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Visual Attention Modulates Signal Detectability

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The mechanism by which visual-spatial attention affects the detection of faint signals has been the subject of considerable debate. It is well known that spatial cuing speeds signal detection. This may imply that attentional cuing modulates the processing of sensory information during detection or, alternatively, that cuing acts to create decision bias favoring input at the cued location. These possibilities were evaluated in 3 spatial cuing experiments. Peripheral cues were used in Experiment 1 and central cues were used in Experiments 2 and 3. Cuing similarly enhanced measured sensitivity, $P(A)$ and d', for simple luminance detection in all 3 experiments. Under some conditions it also induced shifts in decision criteria (beta). These findings indicate that visual-spatial attention facilitates the processing of sensory input during detection either by increasing sensory gain for inputs at cued locations or by prioritizing the processing of cued inputs.

When human observers are precued to the probable location of a visual target, they respond more quickly when the target appears at the cued location than when it appears elsewhere (Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980). Although this result is straightforward, its interpretation has been a major point of controversy within the attention literature. Posner and his colleagues attributed the effect to the action of attention on sensory pathways that code information from the cued location. Extending this view, others have suggested that attention could act either to facilitate processing in sensory pathways that code input from expected locations, to inhibit processing in pathways that code input from unexpected locations, or perhaps to exert a combination of these modulatory influences (e.g., Downing, 1988; Hawkins, Shafto, & Richardson, 1988). Rejecting Posner's view, Shaw (1978, 1984) argued that attention has no effect on the sensory processes that subserve detection. Instead, she attributed the reaction time effects of spatial cuing entirely to differences in decision-making strategies at the cued and uncued locations; Because targets are more likely to appear at a cued location, observers may simply require less sensory evidence, and thus less sampling time, to decide that a target has appeared there (see also Sperling, 1984; Sperling & Dosher, 1986).

If Shaw's analysis were correct—that is, that the decision-making process at some stage of processing is attentionally biased to favor a target-present decision at the cued location—then one would expect cued and uncued locations to differ in decision bias (e.g., beta) but not sensitivity. Conversely, if attention modulates the efficacy of sensory processing, one might expect cued and uncued locations to differ in sensitivity (e.g., d'). For example, spatial attention could affect sensitivity by increasing sensory gain at the cued location, that is, by assigning higher weightings at some stage of sensory processing to input from cued (relative to uncued) locations.[1] Alternatively, spatial cuing could determine the order in which information from cued and uncued locations is read out of an early stage of processing, where representations are subject to rapid decay and masking, and transferred into a later stage where detection takes place (cf. Duncan & Humphreys, 1989). If information at a cued location is given priority during readout, the quality of its representation at the second stage will be higher than for uncued locations, yielding a sensitivity advantage.

The source of the cuing effect has proven elusive. In support of the idea that attention modulates sensory processing, Bashinski and Bacharach (1980) reported that spatial cuing increases detection sensitivity but has no discernible effect on decision processes. However, Müller and Findlay (1987) ar-

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[1] The differential weighting of input from cued and uncued locations produces effects on sensitivity provided certain other assumptions are met. These are described in the General Discussion section and the Appendix.

gued persuasively that the method used by Bashinski and Bacharach to calculate d' yields results biased in favor of the cued location. Müller and Findlay adopted a calculation that corrects for this problem and applied it to the analysis of data drawn from a series of four-position spatial cuing tasks. Their results were as expected from the Shaw (1984) analysis: For luminance detection, spatial cuing increased the leniency of decision criteria but had no effect on sensitivity.

In contrast to Müller and Findlay's (1987) results, however, Downing (1988) found that measured sensitivity (d') in luminance detection was higher for cued than for uncued locations. These two sets of studies are distinguished by several design features that might account for their differing outcomes. Downing used a visual display with more alternative target locations (12 rather than 4), presented multiple targets (as many as 4, rather than 1) on each trial, and used less detectable targets than did Müller and Findlay. Perhaps more significant, Downing used a novel posttarget probe technique in which several specific locations of the 12 in the array required a yes–no decision *after* the target(s) had been presented. The cued location was always among those probed on each trial. The posttarget probes were arrows that pointed successively to the locations to be reported. This technique, together with the independence of stimulation at different locations, allowed for a relatively straightforward calculation of d' and beta at each of the probed locations. Because responses were made only for the probed locations, the localization of false alarms and correct detections appears to have been more securely determined than with the Müller and Findlay technique. As pointed out by Shulman and Posner (1988), the Müller and Findlay procedure could have produced deflated estimates of sensitivity for targets at the cued location. Targets appeared on 67% of the trials in the pertinent experiment (Experiment 2), with more than 80% of the targets appearing at a cued location and the remainder at an uncued location. A *hit* was defined as a correctly localized detection, and a *false alarm* was defined as a target-present response on a target-absent trial. Suppose that an observer's uncertainty as to the location of a perceived target is higher for falsely detected than for correctly detected targets. In addition, suppose that when faced with uncertainty about the location of a perceived target, observers tend to base their localization judgments on a priori probabilities regarding target location; that is, they tend to assign perceived targets of uncertain origin to a cued location. If so, the Müller and Findlay procedure could have produced an inflated false-alarm rate, and thus an underestimate of sensitivity, at the cued location.

Our aim in the three experiments reported here was to investigate the effects of spatial cuing in detection tasks designed to alleviate the problems suggested earlier. Shifts in attentional focus were induced by making the cue highly predictive of the single location that subsequently would be probed. The cued location was probed on 76% of the trials, and each of the three uncued locations was probed on 8% of the trials. Thus, subjects were responsible most often for reporting the target status of the cued location only. This procedure should have maximized the likelihood that subjects would focus attention on the cued location rather than distribute it across the entire display. Only one target could appear on each trial, and if a target appeared it was at the probed location. The conditional probability that a target would occur at a particular cued or uncued location, given that it was probed, was .50. Subjects were fully informed of these contingencies. This procedure uses Downing's (1988) posttarget probe technique but carries two possible advantages over her method. First, by setting the probability of target appearance at a probed location to be the same regardless of whether it was precued, we minimized the possibility that subjects would assign falsely perceived targets disproportionately to the cued location, thereby raising false-alarm rates there. Second, by presenting only one target on target-present trials, we minimized the possibility that our results would be influenced by the use of different readout strategies for cued and uncued targets simultaneously present in an early sensory register (cf. Duncan, 1980a, 1980b; Duncan & Humphreys, 1989).

Peripheral cues were used in Experiment 1. Possible target locations were demarcated by four boxes diagonally arrayed around fixation. The peripheral cue was a brief brightening of one box or (in the neutral cue condition) all four boxes. We assumed that the peripheral nature of the cue and the fact that it was highly predictive of the location of the posttarget probe would ensure its control over the subject's attentional focus. Thus we expected a robust attentional-cuing effect in this experiment. This was indeed the outcome, and it set the stage for Experiments 2 and 3, in which we investigated the effects of central cues in luminance detection.

Experiment 1

The effects of peripheral cuing were investigated under two levels of target eccentricity (a between-subjects variable) and two levels of target detectability (a within-subjects variable). The higher and lower detectability levels were roughly equivalent to those of Müller and Findlay (1987) and Downing (1988), respectively. Thus levels provided an assessment of the possibility that differences in target detectability are responsible for the differing outcomes of the two studies.

Method

Subjects. Twelve Catholic University students, 7 men and 5 women, participated in Experiment 1. All had normal or corrected-to-normal vision. The experiment consisted of one calibration session and six experimental sessions, each about 1 hr in length and carried out on separate days. Payment was $5 per session, with a $30 bonus for completing all sessions.

Stimulus display. A computer-controlled video raster monitor was used to generate the display. A chinrest 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 symmetrically arrayed boxes, each demarcating a potential target location. The boxes were constructed of IBM American standard code for information interchange (ASCII) characters and had side-to-side visual angle of 1.6°. The center-to-center visual angle between the fixation and each box was 3.89° in the low-eccentricity condition and 8.3° in the high-eccentricity condition. The fixation frame remained in view for 700 ms and was then replaced

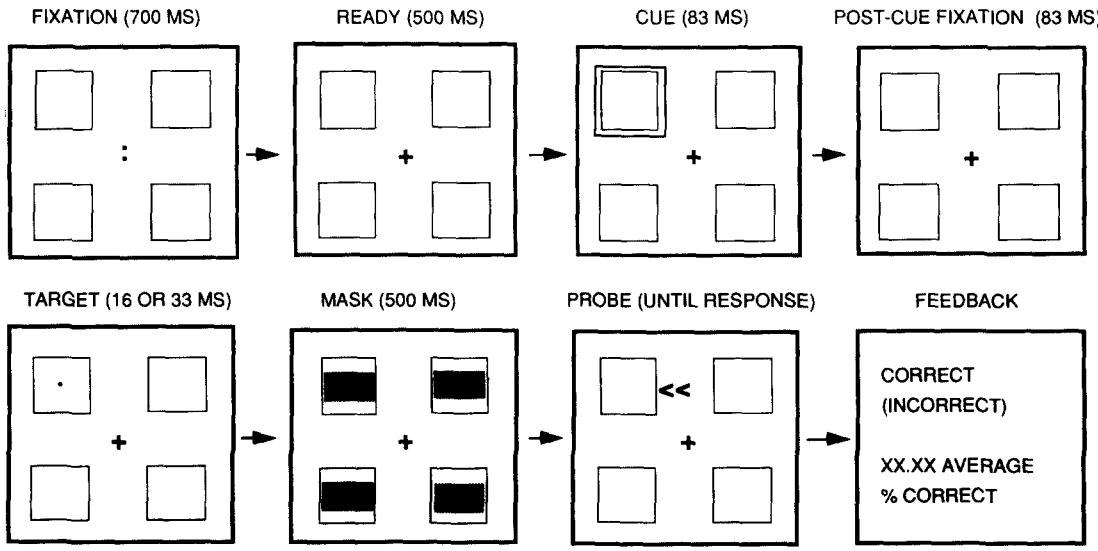

Figure 1. Sequence of frames presented on a given trial in Experiment 1.

by a 500-ms warning frame. The only change between these frames was that the colon was replaced by a plus sign. The third frame contained the peripheral cue, an 83-ms presentation of ASCII characters combined to form two concentric squares at either one or all four of the target boxes. The impression given by the concentric squares was of a brightening of the cued box(es). The cue frame was replaced with an 83-ms postcue 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 briefly appeared at the center of one target box.[2] The duration of the target was determined by the calibration procedure described below. The target frame was replaced by a 500-ms masking frame containing a mask composed of three side-by-side ASCII textural characters situated at the center of each of the four boxes. This was followed by a probe frame in which two inequality signs formed an arrow pointing to one of the four target squares. This remained in view until the subject depressed a key indicating whether a target had been present or absent at the probed location. A 1,000-ms feedback frame then appeared that indicated whether the response on the trial was correct, and on correct trials, the cumulative accuracy of all preceding trials within the block. Following feedback, the phrase "Press space bar when ready" appeared on the monitor. Subjects initiated the succeeding trial at this point by depressing the space bar on a keyboard in front of them.

Task. The task was to judge whether a target had appeared at the probed location and to indicate the confidence with which this judgment was made. These judgments were indicated, without time pressure, by pressing the *1* (no target - high confidence), *2* (no target - low confidence), *3* (target - low confidence), or *4* (target - high confidence) keys at the top of the keyboard.

Procedure. Subjects were tested on 496 trials during each experimental session. Rest breaks were provided every 124th trial. Two levels of target detectability were achieved by varying target duration. Two target durations were selected for each subject such that the longer duration target yielded an overall d' value near 2.0 during the preliminary calibration session, and the shorter duration target yielded an overall d' value between 0.50 and 1.00. Target duration was held constant during each experimental session. The order of testing with the two target durations was counterbalanced across the 6 subjects and six experimental sessions within each eccentricity condition.

A single location was cued on 400 (80.6%) of the 496 trials forming a block, and all four locations were cued (neutral cue trials) on the remainder. On 304 (76%) of the single-cue trials, the cued location was subsequently probed (valid cue trials). A target had appeared at the probed location on 50% of these trials. On the remaining 96 single-cue trials, the location probed differed from that cued (invalid cue trials). On these trials the three uncued locations were equally likely to be probed. Again, a target had been presented at the probed location on 50% of the trials. On neutral cue trials the four locations had an equal likelihood of being probed, and probed locations contained a target 50% of the time. On all trials targets appeared only at probed locations.

Eye movements were not monitored in this experiment. However, the importance of maintaining fixation was strongly emphasized, and the stimulus onset asynchrony (SOA) between cue and target in the experiment was 167 ms, rendering cue-contingent eye movements unlikely to affect performance.

Data analysis. To facilitate comparisons between the present results and those of Müller and Findlay (1987) and Downing (1988), two measures of sensitivity were calculated for each subject. One was d', estimated by treating 1 and 2 as *no* responses and 3 and 4 as *yes* responses. The other was $P(A)$, the area under the receiver operating characteristic curve. Statistical analyses were carried out on the $P(A)$ parameter, considered to be the more robust of these (Green & Swets, 1966). The likelihood ratio at the *yes–no* cutoff, beta, was used as a measure of response bias.

Calibration procedure. A preliminary testing session was carried out to select the two target durations to be used for each subject during the experimental sessions. As noted, our aim was to establish for each subject a longer duration target that produced overall measured sensitivity values comparable to those of Müller and Findlay (1987) and a shorter duration target that produced measured sensitivity values comparable to those of Downing (1988). The calibration procedure was similar to that described previously for experimental

[2] The target was IBM ASCII Character 250 in the low-eccentricity condition and Character 249 in the high-eccentricity condition. Both of the characters are dots, with 249 slightly larger than 250. Masks were composed of three ASCII 178 characters.

sessions except that four different target durations were randomly distributed through the 528 calibration trials. The four durations selected on the basis of pilot work were the refresh-rate multiples 17, 33, 50, and 67 ms. An analysis of the overall d' values produced during the calibration session by each subject at the four durations indicated that 11 of the 12 subjects ought to be tested at 17 and 33 ms; the remaining subject ought to be tested at 33 and 50 ms.

Results and Discussion

Table 1 gives the $P(A)$ values obtained by each subject, and the subject-averaged d' scores, under the three cue validity conditions (valid, neutral, invalid cues) and the two levels of target detectability at each of the two target eccentricities. The $P(A)$ values were subjected to a mixed-model analysis of variance, with cue validity and target detectability treated as within-subjects factors and target eccentricity treated as a between-subjects factor. The analysis revealed significant main effects for cue validity, $F(2, 20) = 33.99$, $p < .01$, target detectability, $F(1, 10) = 77.46$, $p < .01$, and target eccentricity, $F(1, 10) = 4.98$, $p < .05$. No other effects, including interactions, approached significance. Fisher's least significant difference (LSD) test, with the criterion of significance set at .05, was used to evaluate further the differences among cue validity conditions (LSD = .044). This analysis indicated that $P(A)$ was lower for the invalid cue trials than for either of the two others, which indicates costs but not benefits.

Table 2 gives the likelihood ratios (betas) at the *yes–no* cutoff for each subject under the various cue validity, target detectability, and target eccentricity conditions. A mixed-model analysis of variance carried out on these data revealed a significant cue validity main effect, $F(2, 20) = 3.80$, $p < .05$, and a significant Cue Validity × Target Detectability interaction, $F(2, 20) = 7.32$, $p < .05$. The LSD test indicated that beta was lower (i.e., decision criteria were more lenient) for valid than for either neutral or invalid cue trials (LSD = .565).

Table 1
Individual P(A) and Subject-Averaged d' Values Across Cue Validity Trial Types, Target Detectability Conditions, and Target Eccentricities in Experiment 1

	Low detectability			High detectability		
Subject	Valid cue	Neutral cue	Invalid cue	Valid cue	Neutral cue	Invalid cue
			Low eccentricity			
1	.69	.68	.64	.89	.87	.78
2	.69	.61	.55	.86	.91	.76
3	.67	.76	.63	.95	.98	.94
4	.71	.70	.70	.94	.95	.91
5	.81	.76	.75	.98	.97	.94
6	.65	.63	.57	.67	.71	.68
Mean $P(A)$	.70	.69	.64	.88	.90	.84
Mean d'	1.12	1.23	.86	2.74	2.89	2.33
			High eccentricity			
7	.70	.69	.59	.88	.92	.79
8	.72	.74	.70	.91	.93	.73
9	.62	.57	.57	.80	.71	.61
10	.62	.56	.48	.78	.72	.60
11	.60	.61	.53	.69	.63	.54
12	.56	.60	.55	.70	.64	.65
Mean $P(A)$	.64	.63	.57	.79	.76	.65
Mean d'	.63	.70	.34	1.49	1.42	.92

Table 2
Individual Likelihood Ratios (Betas) Across Cue Validity Trial Types, Target Detectability Conditions, and Target Eccentricities in Experiment 1

	Low detectability			High detectability		
Subject	Valid cue	Neutral cue	Invalid cue	Valid cue	Neutral cue	Invalid cue
			Low eccentricity			
1	1.53	2.21	2.22	1.20	4.20	4.85
2	1.29	1.18	1.08	0.59	1.36	2.14
3	0.83	1.66	1.41	0.11	1.16	3.23
4	1.45	1.49	2.11	1.86	0.86	7.06
5	2.15	2.24	2.55	0.49	0.65	1.00
6	1.27	6.78	1.21	1.30	5.16	1.74
M	1.42	2.59	1.76	0.92	2.23	3.34
			High eccentricity			
7	1.12	1.56	1.57	0.74	1.16	3.52
8	0.79	4.48	2.42	0.55	2.04	2.51
9	0.96	1.22	1.48	0.57	1.64	1.89
10	0.90	1.11	0.96	0.86	1.20	1.23
11	1.05	1.13	1.04	0.87	1.27	1.16
12	1.00	0.97	0.96	0.94	1.00	0.73
M	0.97	1.74	1.40	0.76	1.39	1.84

These results demonstrate that the peripheral cuing of visual-spatial attention exerts a pronounced effect on target detectability and that the magnitude of this effect is preserved across reasonably wide variations in target eccentricity and target detectability. The latter finding suggests that the differing results of the Müller and Findlay (1987) and Downing (1988) studies are not attributable to differences between the studies in overall target detectability. Experiment 2 provides further evidence relating to this issue.

The cue validity effect in this experiment was manifested as an attentional cost, that is, as a reduction in target detectability on trials containing invalid (relative to valid and neutral) cues. No attentional benefit was evident. Spatial cuing has been shown to produce benefits both in measured sensitivity and reaction time under a wide variety of conditions (e.g., Downing, 1988; Müller & Rabbitt, 1989; Posner, 1980). However, to our knowledge benefits have never been observed under the general conditions of Experiment 1, where the task was (luminance) detection, the dependent measure $P(A)$ was free of decision-bias effects (cf. Hawkins et al., 1988), the attentional cues were peripheral, and only a single location could contain a target on each trial. Attentional benefit might be absent under these conditions for either of two reasons. First, it is possible that our neutral cue trials, on which all four boxes sharply brightened prior to target onset, were not truly neutral (cf. Jonides & Mack, 1984). The abrupt visual discontinuity appearing in all four display quadrants during these trials may have produced higher levels of arousal than

those occurring during trials on which only one box was brightened. A second, more provocative possibility is that the magnitude of the detection-sensitivity enhancement provided by spatial attention is independent of the spatial extent of the attentional focus. That is, attentional benefits in detection sensitivity are not diluted when attention is broadly distributed (at least across the visual angles studied here). A critical assumption underlying this account is that peripheral cues can distribute attention across multiple cued locations without loss, whereas central cues cannot. Thus, the benefits often observed with central cuing could be due to an incomplete distribution of attention across potential target locations during neutral cue trials. Our design does not permit an evaluation of these two accounts for the absence of attentional benefits in this experiment.

The systematic shift in beta across cue validity conditions was unexpected given that the probability a target had appeared at the probed location was held constant at .50 for all trial types. This criterion difference may be because the a priori probability of a target was .38 at the location of the peripheral cue, .125 at each of the four locations under the neutral cue condition, and .04 at each of the three uncued locations. Subjects may have reacted to these a priori probabilities by setting a more lenient decision criterion for evaluation of input from the cued location. An alternative possibility, however, is that when a single target box was cued, subjects tended to mistake the sensory experience created by the cue for that created by the target, increasing the overall likelihood that they would report a target was present at the cued location. That is, the beta effect may reflect a breakdown in the visual system's spatial and temporal resolution at these target eccentricities. If this is the case, one might expect the beta effect to disappear under central cuing conditions. If the decision-bias account is correct, however, the effect should appear under central as well as peripheral cuing conditions provided that the cue–target relationship is preserved across conditions.

Experiment 2

Experiment 1 was designed to optimize the likelihood that the orientation of spatial attention would be under the control of the cue(s) appearing on each trial. Peripheral cues were used and were expected to draw attention to cued locations automatically (Posner, 1980). Moreover, the cues were highly predictive of the location to be probed on each trial, thus providing subjects with an incentive to orient attention voluntarily on the basis of the information provided by the cues. In Experiments 2 and 3 we investigated whether the attentional effects obtained with peripheral cuing could also be obtained with central cuing. The findings of Müller and Findlay (1987), derived from studies of central cuing, would suggest not. Indeed, Müller and Rabbitt (1989) proposed a dual-mechanism model of spatial attention which implies that cuing effects should be stronger with peripheral rather than central cuing. The principal claims embodied in this model are that (a) central cuing initiates an attentional-orienting process that is readily interruptible by targets appearing at uncued locations, yielding a relatively small cuing effect, but (b) peripheral cuing reflexively engages attention for a time during which it cannot be interrupted and reoriented toward alternative targets in the visual field. Accordingly, the results obtained in our first experiment could reflect the proposed noninterruptibility of attention when oriented by peripheral cuing. Eye movements were not monitored in Experiment 1, which was conducted at the Catholic University of America, but they were monitored in Experiment 3, which was carried out at the University of California, San Diego.

Method

Subjects. Six Catholic University students, 3 men and 3 women reporting normal or corrected-to-normal vision, participated in the experiment. Compensation was as in Experiment 1.

Procedure. The procedure was identical to that of the high-eccentricity condition in Experiment 1 except that cuing was central rather than peripheral and the interval between the onset of the 83-ms precue and the onset of the target was increased from 167 to 233 ms. As illustrated in Figure 2, the cue consisted of two small filled squares that were aligned to project from the central fixation point toward one of the four possible target locations. The neutral cue condition contained four pairs of these squares projecting radially toward the four possible target locations. Eye movements were not monitored. Results from the calibration session indicated that the appropriate target durations for all 6 subjects were 16 and 33 ms, respectively, under the low- and high-detectability conditions.

Results and Discussion

Table 3 gives the $P(A)$ values obtained by each subject, and the subject-averaged d' scores, under the three cue validity trial types and the two levels of target detectability. The $P(A)$ values were subjected to a repeated measures analysis of variance that revealed significant main effects for cue validity, $F(2, 10) = 7.45$, $p < .025$, and target detectability, $F(1, 5) = 36.11$, $p < .01$. The Cue Validity × Target Detectability interaction did not approach significance ($F < 1.0$). Fisher's LSD test (LSD = .088; $p = .05$) indicated that the overall effect of cue validity was attributable to the difference between valid and invalid cue trials (cost plus benefit). Table 4 gives the likelihood ratios (betas) for each subject under all experimental conditions. A repeated measures analysis revealed no reliable main effects or interactions among these data (all Fs < 1.0).

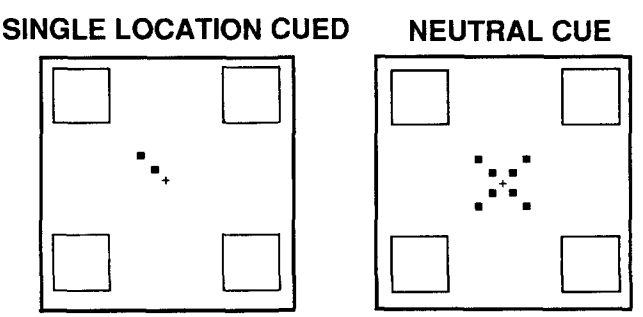

Figure 2. Cues for a single location (left) and for all four locations during neutral cue trials (right) in Experiments 2 and 3.

Table 3
Individual P(A) and Subject-Averaged d' Values Across Cue Validity Trial Types and Target Detectability Conditions in Experiment 2

	Low detectability			High detectability		
Subject	Valid cue	Neutral cue	Invalid cue	Valid cue	Neutral cue	Invalid cue
1	.68	.61	.56	.82	.80	.76
2	.60	.63	.57	.78	.75	.76
3	.66	.54	.58	.88	.76	.74
4	.75	.68	.64	.93	.98	.95
5	.69	.57	.52	.84	.60	.51
6	.54	.54	.49	.69	.66	.62
Mean $P(A)$	.65	.60	.56	.82	.76	.72
Mean d'	.74	.64	.40	1.88	1.72	1.31

Given that the interval between cue and target onsets (SOA) in this experiment exceeded 200 ms, these findings could have been due to cue-driven eye movements, even though subjects were continually admonished to maintain fixation throughout each experimental trial. To evaluate this possibility, we carried out a third experiment in which eye movements were monitored.

Experiment 3

Method

Subjects. Four students at the University of California, San Diego, 2 women and 2 men with normal or corrected-to-normal vision, participated in the experiment. They were paid $5 per hour throughout four sessions of testing.

Procedure. Stimulus displays and the sequence of frames presented on each trial were identical to those in Experiment 2 except that (a) trials were presented continuously rather than being self-initiated, (b) subjects were allotted 1.5 s to make their response on each trial, (c) masks were composed of random dot patterns rather than ASCII character sets, and (d) cumulative accuracy levels were not displayed to the subject following each correct response. The major procedural differences between Experiment 3 and Experiment 2 are that (a) only one level of target detectability was used; (b) subjects were tested on one calibration, one practice, and two experimental sessions, each containing 496 trials; and (c) electrooculograms (EOGs) were recorded to monitor eye movements during each experimental trial. Performance during the calibration session was used to select target durations for each subject that would produce overall performance levels similar to those of the low-detectability condition of Experiment 2. For the 4 subjects these durations were 17, 50, 50, and 67 ms, respectively.

The EOGs were recorded with nonpolarizable electrodes, amplified with a gain of 20,000, band-pass filtered between 0.1 and 100 Hz, and digitized at 250 Hz by a minicomputer. The horizontal EOG was recorded between the left and right outer canthi, and the vertical EOG was recorded between the left suborbital and supraorbital ridges. The EOG waveforms were signal averaged to the onset of the cue stimuli, a method that is sensitive even to very small systematic eye movements.

Table 4
Individual Likelihood Ratios (Betas) Across Cue Validity Trial Types and Target Detectability Conditions in Experiment 2

	Low detectability			High detectability		
Subject	Valid cue	Neutral cue	Invalid cue	Valid cue	Neutral cue	Invalid cue
1	1.20	1.19	1.24	1.05	0.97	1.55
2	0.91	1.27	1.30	0.70	1.69	1.62
3	0.85	1.19	1.14	0.61	2.53	1.42
4	1.09	1.00	1.15	1.86	2.06	2.97
5	1.20	1.80	1.00	1.06	8.41	1.00
6	1.00	1.03	0.99	1.03	1.15	1.45
M	1.04	1.25	1.13	1.05	2.80	1.67

Results and Discussion

Averaged EOG waveforms were obtained during both the experiment and a calibration procedure in which subjects were instructed to saccade to the cued location. From these waveforms it was evident that there were no systematic eye movements toward the cued location. On the basis of the calibration procedure, we determined that the averaged EOG potentials during the experiment corresponded to an average eye movement of less than 0.22° in the direction of the cued target box. The actual eye movements may have been smaller than this, but finer resolution was not possible with the existing signal-to-noise ratio. The averaged EOG deflections, which corresponded to an average movement of less than 0.02°, could have been produced by larger eye movements occurring on a fraction of trials, for example, 0.2° on 10% of the trials, 2.0° on 1% of the trials, and so forth.

For each trial type, Table 5 gives $P(A)$ values and likelihood ratio (beta) values for each subject together with subject-averaged d' scores. The $P(A)$ values were subjected to a single-factor repeated measures analysis which revealed that the

Table 5
Individual P(A) and Subject-Averaged d' Values (Top) and Individual Likelihood Ratios (betas) (bottom) Across Cue Validity Trial Types in Experiment 3

Subject	Valid cue	Neutral cue	Invalid cue
	Sensitivity		
1	.69	.64	.63
2	.60	.53	.50
3	.73	.66	.57
4	.71	.73	.67
Mean $P(A)$	.68	.64	.59
Mean d'	.93	.69	.46
	Likelihood ratio (beta)		
1	0.97	1.20	1.11
2	1.05	1.07	0.99
3	1.00	1.05	1.07
4	0.66	1.30	1.34
M	0.92	1.15	1.13

change in $P(A)$ across cue validity trial types was reliable, $F(2, 6) = 10.47$, $p < .025$. Fisher's LSD indicated that this effect was due to the difference between valid and invalid cue trial types (LSD = .049). In an effort to increase the power of our tests for attentional cost and benefit, we pooled the $P(A)$ data from Experiment 3 with those from the comparable conditions (low detectability) of Experiment 2. Pooling yielded overall mean $P(A)$ values of .57, .61, and .67 for invalid, neutral, and valid cue trial types, respectively. The pooled data were subjected to a single-factor repeated measures analysis that yielded a reliable cue validity effect, $F(2, 9) = 19.98$, $p < .01$. Fisher's LSD test revealed that both costs and benefits were significant in these data (LSD = .033). Considered together, the results of Experiments 2 and 3 provide clear evidence that central cuing can exert a pronounced influence on the detectability of luminance increments, even under conditions in which only a single target may appear on each trial. Qualitative differences appear in the cue validity effect between peripheral (Experiment 1) and central (Experiments 2 and 3) cuing. Under the present conditions peripheral cuing produces attentional cost but no benefit. Central cuing produces both cost and benefit. A possible explanation for the absence of benefit in peripheral cuing is that peripheral events permit attention to be focused broadly without dilution (cf. Briand & Klein, 1987). Another, less probable explanation is that the brightening of all four target boxes under the neutral condition produced higher levels of arousal under peripheral cuing conditions than did the brightening of only one target box, as on valid and invalid cue trials.

Earlier we considered two possible interpretations of the changes in beta across cue validity conditions in Experiment 1. The decision-bias account attributes the effect to the consistent relationship between the location of the cue and the location of the target, a feature of all three experiments reported here. The cue–target confusability account attributes the effect to an imperfect resolution of the sensory effects of the cue and the target. In this latter view the effect should appear under peripheral but not central cuing conditions. An analysis of variance carried out on the beta values obtained in Experiment 3 uncovered no evidence of a cue validity effect ($F < 1.0$). A pooling of beta values from Experiments 2 and 3 likewise failed to produce a significant cue validity effect in the beta data, $F(2, 9) = 3.61$, *ns*. Thus, the results of Experiments 2 and 3 tend to argue against the decision-bias account and in favor of the cue–target confusability account, because reliable cue validity effects were not observed in the beta values of either experiment. Nonetheless, this conclusion must be taken with caution given the rather substantial (but nonsignificant) differences in beta across cue validities under the high-detectability condition of Experiment 2. The possibility that both decision bias and cue–target confusability influence likelihood ratios under peripheral cuing conditions cannot be ruled out by these data.

General Discussion

The present findings indicate that the advance cuing of visual–spatial attention modulates target detectability and that the magnitude of this effect is about as large under central as under peripheral cuing conditions. These findings provide clear evidence that visual–spatial attention modulates the efficacy of sensory processes leading to detection. Consequently, the findings are inconsistent with the proposals of Shaw (1982, 1984), Sperling (1984), and Sperling and Dosher (1986). These authors argued that cue validity effects in luminance detection can be accounted for entirely by changes in decision bias alone, that is, by the idea that observers may simply require less sensory evidence to decide that a target has appeared at a cued (relative to an uncued) location. This line of reasoning cannot be sustained in view of the present finding that both peripheral and central cuing of visual attention exert a consistent effect on target detectability across a broad range of experimental conditions.

Müller and Rabbitt's (1989) two-process model of spatial orienting likewise has difficulty accommodating our findings. In this model peripheral and central cuing activate qualitatively different attentional-orienting mechanisms such that the voluntary orientation initiated by central cuing is readily interrupted by events at uncued locations, whereas the reflexive orientation of attention initiated by peripheral cuing cannot readily be interrupted, at least for some time following cue onset. An important implication of this model is that the effects of peripheral cuing on target detectability ought to be more pronounced than those of central cuing. Our finding that central cues can produce a cuing effect at least as large in absolute magnitude as that yielded by peripheral cues raises serious questions regarding the Müller and Rabbitt formulation.

Our findings apparently conflict with the negative results obtained under somewhat similar conditions by Müller and Findlay (1987).[3] Earlier we suggested two possible reasons for this disparity. First, our method for cuing attention—making the cue predictive of the location of the posttarget probe—may have been particularly effective. Second, the single-target/single-probe procedure allowed our estimates of $P(A)$ and d' to be free of bias (cf. Shulman & Posner, 1988).

We described two distinctly different conceptions of spatial cuing that could account for our major findings. One of these, a straightforward extension of the work of Duncan (1980b) and Duncan and Humphreys (1989), holds that attentional cuing governs the order, or schedule, by which information is read out of an early processing stage where representations are subject to rapid decay and masking. This produces higher quality representations for information at cued (relative to uncued) locations at a later processing stage where detection occurs, thereby enhancing measured sensitivity. Indeed, the 500-ms delay between the target display and the posttarget cue in Experiments 1–3 may be especially conducive to scheduling operations of this kind, (i.e., those carried out

[3] Following preparation of this article, we became aware that a series of experiments by H. Müller and G. Humphreys, carried out simultaneously with ours, yielded results similar in many respects to our own. The Müller and Humphreys (in press) work also analyzes the differing results of the present study and of Müller and Findlay (1987).

following target offset). However, note that Downing (1988) obtained a cue validity effect in luminance detection using a 50-ms mask. Subjects in her experiments were required to make target present–absent responses for as many as four locations, a somewhat time-consuming task. However, the cue validity effect was observed when only one location was probed; it was also observed for the first of four sequentially probed locations. Thus, the present results appears not to be unique to the target-to-probe interval studied.

The second account outlined in our introduction assumes that spatial attention acts to enhance sensory gain for inputs at a cued location. This could be accomplished by a differential weighting of input from cued versus uncued locations provided that noise is added to the input representation at one or more sensory processing stages existing subsequent to the introduction of the weighting factor. This point is developed further in the Appendix.

The locus of the cue validity effect, either early or late in the sequence of stages leading to detection, cannot presently be determined. However, our conclusion that the modulatory effects of visual selective attention occur at the sensory level is supported by two converging lines of evidence. One of them appears in a series of event-related potential (ERP) studies reported by Mangun, Hansen, and Hillyard (1987) and Mangun and Hillyard (1988). In the former, subjects were precued to attend to a location in either the right or the left visual field and then were presented with stimuli at either the cued or uncued location. The ERPs recorded at electrode sites over visual cortex exhibited a higher amplitide when evoked by targets at cued locations rather than targets at uncued locations. In addition, the enhancements appeared in ERP components with latencies occurring as early as 80–100 ms following target onset with maximum amplitudes over prestriate regions of the occipital cortex (Mangun & Hillyard, in press). These results indicate a sensory locus for spatial cuing effects, both in cued and sustained-attention paradigms.

A separate albeit less direct source of evidence favoring a sensory locus of the cue validity effect in luminance detection is the work of Backus and Sternberg (1988) and Hawkins et al. (1988). In both of these studies it was observed that the costs and benefits produced by spatial cuing in simple reaction time interact with target intensity such that the cue validity effect is greater for less intense signals. On the basis of additive-factors logic (Sternberg, 1969), this result indicates that target intensity and cue validity operate at a common stage in the sequence of sensory processes leading up to the detection of luminance increments.[4]

In summary, our finding of improved signal detectability under single-target, central cuing conditions is in accord with prior behavioral (Downing, 1988) and ERP (Mangun et al., 1987) evidence that visual–spatial attention can affect sensory information processing per se, in addition to whatever effects may be produced on higher decision stages. Under the present cuing conditions, it appears that sensory information underlying detection was actually changed in quality or strength by the attentional process. Such an effect might result from (a) a higher sensory gain for inputs from the cued location relative to intrinsic sources of noise in the sensory pathways, (b) the preferential processing of inputs from cued locations (Duncan & Humphreys, 1989), or (c) a finer temporal sampling of information from the cued location. Further research is required to differentiate among these alternatives.

[4] In contrast, the magnitude of the cue validity effect was not greater under the low- relative to the high-detectability conditions in Experiments 1 and 2. The Detectability × Cue Validity interaction has been observed when target detectability varies randomly with trial blocks (Backus & Sternberg, 1988; Hawkins, Shafto, & Richardson, 1988) but not when it is manipulated as a between-blocks variable (see Hughes, 1984, and Experiments 1 and 2 of this article). Hawkins, Shafto, and Richardson (1988) interpreted this pattern in terms of cue-utilization strategies, which may adapt to target detectability when detectability remains invariant within trial blocks.

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Appendix

The differential weighting of input from attended and unattended location has no impact on sensitivity unless noise is added to the input representation at one or more sensory stages existing subsequent to the weighting process. Suppose that at each location-specific input channel there exist n sensory processing stages prior to a detection decision process and that noise, or variance, is added at each of these stages. Suppose further that an attentionally mediated weighting factor, W, is introduced at some point in the sequence of sensory stages, either subsequent (Case I) or prior (Case II) to the nth stage. Finally, suppose that W is larger for an attended than for an unattended channel.

In general, d' is defined as the difference between the means of the probability density functions for signal plus noise (SN) and noise (N) expressed in terms of their standard deviation. That is,

$$d' = \frac{M_{fSN}(x) - M_{fN}(x)}{[\sigma_{fN}(x)^2]^{1/2}}.$$

If the total variance of the noise and signal plus noise distributions is the sum of the variances $\sigma_{fNi}(x)^2$, introduced at each of n processing stages, then

$$d' = \frac{M_{fSN}(x) - M_{fN}(x)}{[\sigma_{N1}(x)^2 + \sigma_{N2}(x)^2 + \cdots + \sigma_{Nn}(x)^2]^{1/2}}.$$

For Case I (Figure A1), where an attentionally mediated weighting is introduced into a location-specific channel subsequent to sensory

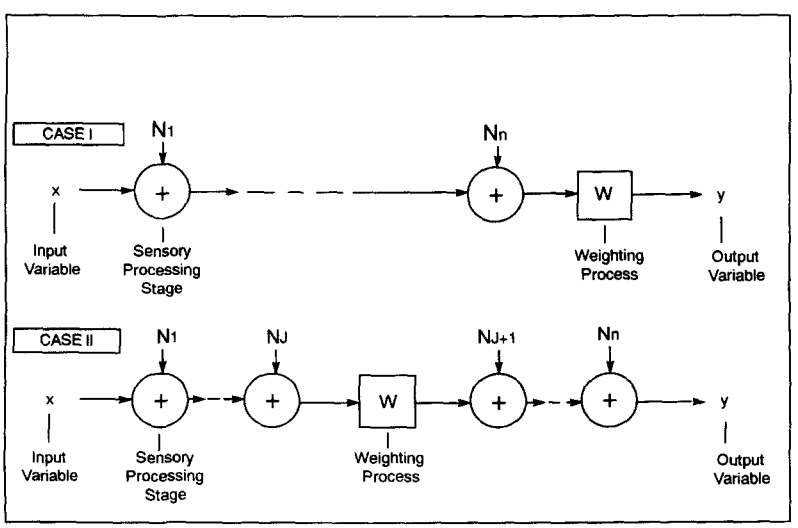

Figure A1. Alternative conceptions of the location of the attentionally mediated weighting of sensory input.

stage n,

$$d' = \frac{W[M_{fSN}(x) - M_{fN}(x)]}{\{W^2[\sigma_{fN1}(x)^2 + \sigma_{fN2}(x)^2 + \cdots + \sigma_{fNn}(x)^2]\}^{1/2}}$$

$$= \frac{W[M_{fSN}(x) - M_{fSN}(x)]}{W[\sigma_{fN1}(x)^2 + \sigma_{fN2}(x)^2 + \cdots + \sigma_{fNn}(x)^2]^{1/2}}.$$

Thus in Case I, d' is unaffected by the value of W.

For Case II (Figure A1), where the weighting is imposed at some intermediate point between sensory stages j and $j + 1$,

$$d' = \frac{W[M_{fSN}(x) - M_{fN}(x)]}{\{W^2[\sigma_{fN1}(x)^2 + \cdots + \sigma_{fNj}(x)^2] + [\sigma_{fNj+1}(x)^2 + \cdots + \sigma_{fNn}(x)^2]\}^{1/2}}.$$

Consider d' a function of W in Case II. The derivative of this function (the rate of change of d' with respect to W) is

$$\frac{[\sigma_{fNj+1}(x)^2 + \cdots + \sigma_{fNn}(x)^2][M_{fSN}(x) - M_{fN}(x)]}{\{W^2[\sigma_{fN1}(x)^2 + \cdots + \sigma_{fNj}(x)^2] + [\sigma_{fNj+1}(x)^2 + \cdots + \sigma_{fNn}(x)^2]\}^{3/2}},$$

which clearly remains nonzero and positive across all possible values of W so long as $[M_{fSN}(x) - M_{fN}(x)] > 0$. Thus for two channels with respective weightings, $W_{attended}$ and $W_{unattended}$, where $W_{attended} > W_{unattended}$, the nonzero d' yielded at the attended channel always exceeds that at the unattended channel.

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