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The Effect of Attentional Spread on Spatial Resolution

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The effects of attentional spread were studied by having subjects detect a luminance increment along a row of evenly spaced dots. The increment could occur for the central, fixated dot (Narrow Attention) or for either the fixation dot or one of the four dots to its left or right (Broad Attention). Narrow Attention enhanced the detection of luminance increments for the fixated dot, and also enhanced spatial resolution near the fixation dot for judgments of vernier alignment and separation. This indicated that the sensitivity of small spatial filters in the fovea was increased more by narrowly focused than broadly spread attention. Effects of attentional spread on spatial resolution were not obtained for judgments of the separation between two peripherally located targets, perhaps because of their dependence on eccentricity (position) rather than separation. © 1997 Elsevier Science Ltd.

Attention Luminance increments Spatial resolution Vernier judgments Separation judgments

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INTRODUCTION

Nakayama & Mackeben (1989) and Mackeben & Nakayama (1993) have reported that spatial resolution for a peripheral vernier target can be enhanced by the prior allocation of attention to its location. More recently, however, Shiu & Pashler (1995) have argued that rather than the enhancement of resolution, the beneficial effects of spatial pre-cueing observed by Nakayama and Mackeben were due to the elimination of noise associated with detecting the target in an uncertain location within an array of similar, non-target stimuli (i.e., distractors). The basis for their argument is that if attention was enhancing spatial resolution, pre-cueing effects would be observed regardless of whether there are distractor stimuli in the visual field, and regardless of the similarity of the distractors to the vernier target. Shiu and Pashler found that the validity of a spatial pre-cue affected vernier acuity when the vernier target (two misaligned vertical line segments) was presented in a field with other vertical line segments (as in Nakayama & Mackeben, 1989), but not when it was presented alone or with perceptually distinctive distractors (ellipses).

It is arguable, however, that location pre-cueing effects are not definitive with respect to whether or not attention can influence spatial resolution. When sufficient time is allowed for attentional shifts following a pre-cue, attention can be brought to the location of the target prior to the appearance of the target stimulus. If, however, attention has not been shifted to the target prior to its appearance, additional processing time will be required, either for the attentional shift to be completed, or because the target must be processed with reduced attention. Either of these alternatives is sufficient to result in longer reaction times, reduced detection accuracy, and lower resolution, but they cannot be distinguished by location pre-cueing. That is, performance may be diminished when there is insufficient time allowed for attention to shift to the target (because there is no pre-cue or the pre-cue is invalid), but this does not exclude the possibility that once attention "fully arrives" at the target, it could enhance processing (spatial resolution) as much as when there was a valid pre-cue.

In contrast with experiments involving spatial pre-cueing, the effect of attention on spatial resolution was investigated in this paper under conditions in which there was no need to shift attention to a peripheral target presented among an array of distractors. A single vernier target was presented just below the central, fixation dot, so there was minimal uncertainty regarding the location of the target (Cohn & Lasley, 1974). Rather than pre-cueing specific spatial locations, attention was manipulated by varying the perceiver's spread of attention (Beck & Ambler, 1973; Eriksen & St. James, 1986; Egeth, 1977; LaBerge, 1983; LaBerge *et al.*, 1991). It was either narrowly focused on the fixation dot or broadly spread over an extended spatial region on either side of the fixation dot.

EXPERIMENT 1

As in Posner's classic study (Posner, 1980), subjects were required to detect luminance increments. Attentional spread was manipulated by varying which of the

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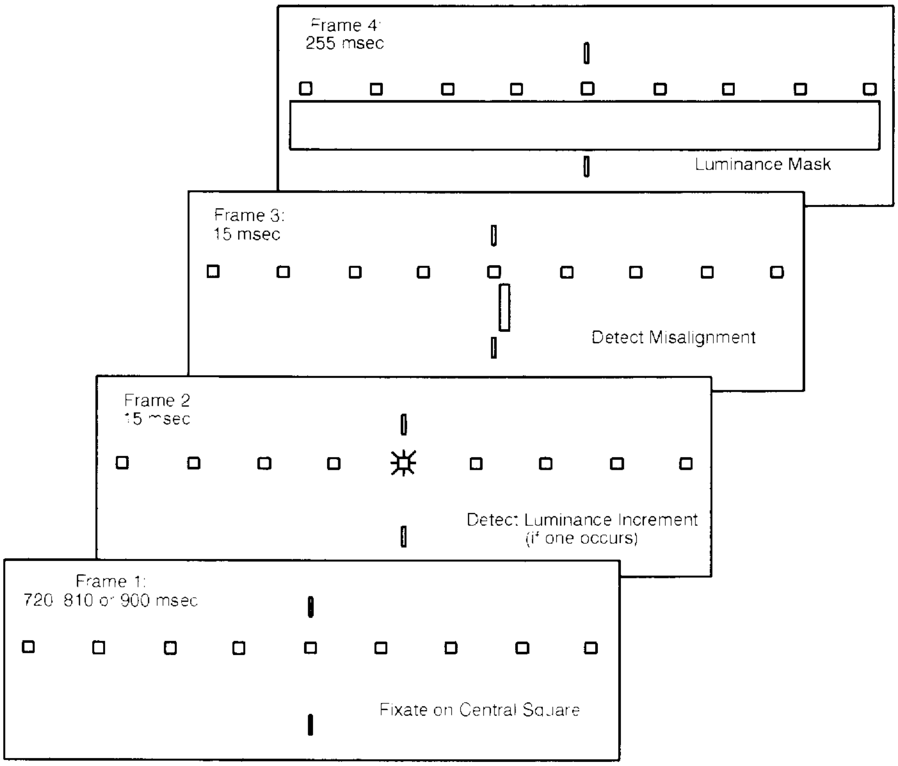

FIGURE 1. The stimuli and the temporal structure for each trial.

dots in a long, evenly spaced row of white dots could change in luminance. This was the primary task in which subjects were instructed to employ their maximum effort. It was accompanied by a secondary, vernier alignment task.

Subjects

Subjects in this experiment and the experiment which follows were students at Florida Atlantic University with normal or corrected-to-normal vision. All but GB (the first author) were naïve with respect to the purpose of the experiments.

Stimuli

The stimuli were white dots and line segments shown on a Macintosh IIcx 13″ color monitor against a full-screen gray background (luminance = 7.9 cd/m^2). Subjects were instructed to fixate on the dot lying between the two vertical, fixation lines. The viewing distance of 126 cm was maintained by a head restraint. Two aligned, vertical line segments (1.0 × 4.8 min; luminance = 21.6 cd/m^2) separated by 29.0 min were presented in the center of the screen. Each trial began with the 720, 810 or 900 msec presentation (randomly determined) of a long (9.8 deg) horizontal row of 19 2.9 × 2.9 min white dots (luminance = 27.1 cd/m^2; dot separation = 30.9 min). The central dot was 5.8 min below the upper fixation line. The luminance of one dot was then increased for 15 msec (on half the trials) and returned to its original luminance value for the remaining 270 msec of the trial. There were no luminance increments for the other half of the trials.

The target for the secondary, vernier alignment task was a vertical white line segment (2.9 × 11.6 min; luminance = 31.9 cd/m^2) presented for 15 msec immediately after the 15 msec interval in which the luminance increment could occur, regardless of whether or not there was a luminance increment. The vernier target, which was the same width as the central, fixation dot, was presented 2.9 min below the row of dots. It was either directly below the central dot or shifted left or right by 0.9, 1.9, 2.9, or 3.9 min (randomly determined). For the final 255 msec of each trial, a large masking stimulus (a 10.0 × 0.27 deg solid white rectangle; luminance = 31.9 cd/m^2) was presented just below the row of white dots and superimposed over the vernier target. The stimuli and the temporal structure for each trial are illustrated in Fig. 1.*

In both the Broad and Narrow Attention conditions, the

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*The experimental design minimized the possibility that vernier acuity would be affected by masking of the central dot (or the vertical line segment below it) by the flanking dots on either side of the fixation dot. The inter-dot distance, 30.9 min, was an order of magnitude greater than the distance over which flanking lines have been found to affect vernier acuity (Westheimer & Hauske, 1975; Levi *et al.*, 1985). Moreover, masking effects occur when flanker-onset follows the onset of the vernier stimulus, optimally by approximately 50 msec (Westheimer & Hauske, 1975; Breitmeyer, 1978): they are not observed when the flanker-onset precedes the onset of the vernier stimulus and are either not observed (Breitmeyer, 1978) or are relatively small (Westheimer & Hauske, 1975) for simultaneous onsets. In Experiments 1 and 2, the onset of the flanking and central dots was simultaneous, preceding the onset of the vernier target by 720–900 msec.

to-be-detected luminance increment occurred on a random basis for 50% of the trials. In the Broad Attention condition the luminance increment, when it occurred, was randomly distributed between the central, fixation dot (20% of the luminance increments) and the eight dots on either side of the central, fixation dot (four dots on the left and right, each with 10% of the luminance increments). Half of the luminance increments for the central dot served as the Broad Attention confirmation check (described below). In the Narrow Attention condition the luminance increment, when it occurred, was randomly distributed between the central fixation dot (90% of the luminance increments) and the two most peripheral positions receiving luminance increments in the Broad Attention condition (the fourth dot, 2.1 deg to the left or right of the central dot, each with 5% of the luminance increments). The luminance increments for the peripheral dots served as the Narrow Attention confirmation check (described below).

Procedure

At the start of every 20 trials the subject was reminded of the required attentional spread by a static display (duration controlled by subject key press) of the row of dots with either the center dot brightly illuminated (Narrow Attention condition) or the central nine dots brightly illuminated (Broad Attention condition). Subjects were instructed to maintain fixation on the central dot (the dot between the vertical fixation lines) prior to and throughout each trial, and to maintain their attentional spread (Narrow or Broad) throughout the trial. They did not respond until the end of each trial. If a luminance change was detected, subjects responded "yes" (by pressing a designated key on the Macintosh keyboard); otherwise they responded "no" by pressing another key. Then, using the same keys, they responded "yes" if they clearly detected that the white line segment was misaligned with the central luminance-detection dot and "no" otherwise.

Audio feedback was provided to help subjects maintain a level of luminance detection close to their calibration values (defined in the next paragraph), as well as the required attentional spread. A brief tone sounded when subjects wrongly indicated a luminance increment (false alarm) or when they failed to detect an actual luminance increment (miss). Subjects were instructed to keep their false alarm errors to a minimum. For the Broad Attention condition, if the subject failed to detect luminance increments in either of the two leftmost or two rightmost locations on either side of center, the tone sounded twice. Feedback was not provided when subjects failed to detect the small percentage of luminance increments associated with the Narrow and Broad Attention confirmation checks.

Calibration

Subjects were individually calibrated with respect to the detection of luminance increments for approximately 12 sessions prior to the start of the experiment. Increments that were detectable on 75% of the trials (hit rate = 75%) were determined at each of the nine possible dot locations for the Broad Attention condition, and at the one, central location, for the Narrow Attention condition.

Narrow attention confirmation check. In order to confirm that the Narrow Attention condition was achieving its intended effects on the perceiver's distribution of attention, 10% of the luminance changes in the Narrow Attention condition occurred for the dots that were the most peripheral in the Broad Attention condition (either +2.1 or −2.1 deg from center, randomly selected). The size of the luminance increment for these dots was the value the subject detected on 75% of the trials in the final calibration of the Broad Attention condition. Subjects were told to expect occasional peripheral luminance changes, but to be primarily concerned with luminance changes of the central, fixation dot. That subjects were indeed focusing their attention on the central dot in the Narrow Attention condition was confirmed if their detection rates for the +2.1 and −2.1 deg peripheral dots were lower than their detection rates for the same luminance increment in the Broad Attention condition.

Broad attention confirmation check

In order to confirm that the Broad Attention condition was achieving its intended effects on the perceiver's distribution of attention, 10% of the luminance increments in the Broad Attention condition occurred for the center dot at the value which the subject detected on 75% of the trials in the final calibration of the Narrow Attention condition. Confirmation that subjects were indeed spreading their attention in the Broad Attention condition was obtained if their detection rate for the central dot was lower for this luminance increment than the detection rate obtained in the Narrow Attention condition.

Design

There were four testing sessions, each with one block of Narrow Attention trials and one block of Broad Attention trials (their order was alternated during successive sessions). Each block was composed of 11 sub-blocks of 20 order-randomized trials. The horizontal shift of the vernier target relative to the central dot was 0, 0, +0.9, −0.9, +1.9, −1.9, +2.9, −2.9, +3.9 or −3.9 min. Each was presented twice per sub-block, once accompanied by a luminance increment, once not. The conditions of the luminance-increment detection task and the position of the vernier target were uncorrelated. The data for the initial 20 trials were deleted from the final data tabulation.

Results: luminance increments

Correct detection. Each set of graphs in Fig. 2 presents the luminance increments for each subject that resulted in 75% detection accuracy at the conclusion of the pre-experimental, calibration phase. Directly above each

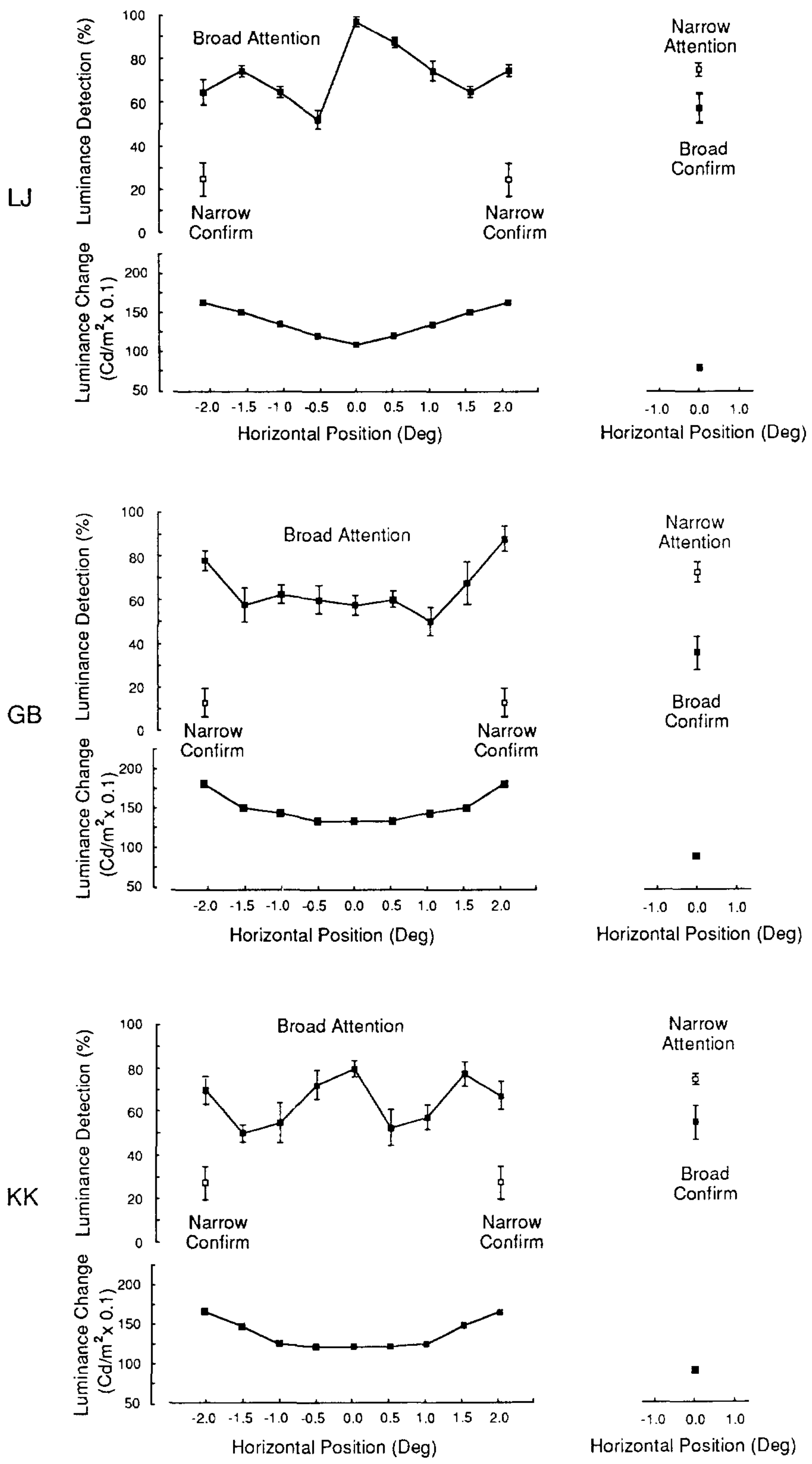

FIGURE 2. Experiment 1: The luminance increments for each subject that resulted in 75% detection accuracy during the pre-experimental, calibration phase. Directly above each luminance-increment is the detection rate for that increment in the Narrow and Broad Attention conditions of the experiment, including the Broad and Narrow confirmation trials (see text).

luminance increment is each subject's detection (hit) rate for that increment in the Narrow and Broad Attention testing conditions. It can be seen that with the exception of the confirmation trials, the 75% detection rate was maintained in the Broad and Narrow Attention conditions. It can also be seen that equal peripheral luminance increments were detected more readily in the Broad Attention condition than for the Narrow Attention confirmation check, whereas equal central luminance increments were detected more readily in the Narrow

Attention condition than for the Broad Attention confirmation checks (all differences were substantially greater than the standard error of measurement for all three subjects). Thus, subjects focused their attention sufficiently in the Narrow Attention condition to reduce their detection of peripheral luminance increments and spread their attention sufficiently in the Broad Attention condition to reduce their detection of luminance increments of the central, fixation dot.

False alarms. The frequency with which subjects incorrectly indicated that they detected a luminance increment when the dot-luminance remained constant was greater in the Narrow than the Broad Attention condition, particularly for subject KK (Table 1). This difference may have been due to the 15 msec flash of the vernier target inducing a perceptual luminance change in the nearby central dot. If this was the case, the induced change of the central dot would be more likely to be noticed in the Narrow than in the Broad Attention condition, resulting in more false alarms for the former (such induced luminance changes, if they occurred, were apparently indistinguishable from actual luminance changes).

d'. It is also possible, however, that rather than induced perceptual changes in luminance, the difference in false alarms reflected differences in response criteria in the Narrow and Broad Attention conditions. That is, subjects may have been more disposed to respond "yes" in the Narrow than the Broad Attention condition. A signal detection analysis was performed in order to evaluate whether such differences in response criteria could account for the critical Narrow/Broad differences in luminance detection. *d'* values based on the correct detection (hit) and false alarm rates (Swets, 1964) provided a criterion-free measure of sensitivity to luminance increments. It can be seen in Table 1, again for all three subjects, that *d'* for the same luminance increment of the central dot was greater for the Narrow Attention than the Broad Confirmation trials. It also can be seen in Table 1, for all three subjects, that *d'* for the same luminance increment of the peripheral dots (±2.1 deg) was greater for the Broad Attention than the Narrow Confirmation trials.

In the above analysis, it was assumed that the false alarm rates were the same for the central and peripheral dots (one rate for the Narrow Attention condition, another for the Broad Attention condition). A further analysis was performed for the peripheral dots in order to account for the possibility that the distribution of false alarms in the Narrow Attention condition reflected the substantial discrepancy in probability of luminance change for the central vs the peripheral dots (0.9 vs 0.1). That is, if subjects were not sure whether or not they detected a luminance change, they may have hesitated to respond "yes" when they thought that a peripheral dot might have changed because they were aware that such changes occurred infrequently. Assuming that false alarms occurred for "possibly-detected-luminance-changes" of the central and peripheral dots in the same 9:1 ratio as the probabilities of luminance change, *d'* values were recomputed on the basis of modified false alarm rates for the Narrow Confirmation trials (peripheral dots). As can be seen in Table 2, *d'* for the peripheral dots remained greater for the Broad Attention than the Narrow Confirmation trials (the effect of modifying false alarm rates to reflect the 0.9 probability of a luminance change for the central dots was negligible). It was concluded, therefore, that the Broad/Narrow Attention conditions differed with respect to their effects on perceivers' *sensitivity* to central vs peripheral luminance increments rather than differences in response criteria.

Results: vernier alignment

Psychometric functions. The proportion of trials for which subjects reported that the central dot and target line were misaligned is plotted as a function of vernier misalignment in Fig. 3. These psychometric functions, given separately for the two attention conditions, are based on averaged judgments across the luminance-increment and no-luminance increment conditions of all three subjects. Overall levels of vernier acuity were poorer than typically observed (e.g., Westheimer, 1975), probably because of the brief, 15 msec presentation of the target line (Hadani *et al.*, 1984; Watt, 1987). Measures of performance were computed by fitting a cumulative normal distribution to the psychometric function derived from each subject's judgments. Using probit-computed coefficients, 50% detection rates and JNDs (just-noticeable-differences) based on the slope of the line defined by the 25% and 75% detection rates were calculated (illustrated in Fig. 3).

The stimulus misalignments resulting in 50% detection reflected subjects' ability to detect misalignment, but were potentially influenced by their response criterion. For example, if subjects were strongly biased to respond that the target line and central dot were misaligned, the psychometric functions illustrated in Fig. 3 would have been shifted sharply to the left. Thus, differences in misalignment detection for the Narrow and Broad Attention conditions were potentially confounded with differences in response criteria.

In contrast, the inverse of the slope of the psychometric function (the difference threshold, or JND) provides a criterion-free measure of spatial resolution. It remains the same regardless of whether differences in response criterion shift the psychometric function to the left or right. The JND measures the extent to which subjects' "misalignment" judgments differentiated between different degrees of misalignment; the greater the JND, the lower the perceiver's spatial resolution (i.e., a larger stimulus difference is required in order to produce an equal difference in "misaligned" responses).

50% detection. Narrow/Broad differences in response criterion for the vernier judgments could potentially have resulted from effects associated with the luminance-increment detection task. For example, broadly spread attention could have resulted in a greater tendency to respond "no" in the vernier task if confidence in

TABLE 1. False alarm rates and d' for the luminance-detection task of Experiment 1

	LJ	GB	KK
		False alarms (%)	
Narrow Attention (N)	12.3	9.9	18.4
Broad Attention (B)	8.8	8.6	8.9
		d' for central dot	
Narrow Attention (N)	1.83	1.87	1.58
Broad Confirm (Bc)	1.55	1.03	1.48
N–Bc	0.28	0.84	0.10
		d' for peripheral dots	
Broad Attention (B)	1.87	2.35	1.85
Narrow Confirm (Nc)	0.53	0.11	0.33
B–Nc	1.34	2.24	1.52
		d' for peripheral dots (based on modified false alarm rates)	
Broad Attention (B)	1.87	2.35	1.85
Narrow Confirm (Nc)	1.57	1.14	1.47
B–Nc	0.30	1.21	0.38

d' values confirm that sensitivity to luminance increments for the central dot was better in the Narrow than the Broad Attention condition, and vice versa for sensitivity to luminance-increments of the peripheral dots (±2.1 deg). Also included are d' values assuming that false alarms in the Narrow Attention condition are distributed in proportion to the probability of luminance increments for the central dot (0.9) and the peripheral dots (0.1)

misalignment judgments was reduced because luminance-increment detection seemed more effortful in the Broad than the Narrow Attention condition. However, it can be seen in Table 2 that Narrow/Broad differences in the stimulus-misalignment resulting in 50% detection were small for subjects LJ and KK, and less than the standard errors derived from the fit of their data to cumulative normal distributions. Although the Narrow/Broad differences were larger for GB, they too were small with respect to the standard error. Thus, differences in response criterion between the Narrow and Broad Attention conditions were, at best, minimal (excluding the unlikely possibility that differences in response criteria were compensated for by differences in the detectability of misalignment; i.e., subjects were better able to detect misalignment in one of the attention conditions, but were biased in that condition to respond that the dot and line were aligned).

Just-noticeable-differences. For the Narrow as well as the Broad Attention condition, spatial resolution, as measured by the inverse of the slope of the psychometric function, or JND, was higher (JNDs were smaller) for trials in which there was no luminance increment compared with trials for which there was a luminance increment (Table 2). That is, a smaller increase in stimulus misalignment was sufficient to produce an equal increase in "misaligned" responses in the no-luminance-increment compared with the luminance-increment condition. The interfering effect of changing the luminance of the central dot may have been due to the momentary loss of attention following the luminance increment (Raymond *et al.*, 1992), but if there was such an attentional "blink", it occurred over a much briefer interval than has previously been observed (the vernier target was presented for 15 msec immediately following the luminance increment, and then masked). Alternatively, transients produced by the sudden onset of the luminance-increment could have reduced spatial resolution in the vernier task by momentarily reducing the sensitivity of high spatial frequency channels (Breitmeyer & Julesz, 1975). The latter would be consistent with evidence that vernier acuity can be reduced when the high spatial frequency content of vernier stimuli is reduced by blurring (Stigmar, 1971; Toet *et al.*, 1987; but see also Williams *et al.*, 1984).

JNDs were, on average, 73% larger in the Broad than the Narrow Attention condition, indicating higher spatial resolution for the latter (Table 2). Although the effect of the luminance change on vernier judgments indicated that there was some interaction between the luminance detection and vernier alignment tasks (see preceding paragraph), the Narrow/Broad difference in JNDs was greater than the standard error for each of the three subjects, with and without the occurrence of the luminance increments (although somewhat reduced for the latter). Obtaining smaller JNDs in the Narrow Attention condition on trials for which there was no luminance increment indicated that it was the perceivers' prior preparation for the luminance increment that affected their spatial resolution. Although unlikely, it remained possible that additional benefits to resolution in the Narrow Attention condition resulted from the frequent luminance charges of the central dot pre-cueing the location of the vernier target; the attentional shift required to benefit from the pre-cue would have had to be extremely fast, within 15 msec. If nonetheless there was a pre-cueing benefit, it was obscured by other factors (possibly attentional blinks or transient effects on the sensitivity of high spatial frequency channels) that resulted in lower resolution on trials with a luminance increment than trials with no luminance increment.

TABLE 2. Experiment 1: Probit-based just-noticeable differences (JNDs) and misalignments resulting in 50% detection for vernier alignment task in the Narrow and Broad Attention conditions

	JND (arc min)				Misalignment for 50% detection (arc min)			
	LJ	GB	KK	Means	LJ	GB	KK	Means
				Trials with luminance increment				
Narrow (N)	1.42	1.17	1.20	1.26	1.88	1.11	2.43	1.81
	(0.10)	(0.09)	(0.09)	(0.09)	(1.09)	(0.35)	(1.62)	(1.02)
Broad (B)	1.73	4.36	1.64	2.58	1.96	1.51	2.31	1.93
	(0.13)	(0.59)	(0.13)	(0.28)	(1.17)	(0.92)	(1.50)	(1.20)
B−N	0.31	3.19	0.44	1.31	0.08	0.40	−0.12	0.12
				Trials with no luminance increment				
Narrow (N)	0.94	1.04	0.95	0.98	1.77	0.94	2.17	1.63
	(0.07)	(0.09)	(0.08)	(0.08)	(0.97)	(0.19)	(1.37)	(0.84)
Broad (B)	1.19	2.23	1.10	1.51	1.85	1.85	2.08	1.93
	(0.09)	(0.19)	(0.08)	(0.12)	(1.05)	(1.09)	(1.28)	(1.14)
B−N	0.25	1.20	0.15	0.53	0.08	0.92	−0.09	0.30

Standard errors of measurement (in parentheses) are derived from the Probit-fits to the psychometric functions.

EXPERIMENT 2

In this experiment, subjects judged the horizontal separation between two parallel, vertical line segments rather than the alignment of the central dot with a vertical line segment. The experiment tested whether the effects of Narrow vs Broad Attention on central spatial resolution would be obtained for separation as well as vernier judgments, and whether the effects of attentional spread on spatial judgments would extend to locations that were relatively far from the point of fixation.

Method

Stimuli. Instead of a single vernier target, two white vertical line segments (2.9 × 11.6 min; luminance = 31.9 cd/m^2) were presented simultaneously for 15 msec immediately after the 15 msec interval in which the luminance increment could occur. The lines were presented alongside each other and symmetrically centered 2.9 min below the central dot of the row of luminance-detection dots. There were three sets of nine inter-line separations. For the "small" set, the nine inter-line separations ranged from 7.7 to 23.2 min in nine increments of 1.9 min; the middle value, 15.5 min (0.26 deg), corresponded to the mean separation. For the "intermediate" set, the nine separations ranged from 38.6 to 115.9 min in increments of 9.7 min; the middle value, 77.3 min (1.29 deg) corresponded to the mean separation. Finally, for the "large" set, the nine separations ranged from 77.3 to 231.8 min in increments of 19.3 min; the middle value, 154.6 min (2.58 deg), corresponded to the mean separation). A large white rectangle (10.0 × 0.27 deg; luminance = 31.9 cd/m^2) masked the line segments for the final 255 msec of each trial.

Procedure. Attentional spread was manipulated with the luminance-increment detection task, as in Experiment 1. After each trial, subjects again indicated whether or not they detected a luminance increment, but now their second response indicated whether the horizontal separation between the vertical line segments was larger or smaller than the average for the group of nine inter-line separations (as in Burbeck & Yap, 1990). Subjects were familiarized with each set of separations during numerous practice sessions prior to starting the experiment.

Design. There were 12 testing sessions (each with one block of Narrow Attention and one block of Broad Attention trials), four sessions for each of the three sets of inter-line separations. The order of testing for the three "separation sets" was Latin-Square counterbalanced over the 12 testing sessions and three subjects, and the order of the Narrow/Broad blocks was alternated during successive sessions. Each block of trials consisted of 11 sub-blocks of 20 trials. The nine separations in each set were presented twice (except the mean separation, which was presented four times) in each order-randomized sub-block of 20 trials. Ten of the trials in a sub-block incorporated a luminance increment and 10 did not. The conditions of the luminance-increment detection and the separation judgment task were uncorrelated. The data for the initial 20 trials were not included in the final data tabulation.

Results: luminance increments

Correct detection. The results for the luminance-increment detection task were as in Experiment 1. With the exception of the confirmation trials, detection (hit) rates were close to 75% for all three subjects in the Narrow Attention condition and each of the nine locations in the Broad Attention condition. Only the results for the confirmation checks (the central and ±2.1 min dot-locations) are presented in Fig. 4. For each set of separations, peripheral luminance increments were detected more readily in the Broad Attention condition than for the Narrow Attention confirmation checks, whereas central luminance increments were detected more readily in the Narrow Attention condition than for the Broad Attention confirmation checks (all differences were substantially greater than the standard error of measurement for all three subjects). Thus, subjects

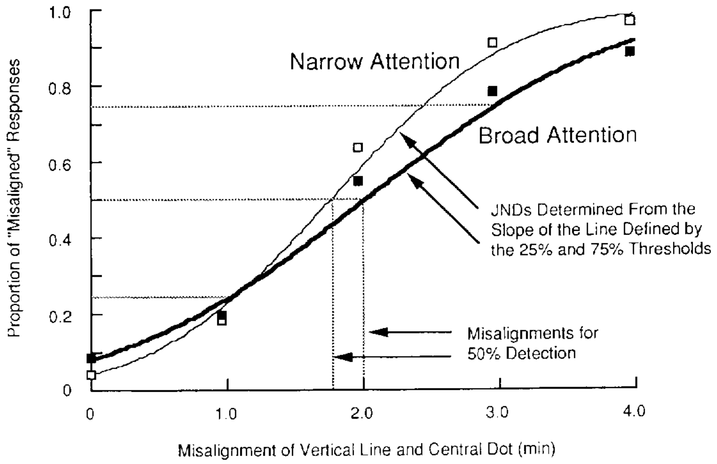

FIGURE 3. Experiment 1: Psychometric functions fit to mean "misaligned" judgments across subjects for the Narrow and Broad Attention conditions.

focused their attention sufficiently in the Narrow Attention condition to reduce their detection of peripheral luminance increments and spread their attention sufficiently in the Broad Attention condition to reduce their detection of luminance increments of the central, fixation dot.

False alarms. The distribution of false alarms (Table 3) was consistent with the possibility, proposed in Experiment 1, that briefly presented vertical line segments induced perceptual changes in the luminance of the dots above them. Assuming this was the case, when the vertical line segments were presented centrally (the set of "small" separations), induced luminance changes of the central dot were noticed more often (there were more false alarms) in the Narrow Attention condition (as in Experiment 1). However, when the vertical line segments were presented peripherally (the sets of "intermediate" and "large" separations), induced luminance changes of peripheral dots were noticed more often (there were more false alarms) in the Broad Attention condition.

d′. As in Experiment 1, it was possible that the differences in false alarms reflected differences in response criteria in the Narrow and Broad Attention conditions rather than induced perceptual changes in luminance. However, an explanation of the results in these terms would lead to the unlikely conclusion that Narrow/Broad differences in response criteria reversed as the average "inter-line" separation was increased. Furthermore, a signal detection analysis (Table 3) indicated that for all three subjects and all three sets of separations, *d′* for the same luminance increment of the central dot was greater for the Narrow Attention than the Broad Confirmation trials, and *d′* for the same luminance increment of the peripheral dots (±2.1 deg) was greater for the Broad Attention than the Narrow Confirmation trials.

TABLE 3. Experiment 2: False alarm rates for the luminance-detection task for the sets of small, intermediate, and large inter-line separations

	Small separations			Intermediate separations			Large separations		
	LJ	GB	KE	LJ	GB	KE	LJ	GB	KE
				False alarms (%)					
Narrow Attention (N)	12.8	10.8	15.0	6.3	6.5	8.3	4.3	4.3	7.3
Broad Attention (B)	9.5	8.0	13.0	12.5	9.8	19.5	17.8	16.5	22.5
				d′ for central dot					
Narrow Attention (N)	1.98	2.37	1.68	2.48	2.64	2.22	2.60	2.56	2.29
Broad Confirm (Bc)	1.51	0.63	1.08	1.68	0.41	1.36	1.45	0.39	−0.90
N−Bc	0.47	1.74	0.60	0.80	2.23	0.86	1.15	2.17	3.17
				d′ for peripheral dots					
Broad Attention (B)	1.99	2.58	1.71	2.20	2.06	1.42	1.53	1.10	1.53
Narrow Confirm (Nc)	0.99	0.23	0.27	1.06	0.70	−0.67	0.68	0.440	0
B−Nc	1.34	2.24	1.52	1.14	1.36	2.09	0.85	0.66	1.53
				d′ for peripheral dots (based on modified false alarm rates)					
Broad Attention (B)	1.99	2.58	1.71	2.20	2.06	1.42	1.53	1.10	1.53
Narrow Confirm (Nc)	2.06	1.28	1.40	1.85	1.52	0.27	1.28	1.04	0
B−Nc	−0.07	1.30	0.31	0.35	0.54	1.15	0.25	0.06	1.53

d′ values confirm that sensitivity to luminance increments for the central dot was better for Narrow than Broad attention, and vice versa for sensitivity to peripheral (±2.1 deg) luminance increments. Also included are *d′* values based on the assumption that false alarms in the Narrow Attention condition are directly proportional to the probability of luminance increments for the central (0.9) and the peripheral dots (0.1).

TABLE 4. Experiment 2: Probit-based just-noticeable differences (JNDs) and inter-line separations resulting in 50% "larger/smaller than average" responses in the Narrow and Broad Attention conditions

	JND				Inter-line separation for 50% larger/smaller responses			
	LJ	GB	KE	Means	LJ	GB	KE	Means
Mean inter-line distance = 0.26 deg								
Narrow (N)	1.68	1.84	1.60	1.71	1.06	1.12	1.23	1.14
	(0.16)	(0.17)	(0.16)	(0.16)	(0.20)	(0.21)	(0.25)	(0.22)
Broad (B)	2.24	2.84	2.18	2.42	1.03	1.20	1.24	1.16
	(0.19)	(0.24)	(0.21)	(0.22)	(0.17)	(0.21)	(0.23)	(0.21)
B–N	0.56	1.00	0.58	0.71	-0.03	0.08	0.01	0.02
Mean inter-line distance = 1.29 deg								
Narrow (N)	1.87	1.92	1.53	1.77	1.03	1.07	1.04	1.05
	(0.17)	(0.18)	(0.15)	(0.15)	(0.19)	(0.20)	(0.20)	(0.18)
Broad (B)	2.16	2.81	1.81	2.26	1.05	1.09	1.10	1.08
	(0.18)	(0.22)	(0.16)	(0.18)	(0.18)	(0.17)	(0.20)	(0.18)
B–N	0.29	0.89	0.28	0.49	0.02	0.02	0.06	0.03
Mean inter-line distance = 2.58 deg								
Narrow (N)	1.32	0.88	0.87	1.02	0.49	0.50	0.51	0.50
	(0.11)	(0.08)	(0.08)	(0.09)	(0.08)	(0.09)	(0.10)	(0.09)
Broad (B)	1.40	0.67	0.95	1.01	0.50	0.48	0.51	0.50
	(0.11)	(0.07)	(0.09)	(0.09)	(0.08)	(0.10)	(0.09)	(1.17)
B–N	0.08	−0.21	0.12	−0.01	0.01	−0.02	0.00	0.00

The JNDs (which are multiplied by 10) and the 50% separations are divided by the mean inter-line distance for each set. Standard errors of measurement (in parentheses) are derived from the Probit-fits to the psychometric functions.

A further analysis was based on the possibility that the distribution of false alarms in the Narrow Attention condition reflected the substantial discrepancy in probability of luminance change in the central vs the peripheral dots (0.9 vs 0.1). It indicated (Table 3) that d' for the peripheral dots remained greater for the Broad Attention than the Narrow Confirmation trials in all cases but the "small" separations for subject LJ (for the latter, however, the detection of equal luminance increments of the central dot remained better for the Narrow Attention condition than the Broad Confirmation trials). With this one possible exception, it could be concluded that the Broad/Narrow Attention conditions differed with regard to their effect on the perceiver's sensitivity to central and peripheral luminance increments, rather than differences in response criterion.

Results: separation judgments

Psychometric functions were obtained based on the proportion of trials for which subjects reported that an inter-line separation was larger than the average of its set. Probit fits determined the separations that resulted in 50% "larger than average" responses and JNDs measured the extent to which subjects' "larger than average" responses differentiated between different separations. The 50% point represented the boundary separating the larger and smaller separations within each set and the JND, or difference threshold, represented subjects' ability to resolve differences in separation near the boundary.

50% boundary. The separation resulting in 50% "larger than average" responses for each subject was divided by the mean separation for each set, so values of 1.0 would indicate that the perceptual boundary was at the mean separation (Table 4). This was the case for the sets of "small" and "intermediate" separations (the boundary shift for the "small" set was less than the standard error derived from the fit to the psychometric function). However, the boundary for the "large" set shifted toward the larger separations; values somewhat smaller than the mean of the set were consistently judged as larger than the mean (the boundary shift was much larger than the standard error for all three subjects). There were, however, no significant Narrow/Broad effects on the boundary for all three sets of separations (differences were less for each subject than the standard error).

Just-noticeable-differences. Spatial resolution is reported in Table 4 as the ratio of the JND to the mean inter-line separation for each set of inter-line separations. For the set of "small" separations, JNDs were, on average, 42% larger in the Broad than the Narrow Attention condition. This difference was greater than the standard error for all three subjects (including LJ, whose Broad Confirmation trials, like those of GB and KE, indicated that her attention was more centrally focused in the Narrow compared with the Broad Attention condition). This higher spatial resolution for the Narrow Attention condition was consistent with the enhancement of spatial resolution near fixation that was observed for vernier alignment judgments in Experiment 1. However, the effect of attentional spread was diminished when the to-be-judged vertical lines were moved away from the focus of narrow attention. That is, the Narrow/Broad difference in JND was reduced for the set of "intermediate" separations (differences were small relative to the standard error for two of the three subjects), and was eliminated for the set of "large" separations (there was a tendency in the opposite direction for one subject). If the Narrow/Broad difference in spatial resolution observed

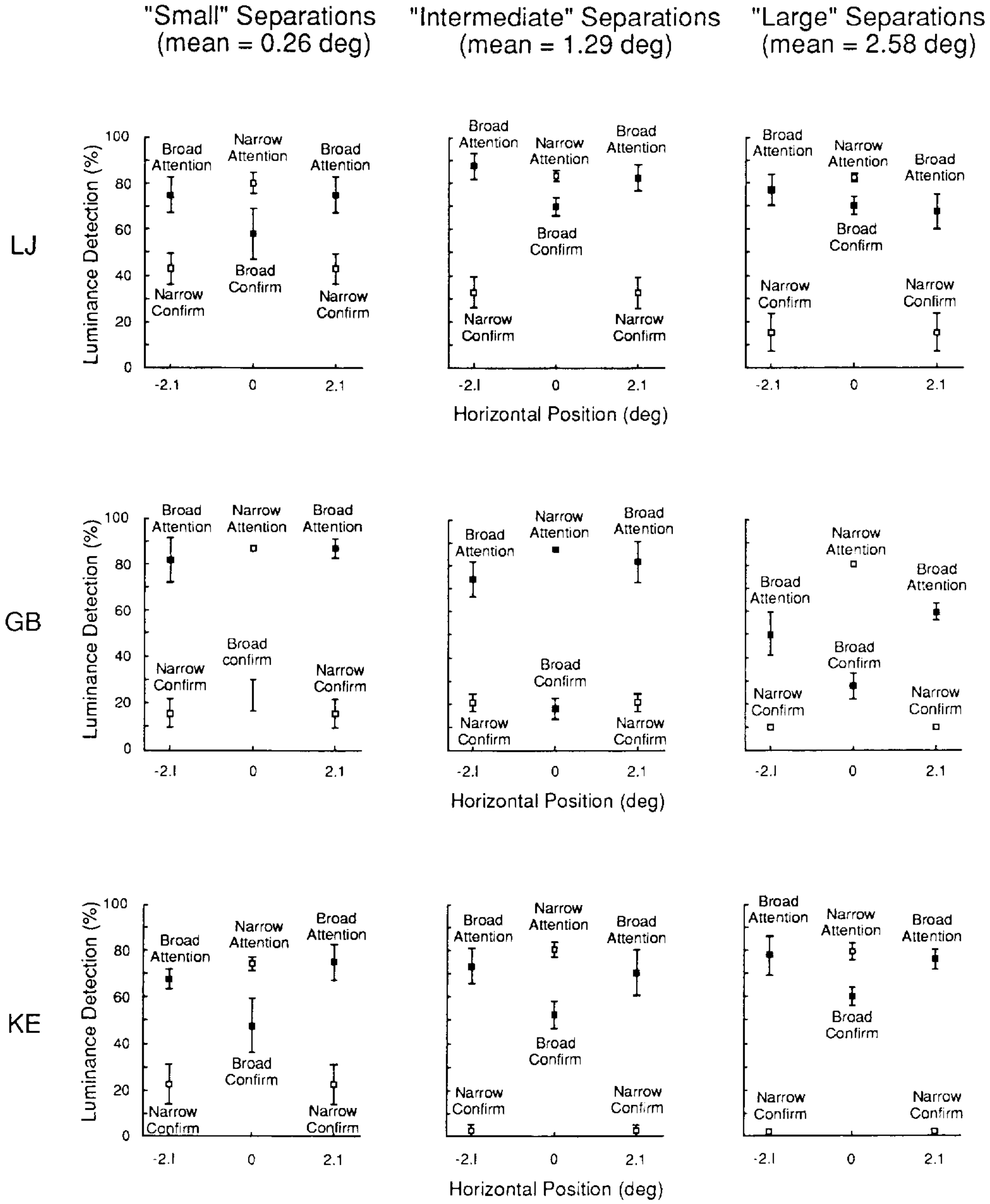

FIGURE 4. Experiment 2: Detection rates in the luminance-increment detection task for the central and most peripheral dots (±2.1 deg) for which there were luminance increments.

for foveal judgments of alignment and separation was due simply to reduced attentional capacity for spatial judgments in the Broad Attention condition, a similar Narrow/Broad difference would have been observed for all three sets of inter-line separations in this experiment.

GENERAL DISCUSSION

Attention was manipulated in this study by requiring subjects to either focus their attention on the central dot of a long, evenly spaced row of 19 dots, or spread their attention across the nine most central dots (a span of ±2.1 deg with respect to the central dot). They were required to detect a brief (15 msec) increment in the luminance of one of these dots. The sizes of the to-be-detected luminance increments were adjusted over many pre-experimental calibration sessions so that the correct-detection rate was close to 75% for all nine dots in the Broad Attention condition and the 1, central dot in the Narrow Attention condition. With overall detection performance approximately matched, we could test for local differences in sensitivity to luminance increments with the Narrow and Broad Confirmation tests. We found that subjects focused their attention sufficiently in the Narrow Attention condition to reduce their sensitivity (measured by *d'*) to equal luminance increments of the most peripheral dots (the Broad Attention vs the Narrow Confirmation trials). In addition, they spread their attention sufficiently in the Broad Attention condition to reduce their sensitivity (*d'*) to equal luminance increments of the central, fixation dot (the Narrow Attention vs the Broad Confirmation trials).

What causes these attention-dependent, local differences in sensitivity to luminance increments? Attention affects the sensitivity of receptive fields to stimulation (Bushnell *et al.*, 1981; Moran & Desimone, 1985; Motter, 1993), so Narrow Attention may *strongly* enhance the sensitivity of receptive fields at the focus of attention (and may also decrease the sensitivity of surrounding receptive fields), whereas Broad Attention may only *moderately* enhance the sensitivity of receptive fields over an extended spatial region. The net effect would be greater sensitivity to central luminance-increments for Narrow Attention, and greater sensitivity to peripheral luminance-increments for Broad Attention.

Foveal receptive fields (most sensitized by narrowly focused attention) have smaller centers than the peripheral receptive fields (most sensitized by broadly spread attention). Moreover, simple cortical receptive fields with narrow centers (small filters) are responsive to a limited band of relatively high spatial frequencies, whereas cortical receptive fields with wide centers (large filters) are responsive to a limited band of relatively low spatial frequencies (De Valois *et al.*, 1982). Since the reduction of high spatial frequencies by blurring can lower spatial resolution (Stigmar, 1971; Toet *et al.*, 1987), it could be concluded from our results that Narrow Attention, by increasing the sensitivity of small, foveal receptive fields (small filters responsive to high spatial frequencies), enhances luminance-increment detection *as well as* spatial resolution in the fovea. This was consistent with Shulman's results (Shulman, 1987), which indicate that attending to the global structure (Broad Attention) vs the local structure of a stimulus (Narrow Attention) affects contrast sensitivity for low vs high spatial frequency sine gratings. It was also consistent with the conclusion that subjects cannot simultaneously attend to stimuli at two spatial scales (Sperling & Melchner, 1978; Farrell & Pelli, 1993). Indeed, differences associated with broadly spread vs narrow attention would not have been obtained in the current study or Shulman's study (Shulman, 1987) if subjects could focus attention on one location and simultaneously spread it across multiple locations.

Watt (1987) has argued that for the first 300–500 msec following the onset of a stimulus, the sensitivity of relatively small spatial filters (detecting units responsive to relatively fine details) increases relative to the sensitivity of large filters (detecting units responsive to coarser spatial information). Likewise, Chung *et al.* (1996) have attributed the elevation of thresholds for moving vernier targets to increases in the relative sensitivity of mechanisms selective to low spatial frequencies (i.e., large filters) for high velocities (Kelly, 1985). The results of the present study indicate that spatial filter sensitivity can be brought under attentional control for the purpose of detecting luminance increments, and moreover, that the further effect of these changes in filter sensitivity is to enhance spatial resolution for foveal judgments of vernier alignment and inter-line separation. Although broadly spread attention increases sensitivity to peripheral luminance increments, there was no Narrow/Broad difference in spatial resolution for the peripherally presented, "large" inter-line separations.

A possible reason for the difference in attentional effects for the sets of "small" and "large" inter-line separations is that they involve different mechanisms. That is, separation judgments are separation-dependent (i.e., they follow Weber's law) when separations are small relative to eccentricity, but are eccentricity-dependent when separations are large relative to eccentricity (Levi & Klein, 1990; Burbeck & Yap, 1990).* The effects of attention for the set of "small" inter-line separations can be accounted for in terms of filter size (Klein & Levi, 1987); e.g., the perceived separation between two lines may be determined by the smallest filter that spans both lines. Thus, narrowly focused attention would enhance spatial resolution for separation judgments by increasing the relative sensitivity of the small filters that are the proposed basis for judging small separations.† Since judgments for relatively large separations are eccentricity—rather than separation-dependent, the separation between two lines is not perceived directly, but is derived from the perceived position of each line. Our results suggest that attentional mediation of spatial filter sensitivity in the retinal periphery may have been of little consequence for separation judgments because it was of little consequence for how precisely the positions of the line segments defining the separations were encoded.

Our evidence that small, foveal filters are activated more for narrowly focused than for broadly spread attention, and Watt's evidence (Watt, 1987) that small filters are activated more for longer than for briefer frame durations, does not mean that the full range of spatial filter sizes can be influenced by attentional spread and/or exposure duration. For example, Watt (1987) estimated, for judgments of line length, that increasing exposure duration produced changes in effective filter size ranging from approximately 70 arc min (0.2 c/deg) to approximately 2 arc min (6.8 c/deg).‡ However, exposure duration did not affect the availability of the very small filters (0.35 arc min; 38.5 c/deg) that were the basis for gap detection. With respect to the effects of attention on spatial resolution, Wilson's line element model (Wilson, 1986) suggests that optimum vernier performance may not be associated with the activation of the smallest available spatial filters, so it is possible that narrowly focused attention enhanced spatial resolution in our study without affecting the very smallest available filters in the central fovea. This is consistent, as well, with evidence for limitations in how narrowly attention can be focused; i.e., it spreads into a surrounding region of approximately

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*Because the vertical line segments for the separation-judgment task were below the fixation dot, the separations for the set of "small" inter-line separations were small relative to their eccentricity.

†There is substantial variation in the center-widths of cortical receptive fields, regardless of their eccentricity. (Hubel & Wiesel, 1974; Dow *et al.*, 1981).

‡The relationship between the size of the spatial filter and its most sensitive spatial frequency follows from Watt (1987, p. 2017).

1.0-deg diameter (Eriksen & Hoffman, 1973; Eriksen & Eriksen, 1974).

Contrary to Shiu & Pashler (1995), it has been found that narrowly focused attention can influence spatial resolution under conditions for which there is no need to shift attention to a target presented in an uncertain peripheral location within an array of similar distractors. This was the case for both vernier alignment judgments in Experiment 1 and separation judgments for the set of "small" separations in Experiment 2 (mean separation = 0.26 deg). We've obtained evidence for enhancement of spatial resolution when attention is narrowly focused on foveal targets. Whether narrowed attention can enhance spatial resolution when it is focused on a peripheral vernier target (as in Nakayama & Mackeben, 1989; Mackeben & Nakayama, 1993) remains an open question. An adequate test based on the current paradigm would require always presenting the vernier target at the same location, but having subjects fixate elsewhere. Attention could again be broadly spread over many dots or focused on the peripheral dot immediately above the location where the vernier target will appear.

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