Contrast discrimination function: spatial cuing effects

Joshua A. Solomon

Institute of Ophthalmology, Bath Street, London, EC1V 9EL, UK

Nilli Lavie

Department of Psychology, University College London, Gower Street, London, WC1E 6BT, UK

Michael J. Morgan

Institute of Ophthalmology, Bath Street, London, EC1V 9EL, UK

Received October 30, 1996; revised manuscript received February 12, 1997; accepted February 13, 1997

The effects of spatial cuing were measured for discriminating between an increment and a decrement on a target's pedestal contrast. Discrimination thresholds measured in the absence of a spatial cue were always higher than corresponding thresholds measured in the presence of a spatial cue, except when pedestal contrast was near zero. Uncued discrimination thresholds rose monotonically with pedestal contrast; cued discrimination thresholds formed a dipper function of pedestal contrast. A spatial-uncertainty model incorporating a nonlinear transducer produced similar results. © 1997 Optical Society of America [S0740-3232(97)00609-1]

1. INTRODUCTION

A popular method for investigating the effect of attention on visual sensitivity is to measure the effect of a spatial cue (indicating the probable location of the target) on the detectability of simple luminance increments[1–5] or gratings.[6] Most of these studies indicate that spatial cuing can influence detection,[1–4,6] yet the cuing effect on detection is small compared with similarly obtained cuing effects for line length,[5] orientation, and form discriminations.[2] In such experiments, a target at one location is to be discriminated from distractors at other locations. A critical difference between detection and discrimination experiments is that just-detectable (threshold) stimuli are used in the former and easily detectable (suprathreshold) stimuli are used in the latter. Below we describe a contrast discrimination experiment in which the contrast of the distractors was systematically varied. This technique allows us to show that the effect of spatial cuing changes as the detectability of the distractors changes.

An important issue in the cuing literature is whether cuing effects can be attributed solely to a reduction in spatial uncertainty.[2–8] That is, a spatial cue is expected to improve performance because it enables observers to ignore irrelevant information from uncued locations. However, it is conceivable that a cuing effect could be so large as to imply a perceptual capacity limitation. For example, visual information may be less precise without a cue than with a cue. Below we demonstrate that no such capacity limitations are necessary to explain our results.

2. METHODS

A. Observers and Apparatus

The first author served as an observer. The other two observers were naïve. All had normal or corrected-to-normal vision. Stimuli were displayed with gamma correction on a monochrome cathode-ray tube in a dark room. Maximum and minimum display luminances were 54 and < 0.05 cd m^{-2}, respectively. The stimuli on the video were displayed with a surround of 27 cd m^{-2}, and the frame rate was 66.7 Hz. Display resolution was 30.3 pixels/cm. Observers viewed the screen from 43.1 cm, resulting in an effective visual resolution of 22.8 pixels/deg. The PSYCHOPHYSICA/CINEMATICA[9,10] software used in these experiments is available on the internet at http://vision.arc.nasa.gov/mathematica/psychophysica.html.

B. Stimuli

Targets and distractors were Gaussian blobs with a half-height diameter of 0.56 deg. These blobs appeared in four positions, each ±3.5 deg above ±3.5 deg to the right of fixation. The spatial cue was a black line, 1 pixel wide, extending from fixation to the nearest spot 2.2 deg from the center of the target. In the uncued condition, all four possible lines were displayed. A sample stimulus in the uncued condition is shown in Fig. 1.

C. Procedure

When ready, the observer pushed a key to initiate the trial sequence: The fixation spot (1 black pixel) was re-

0740-3232/97/0902443-06$10.00

2. *Bias*

Just as the slope of the psychometric function provides a measure of the observer's sensitivity, the mean of the psychometric function provides a measure of the observer's bias. Bias is the target contrast at which "brighter" and "darker" responses are equally likely (specifically, the mean of the fitted psychometric function) minus the pedestal contrast. Biases are plotted in Fig. 3.

On the one hand, when the pedestal contrast is zero, most observers respond without bias. On the other hand, all the observers show biases for most other pedestal contrasts. However, there does not seem to be any systematic pattern of bias across all the observers. JAS's biases are roughly monotonic with pedestal contrast, as are CP's cued biases. CP and SB's uncued biases are generally negative, regardless of the sign of pedestal contrast. SB's cued biases seem to be almost random.

B. Experiment 2

Results of subsequent related experiments (not included here) suggested that SB's sensitivity was improving. To confirm that the results that we report here are robust to practice, we elected to rerun the experiment. Moreover, we wanted to better investigate the apparently qualitative difference between cued and uncued discrimination. Thus, in experiment 2, we used pedestals of low contrast magnitude.

Between experiments 1 and 2, JAS and SB had a considerable amount of practice doing similar tasks. CP had no practice between experiments 1 and 2. As in experiment 1, CP completed two series; staircases begun in the first series were resumed in the second. For JAS and SB, who completed three series each, staircases were begun anew each session.

1. *Sensitivity*

Discrimination thresholds are plotted in Fig. 4.

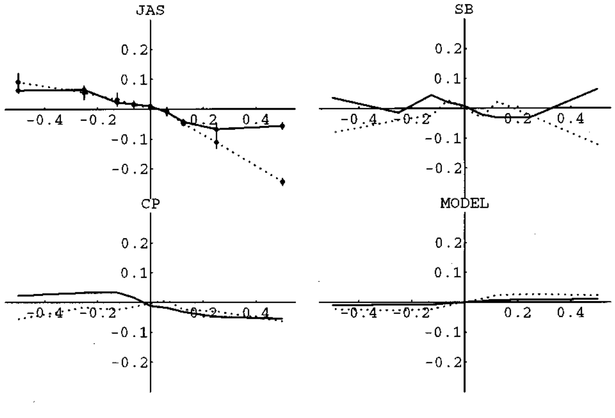

Fig. 3. Biases for cued (solid curves) and uncued (dotted curves) targets. Biases are plotted as functions of pedestal contrast. Standard errors are shown for observer JAS. A nonzero bias for nonzero pedestals is predicted by the model (lower right). This is a consequence of fitting a cumulative Gaussian to its non-Gaussian psychometric function.

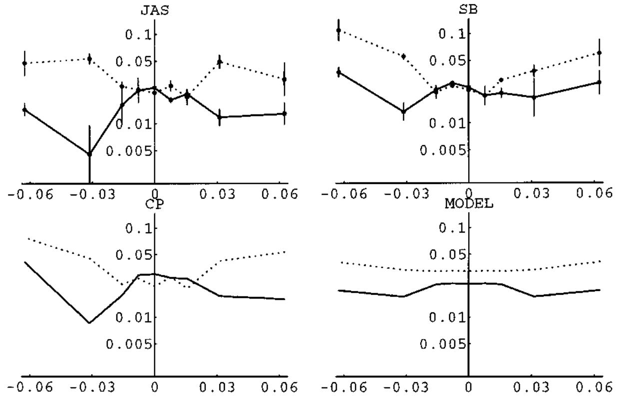

Fig. 4. Discrimination functions for cued (solid curves) and uncued (dotted curves) targets. Thresholds are plotted as functions of pedestal contrast. Uncued discrimination thresholds are always higher than corresponding cued discrimination thresholds, except when pedestal contrast is between −1/64 and +1/64. Cued discrimination functions dip, particularly at pedestal contrast of ±1/32. Uncued discrimination functions do not dip significantly. Standard errors are shown for observers JAS and SB. A spatial-uncertainty model incorporating a nonlinear transducer produces results (lower right) that are similar to those of our human observers.

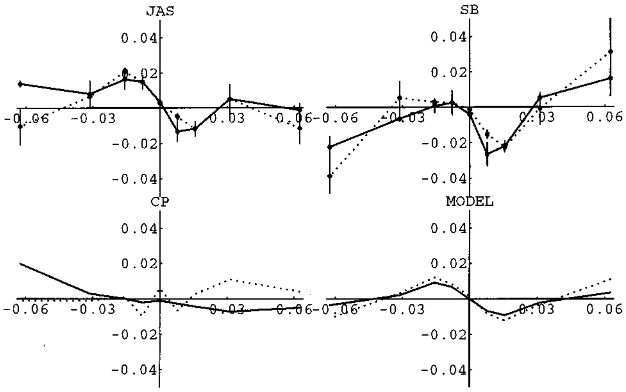

Fig. 5. Biases for cued (solid curves) and uncued (dotted curves) targets. Biases are plotted as functions of pedestal contrast. Standard errors are shown for observers JAS and SB. A nonzero bias for nonzero pedestal is predicted by the model (lower right). This is a consequence of fitting a cumulative Gaussian to its non-Gaussian psychometric function.

Practice has made SB's overall sensitivity similar to that of the other observers. He no longer shows a cuing effect with zero-contrast pedestals. In fact, for all three observers, cued and uncued thresholds are similar for pedestal contrasts between −1/64 and +1/64. Cued thresholds are lowest when the pedestal contrast is −1/32. The results of experiment 2 confirm that discrimination functions for cued and uncued targets are not merely translations of one another. They really have different shapes: The cued one dips; the uncued one does not.

2. *Bias*

Biases are plotted in Fig. 5.

As before, when pedestal contrast is zero, all the observers generally respond without bias. The only exception is CP's uncued threshold. Also, as before, CP's cued biases are nearly monotonic with pedestal contrast. JAS's and SB's biases are decidedly nonmonotonic with threshold contrast. Both cued and uncued biases increase as pedestal contrast is raised to approximately -0.015, then biases decrease as pedestal contrast is raised to approximately $+0.015$ (passing through zero for zero-contrast pedestals), and then they increase again.

4. MODEL

A. Nonlinear Transducer

An important aspect of our data is that thresholds are similar for similar contrast magnitudes. That is, contrast discrimination functions are nearly symmetric about the axis of zero-contrast pedestals (however, see Subsection 5.B below). This result supports the notion that discrimination is limited by noise arising after contrast transduction. This idea can be directly applied to our cued discrimination data. Simply stated, we shall assume that the observer makes a noisy comparison between the transduced target contrast and the transduced pedestal contrast. More formally,

$$\Psi = P[f(x + \Delta x) + \eta - f(x) > 0], \tag{1}$$

where Ψ is the observed frequency of a "brighter" response, x is the pedestal contrast, $x + \Delta x$ is the target contrast, $f(x)$ is the transducer, and η is a random variable. Traditionally, a nonlinear transducer is employed to explain contrast discrimination results.[12,13] For the simulation shown in Figs. 2 and 4, $\eta \sim N(0, 1)$, and

$$f(x) = \frac{a\ \mathrm{sgn}(x)|x|^p}{|x|^q + b^q}. \tag{2}$$

This nonlinearity is of the form favored by Foley.[14] For the simulation shown in Figs. 2–6, $a = 13.0$, $b = 0.0364$, $p = 2.89$, and $q = 2.49$. This model predicts a somewhat bumpy psychometric function (see Fig. 6). Our data set is not sufficiently rich to directly confirm this prediction.

Note that since our trials are blocked by pedestal contrast, the observer need not compare a transduced target contrast with transduced pedestal contrasts from the same trial. We may assume that the observer has seen enough distractors to accurately formulate the expected transduction of pedestal contrast and compares each target with this expectation.

B. Spatial Uncertainty

In the uncued condition the ideal strategy is to compare the noisily transduced contrasts of all four potential targets with the expected transduction of the pedestal contrast. Note that this comparison could be done for all potential targets individually, or the contrasts of all four targets could be pooled (somehow) prior to transduction. We shall ignore the latter possibility and make the conventional assumption that each potential target's transduced contrast is perturbed independently by the same noise that limits cued discriminations. This is an important assumption. It means that the cue effects performance solely by indicating to the observer which three locations can be ignored. To complete the model, we propose that the observer's response is determined by a Minkowski sum of the noisy comparisons. Specifically,

$$\Psi = P\left\{ \mathrm{sgn}[f(x + \Delta x) + \eta_1 - f(x)]|f(x + \Delta x) + \eta_1 - f(x)|^\beta + \sum_{i=2}^{N} \mathrm{sgn}(\eta_i)|\eta_i|^\beta > 0 \right\}, \tag{3}$$

where N is the number of potential target locations (four in our uncued condition). If $\beta = 1$ then responses will depend on the sign of the (linear) sum of all N discrepancies. For large β, responses will depend on only the largest discrepancies. By allowing β to vary, a range of intermediate combination strategies can be produced. For the simulation shown in Fig. 2, $\eta_i \sim N(0, 1) \forall i$ and $\beta = 2$.

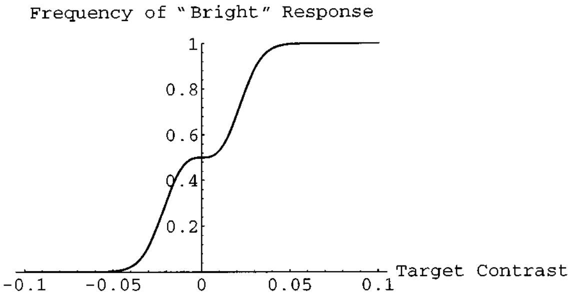

Fig. 6. Theoretical psychometric function for cued discrimination with pedestal contrast equal to 0. The nonlinear transduction model predicts that the psychometric function will have three inflection points when the pedestal contrast is near zero.

A nonlinear transducer model will produce dipper-shaped discrimination functions only when the variance of the noise is small compared with the range of the accelerating portion of the nonlinearity. Because of spatial uncertainty, the total variance of the noise increases as the number of potential target locations increases. In the model, the criterion for dipper production is met when the number of potential target locations is one (i.e., the cued condition). It is not met when the number of potential target locations is four.

C. Capacity Limitations

It is possible that human observers cannot make four comparisons as easily as they can make one. For example, suppose that comparison is a serial process. It is possible that only one or two may be carried out before all the potential targets (or the memories thereof) disappear. Alternatively, it is possible that four comparisons can be made in parallel, but not with the same precision afforded a single comparison. A capacity limitation such as this could be modeled by an increase in the variance of the η_i's in Eq. (3). Yet the spatial-uncertainty model alone provides a satisfactory description of our results without a capacity-limiting modification. In this respect our results are in accordance with those of Palmer and colleagues, who found that a spatial-uncertainty model alone could account for cuing effects in a variety of discrimination tasks,[7,8] including contrast discrimination (one pedestal contrast was tested).[8]

5. DISCUSSION

A. Other Increment/Decrement–Discrimination Studies

Most contemporary contrast discrimination studies employ a two-interval forced-choice procedure. Such studies often produce threshold curves that dip when the pedestal is near its detection threshold.[12,14–22] Although we did not explicitly measure detection thresholds, our cued discrimination functions dip at contrasts of ±1/32. Observers' reports suggest that these contrasts are in fact quite close to detection threshold.

We know of only two studies apart from our own in which observers were required to determine whether a briefly flashed target was brighter or darker than the adapting luminance. Both are discussed below. We know of no studies apart from our own in which observers were required to determine whether a target was brighter or darker than a pedestal different from the adapting luminance (i.e., a non-zero-contrast pedestal).

Krauskopf[23,24] reports increment/decrement–discrimination thresholds and proposes the following model: A linear filter with a biphasic temporal impulse response is applied to the target. If the filter's output exceeds some positive threshold value, the observer responds "brighter." If the filter's output exceeds some negative threshold value, the observer responds "darker." Noise perturbs the filter's output so that sometimes the wrong threshold is exceeded. Thus, when a low-contrast flash exceeds the wrong threshold, it will be detected but incorrectly identified. This model is appealing because it explains why detection thresholds can be lower than discrimination thresholds, but this model is not sufficiently specified to make absolute quantitative predictions. Specifically, it is not clear what happens when both thresholds are exceeded, as is certainly the case even for zero-contrast pedestals.

While Bonnel *et al.* do not report thresholds,[5] they do establish that observers can detect low-contrast flashes at two locations concurrently, with no loss of accuracy compared with detection of low-contrast flashes at a single location. However, when observers are required to judge and to give the response "brighter" or "darker" at two locations concurrently, accuracy suffers as compared with that for a single increment/decrement discrimination. This result, although not a cuing effect (single and concurrent discriminations were run in different blocks), does indicate that uncertainty reduction cannot explain all attentional influence on visual sensitivity.

B. Model Behavior

We have assigned values to the parameters of our model that provide a reasonable fit to all our results. Like the human observers, the model produces cued discrimination functions that dip and uncued discrimination functions that do not. Unlike the human observers, the model produces discrimination functions that are exactly symmetric about the axis of zero-contrast pedestals. While most of the asymmetry of the humans' data appears to be unsystematic, all three observers showed maximum sensitivity with dark pedestals (contrast, $-1/32$).

Our human observers' uncued thresholds were greater than their corresponding cued thresholds, except with near-zero pedestals. In these situations, when the distractors were invisible, cuing effects were variable. JAS never showed a cuing effect with zero-contrast pedestals. CP and SB did in experiment 1, but not in experiment 2. This is reminiscent of documented cuing effects for detection. Often such cuing effects were found,[1–4,6] but sometimes they were not.[5]

The model's uncued thresholds are greater than its corresponding cued thresholds for all the pedestals. The difference between the model's cued and uncued thresholds for zero-contrast pedestals varies inversely with the parameter β. By setting $\beta = 2$, we produce a moderate cuing effect for near-zero pedestals (uncued threshold is 37% higher than the corresponding cued threshold).

Outside the dipper region, the shape of the contrast discrimination function is largely determined by the difference between p and q. We set this difference to be 0.4 (as suggested by the results from Foley's observer KMF[14]) and selected a value for p that provided our data with a reasonable fit. Our value of 2.89 is comparable with the value of 2.72 that describes the data obtained from Foley's KMF. Results from Foley's other observer were fitted with $p = 2.55$ and $q = 2.18$.

Let χ represent pedestal contrast. In experiment 1, when $|\chi| \geqslant 1/16$, our relatively inexperienced observers produced biases that are large in comparison with those produced by the model. In experiment 2, when $|\chi| \leqslant 1/16$, our highly practiced observers (SB and JAS) produced biases that were very similar to those produced by the model. The model's bumpy bias plot in Fig. 5 results from fitting non-Gaussian psychometric functions, like the one shown in Fig. 6, with cumulative Gaussians to determine sensitivity and bias. The bias plots of the data from SB and JAS are similarly bumpy.

6. CONCLUSION

Our paradigm extends previous research on the cuing effects for the detection of simple luminance increments[1–5] by systematically varying the pedestal contrast in a contrast discrimination task. We found that cuing effects vary nonmonotonically with the detectability of potential targets. In particular, they seem to be maximal when potential targets are near the threshold of visibility. This is the dipper region of the contrast discrimination function for cued targets. As the contrast discrimination function for uncued targets has no dipper region, cuing effects are greatest here. Finally, we have demonstrated that a spatial-uncertainty model incorporating a nonlinear transducer can provide a satisfactory description of our results.

ACKNOWLEDGMENTS

We thank John Palmer and one anonymous reviewer for their helpful comments and support. This study was supported by grant G9408137 from the Medical Research Council (UK).

REFERENCES

1. H. S. Bashinski and V. R. Bacharach, "Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations," Percept. Psychophys. **28**, 241–248 (1980).
2. C. J. Downing, "Expectancy and visual-spatial attention: effects on perceptual quality," J. Exp. Psychol. **14**, 188–202 (1988).

3. H. L. Hawkins, S. A. Hillyard, S. J. Luck, M. Mouloua, C. J. Downing, and D. P. Woodward, “Visual attention modulates signal detectability,” J. Exp. Psychol. **16**, 802–811 (1990).
4. H. J. Muller and G. W. Humphreys, “Luminance-increment detection: capacity-limited or not?” J. Exp. Psychol. **17**, 107–124 (1991).
5. A.-M. Bonnel, J.-F. Stein, and P. Bertucci, “Does attention modulate the perception of luminance changes?” Q. J. Exp. Psychol. **44A**, 601–626 (1992).
6. E. T. Davis, P. Kramer, and N. Graham, “Uncertainty about spatial frequency, spatial position, or contrast of visual patterns,” Percept. Psychophys. **33**, 20–28 (1983).
7. J. Palmer, C. T. Ames, and D. T. Lindsey, “Measuring the effect of attention on simple visual search,” J. Exp. Psychol. **19**, 108–130 (1993).
8. J. Palmer, “Set-size effects in visual search: The effect of attention is independent of the stimulus for simple tasks,” Vision Res. **34**, 1703–1721 (1994).
9. J. A. Solomon and A. B. Watson, “Cinematica: a system for calibrated, Macintosh-driven displays from within Mathematica,” Behav. Res. Methods Instrum. Comput. **28**, 607–610 (1996).
10. A. B. Watson and J. A. Solomon, “Psychophysica: mathematica notebooks for psychophysical experiments,” Perception (to be published).
11. A. B. Watson and D. G. Pelli, “QUEST: a Bayesian adaptive psychometric method,” Percept. Psychophys. **33**, 113–120 (1983).
12. J. Nachmias and R. Sansbury, “Grating contrast: discrimination may be better than detection,” Vision Res. **14**, 1039–1042 (1974).
13. C. F. Stromeyer III and S. Klein, “Spatial frequency channels in human vision as asymmetric (edge) mechanisms,” Vision Res. **14**, 1409–1420 (1974).
14. J. M. Foley, “Human luminance pattern mechanisms: masking experiments require a new model,” J. Opt. Soc. Am. A **11**, 1710–1719 (1994).
15. F. W. Campbell and J. J. Kulikowski, “Orientation selectivity of the human visual system,” J. Physiol. (London) **187**, 437–445 (1966).
16. G. E. Legge and J. M. Foley, “Contrast masking in human vision,” J. Opt. Soc. Am. **70**, 1458–1471 (1980).
17. A. Bradley and I. Ohzawa, “A comparison of contrast detection and discrimination,” Vision Res. **26**, 991–997 (1986).
18. J. Ross and H. D. Speed, “Contrast adaptation and contrast masking in human vision,” Proc. R. Soc. London **246**, 61–69 (1991).
19. J. M. Foley and G. M. Boynton, “Forward pattern masking and adaptation: effects of duration, interstimulus interval, contrast, and spatial and temporal frequency,” Vision Res. **33**, 959–980 (1993).
20. J. M. Foley and G. M. Boynton, “A new model of human luminance pattern vision mechanisms: analysis of the effects of pattern orientation, spatial phase and temporal frequency,” in *Computational Vision Based on Neurobiology*, T. B. Lawson, ed., Proc. SPIE **2054**, 32–42 (1993).
21. J. Ross, H. D. Speed, and M. J. Morgan, “The effects of adaptation and masking on incremental thresholds for contrast,” Vision Res. **33**, 2051–2056 (1993).
22. J. Yang and W. Makous, “Modeling pedestal experiments with amplitude instead of contrast,” Vision Res. **35**, 1979–1989 (1995).
23. J. Krauskopf, “Discrimination and detection of changes in luminance,” Vision Res. **20**, 671–677 (1980).
24. Krauskopf’s measurements are comparable with ours. He reports the contrast magnitude necessary for 75% correct discrimination. For flashes with a roughly 30-ms duration and a 225-cd/m^2 surround, his two observers’ thresholds were roughly 0.039 and 0.045, respectively. Inferring from the fitted psychometric functions, JAS’s, CP’s, and SB’s 75% correct thresholds for cued discrimination were 0.020, 0.015, and 0.13, respectively, in experiment 1 and 0.017, 0.020, and 0.017, respectively, in experiment 2.