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The effect of spatial cues on visual sensitivity

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Abstract

Although once doubted, a consensus has emerged from the literature that visual sensitivity can be heightened locally with an appropriate precue. Experiments with partially and totally valid precues suggest an increase in sensitivity of less than one-half log unit at the precued position, as compared with other positions. New experiments with non-informative precues demonstrate that most of this small enhancement is not due to focal attention. Sensitivity can be heightened at eight positions simultaneously, just as much as when a single position is precued. Sensitivities produced by single, totally valid precues and single, non-informative precues were similar. Thus there seems to be no capacity limit for the effect of precues on visual sensitivity.

Keywords: Attention; Contrast; Sensitivity; Signal enhancement

1. Introduction

1.1. History

Many tasks are facilitated when the position of the target is known, even if the observer is fixating elsewhere. For example, Posner, Nissen, and Ogden (1978) showed that reaction times (RTs) for detecting a target were lowered when the target was preceded by a visual cue to its position. Posner et al.'s cues were partially valid, i.e. the target usually appeared at the cued position, but sometimes it appeared elsewhere. Bashinski and Bacharach (1980) extended these results, showing that partially valid cues actually heighten sensitivity. Specifically, they showed that accuracy in a yes/no detection task was improved when the target appeared at the precued position.

Palmer, Ames, and Lindsey (1993) were rather dismissive of partially valid precues. They noted that, in order to interpret the results of experiments with partially valid precues, experimenters had to make certain assumptions about how observers interpreted the cue probabilities. They were also critical of effects on sensitivity measured using the "dual-task" paradigm, in which performance when target detection was the primary (e.g. first-reported) task is compared with performance when target detection was a secondary task. They noted that effects measured in this way might reflect different rates of memory decay rather than different sensitivities per se. Instead, Palmer et al., advocated the use of totally valid precues. When a single target appeared at one of 1, 2, 4 or 8 precued positions, they found the effect of cue number on sensitivity to be in strict accordance with Signal Detection Theory (Green & Swets, 1966). That is, precues appeared to offer no benefit to detection besides allowing observers to ignore spurious visual signals elicited from irrelevant parts of the scene.

Smith (2000) reviewed previous evidence for and against the possibility that covert attention (without eye movements) could improve sensitivity. He concluded that evidence for this so-called "signal enhancement" could be obtained only when backward masks limited target visibility. In particular, he noted that Palmer et al. (1993) did not use backward masks. In Smith's own experiments, without a postmask, not even partially valid precues could heighten sensitivity. On the other hand, with a postmask and an 80% valid precue, Smith found that targets at a cued position could be detected with approximately half the contrast that was required by targets at another position.

1.2. Meta-analysis

Table 1 shows an extension and updating of Smith's (2000) meta-analysis. The top 14 studies are those that appeared in his Table 1. The bottom nine were excluded,

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Table 1
Precueing's enhancement of visual sensitivity ($\Delta \log t_0$)

Studies cited in Smith (2000)			
Bashinski and Bacharach (1980), Experiment 1	80/20, direct, postmasks	$P(A)$	0.12
Davis, Kramer, and Graham (1983)	100/N, symbolic, no masks	$P(C)$	~0
Shaw (1984)	100/N, symbolic, no masks	$P(C)$	~0
Graham, Kramer, and Haber (1985)	AOC, symbolic, no masks	d'	~0
Muller and Findlay (1987)	67/33, symbolic, postmasks	$P(A)$	~0
Downing (1988), detect, discriminate	80/N, symbolic, postmasks	d'	0.12
Hawkins et al. (1990), high eccentricity	76/34, direct, postmasks	$P(A)$	0.16
Muller and Humphreys (1991), Experiment 1, 4 locations	80/20, direct, postmasks	$P(A)$	0.43
Bonnel, Stein, and Bertucci (1992), detection	AOC, direct, no masks	$P(A)$	~0
Palmer et al. (1993)	100/N, direct, no masks	Threshold	~0
Palmer (1994), detection	100/N, direct, no masks	Threshold	~0
Luck et al. (1994), Experiment 2	76/34, direct, postmasks	$P(A)$	0.25
Lee, Koch, and Braun (1997), detection	Dual task, postmasks	Threshold	~0
Smith (1998), Experiment 1	76/50, direct, postmasks	d'	0.4
Other studies			
Cohn and Lasley (1974)	100/N, symbolic, no masks	d'	~0
Lu and Dosher (1998)	Dual task, simultaneous	Threshold	0.07
Lee, Itti, Koch, and Braun (1999), discriminate	Dual task, no masks	Threshold	0.26
Smith (2000), Experiment 1 60 ms MOA	80/20, direct, postmasks	$P(C)$	0.34
Lu and Dosher (2000)	100/N, direct, simultaneous	Threshold	0.05
Carrasco, Penpeci-Talgar, and Eckstein (2000)	100/N, direct, postmasks	Threshold	0.1
Ciaramitaro, Cameron, and Glimcher (2001), observer CS	93/7, symbolic, no masks	d'	0.08
Morrone, Denti, and Spinelli (2002), discriminate luminance	Dual task, no masks	Threshold	0.47
Solomon (2002)	100/N, direct, no masks	Threshold	~0

mostly because they had not yet been published. Where necessary, the first column of Table 1 specifies a study's most relevant condition with respect to the issue of whether a precue can heighten sensitivity.

The second column of Table 1 specifies the paradigm. For example "80/20" indicates that 80%-valid precues were used; performance when the cue actually did indicate the target position was compared with performance when the (so-called "invalid") cue indicated another position. "100/N" indicates that totally valid precues were used; performance with a single cue was compared with performance when all or none of the positions were precued. "AOC" stands for attention operating characteristic (Sperling & Dosher, 1986). In Table 1, it indicates that performances were compared when just one target was to be detected and when two targets were to be detected. The words "direct" and "symbolic" denote precues that appear at or near the cued location and precues that do not, respectively (Wright & Ward, 1998). Finally, the second column notes whether postmasks, simultaneous masks or no masks were used.

The fourth column of Table 1 specifies the increase in sensitivity elicited by the cue, in log units. That is, the value 1.0 would indicate a 10-fold increase in sensitivity; threshold contrast in an uncued or invalidly cued condition should be 10 times threshold contrast in the validly cued condition. Studies which found no evidence for signal amplification show "~0" in this column.

The most straightforward way to quantify a cueing effect is to compare the threshold obtained without a cue (or with an invalid cue) with the threshold obtained with a cue. However, some studies do not provide threshold measurements. For each of these studies, other published quantities were converted into thresholds in order to quantify the cueing effect. The third column of Table 1 specifies these other quantities. $P(A)$ is the area under a receiver-operating characteristic, $P(C)$ is percent correct and d' is a criterion-free measure of sensitivity. Appendix A describes how each of these measures can be converted into contrast thresholds.

1.3. Rationale for yet another experiment

Some studies have suggested that it may not be possible to obtain large cueing effects, like Smith's (1998, 2000) or even Luck et al.'s (1994), without using partially valid cues or a dual-task paradigm. Lu and Dosher (2000) reiterated Palmer et al.'s (1993) criticism of partially valid cues, noting that they effectively provide observers with misleading information, and obtained a 0.05 log unit effect using totally valid precues and either simultaneous masks or no masks. Carrasco et al. (2000) used a postmask with their totally valid cue, but managed only a 0.1 log unit effect.

It should be noted that the totally-valid precue paradigm theoretically pits focal attention against divided attention, whereas attention and *its absence* may be compared using the partially-valid precue paradigm. Consistent with this argument are comparisons between sensitivity with partially valid cues and sensitivity with neutral cues. Luck et al.'s (1994) findings suggest this effect is just about 0.1 log units. (Smith did not use neutral cues.)

Jonides (1981) pioneered the use of non-informative precues for comparing performances in attended and unattended positions. In Jonides' paradigm, when a single precue appears near one of eight possible positions, the target appears in that position on exactly one-eighth of the trials. The cue therefore offers no information to an ideal observer, yet retains the potential to automatically capture attention. This seemed the ideal paradigm in which to compare sensitivities inside and outside the focus of attention, without resorting to partially valid cues or the dual-task paradigm. One slight disadvantage of this paradigm must be noted. It precludes the use of symbolic cues, which necessarily engage non-automatic processes.

1.4. Pilot work

Quite a bit of pilot work was carried out to determine the conditions most likely to produce a large cueing effect. The task of orientation identification was chosen—rather than, say two-alternative forced-choice detection, with which I had previously found no cueing effect (Solomon, 2002)—because of its prior success in producing cueing effects (e.g. Carrasco et al., 2000; Lu & Dosher, 1998). Initially, at least, my choice of target was influenced by Carrasco et al.'s data, indicating the largest cueing effects with high-frequency targets (see their Fig. 4d).

Although I did not investigate different cue-target onset asynchronies (100 ms seems to be the industry standard for precues designed to automatically attract attention), I did try several target-mask onset asynchronies (MOAs). Naturally, orientation identification improves as MOA increases. However, when the target and postmask appeared in the cued position, the MOA required for any desired accuracy was roughly 35 ms shorter than when the target and postmask appeared in the uncued position (only 2 positions were used).

I wanted to know if this cueing effect were due to a "cost," i.e. an inhibition at the putatively unattended position, or a "benefit," i.e. a facilitation at the putative focus of attention (Posner et al., 1978), so conditions were added in which both and neither position were cued. When both positions were cued, accuracy was just as good as when only one position was cued and the target appeared there. Wondering whether there were a limit to the number of positions at which facilitation could occur, I finally opted to use eight positions.

2. Methods

Stimuli were displayed on an Sony GDM-F520 monitor using only the green gun. A video signal with 12-bit precision was attained using an ISR Video Attenuator, which conforms to the specifications described by Pelli and Zhang (1991). Fig. 1 illustrates the central 480×480 pixels of the 640×480 display. At the 115-cm viewing distance, there were 32 pixels per degree of visual angle. The frame rate was 120 Hz and the luminance of the monitor was 10.8 cd m^{-2}.

Eight positions, each 5.25° from fixation, were circumscribed with a square of full-contrast binary noise. Each side of the square was 94 pixels long and 4 pixels wide (see Fig. 1). On each trial, the observer sees this sequence: cue, target, postmask. The cue is a contrast reversal; the noise around one, two, four, all or none of the positions reverses contrast. 17 ms later it reverses back. 91 ms after that, a Gabor target appears. A postmask of full-contrast binary noise appears, 63 ms later, filling the square at the target position.

Every other block contained 25 trials in each of 16 randomly interleaved conditions, for a total of 400 trials. In Conditions 1–8, the target appeared the corresponding number of positions clockwise from a single cued position, such that in Condition 8, it appeared at the cued position. In Conditions 9–12, two positions were cued; the target appeared at a cued location only in Condition 12. Conditions 13 and 14 featured four cues, in Condition 15 all positions were cued and in Condition 16 no positions were cued. In all conditions, the cued positions were randomly determined on each trial. This protocol ensured no correlation between the position(s) of the cues and the position of the target.

The alternate blocks contained 25 trials of Condition 8, not interleaved with anything else, to determine performance with a totally valid cue. All observers understood which blocks contained non-informative cues and which blocks contained totally valid cues.

The experiment was carried out in three phases: In Phase 1, two observers were used, the author and CG, an experienced psychophysical observer, naïve to the purposes of this particular experiment. They used Gabor targets, with central white stripes, whose wavelength and spread were $\lambda = 0.19°$ and $\sigma = 0.45°$, respectively. They were oriented ±11.5° from horizontal. They responded "clockwise" or "anti-clockwise." JAS completed 14 blocks (7 of each kind) with the target appearing at 50% maximum contrast. CG completed 14 blocks with the target at 75% maximum contrast.

In Phase 2 of the experiment (another 14 blocks for each observer) target contrast was controlled by the QUEST algorithm (Watson & Pelli, 2002). A third (very experienced) observer, CFC, was added in Phase 2. He was unable to perform the task using JAS's and CG's target, even at maximum contrast, so wavelength was

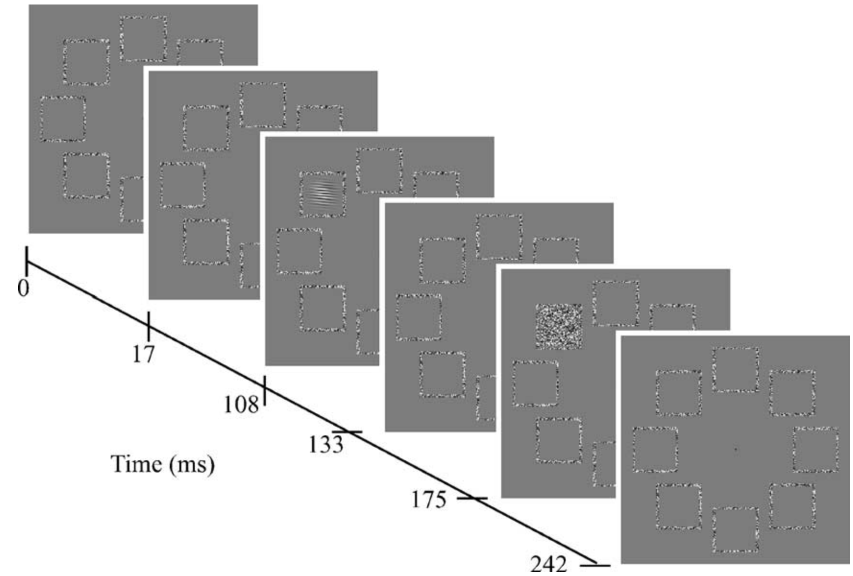

Fig. 1. Example trial sequence. The random noise surrounding zero, one, two, four or all eight positions reverses contrast, twice, providing no information regarding the position of a single Gabor pattern, which appears 108 ms after the first reversal. (In this example, the top and top-left positions are precued.) 175 ms after this precue, a postmask appears at the target position. Observers must report the orientation of the target's tilt (clockwise or anti-clockwise).

increased to $\lambda = 0.27°$ for him, nothing else was changed.

Analysis of Phases 1 and 2 revealed significant individual differences in sensitivity (see Section 3). Thus, prior to Phase 3, informal experiments (with totally valid cues) were run to determine the target wavelengths most likely to produce sensitivities comparable to JAS's. For CG, [1] this was $\lambda = 0.24°$; for TM, an experienced psychophysical observer naïve to the purposes of this experiment, this was $\lambda = 0.27°$. CG ran 20 blocks (10 of each kind) in Phase 3; TM ran 14. Phase 3 was identical to Phase 2 in all other respects.

3. Results

3.1. Threshold estimation

For each condition, contrast thresholds for orientation identification were estimated by maximum-likelihood (Watson, 1979) fitting a Weibull function to all of the psychometric data from each observer:

$$\Psi(t; t_0, \beta) = 0.5 + 0.49(1 - \exp[-(t/t_0)^\beta]). \quad (1)$$

In this expression, the accurate proportion of responses Ψ, is a function of target contrast t and the parameters t_0 (threshold) and β (psychometric slope). Both of these parameters were allowed to vary freely in the fitting procedure. As there was no indication that threshold varied systematically with cue/target separation in Conditions 1–7, psychometric data from these conditions were pooled and threshold was estimated again. Similarly, psychometric data from Conditions 9–11 were pooled. Bootstrapping (Efron, 1979) was employed to determine the 95% confidence intervals about each estimate of threshold.

Log thresholds for each observer are shown, [2] with their corresponding confidence intervals, in Fig. 2, where a value of 0 indicates maximum contrast. White and grey columns show thresholds obtained when the target did and did not appear at a cued position, respectively.

Eight χ^2 analyses [3] (the results of which appear in Table 2) were performed on each observer's data (16 for CG; 8 for each target). Three of these analyses quantified the significance of the number of cued positions when the target did not appear at one. Specifically, they

[1] Having been debriefed following Phase 2, CG was not naïve in Phase 3.

[2] Data from Phases 1 and 2 were combined. When the results of Phase 1 were excluded, confidence intervals were larger, but threshold estimates were similar. In particular, only four estimates changed by more than 0.1 log unit when Phase 1 was ignored: JAS's totally-valid threshold went up 0.10 log unit, CG's 1-cue/uncued threshold went down 0.25 log units, CG's 2-cue/uncued threshold went down 0.19 log units and CG's 2-cue/cued threshold went up 0.12 log units. Even with the results of Phase 1, CG's confidence intervals are still pretty large.

[3] For each pair of conditions i and j, $\Psi_i(t; t_{0i}, \beta_i)$ and $\Psi_j(t; t_{0j}, \beta_j)$ were (maximum-likelihood) fit twice to all responses using (a) no constraints and (b) the constraint that $t_{0i} = t_{0j}$. Twice the natural logarithm of the ratio between their maximum likelihoods $2 \ln \Lambda$, should follow the $\chi^2_{(1)}$ distribution (Mood, Graybill, & Boes, 1974, pp. 440–442). The α values reflect the probability that a random variable having that distribution exceeds $2 \ln \Lambda$ (i.e. the probability of a Type I error).

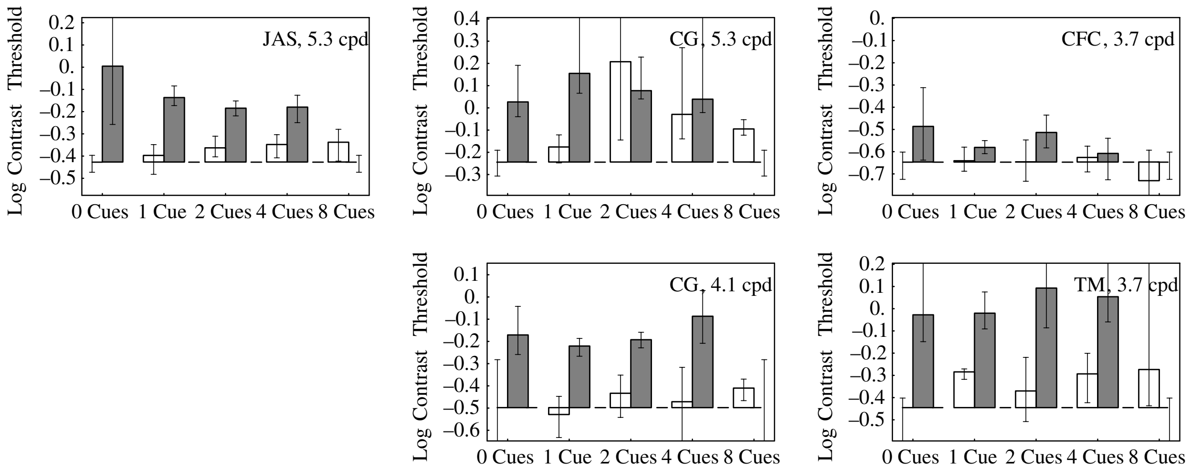

Fig. 2. Estimates of contrast threshold. Estimates for conditions in which the target appeared at a precued position (white columns) are systematically lower than estimates for conditions in which it did not (grey columns). These estimates may be compared with those derived from separate blocks in which target position was identified by a single (totally valid) precue (dashed lines).

Table 2
Probabilities α, of incorrectly rejecting the null hypothesis (equal thresholds) in favour of various alternative hypotheses

Observer	Non-informative uncued targets			Non-informative cued targets			Non-informative targets: uncued ≠ cued	Cued targets: non-informative ≠ totally valid
	0 cues ≠ 1, 2, 4 cues	0, 1 cue ≠ 2, 4 cues	0, 1, 2 cues ≠ 4 cues	1 cue ≠ 2, 4, 8 cues	1, 2 cues ≠ 4, 8 cues	1, 2, 4 cues ≠ 8 cues		
JAS, 5.3 cpd	0.24	0.21	0.55	0.34	0.41	0.59	2.6×10^{-15}	0.0050
CG, 5.3 cpd	0.49	0.55	0.49	0.087	0.85	0.75	0.033	0.00099
CFC, 3.7 cpd	0.38	0.55	0.48	0.69	0.61	0.42	0.00092	0.79
CG. 4.1 cpd	0.79	0.31	0.16	0.23	0.55	0.38	1.2×10^{-9}	0.64
TM, 3.7 cpd	0.68	0.96	0.72	0.63	0.39	0.54	1.3×10^{-6}	0.027

tested the hypotheses that (a) threshold with 0 cues was different from threshold with 1, 2 or 4 cues; (b) threshold with 0 or 1 cue was different from threshold with 2 or 4 cues and (c) threshold with 0, 1 or 2 cues was different from threshold with 4 cues. Three analogous analyses examined the effect of cue number when the target did appear at a cued position. Only one of these effects approached significance ($\alpha < 0.2$): when a 5.3 cpd target appeared in a cued location, CG's threshold with 1 cue was lower than that with 2, 4 or 8.

With the aforementioned possible exception, it did not matter how many cues there were; there was no significant difference in threshold. It seemed therefore reasonable to collapse across cue number for the last two χ^2 analyses. One of these analyses examined whether appearance at a cued position had a significant effect in non-informative conditions (it did; $\alpha < 0.04$). The other analysis examined whether totally valid cues produced significantly different thresholds from non-informative cues when the target appeared at a cued position (it did for some observers, but not others). Because there were some individual differences, each observer's data will be discussed separately.

3.2. JAS (5.3 cpd)

For JAS, all thresholds estimated for conditions in which the target did not appear at a cued position were significantly higher (0.24 log units, on average) than all thresholds estimated for (non-informative) conditions in which the target did appear at a cued position. The totally valid cue was slightly, but significantly ($\alpha < 0.006$) more effective, lowering threshold a further 0.04 log units.

3.3. CG (5.3 cpd)

CG was less sensitive than JAS. With a single, totally valid cue, she required 57% contrast to identify the target at threshold accuracy, JAS required 37%. When the target did not appear at a cued position, threshold accuracy (i.e. 81% correct) could not be obtained, even at maximum contrast. Consequently, upper bounds on the confidence intervals for these thresholds are very high. Nonetheless, we can be reasonably confident that the non-informative cues effectively lowered threshold ($\alpha < 0.04$).

3.4. CFC (3.7 cpd)

CFC found it relatively easy to see his low-frequency target; with a single, totally valid cue, threshold contrast was just 23%.

3.5. CG (4.1 cpd)

After adjusting the target's spatial frequency, not only did CG's threshold for totally validly cued targets become more similar to JAS's, so did the overall pattern of her results. Like JAS, non-informative cues significantly ($\alpha < 10^{-8}$) lowered threshold (0.24 log units, on average). However, unlike JAS, totally valid cues and non-informative cues produced similar thresholds ($\alpha > 0.6$), as long as the target appeared at a precued position.

3.6. TM (3.7 cpd)

For TM, with non-informative cues, the average 0.3 log unit difference between cued and uncued targets was highly significant ($\alpha < 10^{-5}$). The 0.1 log unit difference between totally valid and non-informative cues just approached significance $\alpha < 0.03$.

3.7. Summary

With just one exception (CG's poorly constrained 5.3-cpd results with 2 cues), thresholds were lower when the target appeared at a cued position. With just one exception (again, CG's 5.3-cpd results), as long as the target appeared at a non-informatively cued position, it did not matter how many cues there were; there was no significant difference in threshold. Totally valid cues produced slightly ($\leqslant 0.1$ log unit) lower thresholds than non-informative cues.

4. Discussion

The observed difference between thresholds for cued and uncued targets confirms previous claims (summarised in Table 1) that direct spatial cueing can heighten visual sensitivity. However, since eight simultaneous, spatially diverse cues are no less effective than a single local cue, this enhancement is likely due to something other than focal attention.

Wright (1994) also used Jonides' (1981) non-informative cueing paradigm and found that RT for a identifying the orientation of a single line segment was reduced whenever it appeared in a precued location, even when eight different locations were precued simultaneously. Together our results suggest that there is no capacity limit for either of the classic precueing effects, namely lower RTs and higher sensitivity.

Consistent with the notion that multiple precues can facilitate processing at multiple positions simultaneously are the previous failures to find evidence of signal enhancement when performance with a single, totally valid precue was compared with performances with multiple precues (Palmer, 1994; Palmer et al., 1993; Solomon, 2002). Totally valid precues did facilitate performance when compared with trials in which either no positions were cued (Carrasco et al., 2000) or target and cue appeared simultaneously (Lu & Dosher, 2000).

Exactly how direct precues lower threshold remains to be determined. In this experiment, their spatiotemporal structure was so dissimilar to that of the target, the possibility that they served as a kind of pedestal, upon which an otherwise undetectable target could exceed a sensory threshold (Nachmias & Sainsbury, 1974), seems remote. In a way, the cueing effect reported here is like the opposite of metacontrast effect (Alpern, 1953), in which the visibility of a briefly flashed, peripheral target is reduced by subsequently flashed, adjacent stimuli.

Similar cueing effects in both the presence and absence of an effectively simultaneously presented noise mask led Lu and Dosher (2000) to conclude that the precue served both to amplify visual signals elicited by the target and attenuate spurious signals elicited by the mask. Both of these feats could be accomplished by simply switching from a relatively poorly suited spatial-frequency (and/or orientation) channel, to one more appropriate for the task. Postmasks, unlike simultaneous masks, can also be ignored with suitable temporal filtering. Perhaps precues can also help with that.

Acknowledgements

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Appendix A

In order to compute the cueing effect shown in the fourth column of Table 1 from studies reporting percent correct, Eq. (1) needs to be re-parameterised and inverted. Let

$$\Psi'(t_0; t, \beta) = \Psi(t; t_0, \beta). \tag{A.1}$$

Then

$$\Delta \log t_0 = \log \frac{\Psi'^{-1}(p; t_p, \beta)}{\Psi'^{-1}(q; t_q, \beta)}, \tag{A.2}$$

where p and q are the percents correct for uncued and cued targets, respectively, and t_p and t_q are the corresponding target intensities. Frequently, $t_q = t_p$ and, with no loss of generality, Eq. (A.2) can be re-written:

$$\Delta \log t_0 = \log \frac{\Psi'^{-1}(p; 1, \beta)}{\Psi'^{-1}(q; 1, \beta)}. \tag{A.2$'$}$$

β was estimated from psychometric functions whenever they were provided, but frequently such data were not provided and I was forced to guess. When target visibility was not limited by any mask, I adopted Robson and Graham's (1981) best guess: $\beta = 3.5$. When target visibility is limited by a noise mask, psychometric functions for detection are typically flatter, being consistent with the simplest form of Signal Detection Theory, i.e. one without intrinsic uncertainty or non-linear transduction (Pelli, 1990). The psychometric function predicted by this simple SDT can be closely matched by the Weibull function when $\beta = 1.33$. Thus, whenever any noise mask (simultaneous or backward) was used, in order to summarise the results with the largest possible cueing effect, I assumed the lowest reasonable value for β, i.e. $\beta = 1.33$.

Since $P(A)$ for a yes–no task should equal $P(C)$ for an otherwise-identical two-alternative forced-choice task (Green & Swets, 1966), the procedure described above was also used for the studies that reported $P(A)$ instead of $P(C)$.

Finally, where necessary, d' was converted into two-alternative forced-choice $P(C)$ for use in Eq. (A.2):

$$P(C) = \int_{-\infty}^{\infty} g(x - d')G(x)\,\mathrm{d}x, \tag{A.3}$$

where

$$g(x) = \sqrt{1/2\pi}\exp(-x^2/2) \tag{A.4}$$

and

$$G(x) = \int_{-\infty}^{x} g(u)\,\mathrm{d}u. \tag{A.5}$$

A Mathematica notebook (Wolfram, 1999), containing all of the calculations performed in the construction of Table 1, can be downloaded from http://www.staff.city.ac.uk/~solomon/DeltaLogT0.nb.

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