Pergamon

0042-6989(94)00148-0

Vision Res. Vol. 35, No. 3, pp. 337–343, 1995

0042-6989/95 $7.00 + 0.00

Spatial Attention and Vernier Acuity

LING-PO SHIU,* HAROLD PASHLER*

Received 17 February 1994; in revised form 20 July 1994

This study examined whether or not vernier acuity would be improved if the location of a briefly presented vernier stimulus was pre-cued. The vernier target appeared alone, or together with straight lines or ellipses. Effects of spatial pre-cuing were found only when straight line distractors were present. It is suggested that since the straight lines are confusable with the vernier targets, they introduce statistical noise in decision. Precuing the most probable location that contains a target may help by allowing this noise to be excluded.

Spatial uncertainty Selective attention Spatial pre-cues Vernier acuity

INTRODUCTION

Advance information about location often improves the accuracy of perceptual judgments regarding briefly presented target stimuli surrounded by distractor stimuli (e.g. Grindley & Townsend, 1968). This is true even for basic visual acuity tasks. For example, Nakayama and Mackeben (1989) and Mackeben and Nakayama (1993) found that vernier acuity improved when the location of a vernier target (which appeared amongst straight line distrators) was cued in advance. This improvement increased as the interval between a cue and a target display increased from zero to 200 or 300 msec.

These results are often taken to suggest that pre-cuing a location allows attention to be allocated in advance to the cued location, and that attention enhances the processing of any object that appears in that location (e.g. Nakayama & Mackeben, 1989; Posner, 1980). If this is true, spatial pre-cuing should improve acuity even when a vernier stimulus appears alone without distracting stimuli. Alternatively, if the function of spatial attention is to filter out noise, then pre-cuing should have little effects when a vernier stimulus appears alone.

METHODS

The spatial layout of a target display is depicted in Fig. 1. Stimuli were presented on a CRT (NEC Multisync 2A) controlled by an IBM-compatible PC. Figure 1(a) shows a vernier stimulus appearing alone. This stimulus appeared equally often in one of four possible locations at 4°48′ eccentricity from a typical viewing distance of 60 cm. The vernier stimulus was comprised of two straight lines each with a length of 7.2 mm, or 41′15″. The lines were 1-pixel wide. They were separated by a vertical gap of 0.9 mm (5′9″) and offset to either left or right. There were three sizes of offset: 2′9″, 4′18″, or 6′27″. The observers' task was to discriminate the direction of offset. Stimulus luminance was 50 cd/m^2, as measured with a large test field with a pixel density corresponding to that of the vernier targets. The background luminance was 2 cd/m^2.

In the line-distractor condition, the vernier stimulus was accompanied by three straight line distractors, as shown in Fig. 1(b). These straight lines were 87′39″ long and had the same width as the vernier targets.

The temporal sequence of frames on a trial is illustrated in Fig. 2. First, a fixation sign appeared at the center of the screen for 400 msec. It was then removed, and 100 msec later, a location cue appeared for 50 msec. 70 msec after the offset of the cue was a target display which appeared for 83 msec. The target display might contain a single target only (target-alone), or a target with three distractor lines (line-distractor). The target display was immediately replaced by some masks, which were grids formed by three vertical and five horizontal lines. The masks stayed on the screen for 500 msec. In the target-alone condition, there was just a single mask covering the target location. When the target was accompanied by three straight line distractors, all of the four locations were masked.

A major variable manipulated in this study was the validity of the location pre-cue. A transient pre-cue might appear at one of the four possible target locations (two-thirds of the trials) or at the fixation location (one-third of the trials). When the cue appeared at a target location, a target stimulus appeared at the cued location 75% of the times. These were valid trials. For the remaining 25%, the target appeared randomly in one of the three non-cued locations. These were invalid trials. When the cue appeared at fixation, it provided no information regarding the target location. These were considered neutral trials. On the basis of previous reports (e.g. Posner, 1980), it was expected that the valid condition would produce higher accuracy than the

*Department of Psychology 0109, University of California, San Diego, La Jolla, CA 92093, U.S.A. [*Email* lshiu@ ucsd.edu].

neutral condition (i.e. benefit of pre-cuing), which in turn would be more accurate than the invalid condition (i.e. cost of pre-cuing).

The observers were instructed about the validity of the pre-cues before the experiment started. Their task was to discriminate the direction of displacement of the lower line relative to the upper one. They were told to maintain central fixation and not to move their eyes during a trial. The experiment consisted of six sessions. The target-alone condition was given in half of the sessions; the line-distractor condition in the other half. The session order was random. Each session had six blocks of 144 trials (72 valid, 48 neutral, and 24 invalid trials, subdivided into 3 offsets × 2 directions × 4 positions).

Three observers (undergraduates) were paid for their participation. One of them had experience with psychophysics tasks. All had normal or corrected-to-normal vision.

RESULTS

Experiment 1a

Discrimination accuracy in percent correct for each of the observers is shown in Fig. 3(a,b). Each data point was based on between 144 (invalid pre-cues) to 432 (valid pre-cues) observations, pooled over directions of offset. The predicted standard deviations of the binomial distributions with these number of trials range between 2.4% and 4.2%. The standard errors of the between-session variability are quite comparable to these figures, although observer PS showed larger variability than the other two observers.

For all of the observers, discrimination accuracy increased almost linearly with offset size. This is not surprising. More interesting are the pre-cuing effects in the two display conditions. First, consider the case when the target appeared alone. Observer PP was equally accurate in the three cue conditions. SS was most accurate in the neutral condition, followed by the valid and the invalid conditions. PS showed a slightly less regular pattern, and none of the cue conditions was consistently better than the other two. In short, the predicted pattern of valid better than neutral followed by invalid was not found for any of the observers. On the other hand, when three line distractors were present, an advantage of valid pre-cuing is apparent. SS showed a clear pattern of pre-cuing effects in the order of valid, neutral and invalid. So did PP, although the size of the effects was considerably smaller. PS showed basically the same results, except for a drop in the neutral condition with 2′9″ offset size (with below chance performance).*

We also calculated threshold offsets as a function of pre-cuing validity. First, the accuracy scores were transformed into d' using Elliot's Table II in Swets (1964). The d' values were then linearly regressed on offset, with the constraint that the regression line passes through the origin. Offset size at $d' = 1$ was defined as threshold.† The threshold for each of the conditions was listed in Table 1. The threshold values averaged across observers showed little pre-cuing effects when a target appeared alone. On the other hand, both costs and benefits of pre-cuing were evident when a target was surrounded by straight line distractors. These results suggest that the presence of distractors may be critical for producing pre-cuing effects.

It might be argued that spatial pre-cuing is effective but somehow obscured in single-element displays. Perhaps the sudden onset of a target "grasps" attention

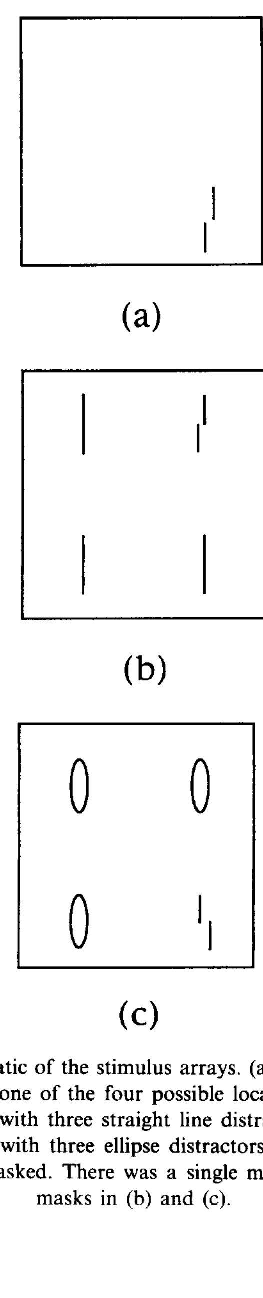

FIGURE 1. Schematic of the stimulus arrays. (a) A vernier stimulus appearing alone in one of the four possible locations. (b) A vernier stimulus appearing with three straight line distractors. (c) A vernier stimulus appearing with three ellipse distractors. The target display was immediately masked. There was a single mask in (a), and four masks in (b) and (c).

*These data, together with those obtained with ellipse distractors discussed later, were analyzed for simple main effects of precuing. We followed the procedure described in Winer (1962, p. 323):

$$F = \frac{MS_{c \text{ at } b_i}}{[MS_{\text{error}(c)} + (q-1)MS_{\text{error}(bc)}]/q}$$

where factor c is precuing validity, factor b is distractor condition and q is the level of factor b. We used the mean squares from a three-way ANOVA with repeated measures on session, distractor, and cue. The results are the same if offset is included as the fourth factor. These tests show that precuing effects were significant ($P < 0.05$) only in the line distractor condition.

†We thank John Palmer for his help with threshold calculations.

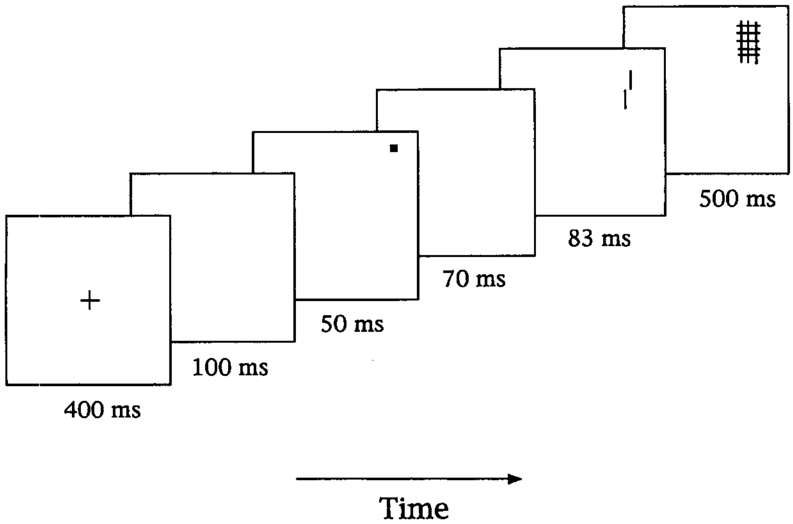

FIGURE 2. The temporal sequence of events on a trial. Illustrated in this figure is a target-alone condition with a valid spatial pre-cue. The target might be accompanied with three straight lines or ellipses. The pre-cues might be valid, neutral or invalid. See text for description.

very quickly if it is the only stimulus on a blank screen. This could conceivably result in advance allocation of attention having minimal effects. To test this, we included a new condition with ellipses as distractors. These distractors were used because, unlike straight lines, they are very dissimilar to a vernier target. We confirmed this with a pilot experiment in which four naive observers were asked to locate a vernier target in the presence of straight lines or ellipses. The viewing conditions of this pilot experiment were the same as those in the preceding experiment. The only change was the response requirement: subjects *localized* the target. The observers made essentially no errors with the ellipse distractors, but many errors with the straight line distractors, confirming that a vernier stimulus "pops out" among ellipses but not among straight lines.

The target display with ellipse distractors was shown in Fig. 1(c). This is a multiple-element display, even though the ellipses are very different from a vernier target. The results are shown in Fig. 3(c) and Table 1.

TABLE 1. Threshold offsets (in min arc) as a function of distractor and pre-cue condition in Expts 1a, 1b, and 1c

		Precues		
Distractors	Observers	Valid	Neutral	Invalid
Experiment 1a				
None	PP	2.86 ± 0.25*	2.53 ± 0.30	2.99 ± 0.32
	SS	1.85 ± 0.13	1.77 ± 0.09	2.09 ± 0.12
	PS	5.08 ± 0.76	4.67 ± 0.53	5.62 ± 0.91
	Mean	3.26	2.99	3.57
Line	PP	3.30 ± 0.40	3.45 ± 0.40	4.13 ± 0.76
	SS	1.74 ± 0.12	1.72 ± 0.12	2.03 ± 0.47
	PS	5.34 ± 0.79	5.56 ± 1.19	5.65 ± 1.13
	Mean	3.50	3.74	4.17
Ellipse	PP	2.80 ± 0.31	3.14 ± 0.36	3.12 ± 0.35
	SS	1.74 ± 0.11	1.72 ± 0.11	2.03 ± 0.11
	PS	6.02 ± 0.40	4.67 ± 0.35	5.15 ± 0.82
	Mean	3.52	3.18	3.43
Experiment 1b				
None	PP	2.26 ± 0.18	2.19 ± 0.17	2.39 ± 0.32
Line	PP	2.36 ± 0.16	2.41 ± 0.18	2.72 ± 0.44
Ellipse	PP	2.64 ± 0.17	2.76 ± 0.25	2.30 ± 0.27
Experiment 1c				
Line	PP	1.97 ± 0.07	2.51 ± 0.22	2.49 ± 0.24

*The regression analyses gave estimates of the SE of the slopes. These values were then used to estimate the SE of the thresholds, by dividing 1 with slope ± SE. This method gave lower and upper bounds of the mean thresholds, but they were not symmetrical around the means. The values in the table are the average of the lower and upper bounds.

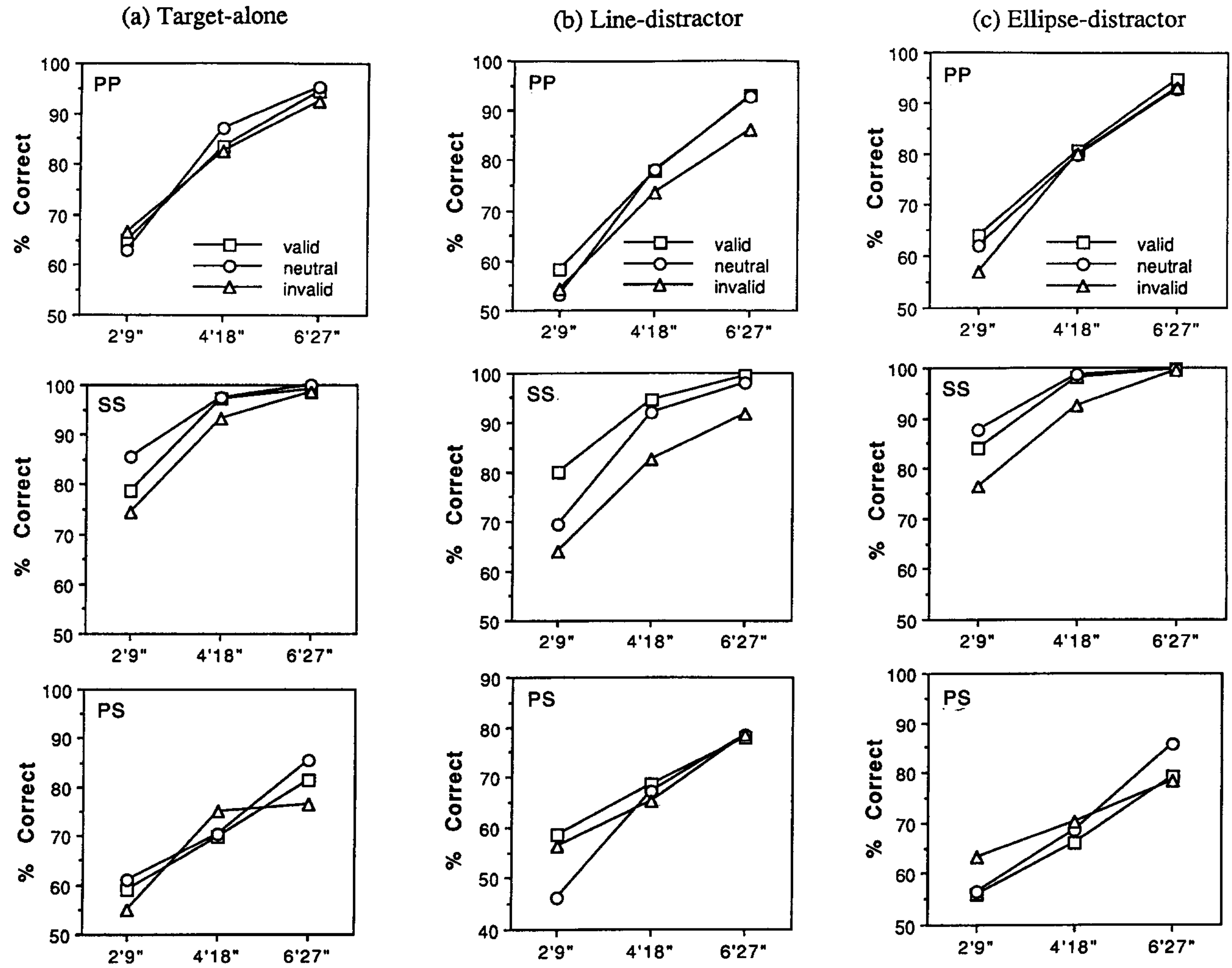

FIGURE 3. Results of the three observers (PP, SS and PS). Each graph shows the percentage of correct discrimination as a function of the size of vernier offset. There were valid (□), neutral (○), and invalid (△) conditions in each graph. (a) Target-alone. (b) Line-distractor. (c) Ellipse-distractor.

There were hardly any consistent pre-cuing effects. These results are in sharp contrast with those found in the condition in which the distractors were straight lines. A rather natural conclusion from these results would be that the similarity of target and distractors, not just the presence of any visual patterns, is critical for obtaining pre-cuing effects.*

Experiment 1b

In the preceding experiment, the distractor conditions were manipulated between sessions. Perhaps observers did not allocate attention as indicated by the cues when they knew that the targets were easy to find (i.e. in target-alone and ellipse-distractor conditions). In Expt 1b, the distractor conditions were mixed within blocks. It was impossible to tell before the target was displayed which distractor condition would occur. This would rule out the possibility of using different pre-planned strategies between distractor conditions.

In this experiment, only observer PP was tested. We also monitored eye movements with horizontal EOG. Signals were picked up by electrodes attached to the left and right temples, and the forehead, filtered with a Coulbourn Model 575-42 EOG/ENG Bandpass Biofilter and amplified on a Coulbourn Model 575-07 Bioamplifier. The data were digitized with a DTC Model DT2801 A/D converter, and transferred to a PC. A computer routine was designed to scan the data in windows of 200 msec. Any changes in the slope of the data within a window greater than a criterion were considered eye movement. This reliably detected horizontal eye movements larger than 1.5°. The trials with eye movement detected were rejected and re-run at the end of the experiment.†

*Since a vernier offset "pops out" among ellipses, it might be argued that the task is done "pre-attentively" and, therefore, could not be benefited by attention allocation. However, this is a confusion of detection and discrimination. Even if the presence of a vernier target among ellipses can be detected pre-attentively, there is no reason to assume that discrimination of the direction of offset can also be achieved pre-attentively (see Kahneman & Treisman, 1984). Consistent with this, Fahle (1991) found that a vernier target with an offset opposite to that of the distractors did not pop out, once the use of orientation cue was prevented by presenting the stimuli at random orientation.

†4% of the trials were re-run because of eye movement.

The results are shown in Fig. 4 and Table 1. They are quite similar to those found in the preceding experiment. Again, spatial pre-cuing effects were not found unless the vernier offsets were surrounded by straight line distractors. The effects were independent of whether the distractor conditions were manipulated between or within blocks.

Experiment 1c

Figure 5 shows the results obtained with modified "straight" line distractors. Each of these distractors was formed by two small aligned line segments vertically separated by the same gap as the vernier stimuli. The results show a larger pre-cuing benefit than that found in the main experiment and Expt 1b (Table 1). Evidently, the more similar the distractors are to the target, the larger the cuing effects.

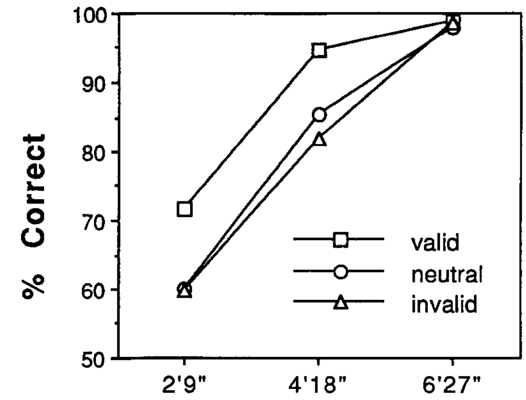

FIGURE 5. Results of observer PP tested with a modified "straight" line distractor condition. The distractors were two small aligned line segments separated by the same vertical gap as a vernier stimulus.

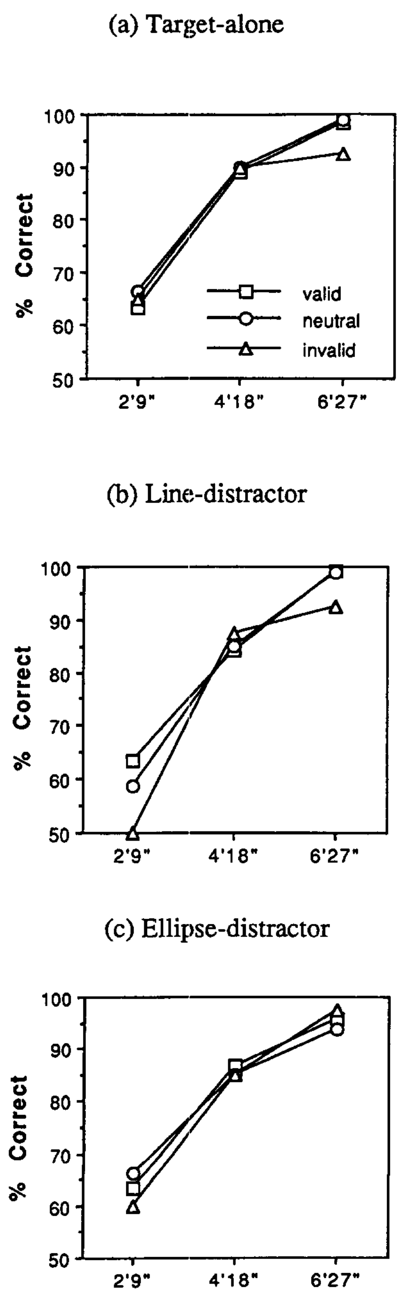

FIGURE 4. Results of Expt 1b, in which the three distractor conditions were mixed within block. Only PP was tested. Eye movement was monitored with EOG. (a) Target-alone. (b) Line-distractor. (c) Ellipse-distractor.

DISCUSSION

If advance location information conveyed by spatial pre-cues leads to differential allocation of attention in space so that a cued stimulus receives enhanced processing, then this stimulus should also enjoy enhanced processing even when it appears alone. Instead, our results show that there was no pre-cuing effect when a target appeared alone, or when the distracting stimuli were unlikely to be confused with a target. An alternative explanation is needed.

Spatial uncertainty and cuing in threshold detection

Before proceeding, it may be useful to consider previous cuing experiments with single targets appearing alone. A well-known study by Cohn and Lasley (1974) reported that the detection threshold for a small spot of light was higher when the location of the light was random than when it was fixed. Their analysis showed that the higher threshold with location uncertainty could be fully accounted for by assuming that monitoring more locations increases statistical noise in decision. That is, the effect of location uncertainty found with human observers was no larger than what would be expected for an ideal observer. Location uncertainty effects have been found in a number of studies involving detection of other kinds of stimuli. Davis, Kramer and Graham (1983) and Graham, Kramer and Haber (1985), for example, reported location uncertainty effects for detection of sinusoidal gratings. In agreement with Cohn and Lasley (1974), these authors found that the uncertainty effects could be accounted for by the inevitable increase in decision noise.

In threshold detection, a target is, by definition of the task, highly confusable with the blank background. Therefore, the background is "noisy", even though the target appears alone. When the target location is fixed, the other irrelevant locations can be excluded from consideration. This exclusion process can either increase the signal-to-noise ratio, or reduce the chances of false alarms, depending on whether decisions are determined by the sum or the maximum of the various inputs. Presumably, cuing the target location in advance when there is more than one possible target location may help detection by allowing similar noise exclusion. Davis *et al.* (1983) used spatial pre-cues in detection of sinusoidal gratings. The pre-cuing benefit they observed was in agreement with what would have been expected on the basis of reduction in decision noise.

Spatial pre-cuing in suprathreshold tasks

When a target is presented at suprathreshold contrast against a blank field, as in the present study, the blank field is not confusable with the target. It is therefore not likely to introduce decision noise. Our results show that under such conditions, location pre-cuing (or reduction in location uncertainty) does not affect performance. Nazir (1992) also found no pre-cuing benefit on gap resolution when a suprathreshold Landolt-ring-like figure was presented alone against a blank field.

On the other hand, we found pre-cuing effects when the vernier targets were surrounded by several straight lines, as did Nayakama and Mackeben (1989) and Mackeben and Nakayama (1993). These results do not necessarily imply that attention enhances the targets, however. Extending the explanation proposed by Cohn and Lasley (1974), Graham *et al.* (1985), and others, one may account for these results by assuming that the straight lines introduce decision noise, which is reduced when location is cued. This is plausible, given that straight lines are quite similar to vernier targets. Furthermore, when very different stimuli are used as distractors (e.g. ellipses), they should not introduce significant noise; hence exclusion of these distractors could not reduce noise. We observed that under such conditions, there were no pre-cuing effects, either. The importance of target-distractor similarity was again shown in Expt 1c, in which even bigger pre-cuing benefit was found when the straight lines were made more similar to the targets by having the same vertical gap.

In this last experiment, the line distractors differed from the vernier target only on the dimension relevant to the discrimination response. This arrangement is similar to the visual search tasks studied by Palmer (1994) and Palmer, Ames and Lindsey (1993). Palmer varied the size of search set and measured how much detection thresholds changed with set size. His decision model, which assumes that distractors introduce decision noise, predicts that the slope of log threshold and log set size would be about 0.25, regardless of stimuli used. This model fits his data well. If it is assumed that in the present experiment, set size is one with valid pre-cues, and four with neutral pre-cues, then the slope of log threshold versus log set size is 0.17. This estimate is within the range of the prediction of Palmer's model. The reason that our slope is small may have to do with the validity of the pre-cues. Our pre-cues have validity of 75% only. Thus, the assumption that set size is one with valid pre-cues most probably under-estimates the set size, and, therefore, gives a smaller slope. Despite this, the present results seem to match well with Palmer's decision model. This suggests that valid pre-cuing may operate in effect by reducing the relevant set size (and hence decision noise).

The noise reduction account assumes that "attention" is an exclusionary mechanism. Exclusion may occur anywhere before decision. Exclusion may or may not improve detection/discrimination, depending on what is there to be excluded. This view does not require the claim that attention enhances the strength of a signal.

This account is also consistent with the finding that there are minimal pre-cuing effects on the accuracy or latency of visual search for a distinct simple feature (e.g. Nakayama & Mackeben, 1989). Here, the target (e.g. a vertical bar) is usually so different from the distractors (e.g. horizontal bars) that they might be processed by non-overlapping channels, so that the distractors would not create decision noise.

Parallel processing of vernier stimuli

Fahle (1991) found that a vernier offset as small as 5′ at 4.5° eccentricity can be detected equally fast regardless of the number of straight line distractors (up to 16) in displays that remained present until response. This indicates that dividing attention over more stimuli did not produce deficit in perception, and that the crowded displays did not produce lateral interference. But with stimulus presentation time limited to 150 msec (and sometimes with backward masks, as in the present study), Fahle found a display size effect on accuracy of detection. Under the latter viewing conditions, discrimination of the vernier stimulus and straight lines is likely to be error-prone. The decrease in accuracy with a larger display set may be completely attributable to an increase in decision noise (see Palmer, 1994; Palmer *et al.*, 1993). If this is the case, then pre-cuing a probable target location in such displays could improve discrimination performance by allowing exclusion of distractors.

Sources of noise

In another recent study, Shiu and Pashler (1994) presented a single digit briefly at suprathreshold contrast against a blank field and masked the digit immediately. Little pre-cuing effects were found, except when there were masks at the irrelevant, non-target locations. It appears then, that the masks, though appearing after the targets, introduced decision noise. This is possible if the perceptual system does not stop sampling information even when the target is turned off, due to temporal uncertainty effects (e.g. Green & Weber, 1980).

The noise reduction hypothesis seems to be able to account for pre-cuing effect (and its absence) with both digits and vernier offsets, though the former are more complex stimuli than the latter. This hypothesis might provide a general framework for understanding spatial pre-cuing effects in visual tasks at very different levels of complexity.

CONCLUSION

There was little or no effect of spatial pre-cuing on vernier acuity when a vernier target was presented well above contrast threshold and alone against an empty background, or when the target appeared among very dissimilar distractors. Pre-cuing effects were found, however, when the target was accompanied by straight line distractors. The effects may be attributable to reduction in decision noise as a result of the non-cued locations being excluded. The results provide no support for the claim that allocation of attention to a position in space can enhance the perceptual analysis of a lone stimulus (Posner, 1980).

REFERENCES

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.

Davis, E. T., Kramer, P. & Graham, N. (1983). Uncertainty about spatial frequency, spatial position, or contrast of visual patterns. *Perception & Psychophysics*, *33*, 20–28.

Fahle, M. (1991). Parallel perception of vernier offsets, curvature, and chevrons in humans. *Vision Research*, *31*, 2149–2184.

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

Green, D. M. & Weber, D. L. (1980). Detection of temporally uncertain signals. *Journal of the Acoustical Society of America*, *67*, 1304–1311.

Grindley, G. C. & Townsend, V. (1968). Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. *Quarterly Journal of Experimental Psychology*, *20*, 11–19.

Kahneman, D. & Treisman, A. (1984). Changing views of attention and automaticity. In Parasuraman, R. & Davies, D. R. (Eds), *Varieties of attention*. Orlando, Fla: Academic Press.

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

Nakayama, K. & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1647.

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

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

Palmer, J., Ames, C. T. & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 108–130.

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

Shiu, L. & Pashler, H. (1994). Negligible effects of spatial pre-cuing on identification of single digits. *Journal of Experimental Psychology: Human Perception and Performance*. In press.

Swets, J. A. (1964). *Signal detection and recognition by human observers*. New York: Wiley.

Winer, B. J. (1962). *Statistical principles in experimental design*. New York: McGraw Hill.

Acknowledgements—This research was supported by a contract from the Office of Naval Research (N00014-91-J-1735). The authors are grateful to MaryLou Cheal, Sheng He, Don MacLeod, Cathleen Moore, and Doug Willen for helpful comments on an earlier draft of this manuscript. John Palmer and an anonymous reviewer gave us valuable suggestions. We also want to thank Marc Becker for assistance with data collection.