PERGAMON

Vision Research 39 (1999) 293–306

Vision Research

Spatial attention improves performance in spatial resolution tasks[1]

Yaffa Yeshurun, Marisa Carrasco *

Department of Psychology, New York University, 6 Washington Place, New York, NY 10003-6634, USA

Received 4 July 1997; received in revised form 2 February 1998

Abstract

This study used peripheral precueing to explore the effect of covert transient attention on performance in spatial resolution tasks. Experiments 1 (Landolt-square) and 2 ('broken-line') measured gap resolution and Experiment 3 measured vernier resolution. In all three tasks the target was presented alone in a large number of possible locations, ranging from 1.5–6° of eccentricity in the vertical or horizontal axes. The precue indicated the target location but did not convey information regarding the correct response. Performance decreased as the gap size or the vernier offset size decreased and as target eccentricity increased. Precueing improved performance in terms of RT and accuracy in all three tasks; the eccentricity effect decreased in the cued trials of the gap resolution tasks. These findings support the idea that the performance improvement at attended locations results, to some extent, from an enhanced spatial resolution at the cued location, and not just from distractor exclusion, diminished uncertainty, or decisional factors. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Covert attention; Gap resolution; Landolt-square; Precue; Spatial attention; Spatial resolution; Vernier

In this study we employed spatial precueing as a tool to identify the mechanisms underlying covert attentional facilitation. Specifically, we explored whether directing observers' attention to a given location would improve their performance in spatial resolution tasks (e.g. Landolt-square and vernier offset). In contrast to previous studies dealing with transient attention (Nakayama & Mackeben, 1989; Nazir, 1992; Mackeben & Nakayama, 1993; Shiu & Pashler, 1995; Balz & Hock, 1997), the present study combines the following characteristics: the exogenous precue provided no information in terms of response probability (the probability that a certain response would be the correct one), the supra-threshold target appeared alone in the display (without distractors), and target location was varied from trial to trial over a range of eccentricities.

Visual attention allows us to select a certain aspect of the visual scene and grant it priority in processing. Indeed, attending to a specific location or a given characteristic of the display has been shown to enhance observers' performance in a wide variety of visual tasks, such as: line length discrimination (Bonnel, Possamai & Schmitt, 1987); visual search (Eriksen & Hoffman, 1972; Yantis & Jonides, 1984; Carrasco & Yeshurun, 1998); sinusoidal grating detection (Davis & Graham, 1981; Shulman & Wilson, 1987); luminance detection (Posner, Nissen & Ogden, 1978; Posner, 1980; Downing, 1988); vernier targets (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993); line segments detection (Kurylo, Reeves & Scharf, 1996); and letter identification (Prinzmetal, Presti & Posner, 1986; Juola, Bouwhuis, Cooper & Warner, 1991). Some studies have found an attentional benefit when the target is presented along with other items (Eriksen & Rohrbaugh, 1970; Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993; Shiu & Pashler, 1995; Balz & Hock, 1997; Carrasco & Yeshurun, 1998); other studies have found such a benefit when the target is presented alone (Shaw & Shaw, 1977; Bashinski & Bacharach, 1980; Posner, 1980; Downing & Pinker, 1985; Van der Heijden, Schreuder & Wolters, 1985; Eagly & Homa, 1991). Yet the nature of the attentional mechanisms underlying this enhancement is still a subject of debate. Different interpretations suggested for the attentional benefit

---

* Corresponding author. Tel.: +1 212 9988328; e-mail: marisa@psych.nyu.edu.

[1] Parts of this study were presented at the Annual Meeting of the Association for Research in Vision and Ophthalmology (May 1997) and at the Annual Meeting of the Psychonomics Society (November 1997) and published in Abstract format (Yeshurun and Carrasco, 1997 and Carrasco and Yeshurun, 1997, respectively).

PII S0042-6989(98)00114-X

include enhanced sensitivity (Bashinski & Bacharach, 1980; Downing, 1988; Tsal & Lavie, 1988), reduction in observers' uncertainty (Kinchla, 1980; Prinzmetal, Amiri, Allen, Nwachuku, Bodanski, Edwards & Blumenfild, 1997; Prinzmetal, Amiri, Allen & Edwards, 1998), or a change in decision criteria (Kinchla, 1980; Shaw, 1984; Sperling & Dosher, 1986; Palmer, 1994; Kinchla, Chen & Evert, 1995).

Many of these studies have employed spatial precues to manipulate observers' attention; a cue is presented briefly to indicate the target location prior to its appearance. When observers know in advance the location of the relevant item, they can allocate their attentional resources to that particular location and improve performance (Eriksen & Hoffman, 1972; Posner, Nissen & Ogden, 1978; Bashinski & Bacharach, 1980; Downing, 1988; Prinzmetal et al., 1986).

A potential difficulty with manipulating attention with spatial precues is that, typically, these precues do not only convey information about location but also about the probability of a response being correct. For instance, the precues commonly indicate that a certain location in the display has a higher probability of containing the target (Bashinski & Bacharach, 1980; Jonides, 1980; Posner et al., 1978; Posner, 1980). Whereas this high probability is assumed to encourage observers to direct their attention to that particular location, it also obscures the source of the attentional effects. If target detection in the cued location were better than at any other location, it would be hard to disentangle whether the enhanced detection was due to facilitation of information coding at that location, or simply to observers adopting a more liberal criterion[2] regarding information that is extracted from that location. This latter proposal is especially viable when distractors are also present in the display.

Another potential difficulty with many studies that have addressed the effect of precueing spatial attention is that they have assessed performance in terms of either latency (Eriksen & Hoffman, 1974; Posner, 1980; Posner, Snyder & Davidson, 1980; Downing & Pinker, 1985; Eriksen & St. James, 1986) or accuracy (Shaw & Shaw, 1977; Bashinski & Bacharach, 1980; Luck, Hillyard, Mouloua, Woldorff, Clark & Hawkins, 1994; Kurylo, Reeves & Scharf, 1996; Balz & Hock, 1997). Given the fact that the possibility of a speed-accuracy trade-off always exists (Pachella, 1974), and that dissociations between accuracy and latency have been reported (Santee & Egeth, 1982), it is important to assess performance in terms of both latency and accuracy (Wickelgren, 1977). In fact, it has been suggested that since these measures do not always reflect the same perceptual process, the convergence of these measures should be demonstrated empirically rather than taken for granted (Santee & Egeth, 1982).

In many visual tasks a performance decrement for more peripheral stimuli has been attributed to the poorer spatial resolution of the periphery (Rovamo & Virsu, 1979; Robson & Graham, 1981; Kitterle, 1986; Banks, Sekuler & Anderson, 1991). This is also the case in visual search tasks in which an eccentricity effect has been found; observers' performance is slower and less accurate as target eccentricity increases (Carrasco, Evert, Chang & Katz, 1995; Carrasco & Frieder, 1997; Carrasco, McLean, Katz & Frieder, 1998). Precueing the target location diminished this eccentricity effect, and suggested that attending to a stimulus location may improve its sensory representation by enhancing the spatial resolution at the cued location (Carrasco & Yeshurun, 1998). To examine this proposal in a more direct way, this study explored the effects of spatial precueing on stimuli specifically designed to measure spatial resolution, such as Landolt-square for gap resolution (acuity) and vernier target for vernier resolution (hyperacuity). If the enhancement of spatial resolution underlies the improved performance for attended items, performance should be facilitated even in basic acuity and hyperacuity tasks, whether the target is presented alone in the display or accompanied by distractors.

Vernier acuity has been shown to improve when observers know in advance, via spatial precues, the location of the vernier target (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993). Similarly, by manipulating the spread of attention using different dual tasks, it has been demonstrated that vernier acuity is highest when attention is narrowly focused on a foveal vernier target (Balz & Hock, 1997). Because in both studies the target was presented among other items, it is hard to tell whether the improvement reflects an enhanced sensitivity for the target, as these authors claimed, or just a more efficient filtering out of the non-relevant items. To distinguish between these two options, the target would have to be presented alone.

Two studies that have specifically explored the effects of spatial precueing on spatial resolution for a target that was presented by itself have found no significant precueing effect (Nazir, 1992; Shiu & Pashler, 1995).[3] But these results may be limited; the absence of the precueing effect could have stemmed from the experimental designs of these studies. In the first study, the precue could have masked the Landolt-square target, because it appeared at the same exact location as the target right before its onset. In the second study, a vernier target was presented in one of only four possible locations, which may not have introduced enough spatial uncertainty and reduced the need for the precue.

---

[2] For information on the effects of criterion on performance in visual tasks, see Green and Swets (1966).

[3] Shiu and Pashler (1995) did find an attentional benefit when their vernier target was presented among line distractors but not ellipse distractors.

The present study examined whether attention improves performance in three different resolution tasks while circumventing the limitations discussed thus far. These tasks are associated with different levels of processing. Experiments 1 and 2 assessed the effects of precueing on tasks that were designed to measure gap-resolution, which is assumed to be limited by the retinal mosaic (Levi, Klein & Aitsebaomo, 1985; Martin, 1986; Olzak & Thomas, 1986). Experiment 3 employed a task designed to measure vernier-resolution, which is presumably limited by cortical processes (Barlow, 1979, 1981; Westheimer, 1982; Levi, Klein & Aitsebaomo, 1985). In all three experiments the target was presented alone, in a large number of possible locations, and its retinal eccentricity was varied systematically. One half of the total trials were cued; a peripheral precue, considered to capture attention in an 'automatic' manner (Posner, 1980; Jonides, 1981; Müller & Rabbitt, 1989; Remington, Johnston & Yantis, 1992; Yantis, 1996), indicated the target location prior to its onset. Whereas this precue always indicated the correct location of the target, it did not convey any information to the observers about the correct response. In addition, to prevent forward spatial masking effects, the precue appeared above the location of the target. On the other half of the total trials, the neutral trials, a small circle appeared in the center indicating that the target could appear anywhere in the display. The effects of precueing on these tasks were assessed by both accuracy and latency to evaluate whether these measures would yield convergent results.

1. Experiment 1

Nazir (1992) presented a Landolt-square target, either in isolation or among three kinds of distractors: One distractor was similar to the target in size and form and the other two distractors did not resemble the target. Because precueing did not improve observers' forced-choice decision regarding the side of the square containing the gap, Nazir concluded that attentional mechanisms cannot affect such a basic visual task. However, the absence of the attentional effect could be attributed to the fact that all items appeared within 2° of eccentricity. Because this near eccentricity does not require a wide spread of attention, the need for the precue may have been reduced. According to the zoom lens metaphor, attention may be expanded to take in the entire display or may be restricted to a single item. The restriction of the scan to include less information within a smaller area results in a faster and more efficient processing of information (Eriksen & St. James, 1986; Shulman & Wilson, 1987; Eriksen, 1990). Moreover, since the cue appeared immediately before and at the exact same location as the target, forward masking may have prevented the emergence of an attentional benefit.

Experiment 1 was designed to examine whether an attentional benefit could be found with a Landolt-square target in a basic 2AFC task, while avoiding the conditions that may have precluded the precueing effect in Nazir's study. To this end, a square with a gap at one of its sides was presented in one of 16 possible locations, at four different eccentricities, ranging from 1.5–6°. To prevent spatial masking effects the precue appeared in a location adjacent to the target. Observers had to indicate which side of the square contained the gap (Fig. 1a). Because the precue appeared equally often above each of the two square types (left-side vs. right-side gap), it did not associate a higher probability with one of the responses and observers could not rely on its presence to reach a decision.

1.1. Method

1.1.1. Observers

Fourteen undergraduates from NYU subject pool. All had normal or corrected to normal vision, and were naive as to the purpose of the study.

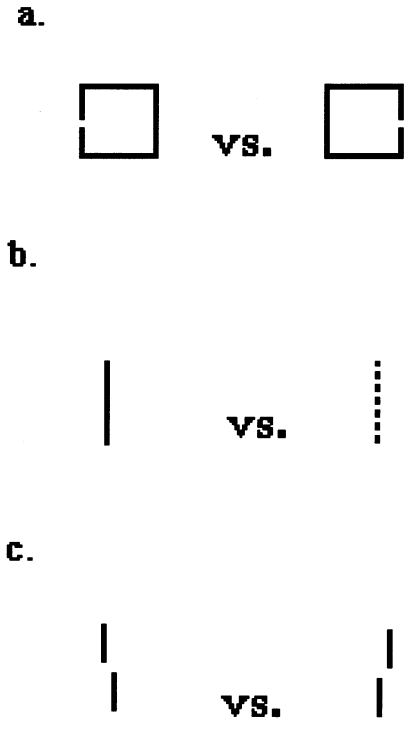

Fig. 1. This figure depicts the three stimuli used in this study: (a) Landolt-square (Experiment 1); (b) 'broken-line' (Experiment 2); (c) vernier target (Experiment 3).

1.1.2. Apparatus

The stimuli were presented using Vscope™ (Enns & Rensink, 1992), whose response timing has an accuracy of 1 ms (Rensink, 1990). The stimuli appeared on a 17 in. monitor of a Power Macintosh 7500/100 computer, whose frame duration equals 13.4 ms.

1.1.3. Stimuli and design

A white square appeared on a black background and subtended 1 × 1° of visual angle (Michelson contrast = 0.9). On each trial this square was presented in one of 16 possible locations, four in each quadrant of the visual field, and appeared on one fourth of the trials at 1.5, 3.5, 5.5, or 6° of eccentricity away from the fixation point[4]. A gap of one of six sizes, 2.2, 4.4, 6.6, 8.8, 11, and 13.2′, was embodied equally often in one of the square's sides. On half of the total trials a precue appeared about 0.3° above the location of the Landolt-square (cued trials). The precue was a green (0.280, 0.595 in standard CIE color space) horizontal bar, subtending 0.5° width × 0.14° height of visual angle. On the other half of the total trials (neutral trials), instead of the bar, a green circle, whose diameter subtended 0.35° of visual angle appeared in the center of the display. This circle indicated that the Landolt-square had equal probability of appearing at any location. Half of the cued trials, and half of the neutral trials contained a square with a left-side gap. The rest of the trials contained a square with a right-side gap. A small fixation dot was present in the center of the screen throughout the experiment. A plus (0.33° height × 0.33° width) or a minus (0.33° width × 0.1° height) sign served as the feedback, and was presented in the center of the screen. A 1.4 × 1.4° square of distorted lines served as the mask and was presented at the location of the square.

1.1.4. Procedure

Observers sat 85 cm away from the monitor and were asked to view the display binocularly. They were read instructions specifying the target, advising them to fixate on the fixation point throughout the experiment, and asking them to indicate, as rapidly and accurately as possible, whether the gap was on the left or right side of the square. Each observer was then given 96 practice trials. The experimental session consisted of twelve blocks of 96 trials, for a total of 1152 trials per observer. The order of the trials was randomized. In each of the trials the bar or the circle appeared for 54 ms, and after an ISI of 67 ms (i.e. a SOA of 121 ms), the square was presented for 80 ms to keep overall performance level at 70–75% correct, so that ceiling or floor effects would be avoided. The mask followed the square, and was presented for 200 ms (Fig. 2). Thus, eye movements could not take place while the display was present; it is estimated that about 250 ms are needed for saccades to occur (Mayfrank, Kimmig & Fischer, 1987). Observers responded by pressing a key on the computer keyboard with the index or middle finger of their dominant hand. Half the observers used their index finger for a 'left' response, and the other observers used their middle finger. Both time to respond (from the onset of the display) and accuracy were recorded. Immediately after observers responded the appropriate feedback sign was presented for 1 s. In addition, at the end of each experimental block, observers received feedback about their error rate for that block.

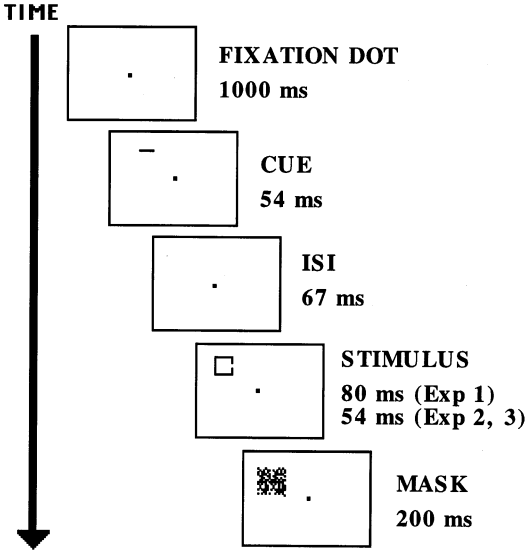

Fig. 2. This diagram depicts the sequence of presentation of each experimental trial in the three experiments of this study.

1.2. Results and discussion

A within-observers four-way ANOVA (cue × eccentricity × visual field × gap size) was performed on the accuracy and on RT data collected on trials with correct responses. (A significant *F*-ratio ($p < 0.05$) indicates that the variability between conditions was higher than the variability among subjects in a given condition). As can be seen in Fig. 3a, performance was significantly better at the left and right than the upper and lower visual fields ($p < 0.05$). This advantage of the horizontal over the vertical fields is consistent with

---

[4] The eccentricities corresponding to the center of the square were used in data analysis. Note that the gap appeared 0.5° to the right (50% of the time) or the left (50% of the time) of this center. Consequently, in the horizontal meridian, the gap of the target centered at 5.5° of eccentricity would appear at 5 or 6° of eccentricity, whereas the gap of the target centered at 6° of eccentricity would appear at 5.5 or 6.5° of eccentricty. Hence, the difference in performance for targets at 5.5 and 6.5° of eccentricety may be underestimated in the present experiment.

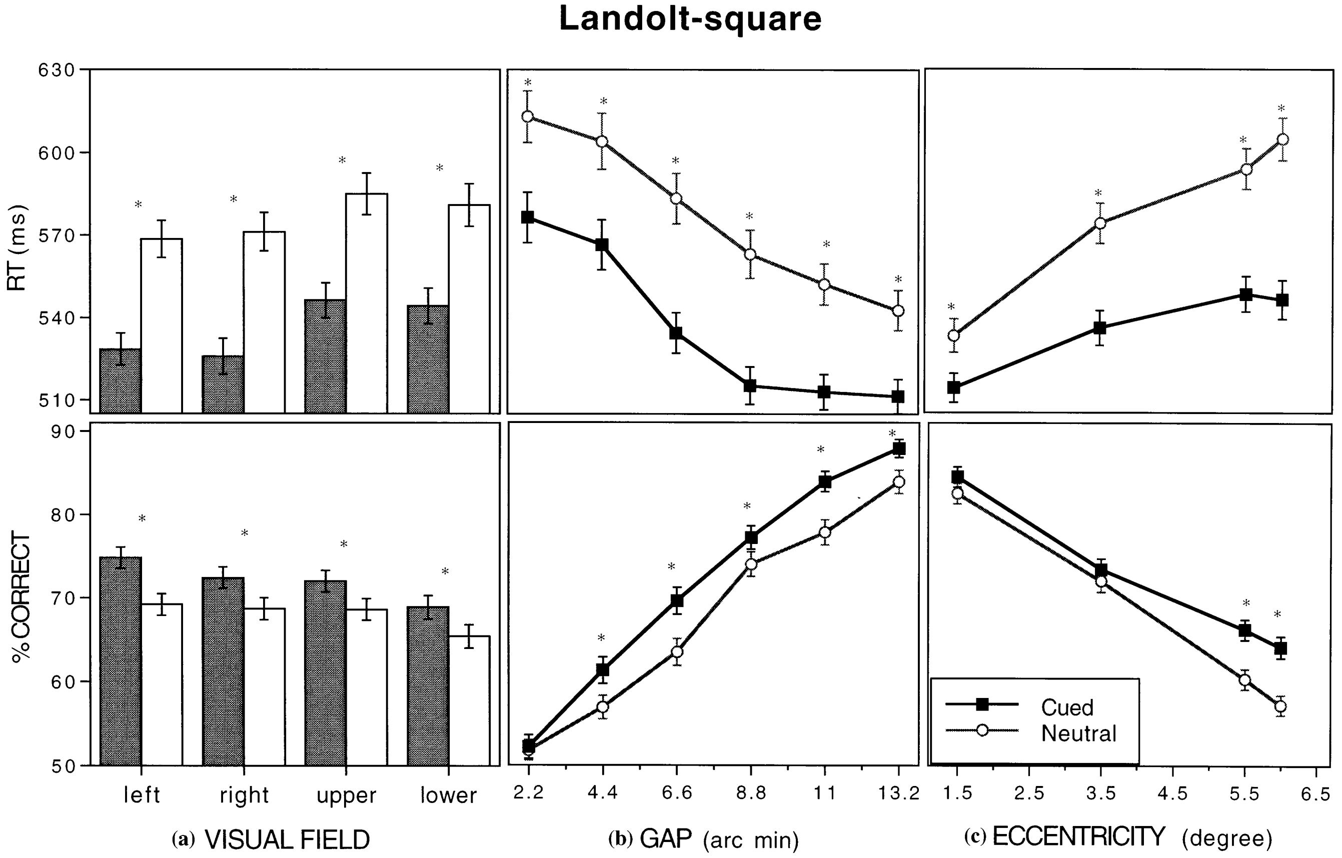

Fig. 3. Mean correct RT and error rate for a Landolt-square as a function of cueing condition and (a) visual field; (b) gap size; (c) target eccentricity (Experiment 1). A cue (54 ms) indicated the location where the stimulus would appear for 80 ms after an ISI of 67 ms. (* simple effect was statistically significant, $p < 0.05$).

previous findings (Engel, 1977; Rijsdijk, Kroon & van der Wilt, 1980; Kröse & Julesz, 1989; Nazir, 1992), and may be due to the higher density of ganglion cells along the horizontal meridian (Perry & Cowey, 1985; Curcio & Allen, 1990) and to the more rapid decline of cone density in the vertical compared to the horizontal direction with increasing distance from the fovea (Curcio, Sloan, Packer, Hendrickson & Kalina, 1987). In addition, performance was more accurate at the upper than at the lower visual field, and at the left than at the right visual field, but only the former difference was statistically significant ($p < 0.05$). This finding does not agree with previous reports of an acuity advantage at the lower visual field (Nazir, 1992). In any case, regardless of the square's position in the visual field, performance deteriorated as the gap size decreased (Fig. 3b). This poorer performance with smaller gaps was seen in both cued and neutral conditions. A gap size × eccentricity interaction ($p < 0.0001$) revealed that as gap size increased performance improved more for the nearer than the farther eccentricities.

More important for this study is that discrimination was significantly faster and more accurate in the cued than in the neutral trials ($p < 0.05$; Fig. 3). Similarly, according to the fitting of a Weibull psychometric function to the accuracy data, the gap threshold for the Landolt-square target was significantly lower in the cued than in the neutral trials (thresholds: 10.31 vs. 12.09'; $p < 0.0001$), suggesting a more accurate stimulus analysis at the cued locations resulting in higher sensitivity for the cued trials.

Finally, in both cueing conditions performance deteriorated significantly as target eccentricity increased ($p < 0.0001$). A cue × eccentricity interaction (RT: $p < 0.0005$; accuracy: $p = 0.1$) showed that this eccentricity effect was less pronounced in the cued than in the neutral conditions (Fig. 3c).[5] This result is consistent with the finding that precueing the target location in a visual search task reduces performance differences between different retinal eccentricities (Carrasco & Yeshurun, 1998), and lends further support to the idea that attention can enhance the spatial resolution at the cued location.

---

[5] We chose to collapse across gap size when we plotted the cueing effects as a function of eccentricity because the ANOVAs' three-way interactions of cue × gap × eccentricity were not significant (except in Experiment 2's accuracy data for the 'broken-line' where the interaction reached significance, but no consistent pattern emerged).

To conclude, this experiment illustrates that an attentional benefit can be found in a 2AFC task designed to measure gap resolution using a Landolt-square target. A significant precueing effect emerged once spatial masking was prevented and the target was presented at eccentricities farther than 2°. These farther eccentricities ensured that observers would need the precue to keep their attentional spread narrow enough to obtain maximal precue facilitation.

The fact that performance in such a basic resolution task improved when observers knew in advance the location of the target is in agreement with studies employing different visual tasks (Bashinski & Bacharach, 1980; Jonides, 1980; Posner, 1980; Graham, Kramer & Haber, 1985; Downing, 1988; Carrasco & Yeshurun, 1998). This precueing effect emerged even though in this experiment the target was presented alone, without other items to introduce decisional noise. Thus, although there was no visual information that had to be filtered out, observers did benefit from advance knowledge of the target location, which presumably allowed advanced allocation of attentional resources (Shaw & Shaw, 1977; Posner, 1980; Eriksen, 1990). Furthermore, given that the precue appeared equally often above the square, regardless of its type (left-side vs. right-side gap), it could not have encouraged observers to adopt a differential decisional criterion for the different cueing conditions.

2. Experiment 2

Previous studies have found an attentional benefit for a variety of visual tasks using a ‘yes–no’ detection task (Bashinski & Bacharach, 1980; Downing & Pinker, 1985; Downing, 1988; Jonides & Yantis, 1988; Carrasco & Yeshurun, 1998). The present experiment examined whether the effects of precueing found in a discrimination task with a two-alternative forced-choice procedure and a Landolt-square target in Experiment 1 would also be found with a ‘yes–no’ detection task and a different gap resolution stimulus. We consider this gap resolution task a ‘yes–no’ detection task because observers were asked to detect the presence of a single feature (a gap). This differs from Experiment 1 in which a gap was always present and observers had to discriminate between two types of Landolt-square: left-side versus right-side gap. The present experiment also differed from Experiment 3 in which observers had to discriminate whether the upper line was displaced to the right or to the left of the lower line in a vernier target.

On each trial a continuous or a broken-line was briefly presented in one of 16 possible locations. Observers had to indicate whether the line was broken or continuous (Fig. 1b). Similar to Experiment 1, the precue appeared equally often above each of the line types (broken vs. continuous); therefore, the precue did not associate a higher probability with one of the responses, and observers could not use its mere presence to reach a decision.

2.1. Method

2.1.1. Observers

Thirteen undergraduates from NYU subject pool who had not participated in the previous experiment. All had normal or corrected to normal vision, and were naive as to the purpose of the study.

2.1.2. Stimuli, design, apparatus and procedure

They were the same as in the previous experiment, except for the following: Instead of the square, a line subtending 1° height × 0.1° width of visual angle was the resolution stimulus. The line was broken on one half of the trials, and continuous on the other half. When the line was broken its segments were separated by gaps of one of six possible sizes 2.2, 4.4, 6.6, 8.8, 11, and 13.2′, which occurred equally often.[6] Observers' task was to indicate whether the line was broken or continuous. The size of the mask was adjusted to 0.67° height × 1.33° width to ensure it matched the stimulus dimensions. The presentation time of the square was shortened to 54 ms to keep overall performance level at 70–75% correct, so that ceiling or floor effects would be avoided.

2.2. Results and discussion

As in the previous experiment, a within-observers four-way ANOVA (cue × eccentricity × visual field × gap size) was performed on the accuracy and correct RT data. Similar to Experiment 1, performance was significantly better at the horizontal than the vertical visual fields ($p < 0.05$; Fig. 4a). Likewise, the interaction of eccentricity × visual field revealed that the deterioration in performance with increasing target eccentricities was more pronounced at the upper and lower than the right and left visual fields. This is reflected in the slopes of the eccentricity effect which were steeper for the former than the latter. According to the least square slope estimates, there was about a three-fold difference for RT (18.59 vs. 6.27 ms) and a two-fold difference for accuracy (-6.18 vs. -3.25% correct). This result is consistent with the fact that the detectability thresholds for all spatial frequencies increase with increasing distance from the fovea, but more rapidly in the vertical than in the horizontal direction (Rijsdijk, Kroon & van der Wilt, 1980), as well as with the more rapid decline

---

[6] A reviewer pointed out that the overall luminance of the ‘broken-line’ and that of the continuous line differ. Note, however, that this luminance cue was present in both the attended and the neutral trials.

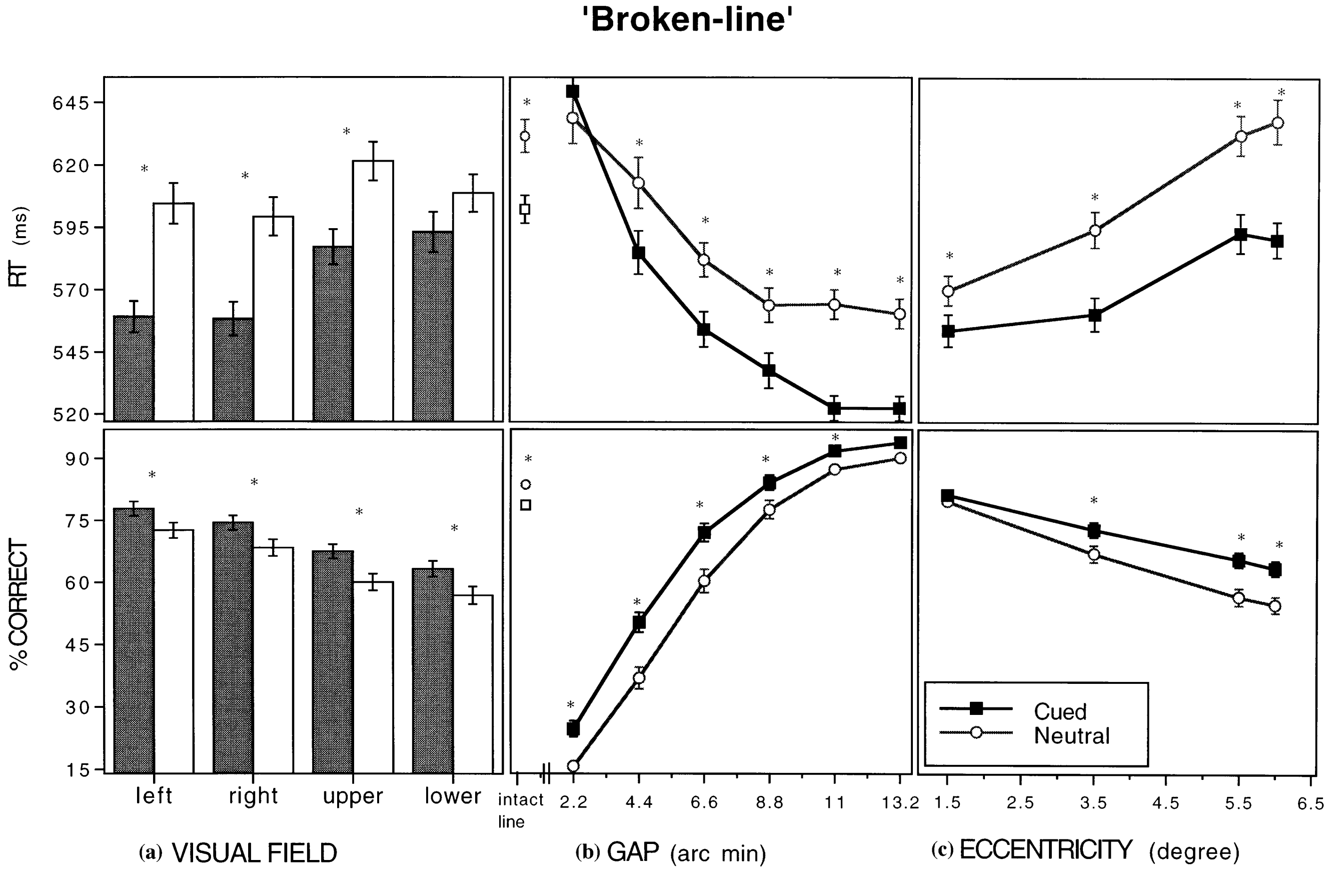

Fig. 4. Mean correct RT and error rate for a 'broken-line' as a function of cueing condition and (a) visual field; (b) gap size; (c) target eccentricity (Experiment 2). A cue (54 ms) indicated the location where the stimulus would appear for 54 ms after an ISI of 67 ms. (* simple effect was statistically significant, $p < 0.05$). Notice that the averaged performance for the continuous line and for the smallest gap of the 'broken-line' would correspond to chance performance ($\simeq 50\%$). Some standard-errors in the lower panels b and c were too small to be seen in this figure.

of cone density with increasing eccentricities in the vertical compared to the horizontal direction (Curcio, Sloan, Packer, Hendrickson & Kalina, 1987). Although performance was faster and more accurate at the upper than the lower visual fields (except for RT neutral), and more accurate for the left than the right visual fields, these differences were not statistically significant. Also as in the previous experiment, performance decreased with smaller gap sizes ($p < 0.0001$; Fig. 4b), and the gap × eccentricity interaction ($p < 0.01$) showed that as gap size increased performance improved more for the nearer than the farther eccentricities.

The same pattern of results obtained with the 2AFC paradigm of Experiment 1 emerged here; there was a significant precueing effect (Fig. 4): performance was significantly better in the cued than the neutral trials for both accuracy and RT ($p < 0.0005$). As was found with a Landolt-square target in Experiment 1, the gap threshold for the cued was lower than that of the neutral trials (9.56 vs. 9.85′). In both cueing conditions performance declined significantly as target eccentricity increased, but the cue × eccentricity interaction showed that this decline was significantly less pronounced in the cued than in the neutral conditions (Fig. 4c). This attentional benefit was found across different eccentricities. According to Newman-Keuls pairwise comparisons, performance was significantly more accurate and faster in the cued than in the neutral trials for all eccentricities ($p < 0.05$, except the nearest; 1.5°).

In sum, this experiment showed that gap detection was faster and more accurate when observers could allocate their attentional resources in advance to the target location. Thus, in this study, an attentional facilitation for an isolated stimulus was consistently found with both tasks, 2AFC discrimination and 'yes–no' detection, as well as for both types of gap resolution stimuli, Landolt-square and 'broken-line'. In addition, for both tasks gap thresholds were lower at the cued than the neutral trials, implying higher acuity at the cued locations. Note that the attentional benefit was found even though the precue could not play any role in decision making processes. Hence, both experiments support the idea that the attentional benefit reflects a change in the sensory representation of the cued stimulus, possibly due to an enhanced spatial resolution at the attended location.

These results imply that attention can affect relatively low, sensory processing of visual information, with tasks designed to measure resolution limited by the retinal mosaic. We wondered whether these results could be generalized to performance with vernier resolution task, which is assumed to be limited by cortical factors. On the one hand, previous studies that have reported an attentional benefit with vernier resolution did not present the target in isolation (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993; Balz & Hock, 1997). On the other hand, when the vernier target was presented in isolation, no such precueing effect was found (Shiu & Pashler, 1995). Thus, the question had remained open: Can resolution for a vernier target be enhanced by attentional deployment when the target is presented in isolation? The following experiment was conducted to address this question.

3. Experiment 3

Because performance with vernier targets is much better than that predicted by inter-cone spacing and the focal length of the eye, the source limiting vernier resolution apparently lies in the visual cortex. Gap resolution, on the other hand, seems to be limited by the photoreceptors' spacing in the retina (Westheimer, 1982; Levi et al., 1985; Martin, 1986; Olzak & Thomas, 1986). It is important, therefore, to examine whether the facilitated performance at the cued location for gap resolution targets could also be found for an isolated vernier resolution target.

Facilitated performance for attended vernier targets has been reported when the target was presented among non-relevant information and attention has been manipulated via concurrent tasks (Balz & Hock, 1997) or spatial precues (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993; Shiu & Pashler, 1995). Nevertheless, when the target was presented in isolation, no attentional benefit was found (Shiu & Pashler, 1995). The fact that a significant precueing effect was found only when the target was presented among other items implies, according to Shiu and Pashler (1994, 1995), that the attentional mechanism is only employed when the display includes decisional noise that has to be filtered out. They suggested that the attentional facilitation reflects a more efficient inhibition of the non-relevant items, rather than improvement of the representation of the relevant item. Alternatively, these authors may not have found an attentional benefit for the isolated target because there was not enough spatial uncertainty to encourage a differential deployment of attention. With only four possible locations, and a constant relatively near stimulus eccentricity (4.8°), observers could have spread their attention across these four locations. This strategy may have been appealing to their observers, because they were instructed that in 25% of the trials the precue indicated an incorrect location. Considering that the precue was not always valid observers may have monitored all four locations instead of just the cued one.

Experiment 3 was conducted to disentangle these two alternative explanations. Like in Shiu and Pashlers' (1995) study, we presented the vernier target alone and manipulated attention using spatial precues. However, to increase the spatial uncertainty, the target in this experiment could appear in one of 12 possible locations and at three different eccentricities ranging from 3.5–6° away from the center.

The eccentricity of the vernier target is relevant because vernier resolution decreases as target eccentricity increases (Levi et al., 1985; Whitaker, Rovamo, Macveigh & Mäkelä, 1992). To further induce observers to take full advantage of the information provided by the precue, the cue was always valid; i.e. the target always appeared at the precued location. In light of previous studies on vernier resolution (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993; Balz & Hock, 1997), as well as the two gap resolution experiments of the present study, we expected to find a significant precueing effect with a vernier resolution task.

3.1. Method

3.1.1. Observers

Ten undergraduates from NYU subject pool who had not participated in the previous experiments. All had normal or corrected to normal vision, and were naive as to the purpose of the study.

3.1.2. Apparatus, stimuli, design and procedure

They were identical to those in Experiment 2 except for the following changes. Instead of the single line, two vertical lines were used (Fig. 1c). One line was presented above the other, and each subtended 0.44° height × 0.1° width of visual angle. The two lines were separated by a vertical gap of 8.8′, and the upper line was displaced 2.2, 4.4, or 6.6′ to the right or left of the lower line. Observers had to indicate whether the upper line was displaced to the left or right of the lower line. The lines were presented at the three farthest eccentricities only (3.5, 5.5, 6°) to avoid ceiling effects and to keep overall performance level at 70–75% correct. A displacement to the right or left of the lower line was cued equally often to prevent changes in decisional criteria regarding the direction of the horizontal offset.

3.2. Results and discussion

A within-observers four-way ANOVA (cue × eccentricity × visual field × offset size) was performed on the

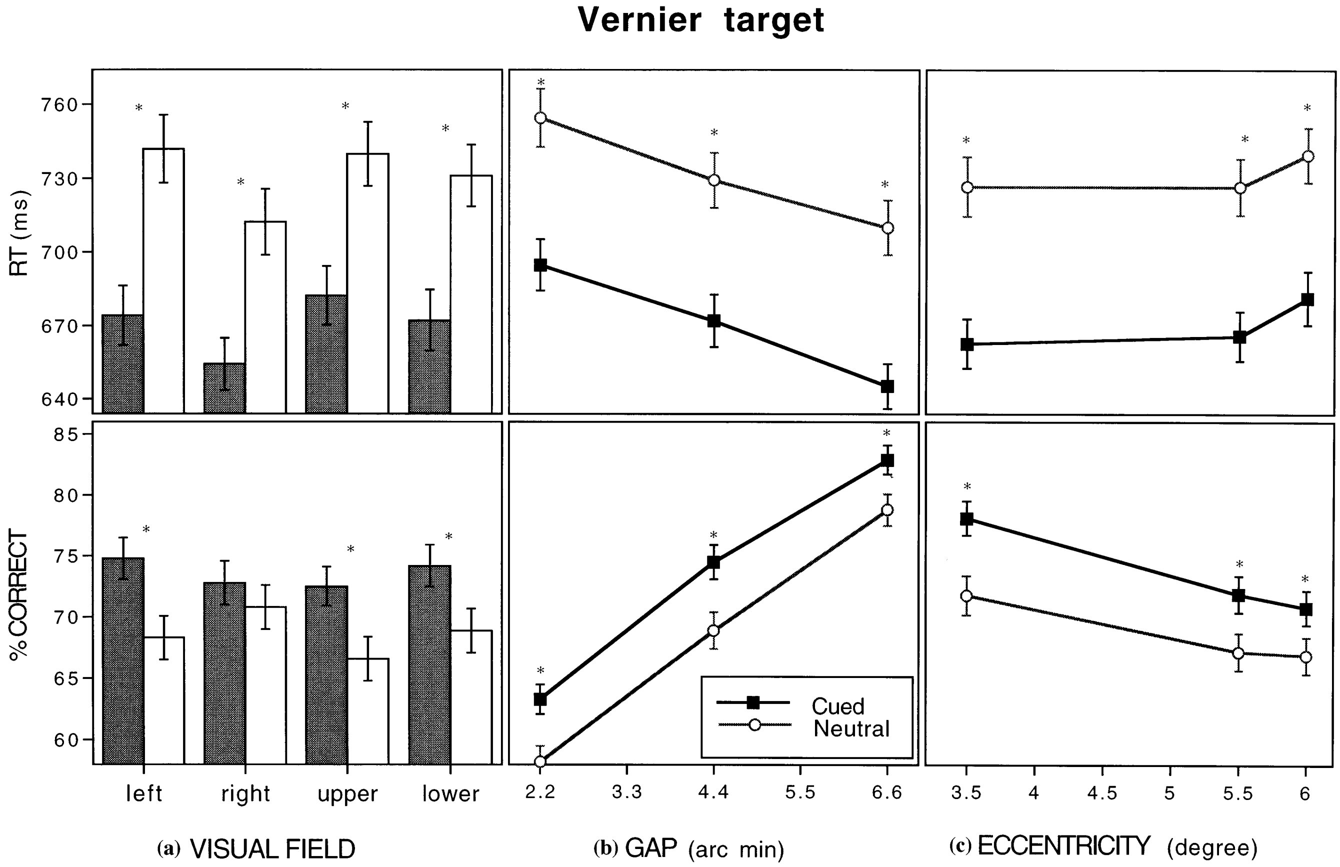

Fig. 5. Mean correct RT and error rate for a vernier target as a function of cueing condition and (a) visual field; (b) offset size; (c) target eccentricity (Experiment 3). A cue (54 ms) indicated the location where the stimulus would appear for 54 ms after an ISI of 67 ms. (* simple effect was statistically significant, $p < 0.05$).

accuracy and correct RT data. As expected, performance was significantly faster and more accurate at the central than peripheral locations ($p < 0.005$) and as the size of the horizontal offset increased ($p < 0.0001$). An interaction between offset size and eccentricity revealed that this improvement was more pronounced at the nearest eccentricity ($p < 0.005$). More importantly, as in Experiments 1 and 2, there was an attentional benefit for the resolution task: Observers were significantly faster and more accurate when the vernier target location was cued in advance ($p < 0.005$; Fig. 5). Similarly, the offset threshold was significantly lower at the cued than neutral trials (6.21 vs. 7.38′; $p < 0.0001$). In addition, this advantage for the cued trials was significant across all eccentricities (Fig. 5c). These findings support the hypothesis that the precueing effect on gap resolution can also be found in a vernier resolution task, even when the target was presented in isolation.

As opposed to Experiments 1 and 2, there were no significant differences between the vertical and horizontal visual fields (Fig. 5a). This could be due to the fact that gap resolution and vernier resolution are mediated by different levels of visual processing (Westheimer, 1982; Levi et al., 1985; Martin, 1986; Olzak & Thomas, 1986). In the present data, however, for the left visual field, the slowest RT occurred at the most central location. This spurious data point neutralized the overall RT difference between the first two eccentricities, which was present for the upper, lower, and right visual fields (Fig. 6). Indeed, like in the previous experiments, there was a significant interaction between visual field and eccentricity ($p < 0.05$) because the eccentricity effect was more pronounced on the vertical than the horizontal meridian.

Although performance at all eccentricities was significantly better in the cued condition, the extent of the eccentricity effect was similar in both cueing conditions. The relative degree of deterioration of performance at farther eccentricities was not affected by the precues (Fig. 5c). This finding differs from the two previous experiments as well as from those of a visual search study (Carrasco & Yeshurun, 1998). Since in this experiment the target was presented only at the three farthest eccentricities to keep performance at about 75%, it is hard to tell whether this difference is due to the differential nature of the vernier task and the processes underlying its eccentricity effect, or simply to this relatively narrow range of eccentricities tested. The eccentricity effect in a vernier resolution task may be mediated by different factors that are less susceptible to precueing effects; alternatively, a wider range of eccentricities could have yielded a larger eccentricity effect which, in turn, could be more sensitive to attentional effects.[7]

To conclude, in this experiment a peripheral spatial precue improved observers' performance on a vernier resolution task with a suprathreshold target presented in isolation. These results are inconsistent with those of Shiu and Pashler (1995) who found no attentional benefit when the vernier target was presented alone. The differences between the experimental procedures of these two studies may explain the inconsistent results. The present results are consistent with studies in which an attentional benefit has been found when a target has been presented alone, either with a resolution target (Experiments 1 and 2 of this study) or with a variety of stimuli (Eriksen & Hoffman, 1974; Shaw & Shaw, 1977; Bashinski & Bacharach, 1980; Posner, 1980; Downing & Pinker, 1985; Van der Heijden, Schreuder & Wolters, 1985; Eagly & Homa, 1991).

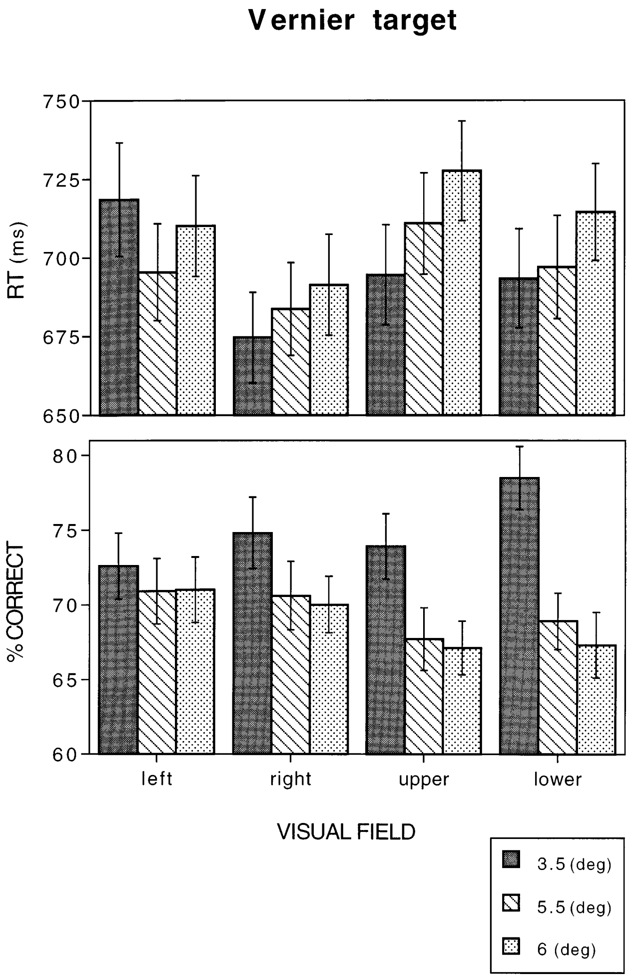

Fig. 6. Mean correct RT and error rate for a vernier target as a function of visual field for different eccentricities. Performance decreased as a function of eccentricity, except for the RT data of the left visual field.

4. General discussion

The first two experiments in this study measured gap resolution and the third assessed vernier resolution, which are basic visual tasks designed to assess performance that is limited by spatial resolution (acuity and hyperacuity). In all three experiments the target was presented in isolation, at a large number of possible locations and eccentricities, and the target was preceded by either a spatial cue appearing in an adjacent location or a neutral circle appearing in the center of the display. Spatial precueing of transient attention improved performance in both gap and vernier resolution tasks. The gaps (Experiments 1 and 2) or the offset direction (Experiment 3) were detected faster and more accurately, and thresholds were lower when observers' attention was directed to the target location beforehand. Indeed, in all three experiments, the cue improved performance for all observers; all 37 observers were faster, and 32 out of the 37 observers were also more accurate, for the cued than the neutral trials. These results are consistent with previous studies which have demonstrated an attentional benefit for a vernier target (Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993; Balz & Hock, 1997), and extend their findings to two gap resolution stimuli (Landolt-square and 'broken-line'), as well as to a situation in which the target was presented in isolation and at a wider range of eccentricities. Likewise, studies showing that after some practice observers are more accurate at performing acuity (Beard, Levi & Reich, 1995) and hyperacuity tasks (Beard, Levi & Reich, 1995; Fahle & Henke-Fahle, 1996) also illustrate that such thresholds are not immutable.

One explanation for precueing effects suggests that the precues encourage observers to adopt a more liberal decisional criterion or to assign more weight to information extracted from the cued location (Kinchla, 1980; Shaw, 1984; Palmer, 1994; Kinchla, Chen & Evert, 1995). This idea is plausible only if the precues imply that one of the optional responses is more probable. For instance, if in a 'yes–no' detection task a precue indicated that the cued location had a high probability of containing the target, it would also indicate higher chances of the target being present, and observers could adopt a liberal criterion regarding information gathered at the cued location. In contrast,

---

[7] A reviewer suggested that the colinearity of the vernier target we used may have enhanced a tendency to perceive an oblique line leaning towards the side of the displacement of the upper segment, which in turn may have diminished the eccentricity effect.

when the precue does not associate higher probability with one of the responses, there is no reason to assign different decisional weights to different locations/responses. In the present study, the precue was not a relevant factor in decision making processes because it always indicated the target location without conveying information about the correct response. This precueing effect indicates, therefore, that the facilitated performance at the cued locations reflects changes in sensory rather then decisional processes.

Different attentional mechanisms have been suggested to be responsible for modulating perceptual discriminability. For instance, several studies have attributed attentional facilitation to an efficient reduction of decisional noise (Cohn & Lasley, 1974; Graham, Kramer & Haber, 1985; Sperling & Dosher, 1986; Palmer, 1994; Shiu & Pashler, 1994, 1995; Kinchla, Chen & Evert, 1995). In some of these studies a near-threshold target has been presented alone and could be confused with the blank at the other locations (Cohn & Lasley, 1974; Graham, Kramer & Haber, 1985) in other studies, a suprathreshold target has been presented with other distractors with which it could be confused (Palmer ety al., 1993; Palmer, 1994; Shiu & Pashler, 1994, 1995; Carrasco & Yeshurun, 1997). These authors have suggested that the precues allow observers to monitor only the relevant location(s) instead of all possible locations. By reducing the number of locations that have to be monitored, the precues reduce the statistical noise that is introduced at these locations. This noise-reduction approach would predict no attentional benefit when a suprathreshold target is presented in isolation because no external noise is presented. Given that in all three experiments of this study a suprathreshold target was presented alone, it could neither be confused with the blank at the other locations nor with distractors (since there were none). Therefore, the present findings suggest that the attentional facilitation reflects more than just an efficient inhibition of the non-relevant information; an enhanced processing of the relevant information must have taken place.

An enhanced processing of the relevant information may result from an improved quality of the stimulus representation corresponding to the cued location. To explain such an improvement different attentional mechanisms have been proposed: One alternative is that attention may modulate perceptual discriminability by reducing the noise in the representation of the relevant stimulus. Attention may reduce the internal noise associated with perceptual processing by decreasing the variance in the perceived quality of the signal (Prinzmetal, Amiri, Allen, Nwachuku, Bodanski, Edwards & Blumenfild, 1997; Prinzmetal, Amiri, Allen & Edwards, 1998). Another attentional mechanism, the one supported by the present study, is that of signal enhancement whereby attention increases the strength of the signal (Bashinski & Bacharach, 1980; Posner, 1980; Downing, 1988; Carrasco & Yeshurun, 1998; Lu & Dosher, 1998).

The idea that attention can affect the quality of the sensory representation agrees with a growing body of physiological evidence (Moran & Desimone, 1985; Spitzer, Desimone & Moran, 1988; Desimone & Ungerleider, 1989; Desimone, Wessinger, Thomas & Schneider, 1990; Motter, 1993; Olshausen, Anderson & Van Essen, 1993; Luck, Hillyard, Mouloua, Woldorff, Clark & Hawkins, 1994; Treue & Maunsell, 1996; Reynolds, Pasternak & Desimone, 1997). For instance, recording event-related potentials (ERP) has shown that spatial precues led to changes in sensory-evoked neural responses from the visual cortex (Luck et al., 1994). Similarly, single-cell recording has demonstrated that directing attention towards the stimulus can alter the responses of V1, V2, and V4 (Motter, 1993), and results in stronger and more selective responses in both V4 neurons (Reynolds et al., 1997; Spitzer et al., 1998) and MT/MST (Treue & Maunsell, 1996) neurons. In the same vein, a recent computational model for attentional modulation of spatial vision suggests that attention strengthens the interactions among visual spatial filters, resulting in both sharpness of tuning and increased gain (Itti, Kock & Braun, 1997).

Given that the three tasks employed in this study were designed to measure spatial resolution, the present findings provide evidence for the hypothesis that attention can improve the sensory representation by enhancing the spatial resolution at the attended location. Physiological studies have shown that in V4 attention contracts the cell's receptive field around the attended stimulus (Moran & Desimone, 1985; Desimone et al., 1990). Because smaller receptive fields allow for better spatial resolution, these findings support the idea that attention can enhance the spatial resolution at the attended location. Note, however, that while performance differences among different retinal locations were reduced in the gap resolution tasks of this study (Experiments 1 and 2), as well as in visual search tasks (Carrasco & Yeshurun, 1998), these differences were not eliminated. Hence, attention may be able to enhance the spatial resolution at the attended location, but it cannot completely overcome the visual limitations underlying these differences.

One possible reason for this constraint on the attentional benefit may be the relatively large size of receptive fields at far eccentricities. According to Balz and Hock (1997), attention may enhance spatial resolution by increasing the sensitivity of small, foveal receptive fields which are responsible for detection of small details. Extending their hypothesis to the periphery, one could suggest that focusing attention at any location increases the sensitivity of the smallest receptive fields of that retinal area. Because the size of the receptive fields increases gradually as retinal eccentricity increases (DeValois & DeValois, 1988) the ability of the attentional mechanisms to increase the spatial resolution may be limited by the size of the smallest receptive fields at the cued location.

In any case, it is reasonable to assume that attentional facilitation in visual tasks reflects a combination of mechanisms such as signal enhancement, distractor exclusion and decisional factors. As we discussed before, the results of this study cannot be explained only by decisional factors or distractor exclusion. Signal enhancement is necessary to account for the present results. Such enhancement could be accomplished by either the contraction of the cells' receptive field or by increased sensitivity of the smallest cells' receptive fields at the cued location. These mechanisms would result in sharpened tuning and increased response selectivity. Further psychophysical and physiological research is required to understand the specific way in which spatial resolution is enhanced, as well as the way in which signal enhancement may interact with distractor exclusion and/or decisional factors.

In conclusion, manipulating transient attention by using an exogenous precue significantly improved observers' performance. They were more accurate and faster in both gap and vernier resolution tasks, even though in all three experiments, the precue did not favor one of the responses, the target was presented alone with no sources of external noise, and the tasks were basic visual tasks aimed at measuring performance limited by spatial resolution. This suggests that the performance improvement at covertly attended locations found in many studies may result, to some extent, from an enhanced spatial resolution at the cued location, and not just from distractor exclusion, diminished uncertainty, or decisional factors. A recent study (Yeshurun & Carrasco, in press) provides convergent evidence for this spatial resolution hypothesis.

Acknowledgements

This study was supported by the National Science Foundation (NYI Grant SBR-9528197) to MC as well as by a predoctoral Summer Fellowship from the GSAS of NYU to YY. We thank the two anonymous reviewers for their comments.

References

Balz, G. W., & Hock, H. S. (1997). The effect of attentional spread on spatial resolution. *Vision Research*, *37*(11), 1499–1510.

Banks, M. S., Sekuler, A. B., & Anderson, S. J. (1991). Peripheral spatial vision: Limits imposed by optics, photoreceptors, and receptor pooling. *Journal of the Optical Society of America*, *8*, 1775–1787.

Barlow, H. B. (1979). Reconstructing the visual image in space and time. *Nature*, *279*, 189–190.

Barlow, H. B. (1981). Critical limiting factors in the design of the eye and visual cortex. *Proceedings of the Royal Society of London B*, *212*, 1–34.

Bashinski, H. S., & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. *Perception and Psychophysics*, *28*, 241–248.

Beard, B. L., Levi, D. M., & Reich, L. N. (1995). Perceptual learning in parafoveal vision. *Vision Research*, *35*, 1679–1690.

Bonnel, A. M., Possamai, C. A., & Schmitt, M. (1987). Early modulation of visual input: a study of attentional strategies. *Quarterly Journal of Experimental Psychology*, *39A*, 757–776.

Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: Target eccentricity affects performance on conjunction searches. *Perception and Psychophysics*, *57*(8), 1241–1261.

Carrasco, M., & Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Research*, *37*(1), 63–82.

Carrasco, M., McLean, T. L., Katz, S. M., & Frieder, K. S. (1998). Feature asymmetries in visual search: Effects of display duration, target eccentricity, orientation and spatial frequency. *Vision Research*, *38*(3), 347–374.

Carrasco, M., & Yeshurun, Y. (1997). Spatial attention improves observers' discrimination. 38*th Annual Meeting of the Psychonomic Society*, *Philadelphia*, *PA*: *Abstracts Psychonomic Society*, *2*, 69.

Carrasco, M., & Yeshurun, Y. (1998). The contribution of covert attention to the set-size and eccentricity effects in visual research. *Journal of Experimental Psychology*: *Human Perception and Performance*, *24*, 673–692.

Cohn, T. E., & Lasley, D. J. (1974). Detectability of a luminance increment: Effect of spatial uncertainty. *Journal of the Optical Society of America*, *64*, 1715–1719.

Curcio, C. A., & Allen, K. A. (1990). Topography of ganglion cells in human retina. *Journal of Comparitive Neurology*, *300*(1), 5–25.

Curcio, C. A., Sloan, K. R., Packer, O., Hendrickson, A. E., & Kalina, R. E. (1987). Distribution of cones in human and monkey retina: Individual variability and radial asymmetry. *Science*, *236*, 579–582.

Davis, E. T., & Graham, N. (1981). Spatial frequency uncertainty effects in the detection of sinusoidal gratings. *Vision Research*, *21*, 705–712.

Desimone, R., & Ungerleider, L. G. (1989). Neural mechanism of visual processing in monkeys. In F. Boller, & J. Grafman, *Handbook of Neuropsychology*. Amsterdam: Elsevier BV, 267–299.

Desimone, R., Wessinger, M., Thomas, L., & Schneider, W. (1990). Attentional control of visual perception: Cortical and subcortical mechanisms. *Cold Spring Harbor Symposia Quantitative Biology*, *LV*, 963–971.

DeValois, R. L., & DeValois, K. K. (1988). *Spatial Vision*. New York: Oxford University.

Downing, C. J., & Pinker, S. (1985). The spatial structure of visual attention. In M. I. Posner, & O. S. M. Marin, *Attention and Performance XI*. Hillsdale, NJ: Erlbaum, 171–187.

Downing, C. J. (1988). Expectancy and visual-spatial attention: effects on perceptual quality. *Journal of Experimental Psychology*: *Human Perception Performance*, *14*, 188–202.

Eagly, R., & Homa, D. (1991). Reallocation of visual attention. *Journal of Experimental Psychology*: *Human Perception and Performance*, *17*, 142–159.

Engel, F. L. (1977). Visual conspicuity, visual search and fixation tendencies of the eye. *Vision Research*, *17*, 95–108.

Enns, J. T., & Rensink, R. A. (1992). *VScope™ software and manual*: *Vision testing software for the Macintosh University of British Columbia*. *Vancouver*, *Canada*: *Micropsych Software*.

Eriksen, C. W., & Hoffman, J. E. (1972). Some characteristics of selective attention in visual perception determined by vocal reaction time. *Perception and Psychophysics*, *11*(2), 169–171.

Eriksen, C. W., & Hoffman, J. E. (1974). Selective attention: Noise suppression or signal enhancement? *Bulletin of the Psychonomic Society*, *4*, 587–589.

Eriksen, C. W., & Rohrbaugh, J. W. (1970). Some factors determining efficiency of selective attention. *American Journal of Psychology*, *83*, 330–342.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics*, *40*, 225–240.

Eriksen, C. W. (1990). Attentional search of the visual field. In D. Brogan, *Visual Search*. London: Taylor and Francis, 3–19.

Fahle, M., & Henke-Fahle, S. (1996). Interobserver variance in perceptual performance and learning. *Investigative Ophtalmology and Visual Science*, *37*(5), 869–877.

Graham, N., Kramer, P., & Haber, N. (1985). Attending to the spatial frequency and spatial position of near-threshold visual patterns. In M. I. Posner, & O. S. Marin, *Attention and Performance XI*. Hillsdale, NJ: Erlbaum.

Itti, L., Kock, C., & Braun, J. (1997). A model for attentional modulation of spatial vision. *Proceedings of Investigative Ophtalmology and Visual Science Suppl*, *38*(4), 5461.

Jonides, J. (1980). Toward a model of the mind's eye's movement. *Canadian Journal of Psychology*, *34*, 103–112.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. B. Long, & A. D. Baddeley, *Attention and Performance IX*. Hillsdale, NJ: Erlbaum, 187–204.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception and Psychophysics*, *43*, 346–354.

Juola, J. F., Bouwhuis, D. G., Cooper, E. E., & Warner, C. B. (1991). Control of attention around the fovea. *Journal of Experimental Psychology*: *Human Perception and Performance*, *17*(1), 125–141.

Kinchla, R. A. (1980). The measurement of attention. In R. S. Nikerson, *Attention and Performance IIX*. Hillsdale, NJ: Erlbaum.

Kinchla, R. A., Chen, Z., & Evert, D. L. (1995). Pre-cue effects in visual search: data or resource limited? *Perception and Psychophysics*, *57*(4), 441–450.

Kitterle, F. L. (1986). Psychophysics of lateral tachistoscopic presentation. *Brain Cognition*, *5*, 131–162.

Kröse, B. J. A., & Julesz, B. (1989). The control and speed of shifts of attention. *Vision Research*, *29*, 1607–1619.

Kurylo, D. D., Reeves, A., & Scharf, B. (1996). Expectancy of line segment orientation. *Spatial Vision*, *10*(2), 149–162.

Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Research*, *25*(7), 963–977.

Lu, Z. L., & Dosher, B. A. (1998). External noise distinguishes attention mechanisms. *Vision Research*, *38*, 1183–1198.

Luck, S. J., Hillyard, S. A., Mouloua, M., Woldorff, M. G., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: Psychophysical and electrophysiological evidence for early selection. *Journal of Experimental Psychology*: *Human Perception and Performance*, *20*(4), 887–904.

Mackeben, M., & Nakayama, K. (1993). Express attentional shifts. *Vision Research*, *33*(1), 85–90.

Martin, G. (1986). Limits of visual resolution. *Nature*, *319*, 540.

Mayfrank, L., Kimmig, H., & Fischer, B. (1987). The role of attention in the preparation of visually guided saccadic eye movements in man. In J. K. O'Regan, & A. Levy-Schoen, *Eye movements*: *From Physiology to Cognition*. New York: North-Holland, 37–45.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, *229*, 782–784.

Motter, B. M. (1993). Focal attention produces spatially processing in visual cortical areas V1, V2, and V4 in the presence of competing stimuli. *Journal of Neurophysiology*, *70*(3), 909–919.

Müller, H. J., & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology*: *Human Perception and Performance*, *15*, 315–330.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1646.

Nazir, T. A. (1992). Effects of lateral masking and pre-cueing on gap resolution in central and peripheral vision. *Vision Research*, *32*, 771–777.

Olshausen, B. A., Anderson, C. H., & Van Essen, D. C. (1993). A neurobiological model of visual attention and invariant pattern recognition based on dynamic routing of information. *Journal of Neuroscience*, *13*(11), 4700–4719.

Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns. In K. R. Boff, L. Kaufman, & J. P. Thomas, *Handbook of Perception and Human Performance*, Vol. 1. New York: Wiley, 1–65.

Pachella, R. G. (1974). The interpretation of reaction time in information processing research. In B. Kantowitz, *Human Information Processing*: *Tutorials in Performance and Cognition*. Hillsdale, NJ: Erlbaum.

Palmer, J. (1994). Set-size effects in visual search: The effect of attention is independent of the stimulus for simple tasks. *Vision Research*, *34*, 1703–1721.

Perry, V. H., & Cowey, A. (1985). The ganglion cell and cone distribution in the monkey retina: Implications for central magnification factors. *Vision Research*, *25*, 1795–1810.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: the role of set for spatial location. In H. L. Pick, & E. J. Saltzman, *Model of Perceiving and Processing Information*. Hillsdale, NJ: Erlbaum.

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology and Genetics*, *109*, 160–174.

Prinzmetal, W., Amiri, H., Allen, K., & Edwards, T. (1998). Phenomenology of Attention: 1. color, location, orientation, and spatial frequency. *Journal of Experimental Psychology*: *Human Perception and Performance*, *24*, 1–22.

Prinzmetal, W., Amiri, H., Allen, K., Nwachuku, I., Bodanski, L., Edwards, T., & Blumenfild, L. (1997). The phenomenology of attention. *Conscious Cognition*, *6*, 372–412.

Prinzmetal, W., Presti, D. E., & Posner, M. I. (1986). Does attention affect visual feature integration? *Journal of Experimental Psychology*: *Human Perception and Performance*, *12*, 361–369.

Remington, R. W., Johnston, J. C., & Yantis, S. (1992). Involuntary attentional capture by abrupt onset. *Perception and Psychophysics*, *51*, 279–290.

Rensink, R. (1990). Toolbox-based routines for Macintosh timing and display. *Behavioral Research Methods Instruments Computing*, *22*, 105–117.

Reynolds, J., Pasternak, T., & Desimone, R. (1997). Attention increases contrast sensitivity of cells in macaque area V4. *Proceedings of Investigative Ophtalmology and Visual Science Suppl*, *38*(4), 3206.

Rijsdijk, J. P., Kroon, J. N., & van der Wilt, G. J. (1980). Contrast sensitivity as a function of position on the retina. *Vision Research*, *20*, 235–241.

Robson, J. G., & Graham, N. (1981). Probability summation and regional variation in contrast sensitivity across the visual field. *Vision Research*, *21*, 409–418.

Rovamo, J., & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research*, *37*, 495–510.

Santee, J. L., & Egeth, H. E. (1982). Do reaction time and accuracy measure the same aspects of letter recognition? *Journal of Experimental Psychology: Human Perception and Performance*, *8*(4), 489–501.

Shaw, M. L., & Shaw, P. S. (1977). Optimal allocation of cognitive resources to spatial locations. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(2), 201–211.

Shaw, M. L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance. In H. Bouma, & D. G. Bouwhuis, *Attention and Performance X*. Hillsdale, NJ: Erlbaum, 109–120.

Shiu, L., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(5), 1037–1054.

Shiu, L., & Pashler, H. (1995). Spatial attention and vernier acuity. *Vision Research*, *35*, 337–343.

Shulman, G. L., & Wilson, J. (1987). Spatial frequency and selective attention to local and global information. *Perception*, *16*, 89–101.

Sperling, G., & Dosher, B. A. (1986). Strategy and optimization in human information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas, *Handbook of Perception and Human Performance*, Vol. 1. New York: Wiley, 1–65.

Spitzer, H., Desimone, R., & Moran, J. (1988). Increased attention enhances both behavioural and neuronal performance. *Science*, *240*, 338–340.

Treue, S., & Maunsell, J. H. R. (1996). Attentional modulation of visual motion processing in cortical areas MT and MST. *Nature*, *382*, 539–541.

Tsal, Y., & Lavie, N. (1988). Attending to color and shape: The special role of location in selective visual processing. *Perception and Psychophysics*, *44*, 15–21.

Van der Heijden, A. H. C., Schreuder, R., & Wolters, G. (1985). Enhancing single-item recognition accuracy by cueing spatial locations in vision. *Quarterly Journal of Experimental Psychology*, *37A*, 427–434.

Westheimer, G. (1982). The spatial grain of the perifoveal visual field. *Vision Research*, *22*, 157–162.

Whitaker, D., Rovamo, J., Macveigh, D., & Mäkelä, P. (1992). Spatial scaling of vernier acuity tasks. *Vision Research*, *32*, 1481–1491.

Wickelgren, W. A. (1977). Speed-accuracy trade-off and information processing dynamics. *Acta Psychologica*, *41*, 67–85.

Yantis, S., & Jonides, J. (1984). Abrupt visual onset and selective attention: evidence from visual search. *Journal of Experimental Psychology Human Perception and Performance*, *10*(5), 601–620.

Yantis, S. (1996). Attentional capture in vision. In A. F. Kramer, M. G. H. Coles, & G. D. Logan, *Converging Operations in the Study of Visual Selective Attention*. Washington DC: American Psychological Association, 45–76.

Yeshurun, Y., & Carrasco, M. (1997). The effects of cueing spatial attention on discrimination tasks. *Investigative Ophthalmology and Visual Science*, *38*, 366.

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature* (in press).