

# Effects of Spatial Cuing on Luminance Detectability: Psychophysical and Electrophysiological Evidence for Early Selection

Steven J. Luck, Steven A. Hillyard, Mustapha Mouloua, Marty G. Woldorff,  
Vincent P. Clark, and Harold L. Hawkins

Three experiments were conducted to determine whether attention-related changes in luminance detectability reflect a modulation of early sensory processing. Experiments 1 and 2 used peripheral cues to direct attention and found substantial effects of cue validity on target detectability; these effects were consistent with a sensory-level locus of selection but not with certain memory- or decision-level mechanisms. In Experiment 3, event-related brain potentials were recorded in a similar paradigm using central cues, and attention was found to produce changes in sensory-evoked brain activity beginning within the 1st 100 ms of stimulus processing. These changes included both an enhancement of sensory responses to attended stimuli and a suppression of sensory responses to unattended stimuli; the enhancement and suppression effects were isolated to different neural responses, indicating that they may arise from independent attentional mechanisms.

Providing advance information about the location of a target stimulus can improve the speed and accuracy with which the target is detected or identified. This well-known attention effect has been studied extensively in spatial cuing tasks in which a warning cue informs the subject of the most probable location of the forthcoming target. Targets occurring at precued locations are generally processed more efficiently than those at uncued locations, as evidenced by speeded reaction times in both simple detection (e.g., Hughes & Zimba, 1985; Posner, 1980) and pattern discrimination (e.g., Eriksen & Yeh, 1985; Jonides, 1981) tasks, and by improvements in detection sensitivity (e.g., Downing, 1988; Hawkins et al., 1990; Mueller & Humphreys, 1991) and discrimination accuracy (e.g., Cheal & Lyon, 1991; Henderson, 1991; Van der Heijden, Wolters, Groep, & Hagenaar, 1987).

The attentional processes responsible for these spatial precuing effects have been conceptualized in several differ-

ent ways. Some authors have proposed that the encoding and transmission of visual information from precued locations is enhanced in relation to that from uncued locations. This selective processing has been described in terms of the opening and closing of sensory gates or filters (LaBerge & Brown, 1989), variations in the rate of encoding or information extraction due to differential concentration of processing resources (Eriksen & Yeh, 1985; Reinitz, 1990), variations in sensory pathway gain (Hawkins et al., 1990), and selective weighting of inputs to higher decision levels (Sperling & Doshier, 1986). Another important explanatory concept has been the temporal ordering of input selection at cued versus uncued locations. Posner (1980) initially proposed that the detection of a stimulus requires the alignment of an attentional spotlight with its location, which can be achieved in advance for precued stimuli but is delayed until after stimulus onset for events at uncued locations. Other investigators (Mueller & Humphreys, 1991; Mueller & Rabbitt, 1989; Yantis & Johnson, 1990; Yantis & Jones, 1991) have extended this idea by proposing that a sequence of selections is carried out from the alternative locations in an order determined both by the initial cuing and by subsequent stimuli.

A major area of theoretical disagreement concerns the level of processing at which the selection of visual information takes place. Both neurophysiological and psychophysical evidence points to a basic distinction between an initial stage at which stimulus features are registered and encoded in parallel across the visual field and a subsequent stage of pattern recognition that requires matching with stored representations in memory. Theories of attention have traditionally been divided according to whether stimulus selection takes place at the earlier stage or the later stage. Early selection theories have proposed that selection occurs at the level of sensory processing and thereby controls which inputs have access to the stage of stimulus identification (e.g., Johnston & Dark, 1986; Kahneman &

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Steven J. Luck, Steven A. Hillyard, Marty G. Woldorff, and Vincent P. Clark, Department of Neurosciences, University of California, San Diego; Mustapha Mouloua, Department of Psychology, Catholic University of America; Harold L. Hawkins, Perceptual Sciences Program, Office of Naval Research.

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Correspondence concerning this article should be addressed to Steven J. Luck, Department of Neurosciences 0608, University of California, 9500 Gilman Drive, La Jolla, California 92093-0608.

Treisman, 1984; LaBerge & Brown, 1989). In contrast, late selection theories typically propose that stimulus identification occurs in parallel over the visual field, with capacity limitations occurring at subsequent stages such as task-specific decision making, semantic categorization, memory rehearsal and storage, or response selection (e.g., Duncan, 1980; Norman, 1968; Shaw, 1984).

The question of whether spatial attention affects visual processing at the level of early sensory representations or only at later, postperceptual levels is fundamental to our understanding of visual perception but has proved difficult to resolve (for a review, see Yantis & Johnston, 1990). Among the lines of evidence that have been brought to bear on this issue are: (a) interactions of cuing validity effects with sensory factors such as stimulus brightness and duration (Hawkins, Shafto, & Richardson, 1988; Hughes, 1984; Reinitz, 1990); (b) degree of interference produced by stimuli at unattended positions (e.g., Eriksen & Schultz, 1979; Yantis & Johnston, 1990); (c) degree of performance deficit in divided versus focused attention tasks (e.g., Duncan, 1980; Shiffrin, McKay, & Shaffer, 1976); (d) presence of spatial gradients of stimulus detectability (Downing, 1988; LaBerge, 1983); (e) spatial cuing effects on detection sensitivity in signal detection tasks (Bashinski & Bacharach, 1980; Downing, 1988); and (f) changes in sensory-evoked brain activity as a function of the direction of attention (Harter, Miller, Price, LaLonde, & Keyes, 1989; Mangun, Hansen, & Hillyard, 1986; Mangun & Hillyard, 1991).

In the present study, we use both signal detection and electrophysiological approaches to investigate the level at which spatial cuing affects visual processing during the detection of threshold-level luminance targets. The point of departure for this work is the initial report by Bashinski and Bacharach (1980) that the cuing of target location improves detection sensitivity ( $d'$ ) without producing a discernible effect on decision criterion (Beta). This effect was taken to support theories of attention that posit "perceptual tuning" and "very early selective control." More recently, however, researchers have questioned both the results and the interpretation of Bashinski and Bacharach's study. For example, Mueller and Findlay (1987) found that although spatial cuing produced increased accuracy for pattern discrimination, luminance sensitivity was unaffected by attention-directing cues. They suggested that discrimination performance reflects capacity limitations that are subject to attentional modification, whereas luminance increment detection does not. One potential explanation for the discrepant luminance detectability findings in these studies is that subjects reported only the presence or absence of the luminance targets and did not report the location at which the luminance signal was perceived. Consequently, false alarms could not be unambiguously assigned to a validly or invalidly cued location, and the calculation of  $d'$  values for these locations was therefore uncertain.

This problem of false-alarm assignment was addressed in a subsequent study by Downing (1988), who used a "postcue" technique to designate which locations in a 12-position array required a present-absent decision for luminance targets. The postcue stimuli were arrows presented in succes-

sion to the to-be-reported locations following the targets (from 0-4 presented per trial) and masks. This technique allowed for a more straightforward calculation of  $d'$  and Beta, because false alarms could be assigned to specific postcued locations. Using this method, Downing found that valid spatial cues led to higher  $d'$  scores for luminance detection (as well as for brightness, feature, and pattern discriminations). She concluded that the spatial cuing of target location produced a facilitation of perceptual processing. In a similar design using both central and peripheral cues, Mueller and Humphreys (1991) replicated and extended Downing's finding that spatial cuing improves  $d'$  for luminance detection. They concluded that luminance detection involves a limited-capacity selection process but argued that such results could be compatible with either sensory- or decision-level selection mechanisms (see below).

A problem with both the Downing (1988) and Mueller and Humphreys (1991) studies is that their experimental designs may have allowed the luminance sensitivity measures to be confounded by errors in target localization. Because multiple targets (0-4) could appear at any of 8 or 12 locations, 4 of which were subsequently postcued, the subjects not only had to detect the presence or absence of multiple targets but also had to assign each of those decisions to a particular location and to remember those relationships until the postcues were presented. Such a design clearly places high information and memory loads on the observer. Thus, if the effect of the initial cue were to allow the subject's location judgment (or its memory trace) to be more secure at the precued location, an improvement in  $d'$  might be produced even though there was no change in the perceptual processing of luminance information.

These methodological concerns were addressed in a study by Hawkins et al. (1990), who used the postcue technique in a simplified design with only four possible stimulus locations (one in each visual field quadrant), only zero or one luminance target per trial, and only one postcued location. In this study, each trial began with a precue that directed the subject's attention to one (or all) of four locations. After a brief delay, luminance information was presented at one of the four locations, followed by masks at all locations. On 50% of the trials the luminance information consisted of a brief luminance increment target and on the other 50% a brief target-free interval occurred. After a delay of 500 ms, a pair of arrows was presented next to one of the four locations; this postcue indicated that the subject should report the presence or absence of the target at that location. The target (when present) could occur only at the postcued location, thereby minimizing the possibility that it would be mislocalized. To motivate subjects to attend to the precued location, the postcue was presented much more frequently at the precued location ( $p = 0.76$ ) than at any of the other locations ( $p = 0.08$  each). Thus, whereas target probability was 0.50 at the postcued location for all types of trials, subjects had to report the presence or absence of the target at the precued location much more frequently.

This paradigm was used with various stimulus eccentricities, levels of target brightness, and cue types. When a central arrow cue was used, detection sensitivity was higher

for valid trials than for neutral trials (benefits) and lower for invalid trials than for neutral trials (costs). When a peripheral cue was used (the brightening of a box around one location), the overall effect of attention (costs + benefits) was about the same as for the central arrow cue, but only the costs were significant. Hawkins et al. (1990) interpreted these effects of precuing on luminance detectability as evidence for an increase in sensory gain for information presented at the attended location relative to the unattended location.

Whereas the findings of Hawkins et al. (1990) are clearly in line with the view that spatial cuing leads to changes in sensory processing that in turn produce increases in luminance detectability, there are several postsensory explanations that might also account for their results. One such alternative explanation would posit that memory for the luminance information decayed during the 500-ms delay between target occurrence and the postcue and that subjects preferentially rehearsed the information from the precued location, resulting in less degradation at the time of decision for valid trials (see Palmer, Ames, & Lindsey, 1993). A related possibility is that subjects made the target present-absent decision at the precued location as soon as the masks appeared, without waiting for the postcue. When the postcue appeared, they could simply report this decision if the postcue was at the precued location; on invalid trials, however, a new decision must have been made for the postcued location on the basis of information that had decayed during the mask-postcue interval, resulting in the lower sensitivity values.

The results of Hawkins et al. (1990) could also be explained by a model similar to that proposed by Mueller and Humphreys (1991), in which different locations are assigned different priorities for entering a limited capacity decision system. According to one version of this model, the sensory information at all four locations would be processed equivalently, but information from the precued location would be given higher priority in a sequential "selection stack" and thus achieve earlier access to subsequent decision-level processes. Because information from the precued location would reach the decision level earlier and with less decay, detection sensitivity would be enhanced on valid trials.

The present experiments were designed to provide additional tests of the hypothesis that spatial attention operates at the sensory level by evaluating some of these postsensory explanations of cue-induced changes in luminance detectability. In Experiment 1, the hypothesis that the sensitivity changes observed by Hawkins et al. (1990) were due to differential rehearsal at cued and uncued locations was tested by varying the interval between the target information and the postcue. In Experiment 2, the hypothesis that attention acts by assigning a higher priority to the precued location, thereby giving it preferred access to decision processes, was tested by using an isolated, abruptly onsetting postcue that was designed to interrupt the priorities set by the precue and assign an immediate high priority to the postcued location on both valid and invalid trials. In Experiment 3, we attempted to enhance the ability of an isolated

postcue to equalize attentional priorities by using a central, symbolic precue instead of a peripheral precue; in addition, the delay between the precue and the target-postcue complex was randomly jittered so that subjects could not make the luminance judgment at the precued location without waiting for the postcue. Finally, event-related brain potentials (ERPs) were recorded in Experiment 3 to provide converging physiological information about the level of processing at which selection occurs.

## Experiment 1

In this experiment we assessed the role of the delay that was interposed between the masks and postcue in the study of Hawkins et al. (1990). If target detectability was reduced on invalid trials because information at the uncued locations decayed during the interval between the masks and the postcue (see Palmer et al., 1993), then decreasing this interval should improve performance for invalid trials and decrease the size of the overall attention effect. In the present experiment we tested this hypothesis by varying the duration of the mask-postcue interval.

In one condition, the postcue was presented simultaneously with the masks at the offset of the target information. The elimination of the mask-postcue delay in this condition should markedly reduce any preferential rehearsal of information presented at the precued location. Even with this zero mask-postcue delay, some differential decay of information at the precued and nonprecued locations may occur because of the time required to decode the postcue. However, the amount of decay during this short interval should be substantially less than the amount of decay that would occur over a delay of 500 ms. Therefore, if the effects of attentional precuing are caused by differential memory decay, these effects should be at least somewhat attenuated when the mask-postcue delay is eliminated.

## Method

*Subjects.* Eighteen Catholic University students between the ages of 19 and 26 participated in this experiment. All subjects had normal or corrected-to-normal vision, and they were paid for their participation.

*Stimuli and task.* A computer-controlled video monitor was used to generate the display. A chin rest was used to ensure that subjects viewed the monitor from a distance of 50 cm. Figure 1 illustrates the sequence of white-on-black frames presented on each trial.

Trials began with a fixation frame consisting of a central fixation colon and four  $1.6^\circ \times 1.6^\circ$  boxes, each demarcating a potential target location. The center-to-center visual angle between the fixation and each box was  $3.9^\circ$ . The fixation frame remained in view for 700 ms and was then replaced by a 500-ms warning frame in which the colon was replaced by a plus sign. The third frame contained the peripheral cue, an 83-ms presentation of two concentric squares at either one or all four of the location marker boxes that produced the impression of a brightening of the cued box(es). The cue frame was replaced with an 83-ms fixation frame that was identical to the earlier warning frame. This was followed by a target frame in which, on 50% of the trials, a target dot (IBM

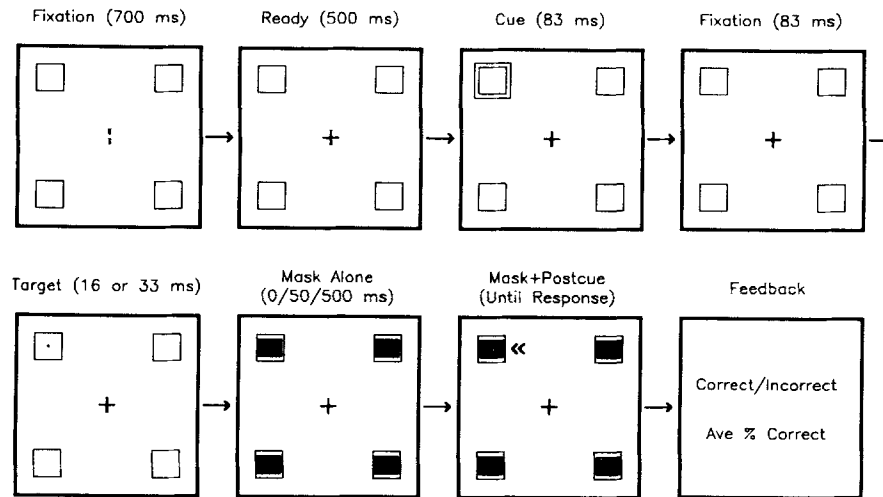


Figure 1. Sequence of stimuli presented on each trial in Experiment 1. (Ave = Average.)

Character Code No. 250) briefly appeared at the center of one location marker box; on the remaining 50% of trials, an equal duration target-free interval occurred. The duration of the target was determined by a calibration procedure described below. The target frame was replaced by a masking frame comprised of three abutting side-by-side textural characters (No. 178) situated at the center of each of the four boxes. The masking frame remained in view until a response was made. A postcue, consisting of an arrow pointing toward one of the four masked target boxes, appeared either 0, 50, or 500 ms following onset of the masking frame. Subjects responded by depressing a key to indicate whether a target had been present at the postcued location and their confidence in this judgment. Following the response, a 750-ms feedback frame appeared, indicating whether the response on that trial was correct and, on correct trials, indicating the cumulative accuracy of all preceding trials within the block. Subjects initiated the subsequent trial at this point by depressing the space bar on a keyboard situated before them.

Subjects indicated their judgments of target presence-absence and confidence by pressing the "1" (no target-high confidence), "2" (no target-low confidence), "3" (target-low confidence), or "4" (target-high confidence) key located at the top of the keyboard. Subjects were instructed to be as accurate as possible and were told that speed was unimportant.

**Procedure.** A single location was cued on 400 (80.6%) of the 496 trials that comprised a session. On 304 (76%) of the single cue trials, the cued location was subsequently postcued (valid cue trials). On the remaining single cue trials, the postcued location was chosen at random from the three uncued locations (invalid cue trials). All four locations were simultaneously cued on 96 trials per session, and on these trials each location had an equal likelihood of being postcued (neutral cue trials). Targets were presented on 50% of trials for all trial types and appeared only at the postcued location. Table 1 summarizes these probabilities.

Target duration was 33 ms during the practice session for all subjects. If a subject's overall accuracy was greater than 75% during this session, the duration was reduced to 17 ms for the six subsequent experimental sessions. Target duration was maintained at 33 ms for the remaining subjects.

The experiment consisted of one practice session and six experimental sessions, each about 1 hr in length and carried out on separate days. Each session included 496 trials and was divided

into three blocks separated by rest breaks. The delay between target offset and postcued onset (0, 50, or 500 ms) was held constant during each session. The order of testing for the three delays was counterbalanced across subjects.

**Data analysis.** Two measures of sensitivity were calculated for each subject, the standard  $d'$  measure and P(A), the area under the receiver operating characteristic (ROC) curve. Statistical analyses carried out on these sensitivity measures yielded comparable results, and so results are reported here only for P(A), the more reliable of the two measures (Green and Swets, 1966). The likelihood ratio at the yes-no cutoff, Beta, was used as a measure of response bias. These data were subjected to separate repeated measures analyses of variance (ANOVAs) with cue validity and postcue delay as factors. Planned pairwise comparisons were used to assess differences between valid, neutral, and invalid trials.<sup>1</sup> The Greenhouse-Geiser epsilon adjustment (Jennings & Wood, 1976) was used in all ANOVAs to mitigate any effects of nonsphericity.

## Results

Table 2 and Figure 2 summarize the P(A) values obtained for the different combinations of cue validity and postcue delay. Detection sensitivity was highest on valid trials, lowest on invalid trials, and intermediate on neutral trials. In addition, overall sensitivity increased as the target-postcue delay interval increased. However, the size of the cue validity effect was approximately equal for all three delay conditions (see Figure 2). In support of these observations, the statistical analysis yielded significant main effects of cue validity,  $F(2, 34) = 20.83, p < .001$ , and postcue delay,  $F(2, 34) = 6.12, p < .02$ , but the interaction between these factors did not approach significance ( $F < 1$ ). Planned comparisons indicated that costs (sensitivity on neutral vs. invalid trials) and benefits (sensitivity on valid vs. neutral

<sup>1</sup> Pooled error variance estimates from the omnibus ANOVAs were not used for these comparisons because of the inflated Type I and Type II error rates that may occur if the variance-covariance matrix is nonspherical, especially in within-subjects designs.

Table 1  
Number of Occurrences of Each Combination of Precue Position and Postcue Position in a Single Session of Experiment 1

Precue	Postcue Position			
	UL	UR	LL	LR
UL	76	8	8	8
UR	8	76	8	8
LL	8	8	76	8
LR	8	8	8	76
Neutral	24	24	24	24

Note. UL = upper left; UR = upper right; LL = lower left; LR = lower right. Targets were present on 50% of each of these trial types.

trials) were both statistically significant (costs:  $F[1, 17] = 35.33, p < .001$ ; benefits:  $F[1, 17] = 4.87, p < .05$ ).

Table 2 also includes the Beta measure of response bias, which was lowest on valid trials, highest on invalid trials, and intermediate on neutral trials. A significant main effect of cue validity was obtained for this measure,  $F(2, 32) = 7.63, p < .01$ , but no other main effects or interactions approached significance. Planned comparisons indicated that the difference between valid and neutral trials was highly significant,  $F(1, 17) = 15.74, p < .001$ , whereas the difference between invalid and neutral trials was only marginally significant ( $p < .08$ ), presumably due to the high variance that was observed on invalid trials.

### Discussion

The principal findings of this experiment were that cue validity exerted a substantial effect on target detectability, producing both significant costs and benefits, and that the magnitude of this effect was unaffected by postcue delays over a range of 0 to 500 ms. This latter finding indicates that the effect of attentional precuing on luminance detection observed in previous studies (Downing, 1988; Hawkins et al., 1990; Mueller & Humphreys, 1991) was not simply a consequence of differential decay of sensory information or rehearsal at cued versus uncued locations during the target-postcue delay interval. These results are consistent with the hypothesis that attention acts at the sensory level to enhance the quality of perceptual information (Hawkins et al., 1990), although they might also be accounted for by certain decision-level mechanisms, as discussed in subsequent sections. Cue validity also significantly affected response bias, but because bias effects can arise from any number of sources in an experiment such as this, these effects have no obvious implications for the models of attention under consideration here.

An additional finding was an overall increase in target detectability as a function of increasing target-postcue delay, an effect that was independent of cue validity. This effect is the opposite of what would be expected from a decaying sensory memory trace for the target information. One possible explanation for this result might be that the

appearance of the highly salient postcue at the side of the postcued location marker attracted attention away from the critical target position at the center of the marker, thereby interfering with perceptual analysis of the target information. Another possibility might be that the postcue disrupted the analysis of the display information by signaling that an immediate decision must be made. Whatever the cause of this reduced detectability at short target-postcue intervals, it was clearly dissociable from the cue validity effects, which did not differ across intervals.

### Experiment 2

Mueller and Humphreys (1991) argued that, although the effects of spatial cuing on luminance detection clearly demonstrate capacity limitations in visual processing, these effects do not indicate whether the limitations arise at an early or late level of processing. In their view, a late selection model in which attention controls the order of entry of information into a limited-capacity decision system could instead account for these results; the reduction in detectability observed at the uncued location would then result from delayed access into this decision stage rather than degraded sensory-level processing. However, it would appear that late selection effects of this nature could be eliminated if the postcue induced subjects to assign equally high decision priorities to the postcued location on both valid and invalid trials. The small, relatively unobtrusive arrow postcue used in the previous experiment may have been unable to interrupt the attentional priorities set by the precue, however, such that the precued location maintained its high level of priority even when the postcue was presented elsewhere.

In Experiment 2, we addressed this possibility by using a postcue consisting of an isolated, abrupt stimulus onset that was designed to allow rapid reorienting of attention before the onset of decision-level processing. Mueller and Rabbitt (1989) demonstrated that this type of stimulus can interrupt a preset focus of attention, even when the original attentional focus was engendered by a peripheral cue (see also

Table 2  
Mean  $P(A)$  and Beta Values for Each Mask-Postcue Delay Condition in Experiment 1

Condition	P(A)		Beta	
	M	SE	M	SE
0-ms delay				
Valid	.710	.027	1.16	.07
Neutral	.691	.120	1.69	.19
Invalid	.647	.098	2.84	.77
50-ms delay				
Valid	.741	.127	1.08	.07
Neutral	.701	.134	1.67	.16
Invalid	.665	.137	2.97	.66
500-ms delay				
Valid	.791	.138	1.15	.11
Neutral	.775	.143	2.13	.37
Invalid	.728	.147	2.64	.58

Note.  $P(A)$  = a measure of sensitivity (see text for details).

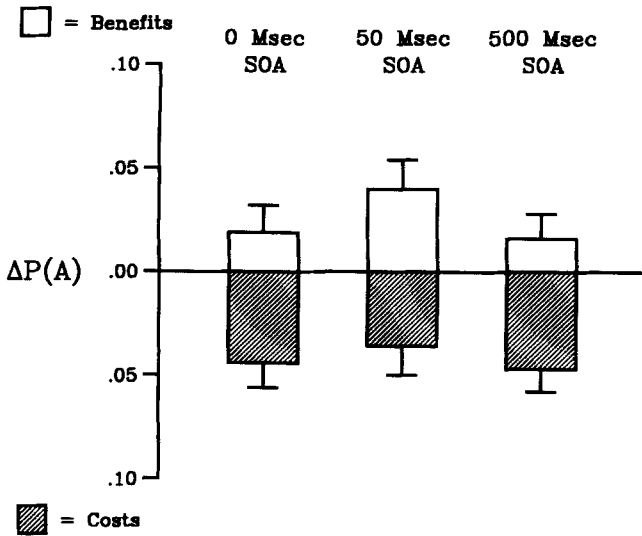


Figure 2. Summary of the effects of cue validity on mean detection sensitivity (plus or minus the standard error) in Experiment 1. For each stimulus onset asynchrony (SOA), benefits are plotted as the difference in P(A) between valid and neutral trials (open bars), and costs are plotted as the difference in P(A) between invalid and neutral trials (filled bars).  $\Delta P(A)$  = Change in the sensitivity measure P(A) relative to neutral trial.

Jonides, 1981; Yantis & Jonides, 1984). To create an isolated, abrupt postcue, the four masks and arrow postcue used in the preceding experiment were replaced by a single mask presented at the location to be reported, and this stimulus served both as a mask and as the postcue. As in the preceding experiment, the onset of the mask was simultaneous with the offset of the luminance target information. This combined mask-postcue stimulus can presumably produce a very rapid assignment of high attentional priority to the postcued location, thereby allowing any information

held in sensory memory from the postcued location to be moved directly into the decision stage. As a result, access to decision-level processing should be equalized for valid and invalid trials, and any differences in detectability for valid and invalid trials should therefore be attributable to differences in earlier processing stages.

To summarize, if attention operates at a late level, the effects of precuing should be greatly diminished by the use of an abruptly onsetting, isolated mask-postcue stimulus. Even if this postcue were only partially effective in reassigning attentional priorities, a reduction in the magnitude of the cuing effect should be observed relative to the four-mask case. Alternatively, if attention operates by improving the quality of sensory processing at the precued location, then the nature of the postcue should have little influence on the size of the cue validity effect.

There were several minor differences between Experiments 1 and 2 in addition to the use of the single mask-postcue. Accordingly, subjects were tested with four masks and an arrow postcue as in Experiment 1 as well the single mask-postcue to allow a direct comparison of the two mask-postcue configurations.

Method

Subjects. Sixteen University of California, San Diego (UCSD) students between the ages of 18 and 25 participated in this experiment. All subjects had normal or corrected-to-normal vision, and they were paid for their participation.

Stimuli. The stimuli and procedure used in Experiment 2 were very similar to those used in Experiment 1, but the use of a different computer system necessitated a number of small changes.

Stimuli were presented on a color video monitor at a distance of 70 cm from the subject. A fixation dot was continuously visible at the center of the display, as were location markers at the four potential locations (see Figure 3). The location markers consisted of red dotted box outlines, each  $1.2^\circ \times 1.2^\circ$  square and centered  $6.1^\circ$  from the fixation point. Each trial began with a cue stimulus, which was created by surrounding one (or all) of the location

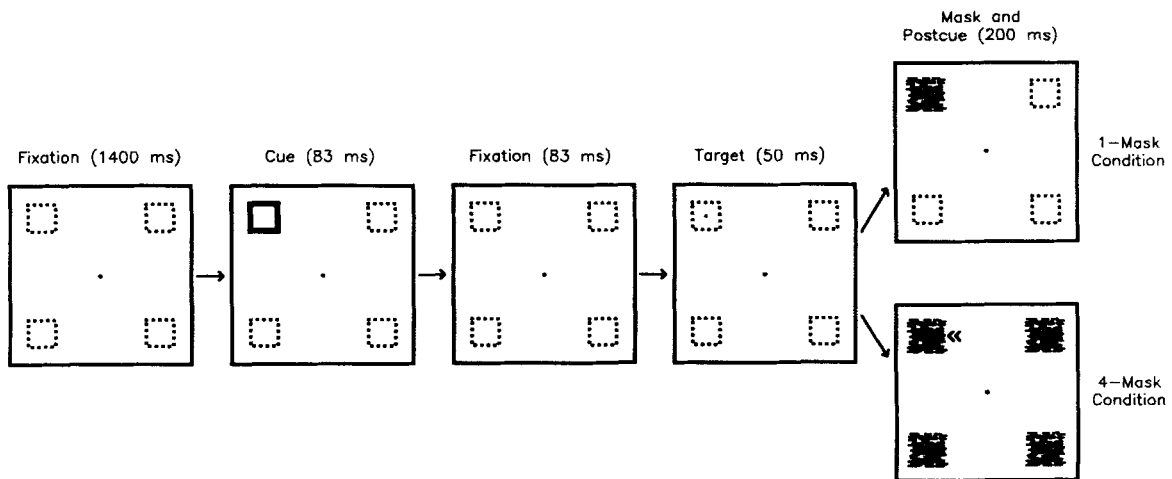


Figure 3. Sequence of stimuli presented on each trial in the 1-mask and 4-mask conditions of Experiment 2. The filled boxes are the actual mask-postcue stimuli.

markers with thicker, solid, red lines for 83 ms. This produced an apparent brightening at the cued location(s). Luminance information was presented 167 ms after cue onset and consisted of a 50-ms duration target (a single white pixel in the center of one of the location markers) or a 50-ms interval with no stimulus.

A masking stimulus was presented immediately after the target interval, with no delay. In one condition, this consisted of a single mask that was presented at the to-be-reported location, which was also the target location on target-present trials (the "1-mask" condition). In a second condition, masks were presented at all four locations and a pair of arrows was simultaneously presented adjacent to the to-be-reported location to serve as a postcue (the "4-mask" condition). The masks consisted of arrays of 100 white, horizontal line segments, each .15° long, randomly positioned within a 1.7° × 1.7° square. The duration of the mask-postcue complex was 500 ms. An intertrial interval of 1,100 ms was interposed between mask offset and the beginning of the next trial.

**Procedure.** A single location was precued on 80% of trials, and all four locations were precued on the remaining trials. When a single location was precued, the target information was presented at the precued location on 75% of trials and at one of the three remaining locations, selected at random, on 25% of trials. The luminance target was present on 50% of trials regardless of cue validity and, when present, always appeared at the postcued location. Subjects were informed of these probabilities and were instructed to attend to the cued location in order to maximize their target detection performance.

Half of the subjects signaled target presence with a left-hand button press and target absence with a right-hand button press; this assignment was reversed for the remaining subjects. Subjects were instructed to respond as accurately as possible without regard to response speed. To ensure an adequate number of false alarms for the calculation of reliable sensitivity and criterion parameters, subjects were instructed to make approximately equal numbers of target-present and target-absent responses, regardless of cue validity. Feedback about performance was provided at the end of each block of 144 trials in this experiment, rather than after each trial. Subjects were instructed to maintain fixation during performance of the task, and fixation was monitored through electrooculographic (EOG) recordings, as described in Hawkins et al. (1990).

Each subject participated in a single experimental session lasting between 3 and 4 hr. Subjects were given extensive practice with the task before data collection began. A bright luminance signal was used initially, and as subjects learned the task its brightness was gradually decreased such that overall detection sensitivity remained at an intermediate level ( $d'$  approximately 1.5). Practice continued until performance stabilized, but additional small adjustments in target luminance were sometimes necessary between trial blocks to maintain this level of performance; because cue validity varied within blocks, luminance was adjusted equally for all trial types.

After the practice period, data were recorded over a series of 14 blocks of 144 trials, each block lasting approximately 5 min (including a 30-s rest period in the middle). There were a total of 1,344 valid trials, 336 invalid trials, and 336 neutral trials over the course of the session. Valid, invalid, and neutral trials were presented in unpredictable order within trial blocks. Half of the subjects received the 1-mask condition first and half received the 4-mask condition first.

**Data analysis.** The signal detection parameters  $d'$ , Beta, and P(A) were computed and entered into separate repeated measures ANOVAs with three factors: cue validity (valid, invalid, or neutral); postcue type (1-mask or 4-mask); and postcue location (upper left, upper right, lower left, or lower right). Planned com-

parisons were also conducted to assess the significance of costs and benefits in the 1-mask and 4-mask postcue conditions. As in Experiment 1, ANOVA results are presented only for P(A) and Beta; the  $d'$  and P(A) results were very similar.

## Results

The effects of cue validity are summarized in Table 3 and Figure 4. Cue validity significantly affected detectability in the omnibus analysis of the P(A) measure,  $F(2, 30) = 103.51, p < .001$ , and the effects were virtually identical for the 1-mask and 4-mask conditions ( $F < 1$  for the Cue Validity × Postcue Type interaction). Costs and benefits were both larger in this experiment than in Experiment 1 (costs = 0.11; benefits = 0.10) and were highly significant in both the 1-mask and 4-mask conditions [ $F(1, 15) > 20, p < .001$ , for both costs and benefits in both conditions].

There were no significant differences in overall detectability between the 1-mask and 4-mask conditions ( $p > .05$ ), but it should be stressed that target luminance was adjusted between trial blocks to maintain a constant level of detectability, thereby eliminating any potential difference in detection performance between these conditions. There were also no significant main effects or interactions involving the visual field location of the postcued location.

As in Experiment 1, subjects used a lower decision criterion (Beta) on valid and neutral trials than on invalid trials in both conditions, resulting in a significant main effect of cue validity on Beta,  $F(2, 30) = 15.03, p < .001$ . Beta was somewhat higher in the 1-mask condition than in the 4-mask condition,  $F(1, 15) = 5.07, p < .05$ , but the Cue Validity × Condition interaction was not significant ( $F < 1$ ).

## Discussion

In this experiment, the attention-directing precue had substantial effects on luminance detectability that were equivalent for the 1-mask and 4-mask conditions, even though the 1-mask postcue was designed to allow rapid transfer of target information to decision processes, independent of cue validity. Thus, although subjects should have been able to assign top priority to the target location immediately after target offset for both invalid and valid trials,

Table 3  
Mean P(A) and Beta Values for Experiment 2

Condition	P(A)		Beta	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
	1-mask			
Valid	.818	.008	0.98	.11
Neutral	.722	.013	1.09	.09
Invalid	.609	.012	1.69	.11
	4-mask			
Valid	.841	.007	0.82	.09
Neutral	.733	.013	0.97	.09
Invalid	.628	.015	1.42	.11

Note. P(A) = a measure of sensitivity (see text for details).

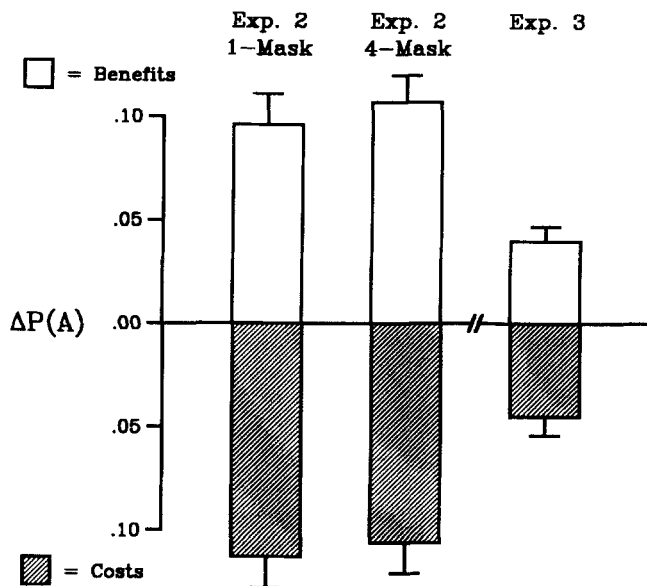


Figure 4. Summary of the effects of cue validity on mean detection sensitivity (plus or minus the standard error) in Experiments 2 and 3. As in Figure 2, benefits are plotted as the difference in  $P(A)$  between valid and neutral trials (open bars), and costs are plotted as the difference in  $P(A)$  between invalid and neutral trials (filled bars). Exp. = experiment;  $\Delta P(A)$  = change in the sensitivity measure  $P(A)$ ; 1-mask = 1-mask condition; 4-mask = 4-mask condition.

luminance detection was substantially more accurate when attention could be focused on the target location before target onset. These results are consistent with an attention mechanism that operates by modulating the efficiency of processing in the sensory pathways.

The 4-mask condition of the present experiment was similar to the zero-delay condition of Experiment 1. However, although costs were generally larger than benefits in Experiment 1, costs and benefits were approximately equal in the present experiment, and the overall attention effect was considerably larger. There are several possible explanations for the larger overall attention effect, such as differences in the precue and mask stimuli, the absence of trial-by-trial feedback, the frequent adjustment of target brightness to maintain a constant level of task difficulty, and the use of one long session rather than several short sessions, but it is not clear which of these was the critical factor.

Whereas the results of Experiment 2 may be difficult to reconcile with an attentional queuing mechanism at the decision level (e.g., Mueller and Humphreys, 1991), further considerations suggest that this model and other decision-level mechanisms cannot be ruled out completely. First, the attentional priorities set by the precue may have been so strong that even an abrupt, isolated postcue was unable to reassign a high priority to the postcued location on neutral and invalid trials. Although some evidence suggests that the single-mask postcue used in Experiment 2 should have been able to overcome the attentional priorities set by the precue

(Mueller & Rabbitt, 1989), other studies have found that abrupt onsets may be ineffective in disrupting a previous attentional focus under some conditions (Yantis & Jonides, 1990). It is also possible that the isolated postcue did cause a reassignment of attentional priorities on invalid trials, but because the postcue occurred at target offset, this reassignment occurred too late to allow immediate transfer of target information to the decision stage, allowing some effects of precue validity to persist. This would be consistent with the finding that the facilitatory effects of peripheral cues may not reach their maximum until 50–100 ms after cue onset, at least when accuracy is the dependent variable (Lyon, 1990). Therefore, a decision-level attentional queuing mechanism cannot be ruled out completely by the presence of equivalent cuing effects in the 1-mask and 4-mask conditions.

A second decision-level explanation of these results was made possible by the fixed-duration delay that was interposed between the cue and the target. This fixed delay may have led to a decision-timing strategy in which subjects began making the luminance judgment at the precued location at the expected time of target onset, without waiting for the postcue. On valid trials, this judgment would simply be reported, whereas on invalid trials a subsequent decision would be required for the location that was actually postcued. By allowing the decision process to begin earlier on valid trials than on invalid trials, this strategy may have led to attentional costs and benefits in the absence of any changes in sensory-level processing.

A third decision-level explanation of these results would propose that a limited-capacity decision process receives information continuously from all four locations, but allows the information from the precued location to be more heavily weighted because it is more likely to be used (e.g., Sperling, 1984; Sperling & Doshier, 1986). When the mask-postcue is presented, the flow of information into this decision mechanism terminates, and the decision must be made on the basis of the weighted noise or signal-plus-noise information that has accumulated at each location. If additional noise is added from within the decision mechanism itself or from other external sources, then the total signal-to-noise ratio at this stage would be greater for a location that has a higher initial weight, thus leading to greater detectability on valid trials. Although this hypothesis places the selection process at the decision level rather than the sensory level, it is otherwise very similar to the sensory gain control mechanism favored by Hawkins et al. (1990).

### Experiment 3

Although increases in luminance detectability have been taken as *prima facie* evidence for improvements in sensory quality, the previous discussion indicates that the higher  $P(A)$  values observed for precued locations in Experiments 1 and 2 do not provide incontrovertible evidence for a sensory-level attentional mechanism. Because of the multiplicity of possible decision-level mechanisms and the lack of a generally accepted operational definition of “sensory”



and "decision" processes, it is not readily apparent how this locus-of-selection issue can be fully resolved on the basis of behavioral evidence alone. To provide a converging source of evidence indicating the level at which attention affects processing, we used the ERP technique in Experiment 3 in conjunction with a paradigm similar to the 1-mask condition of Experiment 2. This experiment thus addressed the locus-of-selection issue more directly by attempting to specify the latency at which stimulus processing is first modulated by attention and the brain regions in which this modulation occurs.

ERPs are voltage fluctuations in the ongoing electroencephalogram (EEG) that typically reflect postsynaptic potentials generated in large populations of cortical neurons that are activated in synchrony during the processing of information. The small ERP signals can be extracted from the larger EEG by averaging together the responses from many trials, using an event such as stimulus onset to provide a time-locking point. The resulting averaged ERP waveform consists of a sequence of positive and negative waves (also called "components"), each of which has a latency that indicates the time course of neural activation and a scalp distribution that reflects its neuroanatomical source. Changes in the amplitude and latency of these components can be used to provide measures of sensory, cognitive, and motor processing (for reviews, see Donchin, Karis, Bashore, Coles, & Gratton, 1986; Hillyard & Picton, 1987; Näätänen, 1992).

If attention operates at the level of sensory processing, then the early sensory ERP components should differ for stimuli presented at validly and invalidly cued locations. In contrast, a decision-level attentional mechanism would be expected to affect only the later components. The sensory gain control hypothesis described by Hawkins et al. (1990) makes the more specific prediction that the amplitude of the early components should be greater for validly cued stimuli than for invalidly cued stimuli. Results consistent with these predictions have been obtained in previous ERP studies in which different spatial attention paradigms were used (e.g., Eason, Harter, & White, 1969; Harter, Aine, & Schroeder, 1982; Harter & Anllo-Vento, 1991; Mangun & Hillyard, 1988, 1990, 1991; Neville & Lawson, 1987; Rugg, Milner, Lines, & Phalp, 1987). Specifically, consistent attention effects have been found for three sensory-level ERP components: P1 (ca. 100 ms), anterior N1 (ca. 125 ms), and posterior N1 (ca. 175 ms).

Although ERP recordings generally offer much better temporal resolution than spatial resolution, some information about the neuroanatomical generator sources of these effects has recently become available. The first attention-sensitive component, P1, appears to be generated in lateral extrastriate cortex (see Aine, Bodis-Wollner, & George, 1990; Mangun, Hillyard, & Luck, 1993), which is consistent with single-unit recordings indicating that attention modulates sensory processing in extrastriate area V4 but not in primary visual cortex (Moran & Desimone, 1985). The generators of the anterior and posterior N1 components have not yet been definitively localized, but the posterior N1 component is similar in scalp distribution to the P1 compo-

nent and also appears to be generated in lateral extrastriate cortex (see Simpson, Scherg, Ritter, & Vaughan, 1990). The anterior N1 component is largest over prefrontal cortex, but its broad distribution over the scalp is consistent with a forward-pointing generator located in the extrastriate visual areas of the inferior occipital and temporal lobes. Thus, the short-latency P1 and N1 components most likely reflect sensory processing within the modality-specific visual areas of occipital and inferotemporal cortex.

In the present study, the luminance targets were too dim to evoke substantial ERP activity. The ERP elicited by the mask-postcue stimulus was therefore used to assess the status of the visual pathways for the location where the luminance information was presented. This approach assumes that any differences in perceptual processing induced by the precue will affect the postcue as well as the luminance target and, conversely, any differences in the ERPs elicited by the postcue at attended and unattended locations will reflect changes in perceptual processing that apply to the luminance targets as well as the postcue. These assumptions have been supported by previous studies in which task-irrelevant probe stimuli were used to assess sensory processing (Heinze, Luck, Mangun, & Hillyard, 1990; Luck, Fan, & Hillyard, 1993; Luck & Hillyard, in press).

Experiment 3 was also designed to minimize the likelihood that the effects of attention on behavioral signal detection performance could be explained in terms of decision-level attentional mechanisms. Mueller and Rabbitt (1989) showed that the voluntary orienting of attention produced by central, symbolic precues can be interrupted much more easily than the automatic orienting of attention produced by peripheral cues; accordingly, in Experiment 3 we used a central arrow precue in conjunction with a combined mask-postcue stimulus. In addition, to minimize the effectiveness of the decision-timing strategy discussed above, a variable cue-target delay of 200–500 ms was used.

The use of a central precue was also necessary to allow a clear interpretation of the effects of cue validity on the ERPs in this paradigm. When two bright stimuli occur in rapid succession at nearby locations, the electrophysiological response to the second stimulus is typically reduced due to physiological refractoriness, and this effect would confound the comparison of targets preceded by a peripheral precue in the same location (i.e., validly cued targets) with targets preceded by a peripheral precue at a different location (i.e., invalidly cued targets; see Anllo-Vento, in press). When central cues are used, however, the relationship between cue position and target position is the same on valid and invalid trials, eliminating any differences in refractoriness.

## Method

*Subjects.* Fifteen UCSD students with normal or corrected-to-normal vision participated in this experiment (for which they received payment). All subjects had participated in previous ERP experiments and were selected for this study on the basis of their ability to produce EEG signals containing a minimum of artifacts such as eye movements, muscle activity, blinks, and so on. The

subjects were naive, however, with respect to the goals of this particular experiment.

**Stimuli and procedure.** The stimuli and procedure used in Experiment 3 were identical to those used in the 1-mask condition of Experiment 2, except for the following differences. The precue stimulus was either a central arrow (subtending  $0.2^\circ$ ) that pointed from the fixation point toward one of the four location markers or, on neutral trials, a set of four of these arrows pointing toward all four location markers. The precue remained on the screen until the offset of the mask–postcue stimulus, which had a duration of 200 ms in contrast to the 500-ms postcue used in Experiment 2. The delay between the onset of the precue and the onset of the luminance information varied randomly between 200 ms and 500 ms rather than being fixed at 167 ms. The mask–postcue stimulus again followed the luminance information with no delay.

**Recording and analysis.** ERPs were recorded from 12 nonpolarizable electrodes located at standard left and right hemisphere positions spanning anterior and posterior areas (International 10/20 System sites: F3, F4, C3, C4, P3, P4, O1, O2, T5, T6) and at a nonstandard pair of lateral occipital sites named OL and OR that were positioned halfway between the standard occipital (O1 and O2) and posterior temporal (T5 and T6) sites. These electrodes were referenced to the algebraic average of unlinked left and right mastoid electrodes. All signals were amplified with a bandpass of 0.01–100 Hz (half-amplitude cutoff) and digitized at 250 Hz.

The cue–target delay interval used in this experiment was sufficiently long to permit eye movements toward the precued location, and EOG recordings were therefore obtained to verify that central fixation was maintained. The horizontal EOG was recorded from a pair of electrodes located 1 cm lateral to the external canthi, and the vertical EOG was recorded from an electrode 2 cm beneath the left eye, referenced to the left mastoid. Trials with eye movements or blinks were automatically excluded from the averages and also from the signal detection analysis. An eye movement calibration procedure was conducted for each subject to determine the voltage produced at the EOG electrodes by eye movements of a known size, using methods described in Hawkins et al. (1990).

In this experiment, the ERP waveform elicited by the cue stimulus continued after the onset of the ERP elicited by the postcue, and the resulting overlap of these waveforms caused substantial distortions. In order to remove this overlap, the ADJAR (adjacent response) filter procedure developed by Woldorff (1993) was applied.<sup>2</sup>

An ERP component is typically labeled according to its polarity and either its peak latency or its ordinal position in the waveform (e.g., P1 or P100 for the first major positive component, peaking around 100-ms poststimulus). In the present study, three sensory-evoked components were measured from the postcue-elicited ERP waveforms: the P1 component, the anterior N1 component, and the posterior N1 component. The amplitude of each component was quantified as the mean voltage within a specified latency window, relative to the mean voltage during a 200-ms prestimulus baseline period (latency windows and scalp sites are listed in Table 5). For each component, an omnibus repeated measures ANOVA was computed using 5 factors: validity (valid, invalid, or neutral); horizontal postcue position (left or right); vertical postcue position (upper or lower); electrode location (in the anterior–posterior dimension); and hemisphere (left or right). Planned comparisons were also conducted to isolate costs and benefits by comparing valid trials with neutral trials and invalid trials with neutral trials, respectively. These analyses used ERP averages that were collapsed over target-present and target-absent trials. Separate averages were also computed for target-present and target-absent trials to determine if the processing of the postcue was affected by the

presence of the dim luminance targets, but virtually identical attention effects were obtained in these averages, and so only the collapsed data will be presented here.

## Results

**Signal detection performance.** The signal detection results from this experiment are summarized in Table 4 and Figure 4. As in Experiment 2, target detectability was highest on valid trials, intermediate on neutral trials, and lowest on invalid trials, resulting in a significant cue validity main effect for the P(A) measure,  $F(2, 28) = 25.67, p < .001$ . Costs and benefits were both highly reliable (costs:  $F[1, 14] = 19.28, p < .001$ ; benefits:  $F[1, 14] = 15.31, p < .002$ ). Response bias (Beta) did not differ significantly as a function of cue validity ( $F < 1$ ).

**ERP waveforms.** The ERPs elicited by the postcue on valid, invalid, and neutral trials are superimposed in Figures 5 and 6. Typical ERP components were observed at both posterior (lateral occipital) and anterior sites. At the posterior sites, the ERP waveform included a P1 peak around 100 ms poststimulus and an N1 peak around 150 ms poststimulus. These components were larger and peaked earlier at scalp sites contralateral to the visual field of the postcue stimulus due to the direct input of visual information into the contralateral occipital lobe (Mangun, Luck, Gazzaniga, & Hillyard, 1991; Saron & Davidson, 1989). The ERP waveforms at anterior sites included a prominent, bilaterally symmetrical anterior N1 component peaking around 120 ms after stimulus onset. Longer latency components were also present in these waveforms, but these components are more difficult to interpret and will not be considered in detail here.

Substantial differences in the early ERP components were observed for valid, neutral, and invalid trials, but the exact pattern of attention effects differed for each component, as shown in Figure 6. Beginning around 60 ms poststimulus, the amplitude of the P1 component was reduced on invalid trials relative to neutral trials (Figure 6, upper right), but was not enlarged on valid trials relative to neutral trials (upper left). In contrast, the posterior N1 component was enlarged on valid trials relative to neutral trials (upper left)

<sup>2</sup> Briefly, this technique estimates overlap by convolving the observed ERP waveform for an adjacent stimulus with the probability distribution of the interval between the current stimulus and the adjacent stimulus. This estimate of the overlap can then be subtracted from the observed waveform for the current stimulus. After the estimated overlap has been subtracted away for each ERP waveform, this procedure is iterated using the new estimates of the ERP waveforms. Because the new ERP waveform estimates are less contaminated by overlap, improved overlap estimates are produced in subsequent iterations, leading to improved estimates of the true ERP waveforms. In the present study, 10 iterations of this procedure were sufficient to remove all signs of overlap from the waveforms. In order to optimize this procedure, a digital implementation of a single-pole causal high-pass filter (half-amplitude cutoff at 1.2 Hz) was used to remove most of the low-frequency content from the waveforms before the ADJAR filter procedure was applied.

Table 4  
Mean P(A) and Beta Values for Experiment 3

Condition	P(A)		Beta	
	M	SE	M	SE
Valid	.770	.010	2.11	.41
Neutral	.730	.011	2.00	.25
Invalid	.685	.012	2.34	.25

Note. P(A) = a measure of sensitivity (see text for details).

but was not reduced on invalid trials (upper right).<sup>3</sup> A third pattern was observed for the anterior N1 component, which exhibited both larger amplitudes on valid trials (lower left) and smaller amplitudes on invalid trials (lower right) with respect to neutral trials. The relative suppression of the P1 component on invalid trials parallels the "costs" of attention, the reduction in target detectability on invalid trials relative to neutral trials. Likewise, the larger posterior N1 component observed on valid trials parallels the "benefits" of attention, the improved target detectability on valid relative to neutral trials. By similar reasoning, the anterior N1 showed effects mirroring both costs and benefits, although the costs were substantially larger than the benefits.

Statistical analyses supporting these observations are presented in Table 5. Briefly, the omnibus main effect of cue validity was significant for each of the three ERP components, whereas significant suppression on invalid trials (relative to neutral trials) was observed for the P1 and anterior N1 components, and significant enhancement on valid trials (relative to neutral trials) was observed for the posterior N1 and anterior N1 components.

### Discussion

The luminance detection results from this experiment extend the findings of Experiments 1 and 2, demonstrating that detection sensitivity is enhanced at an attended location even when a central, symbolic precue is used to direct attention and a variable-duration delay is interposed between the precue and the target. These results are consistent with a sensory-level mechanism of attention and narrow the range of possible decision-level attention mechanisms (see the General Discussion section).

The electrophysiological recordings provide converging evidence concerning the level of attentional selection, demonstrating increases in sensory-level neural responses for stimuli presented inside the focus of attention and decreases in these responses for stimuli outside the focus of attention. These effects began in the first 60–100 ms of stimulus processing, within 30–40 ms of the arrival of sensory information into primary visual cortex (Robinson & Rugg, 1988), and were largest over the visual cortical areas of the occipital lobe. Although the neural generators of these effects have not yet been localized to precise cytoarchitecturally defined areas, Mangun et al. (1993) used a combination of high-density electrode arrays and magnetic resonance brain images to provide evidence that the P1 attention effect is generated in lateral extrastriate visual

cortex, consistent with attention effects observed in single-unit recordings from monkey extrastriate areas (Moran & Desimone, 1985). Thus, both the latency and neural localization of these ERP results clearly support sensory-level models of attentional selection, such as the sensory gain control hypothesis described by Hawkins et al. (1990).

There are several additional reasons to believe that the attention-related modulation of the P1 and N1 components observed in this study reflect changes in sensory-level processing rather than decision-level processing. First, these components are sensitive to physical features of the evoking stimuli such as brightness, spatial frequency, and wavelength, even when these features are task irrelevant (Regan, 1989). Second, these components are observed whether the evoking stimuli are attended and are present even when subjects are not performing a task. Finally, modulation of the P1 and N1 components may be observed for task-irrelevant "probe" stimuli presented at or near a location where attended, task-relevant stimuli are presented (Heinze et al., 1990; Luck, Fan, & Hillyard, 1993; Mangun & Hillyard, 1990), and these effects are observed even when the probe stimuli are easily discriminable from the task-relevant stimuli. This indicates that the processing of all stimuli within the attended zone is facilitated at an early level, prior to the complete analysis of the relevant stimulus features.

Although spatial cuing affected both signal detectability and sensory-evoked neurophysiological responses in this experiment, it is difficult to prove that the observed changes in neural activity were directly responsible for the changes in detection performance. Although attention clearly affected sensory processing, it is conceivable (although unlikely) that these sensory-level effects did not influence the detectability of the luminance signals, and that the observed changes in signal detection performance were caused instead by higher level mechanisms that operate concurrently with the sensory-level mechanisms. Even if this were true, however, the present results would still provide strong evidence that spatial attention modulates sensory-level processing, and in a manner consistent with an increase in sensory gain inside the focus of attention or a decrease in sensory gain outside the focus of attention.

### General Discussion

#### Attention and Luminance Detectability

Over the past several years, a large number of studies have addressed the question of whether attention can affect luminance detectability, and whereas some studies have found robust attention effects (Bashinski & Bacharach,

<sup>3</sup> Posterior N1 amplitude was actually greater (more negative) on invalid trials than on neutral trials, but this was probably due to overlapping P1 and P2 attention effects that extended into the N1 latency range rather than a change in the amplitude of the underlying N1 component. This same pattern has been observed in previous studies in which the posterior N1 attention effect was eliminated (e.g., Luck, Heinze, Mangun, & Hillyard, 1990).

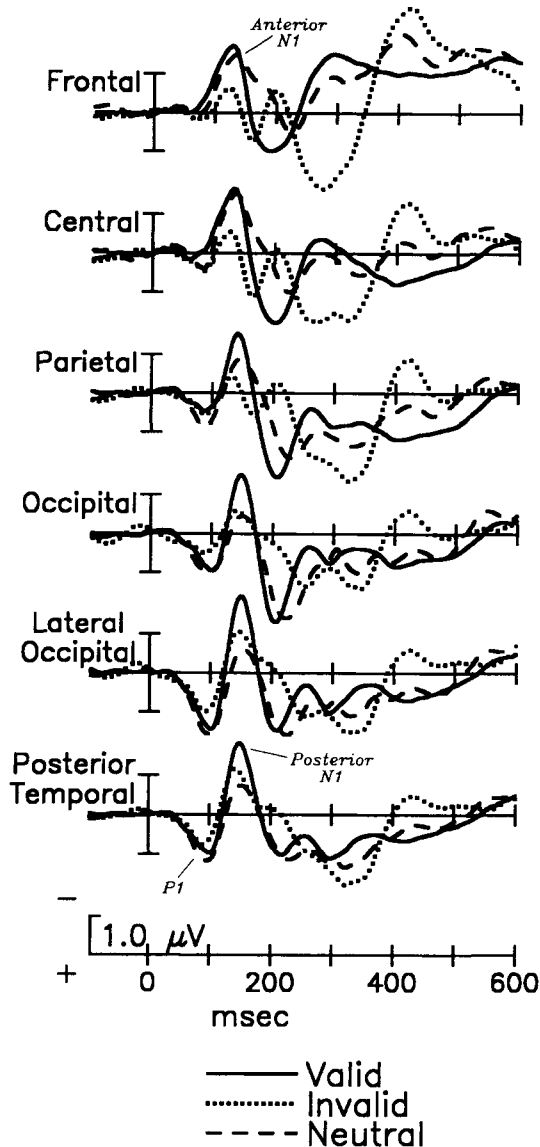


Figure 5. Event-related brain potential (ERP) waveforms elicited by the mask-postcue stimuli in Experiment 3 under three conditions of precue-postcue validity. These waveforms are grand averages over the 15 subjects and are collapsed over the four stimulus positions. Each set of overlaid traces shows ERPs from a single electrode site that were elicited by stimuli in the contralateral visual field. That is, each averaged waveform includes ERPs recorded from a left hemisphere site in response to right visual field stimuli and ERPs recorded from a right hemisphere site in response to left visual field stimuli. Note that negative is plotted upward. These waveforms were corrected by the ADJAR filter procedure described above (Woldorff, 1993) and were low-pass filtered with a gaussian digital filter (50% amplitude cutoff of 35 Hz).

1980; Downing, 1988; Hawkins et al., 1990), these effects have been small or absent in other studies (Bonnell, Stein, & Bertucci, 1992; Mueller & Findlay, 1987; Shaw, 1984). The precue-postcue paradigm used in the present study, how-

ever, has produced reliable attention effects in a number of experiments and under a variety of conditions, including central and peripheral precues, small and large eccentricities, a broad range of target intensities, single and multiple targets, various delays between precue and target and between mask and postcue, and different mask-postcue configurations (see Downing, 1988; Hawkins et al., 1990; Mueller & Humphreys, 1991). Thus, there is considerable evidence that focusing attention onto a location can increase luminance detectability at that location.

Several attributes of the precue-postcue paradigm may have contributed to the consistent results it has produced. First, the postcue indicates a single location for which target presence or absence must be reported, making the calculation of signal detection parameters more straightforward. Second, whereas the location of the postcue is predicted by the precue, the presence or absence of the luminance target is independent of cue validity. Because the precue indicates the location at which the signal must be distinguished from the background noise, subjects have an incentive to increase the signal-to-noise ratio of visual processing at the precued location and would gain nothing by adopting a different decision bias at the precued location. An additional feature of the present design is that target luminance was individually adjusted for each subject to maintain an intermediate level of detectability, thereby avoiding ceiling and floor effects (see Hawkins et al., 1988). In fact, the largest validity effects were observed in Experiments 2 and 3, in which target luminance was adjusted continuously over the course of each session to ensure a constant level of difficulty.

#### Locus of Selection

Although the observed differences in sensitivity at cued and uncued locations provide strong evidence that luminance detection requires limited capacity processing resources, it is more difficult to determine the level of processing at which these capacity limitations operate. In Experiment 1, we explored the possibility that the capacity limitations occur relatively late, at the stage of memory rehearsal, and that the reduction in sensitivity observed at uncued locations is due to a lack of rehearsal during the mask-postcue delay interval. The attention effects were found to be unaffected by the duration of the delay interval, however, indicating that these effects were not caused by capacity limitations in memory rehearsal.

Experiment 2 was designed to determine whether these capacity limitations occur during sensory analysis or during decision processes. The sensory-level account proposes that attention improves the quality or quantity of sensory information at the attended location. In contrast, decision-level accounts propose that sensory analysis is unaffected by attention and that attention instead controls the transfer of sensory information into a limited-capacity system that is responsible for making the actual target present-absent decision (e.g., Duncan, 1980; Mueller & Humphreys, 1991; Sperling, 1984). On invalid trials, the transfer of target

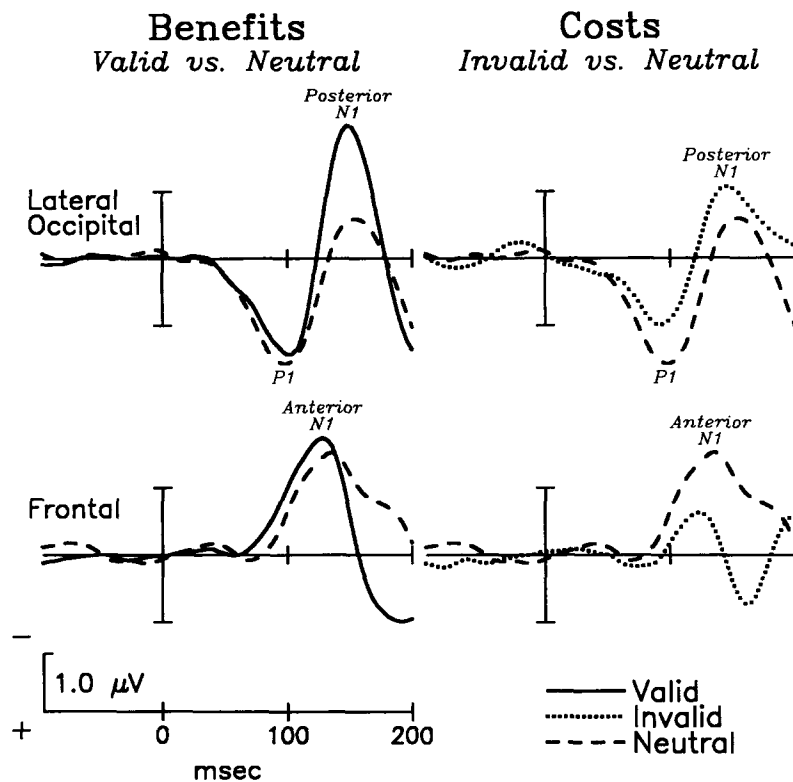


Figure 6. Lateral occipital and frontal waveforms from Figure 5, presented on expanded scales to make the early attention effects clearer. The left traces compare valid and neutral trials to show the benefits of attention, whereas the right traces compare invalid in neutral trials to show the costs of attention.

information into this decision system is proposed to be delayed or degraded, resulting in a reduction in target detectability. This hypothesis was tested by using an isolated, abruptly onsetting mask–postcue stimulus that was designed to override the attentional priorities that were set up by the precue and thereby allow immediate transfer of information from the postcued location into the decision stage. Consistent with sensory-level models of attention, the effects of attention were virtually identical in this single mask–postcue condition, compared to a 4-mask condition in which the postcue was less salient and presumably less able to interrupt the priorities set by the precue. Thus, Experiment 2 provided further evidence against models specifying that attention affects only the order in which memory and decision processes are applied to incoming stimuli, without affecting sensory processing.

In Experiment 3, we obtained significant cue validity effects even though the cue–target stimulus onset asynchrony (SOA) was relatively long and unpredictable. This arrangement should have made it difficult for subjects to make the target present–absent decision at the precued location without waiting for the postcue, which indicated the precise time window of the luminance information in addition to its location. Accordingly, the results of Experiment 3 are difficult to explain by models that specify an ordered sequence of selections from cued and uncued loca-

tions (a “selection stack”). If the validity effects were based on an ordered selection or decision sequence that is triggered by the initial cue and starts at the precued location, this initial decision should be inaccurate when the cue–target interval is unpredictable. If, on the other hand, subjects waited for the postcue before initiating the selection sequence, it would seem highly unlikely that they would make the initial selection from any location other than the postcued one. Accordingly, models that attribute cue validity effects to an ordered selection sequence (e.g., Mueller & Humphreys, 1991; Yantis & Johnson, 1990) do not fit comfortably with the findings of Experiment 3.

The results of Experiment 3 do seem compatible with a class of models in which attention controls the rate of information flow or encoding at cued and uncued locations. Unfortunately, the signal detection data do not appear to distinguish between early selection models in which information flow is controlled at sensory levels (e.g., Hawkins et al., 1990) and late selection models proposing the selection or differential weighting of fully processed sensory information at a higher decision stage (Sperling, 1984). These results could also be explained by a decision-level model in which subjects make decisions continuously at the precued location during the cue–target delay interval and simply report the decision that immediately preceded postcue onset on valid trials; on invalid trials, however, additional time

Table 5  
*Summary of Event-Related Brain Potential (ERP)  
 Component Measurements and Analyses from  
 Experiment 3*

Parameter	P1	Anterior N1	Posterior N1
Measurement window (ms)	60–100	100–140	140–180
Electrode site	O1, O2, OL, OR, T5, T6	F3, F4, C3, C4	O1, O2, OL, OR, T5, T6
Overall effect of validity			
<i>F</i>	6.75	18.29	14.33
<i>p</i>	.005	.001	.01
Valid vs. neutral			
<i>F</i>	3.96	8.72	33.37
<i>p</i>	<i>ns</i>	.02	.01
Invalid vs. neutral			
<i>F</i>	11.18	10.39	0.25
<i>p</i>	.005	.01	<i>ns</i>

*Note.* Validity included valid, invalid, and neutral trials; separate analyses of costs (invalid vs. neutral) and benefits (valid vs. neutral) are presented. The degrees of freedom were (2, 28) for the overall analysis and (1, 14) for the analyses of costs and benefits.

may be required to switch the decision apparatus to the postcued location, thereby resulting in decay of target information and decreased detectability. Thus, it appears that at least some late selection models could be made compatible with the signal detection results of all three of the present experiments. For this reason, we turn to the evidence provided by ERP recordings to assess the level of selection at which these spatial attention effects take place.

The finding that early sensory-evoked activity in visual cortex was enhanced in response to valid-location stimuli provides strong evidence that precuing of location affects early sensory processing. As discussed above, attention-related amplitude modulations of these early (60–150 ms) evoked responses are fully compatible with the proposal that attention controls the flow of information at the level of visual cortex (e.g., by a sensory gain control or filter mechanism), but they appear difficult to reconcile with models proposing exclusively postsensory mechanisms of selection. These results thus provide physiological evidence for early selection in the context of spatial cuing and luminance detection, which accords with previous studies involving the use of different experimental paradigms and different physiological recording modalities, such as single-unit recordings (e.g., Chelazzi, Miller, Duncan, & Desimone, 1993; Luck, Chelazzi, Hillyard, & Desimone, 1993; Moran & Desimone, 1985), and positron emission tomography (e.g., Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991).

### *Costs and Benefits of Spatial Attention*

The pattern of cue validity effects observed for the different ERP components also reveals more fine-grained properties of the mechanisms of spatial attention. If the amplitudes of all the early ERP components had been larg-

est for validly cued stimuli, smallest for invalidly cued stimuli, and intermediate for neutrally cued stimuli, this would have implied a single, unitary selection mechanism that allocates processing resources in a graded fashion according to the probability that task-relevant information will be presented at a particular location. However, the finding that the posterior N1 component was enlarged for stimuli at the attended location whereas the P1 component was suppressed for stimuli at the unattended locations (relative to neutral trials) strongly implies the existence of multiple attention mechanisms. This conclusion is consistent with previous findings indicating that the P1 attention effect may occur in the absence of the posterior N1 attention effect and vice versa (e.g., Heinze et al., 1990; Luck, Fan, & Hillyard, 1993; Luck, Heinze, Mangun & Hillyard, 1990; Luck & Hillyard, in press; Mangun et al., 1986) and corresponds well with behavioral findings from previous studies indicating that attentional costs and benefits can be dissociated by manipulations of cue and masking conditions (e.g., Hawkins et al., 1990).

This distinction between the suppression of processing at unattended locations reflected by the P1 component and the enhancement of processing at the attended location reflected by the posterior N1 component depends on the use of neutral trials to provide a baseline for comparison, and it is possible that this pattern of effects depends upon the particular neutral condition used in the present experiment. However, the same pattern of effects has also been observed in a visual search paradigm in which a very different type of neutral trial was used and subjects were not explicitly cued to attend to a particular location (Luck & Hillyard, in press). Specifically, the posterior N1 component exhibited enhancement at the location of the visual search target and the P1 component exhibited suppression at nontarget locations, both relative to "neutral" trials in which the target was absent from the array. The presence of this distinctive pattern of effects in both spatial cuing and visual search paradigms suggests that it does not depend on a particular neutral cuing condition and that the separate suppressive and facilitatory mechanisms reflected by the P1 and posterior N1 components may be used across a variety of attention-demanding tasks.

This consistent pattern of ERP results provides a new perspective on the long-standing question of whether attention operates through suppression or facilitation. Instead of a single attentional mechanism that uses one or both of these processes, the present results suggest that there are multiple mechanisms of visual-spatial attention that operate in different ways. This proposal is also consistent with several previous dissociations between the P1 and posterior N1 components, dissociations that may be useful in characterizing the proposed suppressive and facilitatory processes more fully. For example, the posterior N1 attention effect is present in choice reaction time tasks but is absent when subjects make the same, nondiscriminative response to all stimuli (Mangun & Hillyard, 1991), suggesting that the N1 effect reflects the application of a discriminative process to attended-location stimuli. The posterior N1 effect may also be eliminated when the attended location is stimulated very

rapidly (Heinze et al., 1990; Luck, Heinze, Mangun, & Hillyard, 1990), indicating that this proposed discriminative process is subject to temporal capacity limitations. In addition, although the P1 component exhibits attentional suppression in visual search tasks when the target is defined by a color-form conjunction, this effect is eliminated when the target is defined simply by its color (Luck & Hillyard, *in press*). This finding suggests that the suppressive process reflected by the P1 may be required only when the distractor items are highly confusable with the target.

These ERP findings also have implications for the attentional strategies used by subjects on neutral trials. In the present experiment, all four locations were cued simultaneously on neutral trials with the implicit assumption that subjects would distribute their attention broadly to include all four locations. However, an alternative strategy for neutral trials would be to focus attention onto a single randomly chosen location by means of the same mechanisms used to attend to a single location on valid trials. With such a strategy, detectability scores and ERP amplitudes on neutral trials would consist of an average of the values observed on valid and invalid trials, weighted by the probability of attention being focused onto the correct location (25%, given the four locations used in the present study). Such a strategy would therefore have resulted in detectability scores and ERP amplitudes that were larger than the invalid values by a factor of 25% of the difference between the valid and invalid values. This pattern was not observed for either the behavioral or electrophysiological measures, indicating that subjects did not focus attention onto a randomly chosen single location on neutral trials.<sup>4</sup>

### *Attention and Noise Reduction*

It is well known that detection sensitivity is reduced when the number of possible target locations is increased, simply because this manipulation increases the number of noise sources and hence the probability of false positives (see Cohn & Lasley, 1974; Eriksen & Spencer, 1969; Lappin & Uttal, 1976; Sperling, 1984). This "display-N" effect (Mueller & Humphreys, 1991) is a statistical consequence of sampling from multiple locations and would obtain even for an "ideal observer" with no capacity limitations. Following this logic, several authors have proposed that spatial precues might improve target detectability by allowing subjects to limit the number of target locations being considered, thus reducing the number of sources of noise (e.g., Palmer et al., 1993; Shaw, 1984; Shiu & Pashler, 1994; Sperling & Doshier, 1986). In this manner, precues could lead to improved detectability even if there were no capacity limitations in sensory processing. According to this "noise reduction" model, attentional selection could be accomplished at either an early or late stage of processing; the essential point is that irrelevant (e.g., uncued) inputs would be suppressed and would therefore contribute less to the final decision about target presence.

Although the greater accuracy observed at validly cued locations could be attributed to a suppression of noise

arising from the uncued locations in some studies (e.g., Henderson, 1991; Shiu & Pashler, 1994; Van der Heijden, Brouwer, & Serlie, 1992), the use of a postcue design makes this interpretation highly unlikely for the present results. According to the noise reduction model, an independent value is computed at each location that reflects the evidence for target presence at that location, and subjects make a target-present response if the largest of these values exceeds some criterion (Graham, Kramer, & Haber, 1985; Shaw, 1984). The probability that this largest value will occur at a nontarget location due to noise will increase as the number of locations increases, thus leading to a decrease in detection sensitivity (see Palmer et al., 1993, for a detailed analysis). When a postcue is used to indicate the single location at which a target may have occurred, however, subjects can simply report whether the value at the postcued location exceeded the target-presence criterion. Because this report is based on the postcued location alone, high target-presence values at other locations caused by noise will not lead to false alarms.

This line of reasoning may be applied most clearly to the results of the 1-mask conditions of the present study, in which the highly salient mask-postcue stimulus served to define the location of the target information. Because subjects were informed that targets could only occur at the postcued location, it is difficult to imagine how a noise fluctuation at one location could be reported as a target if the highly salient postcue appeared immediately thereafter at another location. Thus, the combined mask-postcue design nullifies the basic requirement of the noise reduction model that noisy percepts at nontarget locations must be independently confusable with the target. Accordingly, the effects of cue validity on detection sensitivity in the present study cannot be explained simply by the statistical consequences of sampling from multiple locations.<sup>5</sup>

<sup>4</sup> There may be situations in which such a strategy would be used, however. For example, if there were only two locations, the probability of attention being directed to the correct location by chance on a neutral trial would increase to 50%, thus improving the performance resulting from this strategy. Subjects might also use this strategy in situations wherein target detection is virtually impossible unless attention is focused solely upon the location of the target (e.g., because of the possibility of illusory conjunctions), even if the probability of selecting the target location at random is very low. In such situations, the patterns of behavioral accuracy and ERP amplitudes might be quite different from the patterns observed in the present study.

<sup>5</sup> Although the postcue design eliminates the possibility that large noise values from nonpostcued locations will be incorrectly reported as targets, there are alternative mechanisms by which this noise could lead to decreased detection sensitivity at the postcued location. For example, a large noise value could lead to the allocation of decision resources to the location of the noise, causing subjects to miss true target signals presented elsewhere. Thus, the present signal detectability results are consistent with an attention mechanism that suppresses noise arising from uncued locations, although this suppression is not used to eliminate false alarms caused by noise at nonpostcued locations.

## Conclusion

By using a postcue to confine subjects' luminance judgments to a single location, the present experiments provide strong evidence against several postsensory explanations of spatial cuing effects. In particular, the results weigh against interpretations that are based on: (a) the decay of target information in visual memory; (b) the ordered transfer of inputs into a limited capacity decision stage; and (c) the suppression of statistical noise (the display-N effect). In contrast, the observed effects of cue validity on target detectability were entirely consistent with the hypothesis that spatial attention acts at an early, sensory-level stage of processing. This interpretation was reinforced by ERP recordings showing that spatial precues led to changes in sensory-evoked neural responses from visual cortex beginning within 60–100 ms of stimulus onset. In addition, the ERP results suggested that separate mechanisms were responsible for suppressing information arising from the unattended locations and for enhancing the processing of information at the attended location. These results provide strong support for early selection models of visual-spatial attention.

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