open symbols and dotted lines; peripheral precue condition is represented with filled symbols and solid lines (this is the convention for all graphs in this paper). Attention shifts the psychometric function to the left and, less consistently, decreases the slope for all observers at all SF's.

4.2. Effect of location on performance: contrast

In order to assess how performance across the visual field is affected by target contrast, we analyzed performance fields for each of the target contrast levels used. An example from an individual observer is shown in Fig. 4 (data replotted from Fig. 3(d)). When performance is at chance (see 5% contrast in the neutral condition) there is no systematic pattern, and when performance is at asymptote (e.g., 12% contrast in both precue conditions) it is relatively homogeneous across the visual field. However, at contrasts within the dynamic range of the psychometric function (above chance and below asymptote) a heterogeneity emerges—performance is best for targets on the horizontal meridian, intermediate for targets on the non-cardinal axes, relatively poor for targets on the vertical meridian and the worst for targets at the "N" location. This pattern of results was consistent across the three observers. In addition, consistent with our previous results (Carrasco et al., 2001a), we found that the heterogeneity of the performance field becomes more pronounced as spatial frequency increased. The example in Fig. 4 (a high spatial frequency, 8 cpd) shows a strong heterogeneity in performance fields. [4] We also found (data not shown) that reaction times were typically slower on the vertical than the horizontal meridian, and were the slowest at the "N" location. As noted above, reaction time decreased as contrast increased.

Given that performance is not uniform across the visual field, even at a given eccentricity (e.g., Carrasco et al., 2001a), and that the performance fields are affected by contrast level (Fig. 4), it is quite likely that psychometric functions vary with target location. If this were the case, then psychometric functions like those shown in Fig. 3 would obscure these differences. Consequently, we examined whether attention decreases the threshold and the slope of the psychometric function, at all locations

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[4] In a control experiment in our previous study, we showed that performance was also superior on the horizontal meridian with targets tilted about horizontal (Carrasco et al., 2001a). In our previous study we also ruled out the possibility that the visual field effects were due to the monitor. For example, we found a similar pattern of results when the monitor was tilted on its side (e.g., the top of the monitor was in the "E" location).

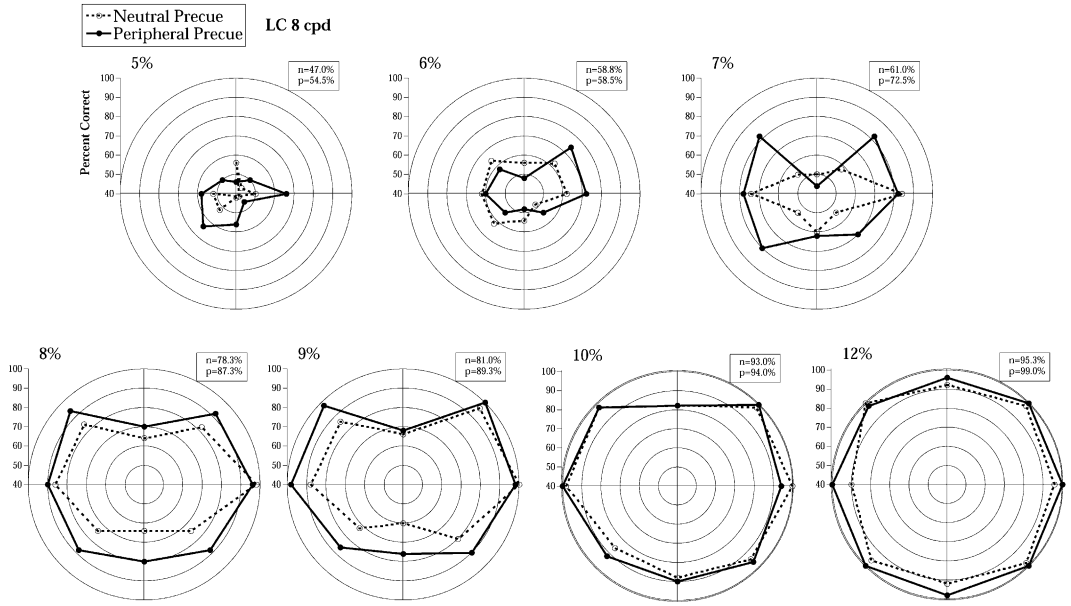

Fig. 4. Sample performance fields (i.e. percent correct as a function of target location) for each contrast level tested (observer LC, 8 cpd). Average percent correct is noted for each contrast level (n: neutral; p: peripheral). Standard error bars lie within the symbols. See text for a description of the results. This example is representative of all four spatial frequency conditions and all three subjects.

tested. We computed psychometric functions for neutral and peripheral precue conditions separately for each of the eight target locations employed in this study.

Fig. 5 shows two examples of such an analysis. In the first example, the data from Fig. 4 are broken down by target location (Fig. 5(a)). It is clear from inspection that the average psychometric function (shown again in the center panel of Fig. 5(a)) is composed of very different psychometric functions that depend on target location. Note that performance is overall better (percent correct was higher at a given level of contrast) for targets on the horizontal meridian (“E” and “W” locations) than it is for targets on the vertical meridian (“N” and “S” locations). Performance is intermediate for targets that lie on non-cardinal meridian (“NW”, “NE”, “SW” and “SE”). A particularly striking illustration of the effect of target location can be seen in a comparison of the psychometric functions for targets presented in the “N” location to the psychometric functions for target presented in the “E” location. For targets at the “N” location, much more contrast is needed for the observer to perform the task above chance (50%). Moreover, for targets at the “N” location performance just barely reaches asymptote at the highest contrast tested (12%), whereas for targets at the “E” location performance approaches asymptote at about 8% contrast, well below the highest contrast tested. Thresholds are much higher for targets at the “N” location than at any other location; e.g., whereas about 7% contrast is required to perform at about 80% correct at the “E” location, about 10% contrast is needed at the “N” location. Whereas there is variability in the effect of attention as a function of location in this particular example, there was no consistent pattern across observers and spatial frequencies. Fig. 5(b) shows data from the naïve observer. Particularly notable in this figure is the strong and consistent effect of the peripheral precue at all locations tested. In addition, performance is better on the horizontal than the vertical meridian and performance is poorest at the “N” location.

An alternative way to illustrate the change in psychometric functions by location is presented in Fig. 6 (data from the third observer, JT). Neutral and peripheral data (top and bottom panels respectively) have been separated and data from targets on the cardinal axes (horizontal and vertical—targets at “N”, “S”, “E” and “W” locations—left panel) have been separated from targets on the non-cardinal axes (obliques—“NW”, “NE”, “SW”, “SE”—right panel). It is clear that for both precue types performance is very similar for targets presented on the non-cardinal axes (see right panel). For targets presented on the cardinal axes, on the other hand, psychometric functions vary greatly as a function of location (see left panel). Both thresholds and slopes were higher for targets on the vertical meridian, particularly at the “N” location. The change in threshold is demonstrated by the shift in the psychometric functions to the right for targets at the “S” and “N” locations relative to the “E” and “W” locations.

Fig. 7(a) summarizes all data and compares thresholds (left panel) and slopes (right panel) for targets on the horizontal and vertical meridian. Given that performance was very similar when targets were presented at the “E” and “W” locations, these data have been

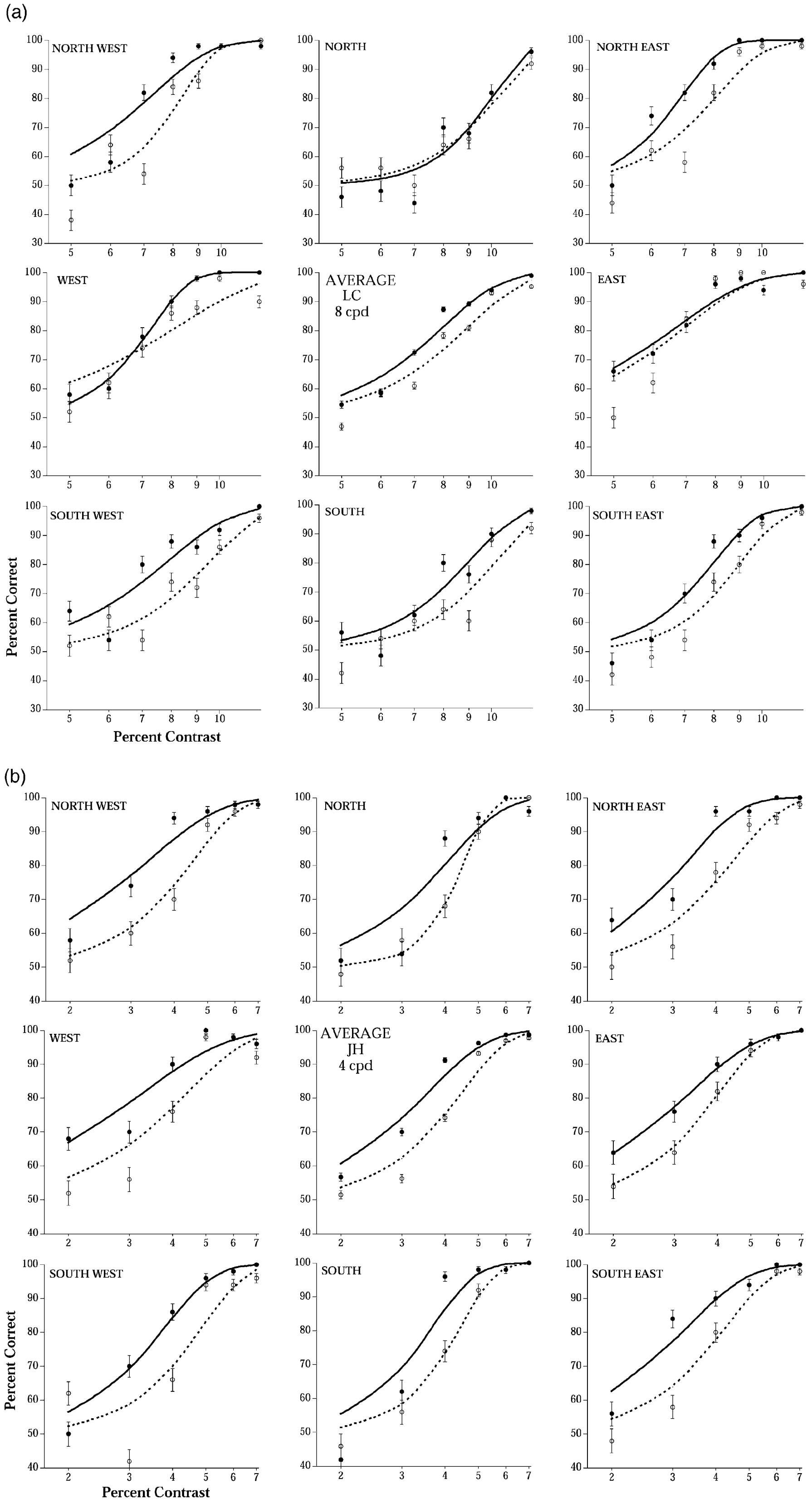

Fig. 5. (a) Psychometric functions for each target location of the neutral and peripheral precue conditions (data from observer LC, 8 cpd). The center graph shows data averaged across visual field location (replotted from Fig. 3(d)). Psychometric functions for each location tested are plotted separately (in positions according to a compass). See text for description of results. (b) Format as in Fig. 5(a) except data are from the naïve observer (JH). Note the strong effect of attention at all target locations.

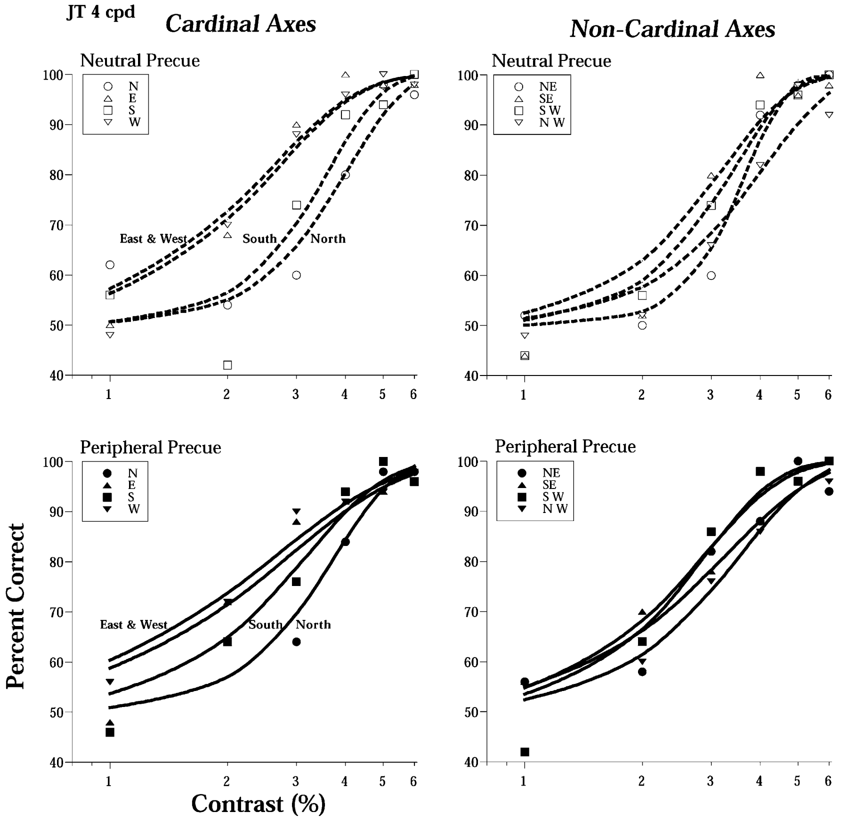

Fig. 6. Psychometric functions by location are shown for cardinal and non-cardinal axes separately (data from observer JT, 4 cpd). Precue types have also been separated. Note that the psychometric functions shift to the left as targets are presented at the "N", "S", and finally "E" and "W" locations. The data from the locations in the oblique axes show relatively uniform performance.

averaged and are plotted against performance when targets were presented in the "N" and "S" locations. Both thresholds and slopes were higher for targets on the vertical ("N" and "S" locations) than the horizontal meridian. This pattern was observed in both neutral (top panel) and peripheral (bottom panel) precue conditions.

Fig. 7(b) illustrates the relatively poor performance for targets in the "N" compared to the "S" location. Thresholds (left panel) and slopes (right panel) are plotted for neutral (top panel) and peripheral (bottom panel) precue conditions. Thresholds and slopes were higher for targets presented in the "N" location compared to the "S" location in both precue conditions.

4.3. *Effect of location on performance: attention*

We have previously argued that attention improves performance similarly at all locations in the visual field (Carrasco et al., 2001a). The current study supports this conclusion. Notwithstanding the differences in psychometric functions at different locations in the visual field, attention did not systematically improve discriminability more at particular locations. This was confirmed in both accuracy and speed analyses. We computed the difference between precue conditions for each threshold and slope. An ANOVA (spatial frequency × location × cue type) indicated that there was no interaction between location and cue type for threshold, nor for slope. That is, no particular location showed a significantly larger effect of attention in either threshold or slope or combined threshold and slope. Fig. 8 shows (a) threshold and (b) slope difference between neutral and peripheral precue conditions for each location tested. Although there was some variability in the attentional effect across the visual field, it is clear that no systematic pattern emerged. [5]

Fig. 9 summarizes the effect of attention on (a) threshold and (b) slope for all psychometric functions, observers, spatial frequencies, and target locations. Data from the neutral and peripheral precue conditions are plotted against each other. If performance were the same under the two precue conditions then the data should fall on the line of slope 1.

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[5] The negative slope difference for targets at the west location was the results of 2 spurious data points (LC 1 and 8 cpd).

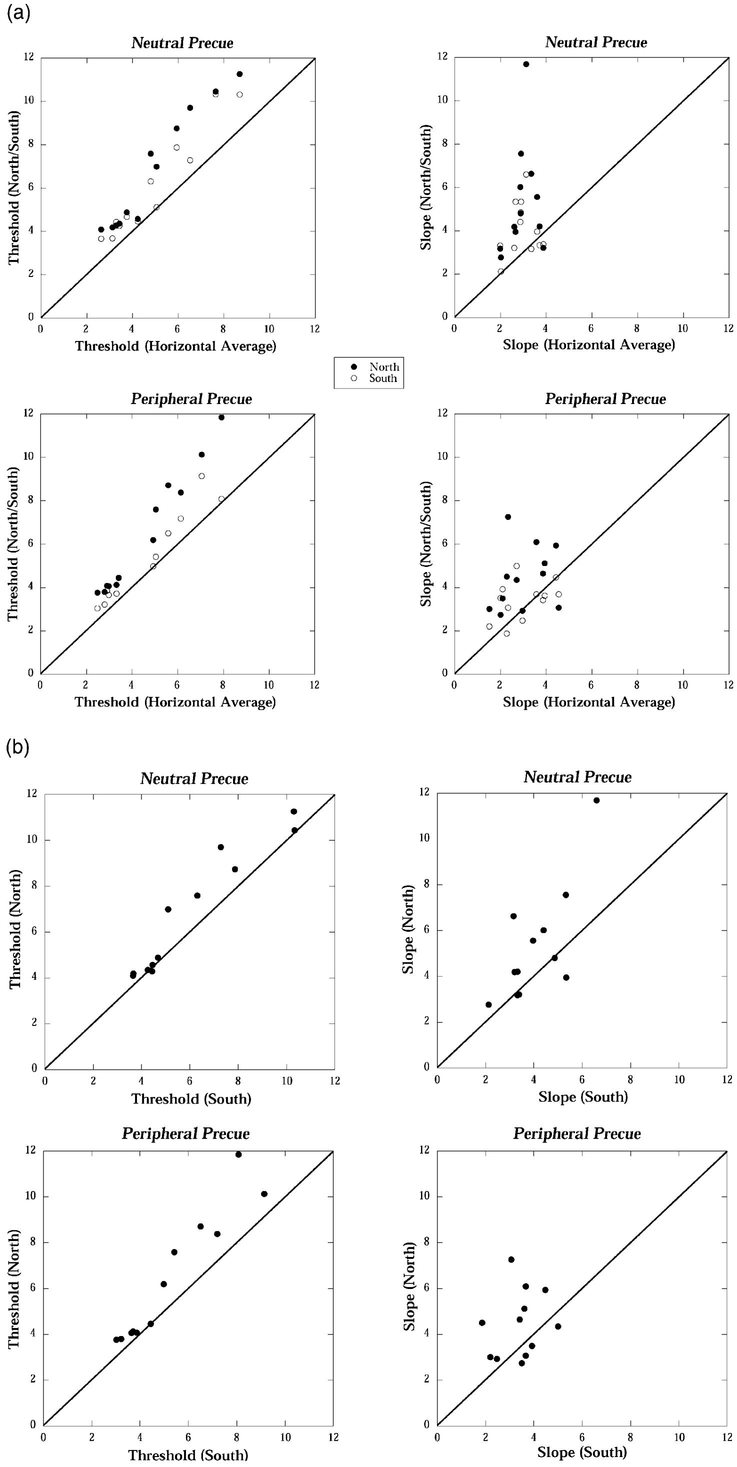

Fig. 7. (a) Threshold (left panel) and slope (right panel) for neutral (upper panel) and peripheral (lower panel). Data from targets on the horizontal meridian (averaged "E" and "W") are plotted against data from targets on the vertical meridian ("N", filled symbols and "S", open symbols). Each data point represents data from one observer at one spatial frequency. Both thresholds and slopes are higher for targets on the vertical meridian. (b) Format as in Fig. 7(a). Data from the "N" and "S" locations are plotted against each other. Each data point represents data from one observer at one spatial frequency. These data indicate that both thresholds and slopes are higher for target at the "N" than the "S" location.

4.3.1. Thresholds

For all spatial frequencies and locations, the vast majority of data points, and all average data, lie below the line of slope 1. This indicates that thresholds were higher in neutral than peripheral precue conditions for all spatial frequencies at all target locations. The average

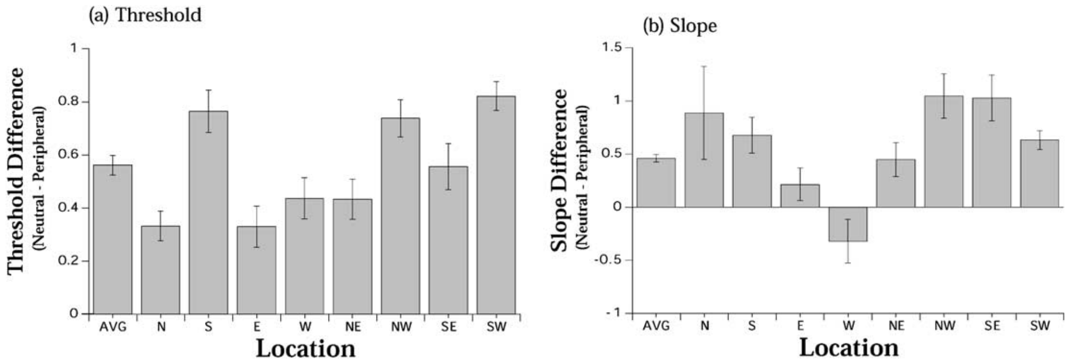

Fig. 8. Attentional difference (neutral – peripheral) in (a) threshold and (b) slope as a function of target location. Data are averaged from the three observers and the four spatial frequencies. Error bars are standard error of the mean. There is no systematic improvement in performance at a particular location in the visual field.

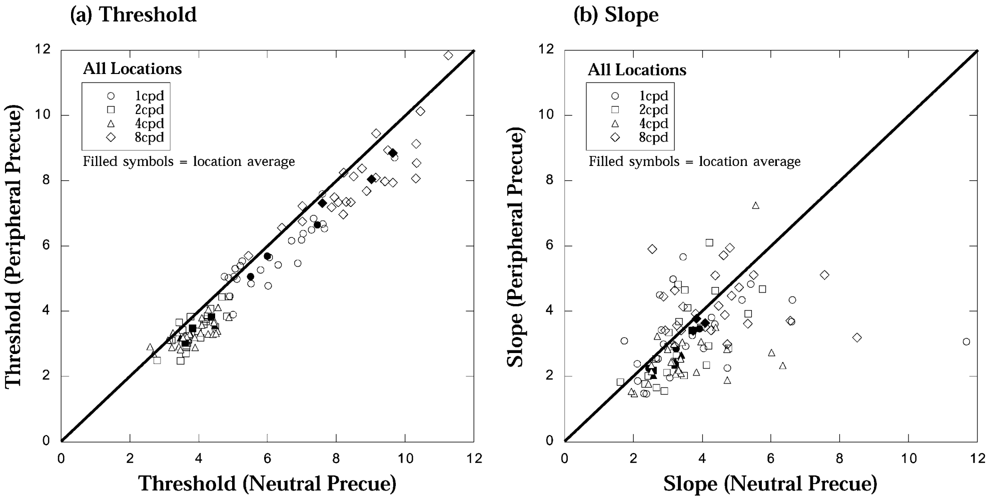

Fig. 9. Summary of effects of attention on (a) threshold and (b) slope. Data from the neutral precue condition are plotted against data from the peripheral precue condition. Each data point represents data from a single observer, spatial frequency and target location. Solid symbols reflect averages across locations. All data lying on the slope of one line indicate no effect of attention. Points below the line indicate relatively higher threshold (a) or slope (b) in the neutral precue condition.

of data across locations (solid symbols) was statistically significant in 7 out of 12 cases, and approached significance in 2 other conditions (see Table 1).

4.3.2. Slopes

Slopes were also typically steeper in the neutral than the Peripheral precue condition—more data points, and all average data, lie below the slope of 1 line. Although the average data reached statistical significance in only one condition, in a third of the cases there was a trend towards more shallow slopes in the peripheral precue condition (see Table 1).

4.4. Control experiments

To investigate the role of spatial uncertainty in the precue effect, we conducted two control experiments. First, we made the discrimination task harder by decreasing the tilt of the targets from ±15° to ±4°. We expected that with a finer orientation difference, observers would require higher stimulus contrasts to perform the discrimination task, and this in turn would diminish spatial uncertainty. Indeed, this is exactly what we found—thresholds were higher for a discrimination task of targets tilted ± 4° (see Fig. 10(a) and (b)). More important for the assessment of spatial uncertainty is the fact that even though the target contrast was higher for the observer to perform the task, a similar attentional effect was observed. [6] This comparison suggests that uncertainty reduction could not account for the results of the previous experiment. In addition, it is critical to

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[6] Given that the control experiment data were collected several months after the original data were collected, we repeated the 15° tilt discrimination task. Even though there were only 40% as many data points in this replication, the data are very similar to the original data (cf. Fig. 3(d)).

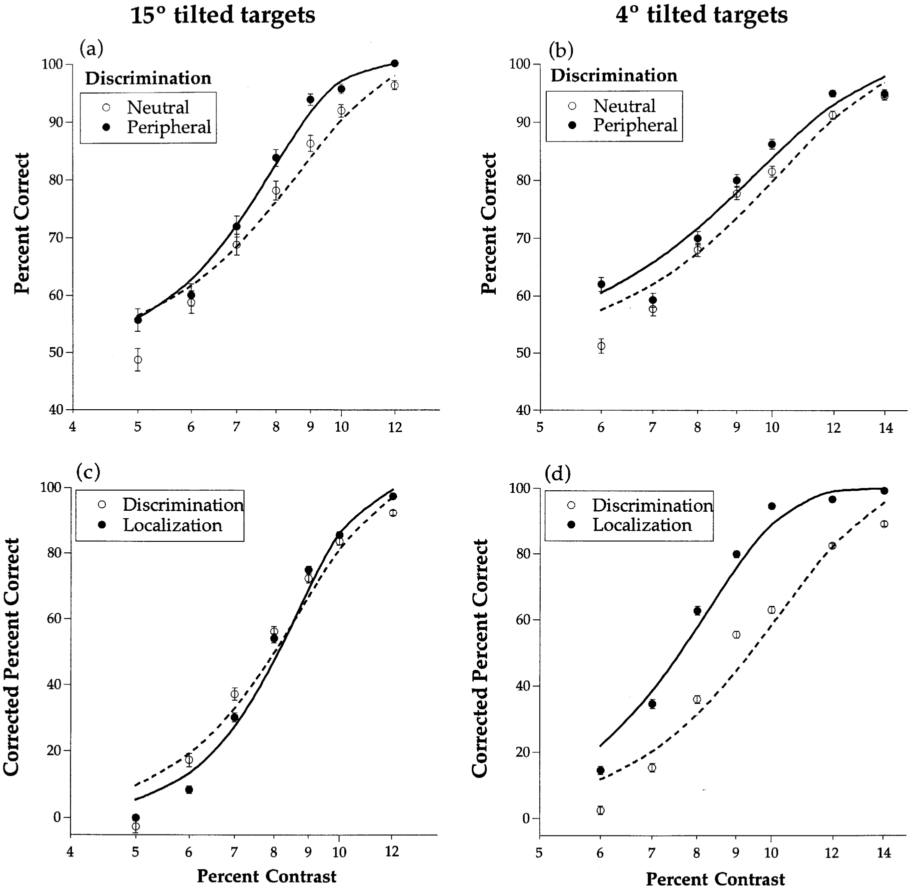

Fig. 10. Results from control experiments. Observer LC, 8 cpd Gabor patch stimuli. (a) Replication of original discrimination task with targets tilted 15°. (b) Fine discrimination task (4° tilt). (c) Comparison of performance on discrimination task (neutral precue condition only) and localization task for 15° tilted targets. (d) Comparison of performance on discrimination task (neutral precue condition only) and localization task for 4° tilted targets. The extent of the effect of attention is comparable in the two discrimination conditions (a and b), even though performance is much higher on the localization task for the fine discrimination targets.

assess whether the precueing benefit still emerges in the discrimination task with stimulus contrasts that enable highly reliable localization. To assess directly the ease with which observers can localize the stimulus, we also performed a localization task for targets tilted ±15° or ±4°. When the targets were tilted ±15° (Fig. 10(c)), localization performance increased as a function of contrast, in a similar manner to the way in which it increased in the discrimination task [7]—discrimination and localization performance were tightly coupled. When the targets were tilted ±4° (Fig. 10(d)), performance on the localization task was much better than performance on the discrimination task. Notwithstanding the superior localization performance on the ±4° task, the attentional effect was comparable between the two tasks. Importantly, at contrasts that yielded perfect localization, there was still an attentional effect in the discrimination task. These control data indicate that spatial uncertainty cannot fully explain the precue effect obtained in this study.

5. Discussion

Our four main goals in the present study were: (1) to characterize the effect of covert attention across the psychometric function of contrast sensitivity for targets presented alone over a wide range of spatial frequencies; (2) to assess the mechanisms by which attention can affect performance; (3) to establish how the performance varies as a function of contrast and location in the visual field; and (4) to address whether transient covert attention affects psychometric function differentially across the visual field.

5.1. The effect of attention on the psychometric function

The results reported here show that attention decreases threshold as indicated by a leftward shift in the psychometric function of contrast sensitivity. The data

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[7] Performance on both tasks was corrected for guessing using the equation PC (corrected) $= (N \times PC$ (observed) $- 1)/(N - 1)$, where N is the number of alternatives (2 for discrimination, 8 for localization).

also indicate that attention may also modestly decrease the slope of the psychometric function.

5.1.1. Threshold

The result that covert attention decreases threshold builds on a growing psychophysical and neurophysiological literature of the effects of attention on early visual processing (e.g., Carrasco et al., 2000; Reynolds et al., 2000; Treue & Martinez Trujillo, 1999; Yeshurun & Carrasco, 1999). Whereas attention has been shown to improve performance on a wide variety of tasks, including contrast sensitivity, this is the first study to characterize the effect of attention across the psychometric function when targets are presented alone. Others have shown an effect of attention at threshold (Carrasco et al., 2000; Foley & Schwartz, 1998; Lee et al., 1999, 1997; Lu & Dosher, 1998; Solomon et al., 1997), but here we have also been able to characterize the effect of attention above and below threshold. Indeed, while the effect of attention was often more pronounced within the dynamic range, there were also effects of attention near chance levels of performance.

5.1.2. Slope

A decrease in the slope of the psychometric function in the peripheral precue condition would mean that performance increased relatively more at low contrasts where performance was near chance in the neutral precue condition. This would suggest that attention could, in addition to making a stimulus "more visible" when it is nearly visible, also make a stimulus "visible" that was not visible. Although our results suggest that attention decreases slope, they are not conclusive.

If a low contrast stimulus elicits chance performance, then the presence of a peripheral precue could serve two functions. It could decrease spatial uncertainty and/or boost the representation of the signal (i.e. signal enhancement). At higher contrast levels the peripheral precue cannot decrease uncertainty (because spatial uncertainty is already minimal given the visibility of the target), then effects at that level would be attributed to signal enhancement. Therefore, if both mechanisms (spatial uncertainty reduction and signal enhancement) were implicated, then a larger effect would be expected at low contrast.

There are some reasons why we may not have observed a robust decrease in slope. First, given that Quick fits of the psychometric functions weight the lowest contrast less than the contrasts within the dynamic range, the slope estimates for the peripheral precue may have been overestimated. Second and more importantly, the inherent variability of slope estimates makes it difficult to demonstrate significant changes in the slope of the psychometric function (e.g., Watson, 1979). Third, this variability may have been exacerbated by the visual field asymmetries we documented (e.g., Fig. 5(a)).

5.1.3. Little or no effect of spatial frequency

Unlike most studies of attention, we have examined effects across the contrast sensitivity function and shown that attention improves performance at all spatial frequencies tested. There was no systematic interaction between the effect of attention and the spatial frequency of the stimuli. This is consistent with previous results (e.g., Carrasco et al., 2000), and indicates that attention does not simply enhance performance for resolution tasks, which are more dependent on high spatial frequencies (e.g., Balz & Hock, 1997; Nakayama & Mackeben, 1989; Yeshurun & Carrasco, 1999); rather, attention affects the perception of a range of objects in the environment that are composed of a wide spectrum of spatial frequencies.

5.2. Models and mechanisms

5.2.1. Psychophysics

The effect of attention on contrast threshold has been attributed to spatial uncertainty reduction (Solomon et al., 1997), signal/stimulus enhancement (Carrasco et al., 2000; Lu & Dosher, 2000), external noise reduction (Lu & Dosher, 1998, 2000), or accounted for in terms of contrast gain and tuning of visual cortical neurons (Lee et al., 1999). We used a peripheral precue as a means of manipulating transient attention. Given that our display included neither distracters nor masks, all sources of external noise were eliminated (see also Carrasco et al., 2000, 2001b). The present results are consistent with the signal enhancement model and cannot be accounted for simply by uncertainty reduction. This is because attention shifted the psychometric function towards lower contrasts and it improved performance even with supra-threshold targets, at high performance levels, but did not significantly decrease the slope. The effects of attention at low contrast may reflect both signal enhancement and spatial uncertainty reduction. The finding that the degree of the precue effect was rather similar for stimuli that differed in spatial uncertainty indicates that the attention benefit cannot be due simply to a reduction of spatial uncertainty.

Other studies have identified conditions in which spatial uncertainty models have not been able to account for observed attentional effects. For instance, the way in which the near absence of attention affects visual thresholds could not be accounted for by a spatial uncertainty model (Lee et al., 1999). Moreover, with brief displays (100 ms) cueing the target location improves performance more than predicted by the signal-detection model of spatial uncertainty (Morgan et al., 1998). Finally, it has been found that attention increases contrast sensitivity when the display characteristics eliminate all sources of external noise and localization performance indicates that there is no stimulus uncertainty with regard to its location (Carrasco et al., 2000).

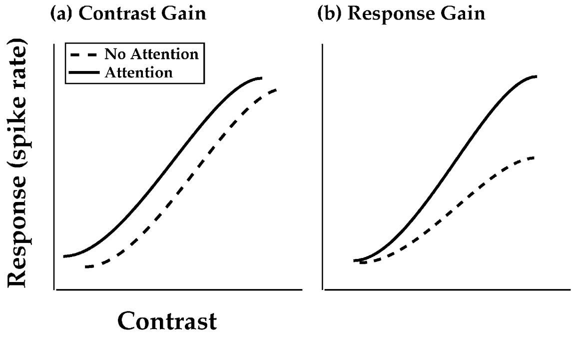

Fig. 11. Schematic of neural contrast response functions and how they may be affected by attention. (a) Contrast gain and (b) response gain. See text for details.

5.2.2. Neurophysiology

Some authors have addressed the link between perception and the underlying neural basis of perception by measuring psychophysical and neuronal responses simultaneously (e.g., Newsome, Britten, & Movshon, 1989; Shadlen & Newsome, 1996). A similar approach is currently being undertaken in the literature on the psychophysics and neurophysiology of attention.

Two sorts of effects are typically observed in neural responses—contrast gain and response gain—that can be due to, for example, contrast adaptation (e.g., Sclar, Lennie, & DePriest, 1989). Fig. 11 shows an example of (a) contrast gain and (b) response gain changes after Reynolds et al. (2000). The signature of a contrast gain change is a shift in the contrast response function to the left. In the case of attention, this reflects a decrease in the contrast required for the neuron to respond at the same level as in a "non"—attentional (neutral) condition. On the other hand, the signature of a response gain change is an increase in firing of a neuron only at relatively high contrasts. In the case of attention, this reflects an increase in the strength of the response of a neuron, particularly at high contrasts. An open question in the literature on attention is how changes in psychophysical responses are manifested at the neural level. How could attention affect the contrast response functions? Whereas Reynolds et al. (2000) have supported a contrast gain model, McAdams and Maunsell (1999) and Treue and Martinez Trujillo (1999) have supported a response gain model.

The present results provide related psychophysical findings. Obviously, comparisons between psychophysical and neurophysiological results need to be made with caution. First, as is the case for all psychophysical studies, our results are based on the response of the entire visual system. The neurophysiological results are based on the response of single neurons or groups of neurons confined to particular regions of the visual system. Second, the dependent variable in our psychophysical task has a true limit—performance can be, at best, 100% correct. Therefore, for cases in which performance in the neutral precue condition is at or near 100% correct, it is impossible for attention to improve performance. While there is an upper limit to the response rate of a neuron, it is conceivable to increase the firing rate of a neuron that is already firing fast. Thus, psychophysical results equivalent to a neuronal contrast gain change are impossible to observe in our paradigm. (Note that Lee et al. (1999) have proposed a model that predicts that attention increases both contrast and response gain.) Finally, a particular difference between our methods and those employed in most neurophysiological studies of attention is that we invoke transient attention with brief peripheral precues whereas studies with awake-behaving monkeys have invoked sustained attention with central precues. [8] Notwithstanding these caveats, our results show a shift in the psychometric function with attention, consistent with a contrast gain change.

5.3. Performance is affected by target location and contrast

5.3.1. Performance fields by contrast

Previous findings have shown that performance is heterogeneous across the visual field (e.g., Mackeben, 1999; Regan & Beverley, 1983; Rijsdijk, Kroon, & van der Wilt, 1980; Skrandies, 1985), and we have shown that this heterogeneity becomes more pronounced as eccentricity, spatial frequency and set size increase (Carrasco et al., 2001a). When targets are presented near the fovea or are low spatial frequency stimuli, performance is independent of location. The current study demonstrates how performance fields vary with contrast level. As expected, when overall performance is at chance or at asymptote, performance does not vary systematically with location. However, as contrast is increased to levels that elicit performance just above chance, the heterogeneity emerges—performance is better on the horizontal meridian than the vertical meridian and worst in the "N" location, directly above fixation. This pattern of results is maintained at all but the asymptotic levels. Even when performance is greater than 90% correct, there is a heterogeneity—performance is still worst at the "N" location. The heterogeneity reported here is also present in spatial resolution tasks, such as acuity (Carrasco et al., 2001b) and texture segmentation (Talgar & Carrasco, in press).

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[8] According to the results of Dosher and Lu (Dosher & Lu, 2000, 2001; Lu & Dosher, 1999), who found similar effects of attention at three performance levels, it seems that sustained attention does not affect the slope of the psychometric function.

5.3.2. *Psychometric function by location*

Our results also indicate that psychometric functions have higher thresholds and slopes for targets presented on the vertical meridian — particularly at the "N" location — than for targets presented at other locations. The change in threshold reflects the fact that observers require higher contrast in order to perform the task at a given level when targets are presented at the "N" location vs. other locations. The steeper slope indicates that observers are sensitive over a smaller range of contrasts. Whereas there is inherent variability in slope estimates of psychometric functions (e.g., Watson, 1979) we suggest that visual field location may affect slope. For example, slopes were almost always higher for targets on the vertical than horizontal meridian (Fig. 7(a)), and particularly for targets at the "N" location (Fig. 7(b)).

These results are worth bearing in mind given that many studies in the literature use tasks that require observers to make judgements about targets that are presented at a variety of locations across the visual field. The visual field inhomogeneity has a number of implications. First, at the level of experimental design it indicates that, particularly for threshold tasks, subjects do not see stimuli that are presented directly above, or to a lesser extent below, fixation as well as they see stimuli on at other locations in the visual field. Second, averaging data from many locations may mask a wide range of performance levels, which would obscure potentially significant visual field asymmetries. Such averaging could also lead to misleading results. In the present experiment, results showed that target location did not interact with other effects of interest (such as attention). In other studies, however, it could be concluded that some variables do not affect contrast sensitivity when, in fact, they may at some but not all performance levels. Third, the finding that perception is dependent on visual field location could help in the design of more effective devices, for example, user interfaces.

5.4. *Anatomical and physiological correlates of visual field asymmetries*

The present results are consistent with our previous results indicating that visual factors account for visual field asymmetries (see Carrasco et al., 2001a).

The advantage for stimuli on the horizontal compared to the vertical meridian is consistent with previous psychophysical studies (e.g., Carrasco & Frieder, 1997; Carrasco et al., 2001b; Kröse & Julesz, 1989; Mackeben, 1999; Nazir, 1992; Regan & Beverley, 1983; Rijsdijk et al., 1980; Rovamo & Virsu, 1979; Yeshurun & Carrasco, 1999). Anatomical and physiological research in macaque monkeys provide a possible neural correlate: A lower density of ganglion cells (Curcio & Allen, 1990; Perry & Cowey, 1985) and a faster decline of cone density with increasing distance from the fovea (Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987) along the vertical than horizontal meridian. Moreover, evidence of such a horizontal meridian advantage also exists in the LGN (Connolly & Van Essen, 1984) and V1 (Tootell, Switkes, Silverman, & Hamilton, 1998; Van Essen, Newsome, & Maunsell, 1984).

The relatively poor performance at the "N" than the "S" location is also consistent with an advantage of the lower visual field in a variety of psychophysical tasks (Carrasco et al., 2001b; Edgar & Smith, 1990; Nazir, 1992; Previc, 1990; Rijsdijk et al., 1980; Rubin, Nakayama, & Shapley, 1996; Talgar & Carrasco, in press). Possible neural correlates include the greater cone and ganglion cell densities in the lower than upper visual field (Perry & Cowey, 1985), and slightly more area is devoted to the inferior than superior visual field in the LGN (Connolly & Van Essen, 1984) and V1 (Tootell et al., 1998; Van Essen et al., 1984). Moreover, there appears to be less direct input from layer 4B in V1 to the upper than the lower map in V3/VP (Lennie, 1998). It is worth noting that the our results do not simply point to an upper vs. lower hemifield disadvantage, but are particularly striking on the vertical meridian. Indeed, performance for targets at the non-cardinal locations was similar to each other. The physiological underpinnings of the vertical meridian asymmetry are, as yet, unknown.

5.5. *Effect of spatial frequency*

The result that the effect of attention did not interact with spatial frequency indicates that attention affects performance similarly across the range of spatial frequencies tested. This finding is consistent with other studies that have measured attentional effects at a range of spatial frequencies, when the target is presented in isolation (Carrasco et al., 2000), and when the target is presented amid distracters (Cameron et al., 2000). On the other hand, performance fields were affected by spatial frequency. The visual field heterogeneity increased with spatial frequency (see also Carrasco et al., 2001a; Rijsdijk et al., 1980). This heterogeneity manifested itself in higher thresholds and shallower slopes for stimuli on the vertical meridian, particularly at the "N" location, consistent with the anatomical and physiological studies cited above.

5.6. *No interaction between visual field location and attention*

Not withstanding the visual field asymmetries, we find that the effect of attention is constant across location—attention improves performance at all locations in the visual field, but at no location preferentially. Attention changes the psychometric function (mostly decreases threshold), but it does not do so in a preferential way at any location. According to the uncertainty reduction hypothesis, attention should affect the "N" more than the "S" location and the "E & W" locations the least. This is not what we observed—the ANOVA indicated that there was no significant interaction between precue and location. This pattern of results is consistent with our earlier results (Carrasco et al., 2001a) and with results in a visual search task (Ellison & Walsh, 2000), but inconsistent with a number of reports in the literature (Altpeter et al., 2000; He et al., 1996; Mackeben, 1999). One possible explanation for this difference is that the other studies cited did not compare performance under an attentional and a neutral condition, nor did they manipulate transient attention. Thus, it is likely that the results attributed to attention could result from visual constraints (see Carrasco et al., 2001a).

6. Conclusion

Attention decreases threshold of the psychometric function over a range of spatial frequencies and target locations. This is consistent with a contrast gain mechanism. In addition, performance is better on the horizontal than the vertical meridian and particularly poor at the "N" location throughout the dynamic range of the psychometric function. Notwithstanding the visual field inhomogeneities, the effect of attention is robust and similar across the visual field, indicating that the effect (and mechanism) of attention is comparable across the visual field. Differences in performance across the visual field are due to visual factors (see Carrasco et al., 2001a).

The modest decrease in the slope of the psychometric function with transient attention suggests spatial uncertainty reduction may play a role in the precue effect, but the control experiments indicate that it cannot explain the entire effect. Given that our experiment was designed to exclude factors of external noise reduction, our results support signal enhancement as the main mechanism by which attention improves performance in this orientation discrimination task.

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