

Spatial uncertainty explains exogenous and endogenous attentional cuing effects in visual signal detection

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Attentional cues may increase the detectability of a stimulus by increasing its signal-to-noise ratio (signal enhancement) or by increasing the efficiency of the observer's decision making by reducing uncertainty about the location of the stimulus (uncertainty reduction). Although signal enhancement has typically been found in detection tasks only when stimuli are backwardly masked, some recent studies have reported signal enhancement with unmasked stimuli under conditions of spatial uncertainty (E. L. Cameron, J. C. Tai, & M. Carrasco, 2002; M. Carrasco, C. Penpeci-Talgar, & M. Eckstein, 2000). To test whether these increases in sensitivity in unmasked displays were due to signal enhancement or uncertainty reduction, observers judged the orientation of unmasked Gabor patch stimuli in the presence or absence of fiducial markers that indicated their position in the display. Consistent with an uncertainty reduction hypothesis, cues produced large increases in sensitivity when stimuli were not localized perceptually but produced little or no systematic increase when they were localized by fiducial markers. The same general pattern of results was obtained with cues designed to engage the exogenous and endogenous orienting systems. The data suggest that, in practiced observers, the cuing effect for detecting unmasked stimuli is mainly due to uncertainty reduction.

Keywords: attention, signal detection, signal enhancement, uncertainty reduction

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Introduction

In a typical covert attention task, a stimulus to be detected or identified is preceded by a cue that draws attention to a location in the visual field while the observer maintains central fixation. The stimulus is then presented, with some probability, at the cued location or at some other location. There have been numerous reports of increased sensitivity to cued stimuli, but these effects are found only under some conditions and the mechanisms responsible for them remain controversial.

In detection tasks, in which near-threshold stimuli are presented against a uniform background, two general mechanisms have been proposed to explain how cues might affect sensitivity. The first, signal enhancement, is a local increase in the quality of the stimulus information at cued display locations (Lee, Itti, Koch, & Braun, 1999; Lu & Doshier, 1998). The second, uncertainty reduction, is a reduction in the effects of noise or distractor stimuli due to foreknowledge of the target location (Cohn & Lashley, 1974; Pelli, 1985; Tanner, 1961). Uncertainty effects are usually thought to arise at the decision-making level and occur when observers lack foreknowledge of where target stimuli will be presented.

Uncertainty and variations in uncertainty are features of most attentional tasks. In a typical attentional manipulation, the probability of a target stimulus occurring at one of several display locations is indicated by means of cues or instructions. Such manipulations alter the observer's belief about which display locations are relevant to the perceptual judgment and so are also manipulations of uncertainty. Because attentional tasks involve judgments under uncertainty and because this can covary with manipulations of attention, signal enhancement can only be inferred experimentally once uncertainty effects have been eliminated or controlled for (Shaw, 1984).

In practice, this can be done either by modeling the effects of uncertainty mathematically using multichannel signal detection models (e.g., Baldassi & Burr, 2004; Palmer, Verghese, & Pavel, 2000; Shaw, 1982; Smith, 1998) or by using stimuli that are perceptually localized (Smith, 2000). This latter approach seeks to decouple the effects of cues on the observer's ability to localize a stimulus, which is strongly affected by uncertainty, from their effects on the quality of the information available at a cued location. This is the approach we adopt in this article.

The need to distinguish between the perceptual (signal enhancement) and the decisional (uncertainty reduction) effects of cues was highlighted in recent articles by

Eckstein, Shimozaki, and Abbey (2002) and Shimozaki, Eckstein, and Abbey (2003). These authors showed that, in tasks in which attention is manipulated using probabilistic cues, an optimal Bayesian decision maker predicts a higher proportion of correct detections at the cued location in the absence of any form of signal enhancement. This occurs because the Bayesian decision maker uses its knowledge of the prior probabilities of the cue validities to optimally weight the information in the display. This results in a higher weight being assigned to the information from the cued location and consequently to a higher proportion of correct detections of cued stimuli.

In a review of the detection literature, Smith (2000) pointed out that signal enhancement is typically reported only when stimuli are backwardly masked; when no masks are used, signal enhancement is not usually found. Studies investigating the effects of covert attention on detection using backwardly masked stimuli by Bashinski and Bacharach (1980), Downing (1988), Hawkins et al. (1990), Luck et al. (1994), Müller and Humphreys (1991), and Smith (1998) found evidence of signal enhancement; studies by Bonnel, Stein, and Bertucci (1992), Davis, Kramer, and Graham (1983), Foley and Schwarz (1998), Graham, Kramer, and Haber (1985), Lee, Koch, and Braun (1997), Müller and Findlay (1987), and Palmer, Ames, and Lindsey (1993) using unmasked stimuli found no evidence of signal enhancement. Consistent with this, in a series of detection studies by Smith et al. using displays that controlled the effects of uncertainty, signal enhancement was found with masked but not unmasked stimuli (Smith, 2000; Smith, Ratcliff, & Wolfgang, 2004; Smith & Wolfgang, 2004; Smith, Wolfgang, & Sinclair, 2004). However, two recent studies by Carrasco et al. reported signal enhancement in cued detection tasks in which no backward masks were used (Cameron, Tai, & Carrasco, 2002, $\pm 15^\circ$ task; Carrasco, Penpeci-Talgar, & Eckstein, 2000).

These latter studies differed from those of Smith (2000), Smith, Ratcliff, et al. (2004), Smith and Wolfgang (2004), and Smith, Wolfgang, et al. (2004) in the way stimuli were presented. Whereas the studies by Smith et al. presented stimuli on top of suprathreshold contrast luminance pedestals that localized them perceptually, the studies by Cameron et al. (2002) and Carrasco et al. (2000) presented

stimuli directly against a uniform field. They compared performance in a cued condition, in which the cue was 100% predictive of the target location, to performance in a neutral condition, in which the cue was uninformative, forcing observers to monitor all potential target locations. They found that accuracy was significantly higher in the cued than in the neutral condition. Because of the large differences in uncertainty between these conditions, however, it is not clear whether these effects were due to signal enhancement or uncertainty reduction.

To test between these two alternatives, we decoupled the effects of attention and spatial uncertainty experimentally. In our “uncertainty condition,” uncertainty was not controlled, and low-contrast stimuli were presented alone, against a uniform gray background, as in the studies by Carrasco et al. (2000) and Cameron et al. (2002). In our “fiducial (FID) condition,” uncertainty was controlled by flanking the stimuli with FID crosses; these were suprathreshold, 100% valid stimuli that allowed observers to localize their decision to the stimulus location (see Figure 1c). We found that spatial precues had a large effect on performance in the uncertainty condition but a negligible effect in the FID condition. The same pattern of results was obtained with cues that were designed to activate the exogenous or reflexive orienting system and the endogenous or voluntary orienting system (Jonides, 1981). Our results provide little evidence for signal enhancement and show that attention-dependent sensitivity differences such as those reported in Cameron et al. and Carrasco et al. can arise due to a reduction of spatial uncertainty alone.

Before describing our experiments, we should clarify our terminology. We use the term “signal enhancement” to refer to a mechanism that improves performance by increasing the signal-to-noise ratio at the target location. We use the term “uncertainty reduction” to refer to a mechanism that improves the efficiency of an observer’s decision making by reducing the influence of noise from elsewhere in the display. Other investigators, such as Shiu and Pashler (1994), make a similar distinction between signal enhancement and noise reduction. We prefer the term “uncertainty reduction” because “noise reduction” can also refer to a local mechanism whose action is confined to the region surrounding the target. For

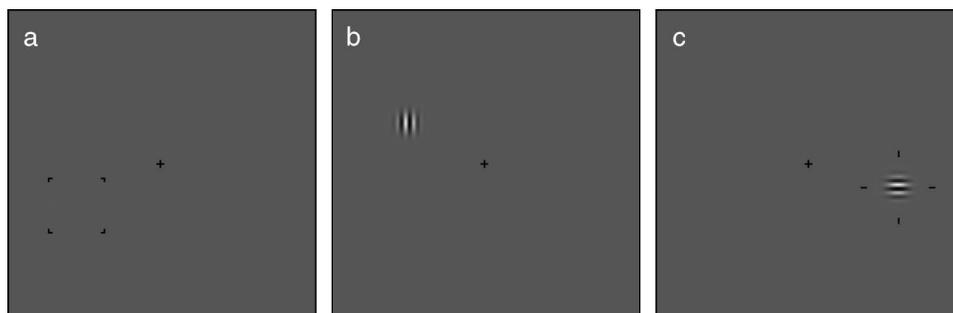


Figure 1. Example stimuli (a) fixation cross and peripheral precue, (b) fixation cross and a high-contrast, vertical Gabor patch, presented alone, and (c) fixation cross and a horizontal Gabor patch, surrounded by an FID cross.

example, Lu and Doshier's (1998) Perceptual Template Model distinguishes between two local mechanisms they term stimulus enhancement and external noise exclusion. These two mechanisms predict different attentional effects when stimuli are imbedded in noise. Here we use the term "signal enhancement" in a model-free way to refer to any mechanism that increases the local signal-to-noise ratio, either by increasing the signal strength or by reducing the effects of noise at the target location.

Experiment 1

Methods

Stimuli were generated on a Cambridge Research Systems VSG 2/5 frame store, presented at 100 Hz on a gamma-corrected Mitsubishi DiamondScan 20-in. CRT monitor. Observers viewed the stimulus in a dimly lit room at a viewing distance of 50 cm with their head positions stabilized by a chin rest. Data were collected from five observers, including one of the authors (I.G.) and four paid undergraduates who were naive to the purposes of the study.

The stimuli were horizontally or vertically oriented, grayscale, sine-phase Gabor patches, presented on a 25° square, 30 cd/m^2 , gray uniform field. The Gabor patches had a bandwidth of 1.06 octaves, had a spatial frequency of 3.5 cycles per degree, and were presented on the

circumference of a 6.4° diameter, imaginary circle, centered on a fixation cross. Stimuli were presented at five different levels of contrast using the method of constant stimuli. The contrast values were chosen for each observer individually during practice to span a range of performance from near chance to near perfect.

The attentional precues consisted of $2.8' \times 5.6'$ black lines that marked the corners of a 1.8° square, centered on a potential target location. On each trial, the angular position of the cued location (α) on the imaginary circle was randomly chosen ($0^\circ < \alpha \leq 360^\circ$). On miscued trials, stimuli were presented at one of two uncued locations, at $\alpha \pm 120^\circ$. The FID cross (adapted from Eckstein, Pham, & Shimozaki, 2004) consisted of four $2.8' \times 8.4'$ black lines centered around the Gabor patches, at a 0.8° separation from the edge of the Gaussian envelope. Pilot testing ensured that precues and FID crosses were perceptually distinct stimuli, and that the precue had no subjectively perceivable forward-masking effects on the FID crosses. Examples of the stimuli are shown in Figure 1.

The display sequence is shown in Figure 2. A central fixation cross appeared at the start of each trial for 1,000 ms, followed by a 60-ms flashed precue. Stimuli were presented after the cues at a stimulus onset asynchrony (SOA) of 140 ms. Stimuli appeared at the cued location on 50% of trials and at each of the two uncued locations on 25% of trials. The combination of peripheral cues, a short cue-target SOA, and a weakly predictive probability manipulation means the cues in this experiment are likely to have engaged

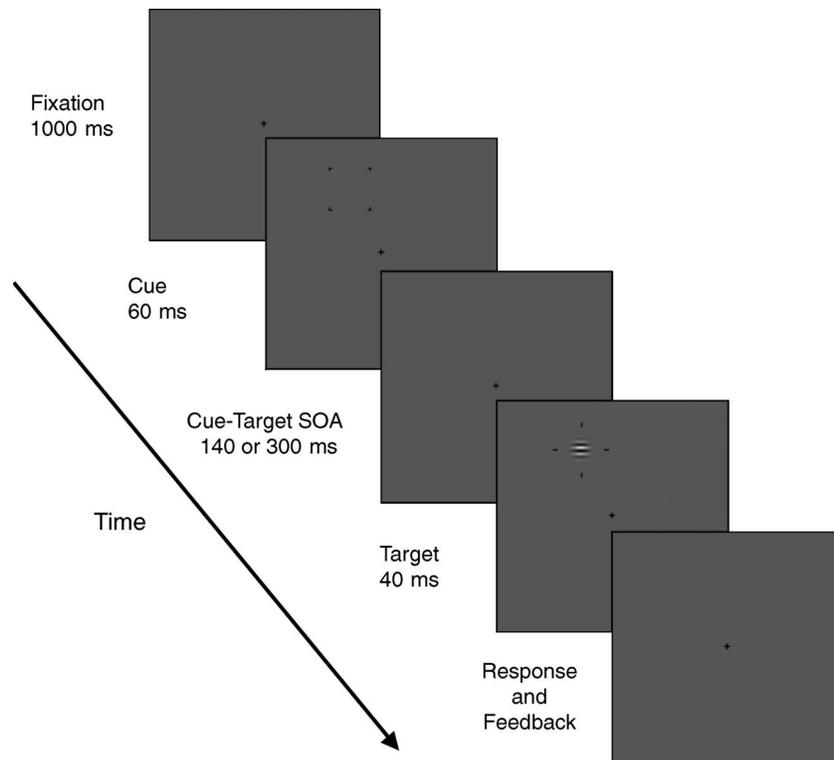


Figure 2. Typical display sequence for an experimental trial. In the trial shown, the cue is valid and an FID cross marks the target location. In Experiment 1, the cue-target was 140 ms. In Experiment 2, it was increased to 300 ms.

the exogenous or reflexive orienting system (Jonides, 1981), wholly or predominantly.¹ We consider the effects of cues designed to engage the endogenous or voluntary orienting system in [Experiment 2](#). Significant cuing effects using weakly predictive peripheral precues of the kind used in [Experiment 1](#) were previously obtained by Smith, Ratcliff, et al. (2004) and Smith and Wolfgang (2007) using backwardly masked stimuli.

On half of the experimental trials, stimuli were framed by an FID cross. On the remaining trials, stimuli were presented alone, against a uniform background. Half of the stimuli were vertically oriented and half were horizontally oriented. The stimuli were extinguished after 40 ms, after which the display remained blank except for the fixation cross until the observer made a response (vertical or horizontal) by pressing one of two buttons on a response box.

Because contrast thresholds for yes–no detection and for orthogonal orientation discrimination are the same (Thomas & Gille, 1979), we follow Lee et al. (1997) and use orthogonal discrimination as a proxy for detection. Cameron et al. (2002) and Carrasco et al. (2000) have similarly argued that orthogonal (or easy) discrimination and yes–no detection tap a common variable of “contrast sensitivity” and treat the two tasks as equivalent for the purposes of drawing inferences about attention. Consistent with this, in our previous studies of the effects of cues on masked and unmasked stimuli, we found the same pattern of mask dependencies in a yes–no detection task, a rating-scale detection task, and an orthogonal discrimination task (Smith, 2000; Smith, Ratcliff, et al., 2004; Smith & Wolfgang, 2004; Smith, Wolfgang, et al. 2004). These results reinforce the idea that detection and orthogonal discrimination are equivalent in their attentional demands. We used the orthogonal discrimination task in preference to yes–no detection in this study because it is relatively unbiased, which simplifies the task of obtaining reliable estimates of the cuing effect.

Observers were instructed to perform the task as accurately as possible but to respond in a timely manner because their response times (RTs) were also being recorded. Each observer completed three calibration and practice sessions, then 16 experimental sessions. Each session comprised 480 trials, yielding a total of 7,680 trials per observer. Observers were given trial-by-trial auditory feedback about the accuracy of their responses but no feedback about their RTs.

Results and discussion

Accuracy

Psychometric functions were fitted to each observer’s proportion of correct detections for each condition using the Weibull function:

$$F(c) = \left\{ \alpha - \left(\alpha - \frac{1}{2} \right) \exp \left[- \left(\frac{c}{\beta} \right)^\gamma \right] \right\}. \quad (1)$$

In this equation, c is the stimulus contrast and α , β , and γ are the asymptote, threshold (dispersion), and slope (shape) parameters, respectively (Wichmann & Hill, 2001). Three Weibull models were compared. The first was a single-function model in which the same Weibull function was fitted to both cued and miscued conditions. The second and third models were two-function models, in which separate Weibull functions were fitted to cued and miscued conditions. In the second model, the threshold parameter (β) was varied between cued and miscued conditions whereas the slope (γ) and the asymptote (α) parameters were constrained to be equal. In the third model, the slope and the threshold parameters were both varied and only the asymptotes were constrained to be equal. To test whether cuing affected only the thresholds or both the slopes and the thresholds of psychometric functions, we compared chi-squares for the single-function model and two-function models using the methods described in Smith, Wolfgang, et al. (2004). Where model fit was significantly improved by varying a parameter between conditions, we inferred that the parameter was significantly affected by cuing. Further details of the model-fitting procedures are summarized in [Appendix A](#).

The smooth curves in [Figure 3](#) are fits of the two-function, slope- and threshold-varying model. The associated fit statistics for the individual observers are reported in [Table 1](#). The row labeled “group” is the mean of the individual–observer statistics, which we treat as a measure of the average experimental effect. The statistics in the table are the improvement in chi-square ($\Delta\chi^2$) obtained by allowing both the slope and the threshold parameter to vary. In the FID condition, neither of the two-function models performed significantly better than a single-function model for any observer. The group statistic shows a similar absence of an effect. These results show that, when stimuli were localized by FID markers, cues had no significant effect on accuracy.

In the uncertainty (no FID) condition, the pattern of results was very different, as [Figure 3](#) and [Table 1](#) show. Accuracy was significantly higher for cued than miscued stimuli for all observers. This difference is also reflected in the group statistic. Although the fits in [Figure 3](#) and [Table 1](#) are for the more general (slope and threshold varying) of the two-function models, for no observer was model fit significantly worse when only threshold was varied. These results show that, when stimuli were not localized by FID markers, cues increased accuracy. Moreover, they did so by selectively reducing the threshold parameter of the psychometric function, in agreement with the findings of Cameron et al. (2002), Ling and Carrasco (2006), and Lu, Lesmes, and Doshier (2002). (There was some evidence of a change in slope in the data of Cameron et al., but the difference was not significant.) A reduction in threshold with no accompanying change in shape represents a uniform compression of the psychometric function on the contrast axis or, equivalently, a uniform leftward shift in logarithmic coordinates.

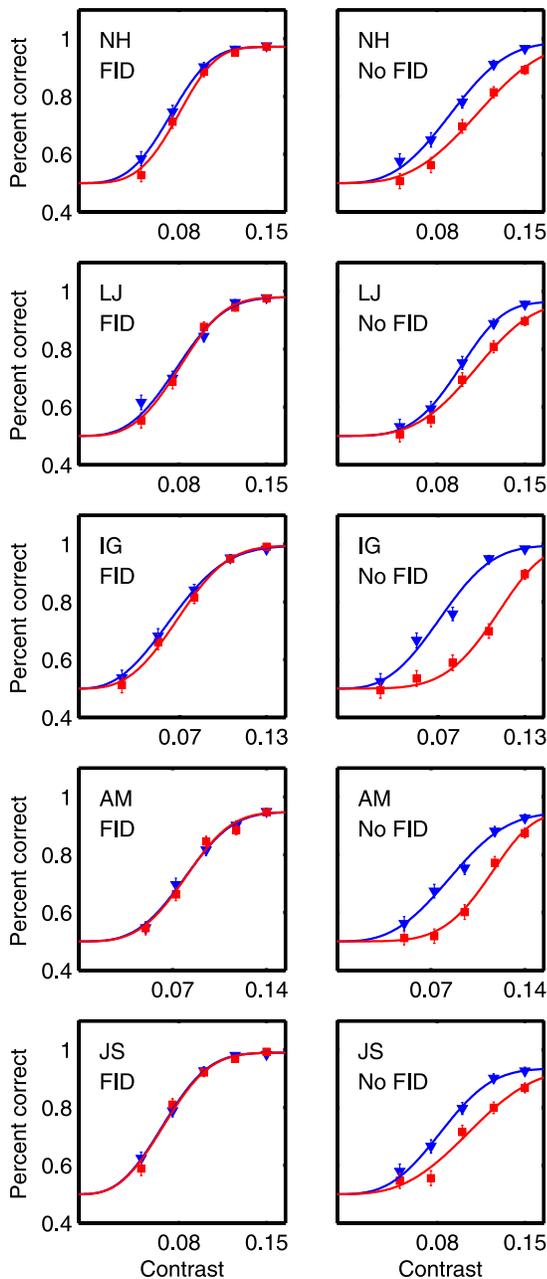


Figure 3. Accuracy (percent correct) as a function of stimulus contrast, for individual observers in [Experiment 1](#), in the FID condition and the uncertainty condition (no FID). The fitted functions are Weibull functions. The blue lines and triangles are fits and data for cued stimuli; the red lines and squares are fits and data for miscued stimuli. The error bars are one binomial standard error.

We also investigated whether the cue combined with an FID cross produced better performance than did the cue alone. The purpose of this analysis was to ascertain whether the addition of an FID cross produced any further benefit once attention had been summoned to the stimulus location by a cue. To do so, we compared fits of single- and two-function Weibull models to the cued FID and

cued no-FID conditions. Four of the five observers showed uniformly higher accuracy in the cue-plus-FID condition than in the cue-alone condition. Chi-square values for the difference in fits of the two- and one-function models ranged from $\Delta\chi^2(2) = 6.02$, $p < .05$ to $\Delta\chi^2(2) = 40.08$, $p < .001$. The only observer who showed no benefit of adding the FID cross was one of the authors, I.G. ($\Delta\chi^2(2) = 4.16$, *ns*). We defer consideration of these findings until the [General discussion and conclusions](#) section.

Attentional gain

The magnitude of the cuing effect in accuracy as a function of contrast can be quantified by calculating the *attentional gain*. We use a measure of gain described by Smith, Wolfgang, et al. (2004). The measure is based on the signal detection sensitivity measure, d' , which provides an estimate of the signal-to-noise ratio at each level of stimulus contrast. Gain is defined as the ratio of d' values for cued and miscued stimuli, expressed in decibels.

To estimate gain, we calculated d' values from the proportions of correct responses to horizontal and vertical stimuli, $P_H(c)$ and $P_V(c)$, for each observer at each level of contrast. We then converted these proportions to d' measures using the formula

$$d' = \frac{z[P_H(c)] + z[P_V(c)]}{\sqrt{2}}, \quad (2)$$

where $z[\cdot]$ denotes the inverse normal (z score) transformation. The factor of $\sqrt{2}$ in the denominator of this

Observer	Percent correct		Mean reaction time	
	FID $\Delta\chi^2(2)$	No FID $\Delta\chi^2(2)$	FID $\Delta\chi^2(2)$	No FID $\Delta\chi^2(2)$
N.H.	3.72	45.78***	83.48***	355.84***
L.J.	0.33	21.69***	42.31***	179.14***
I.G.	1.74	140.07***	135.73***	524.18***
A.M.	0.06	62.02***	146.92***	222.15***
J.S.	0.06	38.75***	46.48***	156.83***
Group	1.18	61.66***	88.99***	287.63***

Table 1. Tests of the cuing effect, [Experiment 1](#): Difference in fit ($\Delta\chi^2$) between a single-function and a two-function model for FID and uncertainty (no FID) conditions. For percent correct, the two-function model was a pair of Weibull functions with the same asymptotes but different slope and threshold parameters. For RT, the two-function model was a pair of power functions (two-parameter Piéron's Law) with different scale and exponent parameters. Fit statistics were tested for significance as chi-square random variables with two degrees of freedom. *Note*: *** $p < .001$.

expression puts d' values obtained from a two-alternative forced-choice task onto the same scale as those from a yes–no task (Macmillan & Creelman, 1991).

We then fitted Weibull functions to the d' values for cued and miscued stimuli for each observer to obtain smoothed estimates of signal-to-noise ratios as a function of contrast (see Appendix A). The attention gain was defined as $20 \log[F_A(c)/F_U(c)]$, where $F_A(c)$ and $F_U(c)$ are the fitted signal-to-noise ratio functions for cued (attended) and miscued (unattended) stimuli, respectively. The average gains for FID and uncertainty conditions are shown in the upper panel of Figure 4. The figure also shows raw gain values, calculated directly from the observed d' values at each level of contrast using the formula $20 \log[d'_A(c)/d'_U(c)]$. Because the smoothed gain values are constrained by the stiffness of the Weibull function, they are somewhat less variable and are less extreme than the raw gains. This serves to offset some of the difficulties associated with measures based on ratios of random quantities, which are inherently noisy.²

Figure 4 shows that gain estimates in the FID condition were zero or near zero at all levels of stimulus contrast, except for the lowest. (Zero gain indicates no cuing effect.) Gain in the uncertainty condition was high at low contrasts and decreased with contrast to a nonzero asymptote of around 3–4 dB. This pattern differs markedly

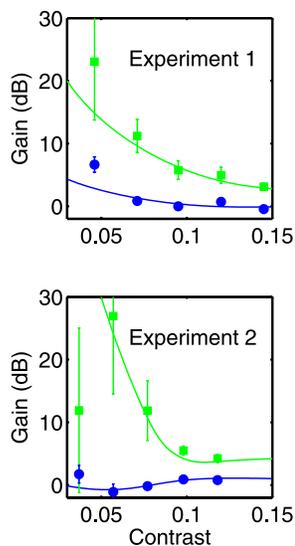


Figure 4. Estimated attentional gain in Experiment 1 (exogenous) and Experiment 2 (endogenous). The blue lines and circles are the FID condition; the green lines and squares are the uncertainty condition. The continuous lines are smoothed estimates of gain obtained by fitting Weibull functions to individual observers' d' values; the circles and squares are raw gain values calculated directly from d' . The abscissas of the plotted points are the averages of each of the five levels of contrast used to obtain psychometric functions for each observer. The error bars are one standard error of the means of the raw gains at the five contrast levels. A gain of zero indicates no cuing effect.

from the gain values previously reported by Smith, Wolfgang, et al. (2004) using backwardly masked stimuli that were localized by luminance pedestals. They found that gain was fairly constant around 3 dB and showed only a very slight tendency to decrease at high contrast. The difference in the patterns of gain found in this study and the previous one is consistent with the idea that the cuing effects found here were mainly due to spatial uncertainty and that uncertainty has its greatest effect at low contrast.

The smoothed gain estimates for the FID condition in Experiment 1 show a tendency to increase with decreases in contrast. This increase is driven mainly by the gain at the lowest contrast. To test whether this effect was significant, we performed a single-factor, repeated measures analysis of variance with polynomial tests for trend. This showed that the linear and the quadratic trends in gain as a function of stimulus contrast were both significant: $F_{\text{Lin}}(1,4) = 29.8, p < .005$; $F_{\text{Quad}}(1,4) = 19.12, p < .05$. A deviations test of other higher order (i.e., cubic and quartic) trends was not significant, $F_{\text{Dev. Lin \& Quad}}(2,8) = 3.17, ns$. This suggests that, at the lowest stimulus contrast, where accuracy was in the range of 53–59%, cues may have produced a small increase in sensitivity. However, this is an average effect only, and none of the individual observer differences on which the gain estimates were based were reliable. The psychometric functions for cued and miscued stimuli in the FID condition in Figure 3 show a slight separation for two observers, but none of the individual effects were significant. As an increase in gain of 3 dB at the 55% point of the psychometric function represents only a 2.5% increase in accuracy, the nonsignificance of the individual observer tests is not surprising.

A comparison of the Weibull model fits to d' used in calculating gain yielded the same results as did the tests of the proportions of correct responses. For no observer was a two-function model better than a single-function model: p values for the chi-square test of the difference ranged from .96 to .20. These tests were based on large samples (360 trials per data point) and so had fairly high power. Thus, although there is some evidence of an increase in average gain in the FID condition at the lowest contrasts, this effect is marginal in comparison to the large and systematic effects in the uncertainty condition, which were highly significant for every observer.

Response time

The mean RT for each observer were fitted with two-parameter Piéron's law functions (Piéron, 1920; see also Smith, Ratcliff, et al., 2004):

$$F(c) = ac^{-\beta}. \quad (3)$$

Piéron's law is a power function that describes the decrease in mean RT with decreasing stimulus contrast, c .

The more usual form of Piéron's law has a third parameter, the so-called "irreducible minimum," which describes the asymptotic value of RT at high contrast. However, this parameter can be difficult to estimate reliably from data (cf. Luce, 1986, p. 62), especially in tasks in which RTs are long. We found, as did Smith, Ratcliff, et al. (2004), that the three-parameter version did not yield any significant improvement in fit over the two-parameter version and showed poorer stability. We therefore used the simpler two-parameter function to characterize the dependence of mean RT on contrast.

We do not ascribe any particular theoretical significance to Piéron's law in characterizing our data in this way. Piéron's law is an empirical rather than a theoretical relationship, which is known to characterize the dependency of RT on stimuli intensity in a variety of tasks (Teichner & Krebs, 1972, 1974). We therefore use it as a benchmark for comparison purposes in presenting our own data. Such a characterization does not preclude the possibility that other, more theoretically based accounts, such as the diffusion model account of Palmer, Huk, and Shadlen (2005), may offer greater insight into the mechanism that underlie the relationship between RT and stimulus contrast. Elsewhere (Smith, 2007), we have developed a detailed quantitative theory of processes that underlie the RT and accuracy effects in attentional cuing tasks like the one considered here. Like the article of Palmer et al. (2005), the theory assumes that the relationship between RT and accuracy reflects the action of an underlying diffusion-process decision mechanism.

Plots of mean RT for each observer are shown in Figure 5; the model fits are given in Table 1. As with accuracy, we quantified the cuing effect by comparing the fits of a single-function model and a two-function model in which the scale (α) and exponent (β) varied with cuing condition (for details, see Appendix A). RTs were significantly shorter for cued stimuli than for miscued stimuli in both the FID and the uncertainty conditions for all observers. This result parallels that of Smith, Ratcliff, et al. (2004) who found a similar dissociation in the cuing effects on RT and accuracy for unmasked and masked stimuli.

Although the RT cuing effects were significant for both FID and uncertainty conditions, the pattern of contrast dependencies in the two conditions was different. In the FID condition, the effect of cues on RT was fairly similar at all levels of contrast. In Figure 5, the Piéron's law curves for cued and miscued stimuli in the FID condition are roughly parallel. In the uncertainty condition, the Piéron's law curves for miscued stimuli are shallower than those for cued stimuli and their estimated exponents were smaller. The reduced dependency of RT on contrast when stimuli were miscued and not localized by FID crosses suggests that factors other than stimulus contrast affect performance in this condition.

As the only difference between FID and uncertainty conditions in this experiment was the presence of localizing information in the display, the differences in

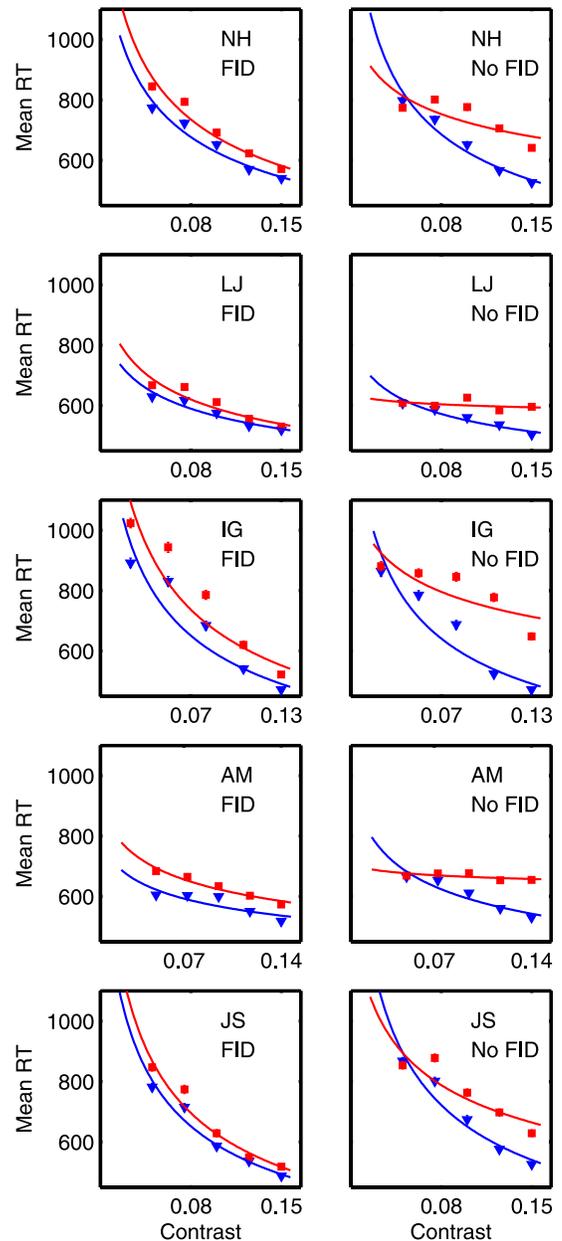


Figure 5. Mean RT (milliseconds) as a function of stimulus contrast, for individual observers in Experiment 1, in the FID condition and the uncertainty condition (no FID). The smooth curves are Piéron's law fits to the data. The blue lines and triangles are fits and data, respectively, for cued stimuli; the red lines and squares are fits and data for miscued stimuli. The error bars are one standard of the mean.

cueing effects in both RT and accuracy can be attributed to uncertainty. The cuing effects for accuracy replicate those found in previous studies which showed that uncertainty reduction affects the detection of weak, unmasked contrast increments presented directly against a uniform field (Cohn & Lashley, 1974; Foley & Schwarz, 1998; Smith, Wolfgang, et al., 2004). They thus provide further evidence for the mask-dependent cuing

hypothesis (Smith, 2000), which holds that, when uncertainty is controlled, attention increases detection sensitivity only for backwardly masked stimuli.

The cuing effects for RT in FID and uncertainty conditions is consistent with previous studies (Posner, 1980) in showing that cues were effective in orienting observers' attention (Jonides, 1981). They are also consistent with recent studies by Prinzmetal, McCool, and Park (2005) and Smith, Ratcliff, et al. (2004) that found significant cuing effects for RT in the absence of accuracy effects with exogenous cues and unmasked stimuli. In addition, the Piéron's law dependencies in Figure 5 show that RT varied systematically with stimulus contrast. Most studies of contrast dependencies in RT have used suprathreshold stimuli, in which error rates are low. Experiment 1 adds to the handful of studies (Palmer et al., 2005; Pins & Bonnet, 1996; Smith, Ratcliff, et al., 2004) that have shown systematic contrast dependencies in RT with near-threshold stimuli.

Exogenous and endogenous orienting systems

A number of recent studies have investigated the psychophysical consequences of the apparent functional segregation of the human attentional system into a fast, transient, reflexive or exogenous system and a slower, sustained, voluntary, or endogenous system (e.g., Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). To date, a somewhat conflicting picture has emerged from these studies. A series of studies by Doshier and Lu (1999) and Lu and Doshier (1998) (summarized by Lu et al., 2002) found evidence that the endogenous system operates purely by external noise exclusion, whereas the exogenous system operates by a mixture of stimulus enhancement and external noise exclusion. External noise exclusion operates only when stimuli are embedded in noisy backgrounds, whereas stimulus enhancement operates in noiseless displays as well.

In a similar vein, Ling and Carrasco (2006) investigated the effects of exogenous and endogenous attention on discriminating the orientation of similar pairs ($\pm 4^\circ$) of grating patches. They found that endogenous cues improved performance only at low stimulus contrast (the rising part of the psychometric function), whereas exogenous cues improved performance at high contrasts (the asymptotic part of the function) as well. Together, these results seem to suggest that, in low-level visual tasks, the exogenous system is the prepotent of the two.

However, a rather different picture comes from a recent study by Prinzmetal et al. (2005). Prinzmetal et al. reported evidence that the reflexive (exogenous) system reduces RT but does not affect accuracy, whereas the voluntary (endogenous) system both reduces RT and increases accuracy. They obtained the same pattern of results for low- and high-level perceptual tasks. Prinzmetal et al. identified the RT effects with a mechanism of

channel selection and the combined RT-and-accuracy effects with a mechanism of channel enhancement. Their results thus seem to imply, contrary to findings of Ling and Carrasco (2006) and the studies of Doshier and Lu (1999), Lu and Doshier (1998), and Lu et al. (2002) that it is the endogenous rather than the exogenous system that is the prepotent of the two.

The combination of short cue-target SOAs and weakly predictive peripheral cues used in our Experiment 1 makes it likely that the cues primarily engaged the exogenous system. Given that the two systems may have different effects psychophysically, and especially in the light of the results of Prinzmetal et al. (2005), we thought it was important to ascertain whether the results of Experiment 1 would be replicated with cues designed to stimulate the endogenous orienting system. We investigated this in Experiment 2.

Experiment 2

In many studies, central cues are used to activate the endogenous orienting system and peripheral cues are used to activate the exogenous system (Jonides, 1981). However, the meaning of "central" can differ from study to study. Some studies have used purely symbolic central cues, such as arrows or arrowheads located at the fixation point (e.g., Lu et al., 2002). These cues must be decoded before attention can be oriented. Others studies have used centrally located cues that contain some spatial information, such as oriented line segments (Ling & Carrasco, 2006) or a linear array of dots (Smith, 2000; Smith, Wolfgang, et al., 2004). When purely symbolic central cues are used, a theoretical distinction between central and peripheral cues can be made in terms of the nature of the cognitive processing needed to interpret the cue: Symbolic cues must be decoded, whereas spatial cues can summon attention directly. Alternatively, when both central and peripheral cues contain spatial information, the distinction has been made in terms of whether attention is "pushed" (centrally) by the cue or "pulled" (peripherally) by it (Prinzmetal et al., 2005).

Prinzmetal et al. (2005) argued that the form of the cue is less important than is the information it contains about the likely location of the target and the time available to process the cue before the stimulus appears. In their experiments, they used a peripheral cue in all conditions but varied both its information content and the cue-target SOA. In some experiments, the cues were nonpredictive (targets occurred at any of the possible display locations with equal probability) and were presented at short SOAs (50–167 ms). In others, the cues predicted the likely location of the stimuli and were presented at comparatively long (300 ms) SOAs to allow time for the voluntary

system to be engaged. Using this manipulation, they found that nonpredictive peripheral cues presented at short SOAs produced only RT effects, whereas predictive peripheral cues presented at long SOAs produced both RT and accuracy effects.

In [Experiment 2](#), we followed Prinzmetal et al. (2005) and used the same peripheral cue we used in [Experiment 1](#) ([Figure 1a](#)), but we made it more strongly predictive of the location of the subsequent stimulus and we increased the cue-target SOA from 140 to 300 ms. Previously, we characterized the cue used in [Experiment 1](#) and Smith, Ratcliff, et al. (2004) as “weakly predictive” because stimuli occurred at the cued location on only 50% of trials. This meant cued and miscued stimuli were equally probable, but the cues were nevertheless predictive, in the sense in which the term was used by Prinzmetal et al. because the probability of a stimulus at the cued location was double that at either of the uncued locations (25%).

The combination of a long SOA and a probabilistic peripheral cue used by Prinzmetal et al. (2005) and our [Experiment 2](#) is likely to have engaged both the exogenous and endogenous orienting systems, at least to some degree. Although exogenous effects diminish at long SOAs (Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989), the use of a peripheral cue means the attentional cuing effects in [Experiment 2](#) probably reflected the combined effects of both systems. We chose to use this manipulation because our primary goal in this experiment was not to isolate the effects of the endogenous system from those of the exogenous system, but rather to maximize the overall attentional effect. Specifically, we were concerned to ascertain whether the additional contribution of the endogenous system would produce accuracy effects similar to those found by Prinzmetal et al. with perceptually well-localized stimuli.

Methods

Data were collected from five observers: one of the authors (P. S.) and four, paid undergraduate volunteers who were naive to the purposes of the experiment. The observers were practiced on the task until their performance had stabilized (3–7 sessions) and then served in between 8 and 12, 480-trial experimental sessions, the number of sessions depending on their availability.

The stimuli, experimental design, and procedure were the same as those in [Experiment 1](#), except the cue-target SOA was increased to 300 ms and the cue-target contingencies were changed: Targets occurred at the cued location on 75% of trials and at each of the uncued locations on 12.5% of trials.

When SOAs are longer than 200–250 ms, there is a possibility (theoretically at least) that observers may refixate the cued location prior to stimulus onset (Hallett, 1986). Clearly, performance benefits found under such

circumstances need not be due to covert attention but may simply be the result of bringing the stimulus into foveal vision. We thought that contamination of our data by eye movement artifacts was unlikely because, subjectively, the 300-ms SOA seemed too short to refixate the display. Nevertheless, we monitored the eye movements of two observers (M.O. and A.A.) using an infrared camera (Surnet KE501A) throughout the experiment. These observers displayed a different pattern of results from the other observers during practice sessions and one that was consistent with overt shifts of gaze prior to stimulus onset. We therefore monitored their eye movements to exclude this possibility. For both observers, eye movements occurred far too infrequently (less than 1% of trials) to account for the results we obtained. We discuss these two observers in more detail subsequently.

Results and discussion

Accuracy

Weibull function fits to the proportions of correct responses are shown in [Figure 6](#). As in [Experiment 1](#), we quantified the cuing effect by comparing the fits of single-function and two-function Weibull fits to the individual observers’ data. These fits are summarized in [Table 2](#). As is clear from [Figure 6](#), the results of [Experiment 2](#) exactly replicated those of [Experiment 1](#). No observer showed any evidence of a cuing effect when stimuli were localized with FID crosses. In the uncertainty condition, every observer showed a large and significant cuing effect. The fits shown in [Figure 6](#) are for a model in which both thresholds and slopes varied across cuing conditions. However, as in [Experiment 1](#), most of the effects of cuing in the uncertainty condition were attributable to changes in threshold. For only one observer (M.O.) were the uncertainty data better fitted by a model in which threshold and slope varied than by one in which only threshold varied ($\Delta\chi^2(1) = 7.31, p < .01$).

As the only difference between FID and uncertainty conditions was the presence of localizing information in the display, the accuracy data from [Experiment 2](#), like those from [Experiment 1](#), are most consistent with an uncertainty reduction account. They extend the results of [Experiment 1](#) by showing that the same interaction between cues and uncertainty is obtained, regardless of whether the exogenous or endogenous orienting systems are engaged.

As in [Experiment 1](#), we investigated whether the cue combined with an FID cross produced better performance than did the cue alone. We found that all five observers showed uniformly higher accuracy in the cue-plus-FID condition than in the cue-alone condition. Chi-square values for the difference in fits of the two- and one-function models ranged from $\Delta\chi^2(2) = 10.03, p < .01$ to $\Delta\chi^2(2) = 93.53, p < .001$. These findings confirm the picture obtained from [Experiment 1](#) that addition of an

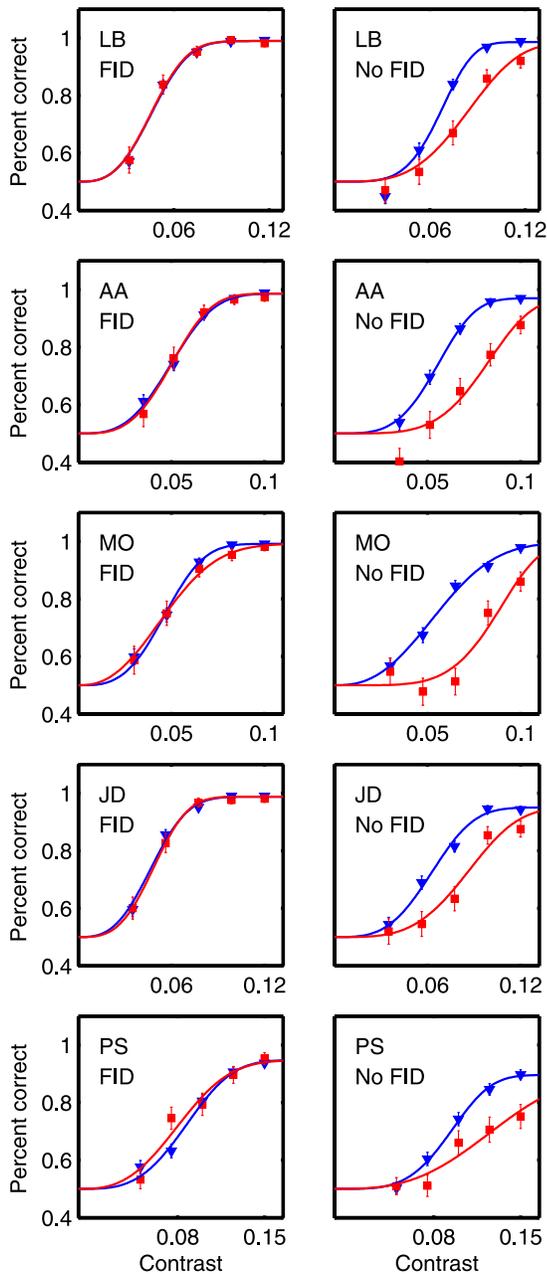


Figure 6. Accuracy (percent correct) as a function of stimulus contrast, for individual observers in Experiment 2, in the FID condition and the uncertainty condition (no FID). The fitted functions are Weibull functions. The blue lines and triangles are fits and data for cued stimuli; the red lines and squares are fits and data for miscued stimuli. The error bars are one binomial standard error.

FID cross benefits performance, even when attention has been directed to the stimulus location by a cue.

Attentional gain

We estimated gain by fitting Weibull functions to the individual observer d' values as we did for Experiment 1.

Smoothed and raw gains are shown in the lower panel of Figure 4. As in Experiment 1, there was a slight tendency for raw gain to increase at the lowest contrast in the FID condition, but the increase was smaller than in that experiment. A repeated measures analysis of variance with polynomial tests for trend showed no evidence of a change in gain as a function of contrast, $F_{Lin}(1,4) = .003, ns$, $F_{Quad}(1,4) = 2.72, ns$, $F_{Dev. Lin \& Quad}(2,8) = 1.075, ns$; nor did mean gain differ significantly from zero, $F(1,4) = 1.84, ns$. The same result was obtained from an analysis of d' for individual observers. For no observer were the d' values in the FID condition better fitted by a two-function model than by a single-function model: p values for the chi-square test of the difference between models ranged from .75 to .25. Both the group analysis and the individual analysis thus show that gain was zero when stimuli were localized by FID markers.

In the uncertainty condition, gain was highest at low contrasts and decreased to a value of around 4 dB at the top of the contrast range. This parallels the result found in Experiment 1, although the detailed pattern of gain values in the two experiments is a little different. The maximum smoothed gain was higher in Experiment 2 than in Experiment 1, and the raw gain in Experiment 2 decreased at the lowest level of contrast whereas the raw gain in Experiment 1 increased. (Because the smoothed gain curve is constrained by the form of the Weibull function, it does not capture the decrease in raw gain at low contrast in Experiment 2.) Although these differences could conceivably reflect differences between the endogenous and exogenous orienting systems, they are more likely to reflect a combination of individual differences between the two groups of observers, the inherent variability of gain estimates at low contrasts, and the fact that the range of contrasts used the two experiments was slightly different. The average contrasts used in Experiment 1 ranged from .046 to .145; those in Experiment 2 ranged from .037 to .118. Consequently, the two sets of gain curves are sampling slightly different parts of the contrast range. This difference appears to be a reflection of individual

Observer	Percent correct		Mean reaction time	
	FID $\Delta\chi^2(2)$	No FID $\Delta\chi^2(2)$	FID $\Delta\chi^2(2)$	No FID $\Delta\chi^2(2)$
L.B.	0.03	32.67***	15.07***	59.07***
A.A.	0.15	61.05***	80.13***	78.36***
M.O.	2.67	76.76***	55.61***	67.18***
J.D.	0.25	34.23***	21.34***	50.82***
P.S.	0.84	23.42***	15.80***	14.65***
Group	0.79	45.63***	37.59***	54.01***

Table 2. Tests of the cuing effect, Experiment 2: Difference in fit ($\Delta\chi^2$) between a single-function and a two-function model. The models were as described in the note to Table 1. Note: *** $p < .001$.

differences between the two groups of observers and possibly also minor procedural differences in the way the experiments were run.

Response time

The individual observer RT data are shown in Figure 7. As in Figure 5, the fitted curves are for a two-parameter

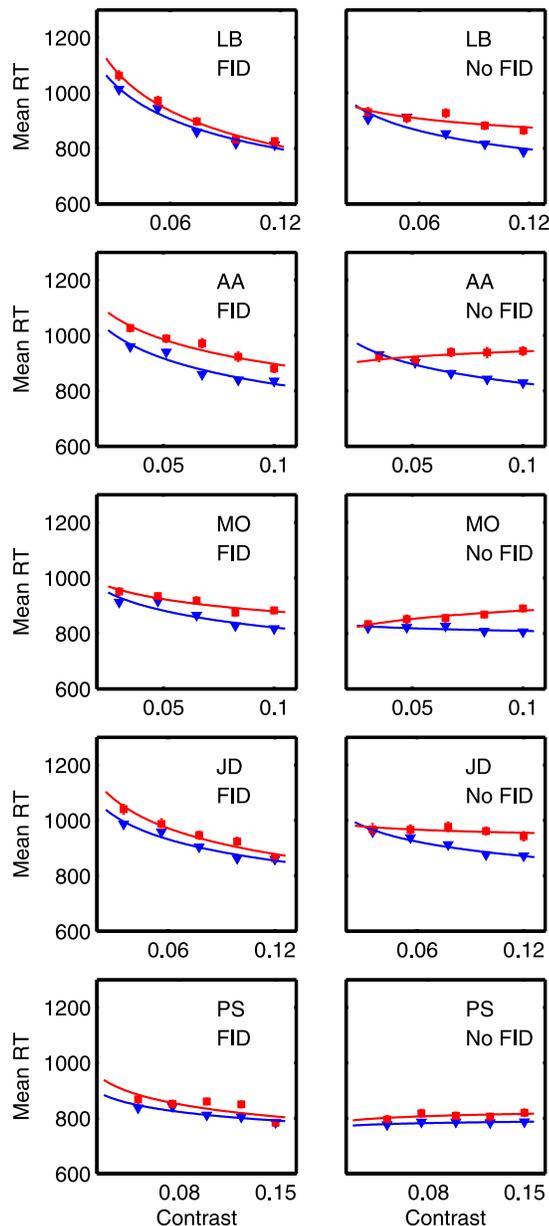


Figure 7. Mean RT (milliseconds) as a function of stimulus contrast, for individual observers in Experiment 2, in the FID condition and the uncertainty condition (no FID). The smooth curves are Piéron's law fits to the data. The blue lines and triangles are fits and data for cued stimuli; the red lines and squares are fits and data for miscued stimuli. The error bars are one standard of the mean.

Piéron's law model. The main features of the pattern of RTs from Experiment 2 replicate those of Experiment 1. In both the FID and the uncertainty conditions, mean RTs were shorter for cued than for miscued stimuli for all observers. When stimuli were localized with FID crosses, the magnitude of the cuing effect in RT was roughly constant; the Piéron functions for cued and miscued stimuli are approximately parallel. In the uncertainty condition, the Piéron's law dependency on contrast is weaker, especially for miscued stimuli. Indeed for some observers, miscued RTs in the uncertainty condition actually increased with stimulus contrast. In these cases, the mean RTs in Figure 7 were fitted with a positive rather than a negative exponent.

The pattern of data in Figures 5 and 7 suggests that observers performed the task using a mixture of time- and information-controlled processing (Ratcliff, 1978). In information-controlled processing, decisions are made by accumulating stimulus information to a response criterion. Low contrasts result in low rates of information accumulation, low accuracy, and long RTs (e.g., Gould, 2004; Ratcliff & Smith, 2004; Smith, Ratcliff, et al., 2004). In time-controlled processing, information is sampled until a deadline (either external or internal) expires (e.g., Carrasco & McElree, 2001). Because initiation of the response is determined by the deadline rather than by an information criterion, the effects of contrast variation are seen mainly in accuracy and only weakly, if at all, in RT. The shallow Piéron functions for miscued stimuli in the uncertainty condition, combined with the lack of a cuing effect at low contrasts, suggests that observers were using a (variable) internal deadline to limit the time they spent sampling the display.

Practice and cuing effects

In one important sense, the results of our comparison of endogenous and exogenous cuing agree with those of similar studies by Lu et al. (2002) and Ling and Carrasco (2006). Those studies suggest that the benefits obtained when attention is voluntarily directed to a stimulus can also be obtained when attention is reflexively summoned by a peripheral cue. They also suggest that reflexive orienting can produce some further effects not produced by voluntary orienting. Similarly, we found that cues designed to engage either the reflexive or the voluntary orienting systems produced the same overall pattern of performance. The one difference was a small increase in average gain at the lowest contrast in the FID condition when attention was oriented reflexively, but not when it was oriented voluntarily. These results differ from those of Prinzmetal et al. (2005), who found that voluntary orienting produces both RT and accuracy benefits whereas reflexive orienting produces RT benefits only.

There are of course many differences among these studies that might be responsible for the differences in

findings. Our studies, like those of Doshier and Lu (1999), Ling and Carrasco (2006), Lu and Doshier (1998), and Lu et al. (2002), have used stimuli designed to engage low-level visual mechanisms and have focused on very simple perceptual judgments. We have investigated detection and its analogues, whereas Doshier and Lu, Ling and Carrasco, Lu and Doshier, and Lu et al. have investigated a variety of simple discrimination tasks. In contrast, many of the experiments of Prinzmetal et al. (2005) used higher level perceptual tasks, such as letter or face discrimination. However, Lu and Doshier have replicated their findings in a task requiring discrimination between complex, letter-like stimuli. Their results suggest that differences in the complexity of the perceptual judgment were not wholly responsible for the differences in findings.

There is, however, a more pervasive difference. Our study, like those of Doshier and Lu (1999), Ling and Carrasco (2006), Lu and Doshier (1998), and Lu et al. (2002), used a psychophysical paradigm, in which data were collected from a small number of highly practiced observers over a large number of experimental sessions. Each observer was treated as an independent replication of the experiment, and data were analyzed on an observer-by-observer basis. In contrast, the paradigm used by Prinzmetal et al. (2005) was of a kind often used in cognitive psychology. Data were collected from 12 observers in each experiment, each of whom served in a single session, and none of whom served in more than one experiment. Around 200–250 trials of data were collected from each observer after 40–50 trials of practice, and data were analyzed at the level of group means only. Consequently, in comparison to the other studies cited here, the observers in the experiments of Prinzmetal et al. were much less practiced at the experimental task.

Could this be the reason for the different patterns of findings among studies? Earlier, we noted that we monitored eye movements from two of the observers in Experiment 2 (M.O. and A.A.) who showed a different pattern of performance during practice sessions to that of the other observers. Specifically, these two observers showed a cuing effect in the FID condition that increased at low contrasts. The data from Sessions 3 to 5 for these observers are shown in Figure 8. Note that the contrasts in these plots are substantially higher than in the corresponding plots in Figure 5.

The observers in our studies typically show large improvements in performance over the first few experimental sessions. Perceptual learning is found in many psychophysical tasks, and considerable effort has been invested by a number of researchers, especially Lu, Doshier, and colleagues (e.g., Doshier & Lu, 1999) to characterize the processes involved. Because of this, during practice, we progressively reduce stimulus contrasts over successive sessions as observers become better at the task. We continue this process until

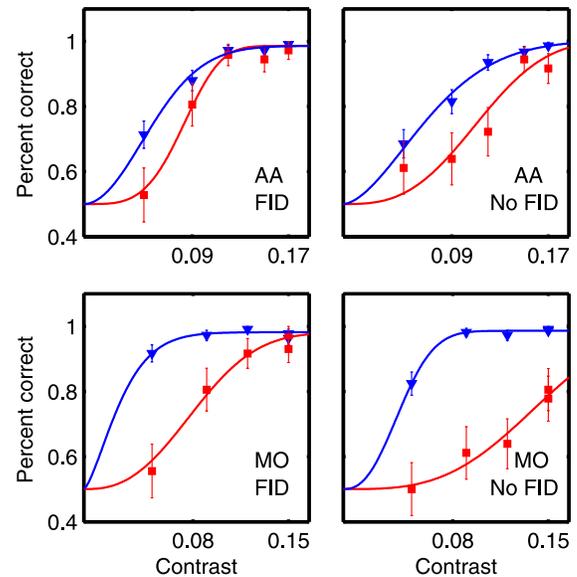


Figure 8. Accuracy data for observers A.A. and M.O. for practice Sessions 3 to 5 in Experiment 2. Psychometric functions based on 108 trials per point for cued trials and 36 trials per point for miscued trials. The blue lines and triangles are fits and data, respectively, for cued stimuli; the red lines and squares are fits and data for miscued stimuli. The error bars are one binomial standard error. The abscissa values are average contrasts over the three sessions.

performance stabilizes. Observers A.A. and M.O. both completed seven practice sessions before we began collecting experimental data.

The cuing effects for the FID condition in Figure 8 are quite substantial, especially for M.O. This pattern differs markedly from that for the other three observers, all of whom showed the same kinds of effects in the practice and experimental sessions. It seems possible to us that, had we collected these data in a similar paradigm to the one used by Prinzmetal et al. (2005) and considered only averaged effects across observers, we might have concluded that voluntary attention increases detection sensitivity, regardless of whether stimuli were localized or not. This pattern of results differed from that in Experiment 1, in which observers' performance rapidly stabilized and in which there was no evidence of an early cuing effect in the FID condition.

Clearly, arguments can be mounted in favor of paradigms of both kinds. If the goal of research is to study the visual mechanisms that set limits on performance, those limits are best studied in practiced observers whose performance on the task is stable. However, it could also be argued that much of our real-world experience is in novel, changing perceptual environments, and that minimum-practice paradigms have greater ecological validity. Our preference is for psychophysical paradigms, but we do not presume to

adjudicate this debate. Indeed, it may be that both kinds of paradigms will contribute to our understanding of attentional processes.

General discussion and conclusions

Our study was motivated by a need to resolve the discrepancies in the published findings on the effects of attentional cues on visual signal detection. Previous studies from our laboratory have suggested that cues increase sensitivity in detection tasks only when stimuli are backwardly masked (the mask-dependent cuing hypothesis). However, recent studies by Cameron et al. (2002) and Carrasco et al. (2000) suggested that the effects of cues are more pervasive than this, and that they can increase contrast sensitivity, even in the absence of masks.

We identified differences in uncertainty as a likely reason for the differences among studies. Uncertainty can have a profound and a pervasive effect on detection sensitivity because it increases the noise in perceptual decision making, as the classical signal detection literature has shown (Cohn & Lashley, 1974; Tanner, 1961). Moreover, a number of well-established findings in the attention literature, like set size effects in visual search, can be explained by models in which the only source of performance limitation is noise in perceptual decision making (e.g., Eckstein, Thomas, Palmer, & Shimozaki, 2000; Palmer et al., 1993). Consequently, it has been argued, most cogently by Shaw (1984), that capacity-limited attentional effects can only be inferred when the effects of uncertainty have been eliminated or otherwise controlled.

We therefore developed a paradigm in which stimuli were either presented under conditions of uncertainty or were localized by FID markers. This paradigm allowed us to manipulate the effects of uncertainty experimentally on a trial-by-trial basis. Our results were as we hypothesized: When stimuli were localized by FID markers, cues produced little or no increase in sensitivity; when they were viewed under conditions of uncertainty, cues produced large and systematic increases in sensitivity. The estimates of attentional gain in our experiments were much greater than those reported previously by Smith, Wolfgang, et al. (2004) using spatially localized, backwardly masked stimuli and showed a different pattern of dependency on contrast. Whereas the gains in the Smith et al. study were fairly uniform across the psychometric function, the gains in the uncertainty conditions in our experiments decreased sharply at high contrasts. This pattern would be expected from an uncertainty reduction mechanism under the assumption that the effects of uncertainty are greatest at low contrasts (e.g., Pelli, 1985).

A strategy used by some researchers to discount uncertainty has been to analyze localization judgments. According to the classical signal detection model, uncertainty degrades performance by increasing the likelihood that decisions will be based on noise from nontarget regions of the display. Thus, it can be argued that if an observer can accurately localize a stimulus, any judgment made about it will have been unaffected by noise from elsewhere in the display, even if it was presented under conditions of uncertainty.

Cameron et al. (2002) collected localization judgments in their study and used them to argue against an uncertainty reduction account of their cuing effect. They compared performance in two orientation discrimination tasks: an easy ($\pm 15^\circ$) task and a difficult ($\pm 4^\circ$) task. Because stimuli in the $\pm 4^\circ$ task were perceptually confusable, higher levels of contrast were needed to achieve the same levels of performance as in the $\pm 15^\circ$ task. Cameron et al. found that localization judgments in the easy task were highly correlated with discrimination accuracy; when observers could not identify the stimulus they were also unable to localize it, and vice versa. This is as predicted by an uncertainty model. However, localization accuracy in the difficult task was uniformly higher than discrimination accuracy at all levels of stimulus contrast, reflecting the higher contrasts needed to do the task.

Cameron et al. (2002) reported that, although there were large differences in localization accuracy, the magnitude of the cuing effects in the two tasks was similar. They argued it was implausible to attribute the cuing effect to uncertainty reduction because the levels of uncertainty in the two tasks were so different. However, as argued by Lu et al. (2002), the results from the high-contrast condition of Cameron et al. do not speak directly to the question of the processes involved at low contrasts. Moreover, in a companion paper to this one (Smith and Wolfgang, *in press*), we found that cuing effects not only depend on *whether* uncertainty is resolved, they also depend on *when* it is resolved. Specifically, we found that cuing effects were increased when there was initial uncertainty and information localizing the stimulus was delayed. Moreover, the effect of delayed localization was greater for low-contrast stimuli. An implication of these findings is that an observer's ability ultimately to localize a stimulus does not mean judgments about it were unaffected by uncertainty. Consequently, the results of localization judgments cannot in themselves be used to reject an uncertainty reduction account.

Uncertainty effects have typically been conceived within a signal detection theory framework (Pelli, 1985; Tanner, 1961), and this has proved to be a powerful tool for explaining a variety of attentional findings (Eckstein et al., 2000; Palmer et al., 2000; Shaw, 1984; Smith, 1998). However, signal detection models are not dynamic models and so offer little insight into the time course of the processes involved in perceptual decision making and the

way this is affected by attention. The fact that cuing effects depend on when uncertainty is resolved points to the need for dynamic models to complement and extend the insights that signal detection theory has provided.

A full theoretical treatment of these issues is outside the scope of this article and will be presented elsewhere (cf. Smith, 2007). In brief, however, our theory assumes that performance in perceptual decision tasks depends on the quality of a representation of the stimulus in visual short-term memory (Sperling, 1960). The quality of this representation depends both on attention and on the saliency of the stimulus, which is assumed to affect how rapidly the uncertainty present at stimulus onset is resolved. Attention, saliency, and visible persistence of the stimulus jointly determine the quality of the visual short-term memory representation. The assumption that the quality of the stimulus representation depends on both saliency and attention is supported by the findings that, for the majority of observers in Experiments 1 and 2, performance was better in the cue-plus-FID condition than in the cue-alone condition.

Our theory predicts that, in detection tasks, large cuing effects in accuracy will be found only when stimulus saliency is low because highly salient stimuli allow the system to rapidly compensate for the effects of miscuing. To model tasks like the one considered here, we assume that saliency depends jointly on the contrasts of the stimulus and the FID cross, but primarily on the latter, because it is several times greater than that of the highest contrast stimulus. Performance is predicted to be poorest when stimuli are unattended, of low contrast, and presented without localizing information, in agreement with the results reported here. When coupled with a sequential-sampling (diffusion process) decision model, the theory predicts the patterns of RT and accuracy found in these experiments.

We also assume that difficult discriminations require higher quality visual short-term memory representations than do easy discriminations, and that the representations needed to discriminate difficult stimuli take longer to develop (Smith, Wolfgang, et al., 2004). The theory naturally predicts larger cuing effects for more difficult perceptual decisions, in agreement with what has been reported in the literature (e.g., Brawn & Snowden, 2000; Lee et al., 1997; Palmer et al., 1993). If, however, the increase in discrimination difficulty is accompanied by an increase in contrast, and thus in stimulus saliency, as in the study of Cameron et al. (2002), the natural tendency to find larger cuing effects with difficult judgments may be offset by the tendency of cuing effects to decrease with increasing saliency, leading to similar cuing effects in both tasks. We conjecture that this may have occurred in the study by Cameron et al.

The results from the present experiments suggest that the same uncertainty reduction processes underlie the cuing effect in detecting unmasked stimuli in noiseless displays, regardless of whether the endogenous or the

exogenous orienting mechanisms are engaged, at least for practiced observers. However, our results leave open the possibility that other mechanisms may influence performance early in practice when attention is cued endogenously, at least for some observers. The small-sample nature of our design does not allow us to draw strong conclusions about whether this is actually so; nor do we attempt to offer a theoretical account of what mechanisms may be involved. If true, it would provide at least a partial resolution of some of the discrepancies in the literature on the effects of voluntary attention.

Appendix A

Model-fitting procedures

Weibull functions were fitted to the proportion of correct responses for each observer by minimizing the statistic

$$\chi^2 = \sum_i \frac{[P_i(c) - F_i(c)]^2}{\text{var}[P_i(c)]}, \quad (\text{A1})$$

using the Matlab implementation of the Nelder–Mead Simplex algorithm (fminsearch). In this equation, $P_i(c)$ is the observed proportion of correct responses, $F_i(c)$ is the fitted Weibull value for stimulus contrast c , and

$$\text{var}[P_i(c)] = \frac{P_i(c)[1 - P_i(c)]}{n} \quad (\text{A2})$$

is the binomial variance for a proportion based on n experimental trials. The index of summation, i , runs over the five stimulus contrasts and the two cue conditions. The above statistic is distributed approximately as a chi-square with degrees of freedom equal to the number of data points (10) minus the number of estimated parameters.

To calculate attention gain, we fitted the observed d' values with modified Weibull functions of the form

$$F(c) = \alpha \left\{ 1 - \exp \left[- \left(\frac{c}{\beta} \right)^\gamma \right] \right\}. \quad (\text{A3})$$

This equation is similar to the one used to fit the proportion of correct responses, but the range of the function is $[0, \alpha]$. The function was fitted by minimizing the chi-square statistic

$$\chi^2 = \sum_i \frac{[d'_i(c) - F_i(c)]^2}{\text{var}[d'_i(c)]}, \quad (\text{A4})$$

where

$$\text{var}(d') = \frac{P_H(c)[1 - P_H(c)]}{2n_H\phi^2\{z[P_H(c)]\}} + \frac{P_V(c)[1 - P_V(c)]}{2n_V\phi^2\{z[P_V(c)]\}} \quad (\text{A5})$$

is the asymptotic variance estimate of Gourevitch and Galanter (1967). In this equation, n_V and n_H are the number of horizontal and vertical stimuli in each condition and $\phi(\cdot)$ is the standard normal density function evaluated at the specified abscissa. The other quantities are as defined in the text. The factor of 2 in the denominator is a reflection of the $\sqrt{2}$ term in the denominator in the definition of d' .

Fits of Piéron's law were performed by minimizing a chi-square statistic in a similar way as was done for the psychometric functions, with the square of the estimated standard error of the mean used as a variance term in the denominator.

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Footnotes

¹It was not our primary aim when designing [Experiment 1](#) to produce an experimental manipulation that engaged the exogenous orienting system only. Rather, our aim was to replicate the cue contingencies used in the study by Smith, Ratcliff, et al. (2004), which found no cuing effect with perceptually localized, unmasked stimuli. However, we agree with the view that the use of weakly predictive peripheral cues and a short SOA means it is likely that the exogenous orienting system was the system most strongly engaged in the experiment.

²If the numerator and denominator of a ratio statistic are independently normally distributed, the statistic will be Cauchy distributed. Although the Cauchy distribution has a similar bell-like shape to the normal distribution, it does not have a finite variance. As a result, the precision of estimates of the mean will not improve with increasing sample size.

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