Flash masking and facilitation by nearby luminance perturbations

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Received June 29, 1998; revised manuscript received November 9, 1998; accepted November 12, 1998

Light-adapted foveal luminance increment thresholds were measured for white photopic targets of 1.5-arc min diameter and 220-ms duration. We aimed to learn about the properties of mechanisms that subserve the detection of these targets. To study this subject we developed a noise probe technique that inserts noise close to the site of the stimulus. Threshold is more than doubled when zero-mean luminance noise is placed at a pair of flanking spots in the horizontal meridian centered on the test spot and 1.5 arc min distant. The detection mechanism thus has a broad field, since noise effects persist at 5-arc min separation. The masking effect increases when the noise is in antiphase at the two flanking spots. Neither even- nor odd-symmetric mechanisms are able to explain these findings, regardless of whether linear or nonlinear processing is employed. The target detection may be mediated in part by a motion-sensitive mechanism. © 1999 Optical Society of America [S0740-3232(99)03003-3]

OCIS codes: 330.1800, 330.1880, 330.4190, 330.5510, 330.6790, 330.6110.

1. INTRODUCTION

Despite considerable contemporary progress in defining the variety of mechanisms that subserve human vision, there remains a good deal of uncertainty as to which of these process the classical objects of visual psychophysical regard: uniform contrast, circular test spots. Such targets have played a role throughout the past 200 years of vision research and retain importance in applied fields such as visual perimetry.

We have been interested in understanding the rules by which detection mechanisms sensitive to spots sum signals in their field of view, as one step in understanding their properties.[1] What makes this objective difficult to reach is that a variety of disparate phenomena can, in some circumstances, masquerade as summation effects. For example, Chen *et al.*[2] showed that gain change can be confounded with a grain change. Uncertainty can mimic a summation change,[3] and the nature of the noise-limiting performance can also cause effects that appear to be, but are not, summation effects.[4] Each of these effects is profoundly influenced by adaptation level, and the obvious stimulus manipulations (e.g., neighboring mask stimuli) affect adaptation level. To circumvent these problems it has been necessary to find stimulus conditions in which adaptation level does not vary with stimulus manipulations. A necessary though not sufficient condition for this is that integrated luminance falling in the supposed receptive field be unchanged.

In this paper we report on experiments that utilize nearby luminance noise probes to mask a small, brief foveal detection target. By placing the noise probe close to the target, we hoped to examine the properties of the mechanism that signals the target. This rationale assumes that the effects of the noise probe and the target are felt in the same mechanism. Thus the approach may be viewed as distinct from, though logically similar to, peripheral effect studies.[5] In the latter no attempt is made to introduce sensitivity-changing peripheral stimuli to the same mechanism as is devoted to coding the target. The measured effects of these noise probes that we employ allow us to reject a number of rather simple schemes by which signals in the receptive field are summed. They lead instead to a rather surprising hypothesis, that detection of these nonmoving targets is mediated in part by mechanisms sensitive to motion.

2. METHODS

A. Noise Probe

The unique feature of these experiments is a luminance noise probe placed symmetrically on either side of a foveal test spot. The noise probe and test spot locations are marked by equal luminance, equal size, equally spaced spots, either 100 or 64 in number, that occupy fixed positions in the horizontal meridian across the fovea of a subject who fixates the center spot. This geometry is illustrated in Fig. 1. The central fixation spot is marked by a pair of vertically oriented fiducial black lines and is also the location of the luminance increment target to be detected. Spots are 1.5 arc min in diameter and are separated by 1.5 arc min. The noise probe is a zero-mean luminance fluctuation, drawn from a Gaussian distribution and added to the background, that appears at a pair of flanking spots equally spaced from the target spot and illuminated to the same mean level as the target spot. We tested only locations from one to five spots removed from the test, so the noise is between 1.5 and 7.5 arc min distant. One of the rationales for this arrangement is that it allows us to inject a masking stimulus near the target

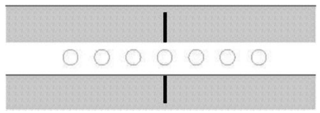

Fig. 1. Schematic representation of target plane. A horizontal array of luminous spots separated by 1.5 or 2.3 arc min is fixed in the field of view. The center (fixation) spot is marked by fiducial lines. Stimuli to be detected are brief luminance changes at the center spot. A pair of flanking spots, equidistant from the center spot, is selected as the locus of luminance perturbation in a given run.

without altering the local adaptation conditions. If the mask is effective, it must have entered the mechanism responsible for detection of the target, and the way in which this transpires supplies clues as to the identity and constitution of such a mechanism or mechanisms.

There were three noise conditions (no noise, identical noise at the two spots, and antiphase noise at the two spots), and these were present in randomly interleaved staircases throughout the runs. For most of our tests the noise had an amplitude that rendered it highly visible, corresponding to a modulation of approximately 25%. The noise was turned on 55 ms before the stimulus interval and was sampled every 11 ms.

B. Stimuli

Stimuli were square-pulse luminance changes lasting 220 ms at the test spot. Targets were generated on a Hewlett-Packard CRT display (Model 1332) driven by two waveform generators (Quatech Model WSB 10) controlled from a PC–AT-compatible computer. Spot luminance was roughly 1000 cd m^{-2}, while the surround, a white paper sheet illuminated by incandescent light, was approximately 10 cd m^{-2}.

C. Subjects

Subjects were fully corrected and ranged in age from 21 to 48. Two were familiar with the purpose and rationale of the experiments, and two were not. Viewing distance was 2.28 m. Viewing was binocular with natural pupils.

D. Procedure

Subjects adapted to the display for approximately 1 min before commencing runs. Runs were set to estimate the luminance increment required for producing 84% correct in a two-temporal-interval forced-choice experiment that used a standard staircase. Stimulus intervals of the test lasted 220 ms and were separated by 275 ms. They were initiated by the subject. The parameters of the staircase included five initial practice (unscored) trials, audible feedback, six reversals, and a minimum step size of 2%. In most runs the separation of noise probe from test spot was fixed. Runs contained at least three randomly interleaved staircases, one for a control condition of no noise probe and two others for the two different noise conditions.

3. RESULTS

A. Experiment 1: Effect of Flanking Perturbation

In the first experiment we examined the nature of the masking supplied by the noise probe as a function of the separation of the probe from the test spot. For every separation between noise probe and target that we tested, ranging from 1.5 to 9.2 arc min, the noise masks the central target as evidenced by an increased threshold on noise trials. We estimated thresholds for noise at spots ranging from 1.5 to 9.2 arc min separation from the test. Results are shown in Fig. 2, where we plot threshold on the ordinate versus separation of noise probes from the test spot on the abscissa. Noise raises threshold of the adjacent test spot by as much as a factor of 3. The effect operates over relatively small distances, showing a maximum influence at separations of 2–3-arc min and dying away at approximately 7-arc min separation. That there is any effect on threshold, coupled with a very limited range of spatial separation over which this occurs, suggests that the noise we injected affects the mechanism responsible for the detection of the spot. Two other effects, not shown here, may be mentioned. First, the noise raises the variability of the threshold estimates by at least a factor of 10, and, second, it flattens the frequency-of-seen functions. Taken together, these findings plus the zero-mean nature of the noise suggest that the noise affects the mechanism(s) responsible for the detection of the test spot by directly entering into it and not, for example, by a light-adaptation effect. Presumably, this mechanism has a response profile comparable in width to the profile of the response function shown in Fig. 2.

These data allow one to draw inferences about the nature of (one of) the mechanism(s) mediating the detection of the test spot. The large threshold raising effect of the noise in the in-phase condition shown in Fig. 2 rules out a single linear odd-symmetric channel, because in that scheme noise effects should cancel. Take the next most immediately appealing possibility, a single linear even-symmetric channel centered on the test spot. Noise operates through the flanking zones on the basis of this hypothesis. But this hypothesis can be ruled out by a simple test. We introduce phase-reversed noise at one of

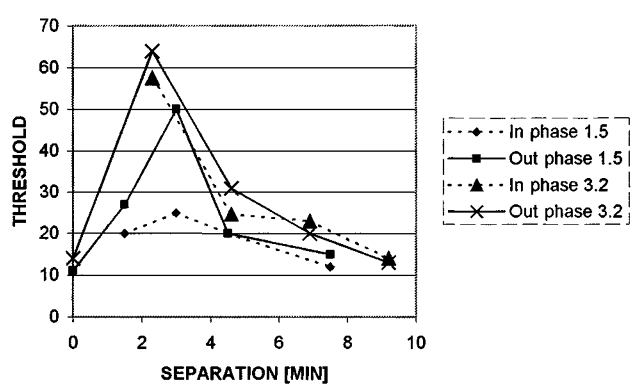

Fig. 2. Threshold (ordinate) versus flank separation (abscissa) for two subjects. Points are averages from several runs. Two different noise conditions are plotted separately. In-phase noise refers to identical waveforms at the two flanking spots. Out-phase noise refers to the case in which the waveform at one spot is inverted with respect to that at the other. Thresholds plotted as out-phase noise at zero separation are the no-noise thresholds. These data are obtained in threshold determination runs with noise and no-noise conditions randomly interleaved. Differences between thresholds at in-phase and out-phase noise reach significance, even for a single observer (e.g., $p < 0.001$—t-test—for the pair at 3-arc min separation).

the probe spots. This is identified as the out-phase noise condition in Fig. 2. We expect no threshold change in a single even-symmetric mechanism, because the noise probes should sum to zero. Referring to Fig. 2, we can see that the threshold curves for both noise conditions are large and nearly the same. This result rules out an even-symmetric mechanism.

This result also rules out a unimodal response mechanism and a scattered-light explanation, because in those models the out-phase noise probes would tend to cancel, leading to lesser thresholds than for the in-phase case. Finally, if the observer has both odd- and even-symmetric filters at his disposal, one or the other of these should enable sensitive detection whichever type of noise is present, contrary to our results. In Section 4 we take up a variety of additional candidate single-element mechanisms and point out that none can explain these data.

B. Experiment 2: Pedestal Test

One hypothesis[6] for the effect that we observed is that uncertainty may be enhanced by the noise, thus distracting the observer and leading to a threshold increase without ever having affected the distal mechanisms responsible for detection of the target. To test this idea we performed an experiment in which target spots appeared superimposed atop luminance pedestals (of the same geometry and time course), which should minimize uncertainty, should any exist.[7] Pedestals equal to threshold and equal to twice threshold were tried. The efficacy of the pedestal is illustrated in Fig. 3, where threshold as a function of pedestal contrast is displayed. This dipper function is typical of pedestal effects and establishes an appropriate contrast for minimizing uncertainty. We tested three subjects. Table 1 lists results for three subjects at two amplitudes of pedestal. When the pedestal is approximately equal to the noise-free threshold, threshold declines. But the effect of the noise probe is not extinguished in the presence of the pedestal, and thus there appears to be no basis on which to ascribe this effect of the noise to uncertainty.

C. Experiment 3: Subthreshold Summation Test

If it is true that the noise probes raise threshold by exerting their influence on the mechanisms responsible for detection, then it follows that helper stimuli at those flanking locations should lower threshold. We therefore performed a subthreshold summation test in which a deterministic luminance change of approximately one half threshold, contemporaneous with the target, is presented at each of a pair of the flanking spots. We tried this test with both an in-phase companion stimulus (a pair of increments) and an out-phase companion (an increment–decrement pair). Both conditions were randomized in a given run with a third condition involving no flanking stimulus. Spacing was 1.5 arc min. Results are summarized in Table 2. For three subjects the in-phase pair always raised threshold, while for one a very slight decrease was shown. The former is a familiar finding[8] of inhibition for closely spaced stimuli in the fovea.

What is not expected is the result for the out-phase pair. These subthreshold flanking spots would sum to zero in a broad-field mechanism and hence would seem, in advance, to be of little use in lowering threshold for the target. All four of our subjects show a reduction of the threshold in the presence of the out-phase pair as compared with the no-flank threshold. This result accords with the out-phase flanking noise result of experiment 1. Figure 2 reveals that out-phase noise gave slightly higher (and in some cases significantly higher) thresholds than did in-phase noise in that experiment. In Table 3 we present a comparison of the findings from experiment 1 at a separation of 3 arc min for out-phase versus in-phase noise for four subjects. In every case the out-phase noise more strongly masks the target stimulus. A weighted average of these results shows that the out-phase noise

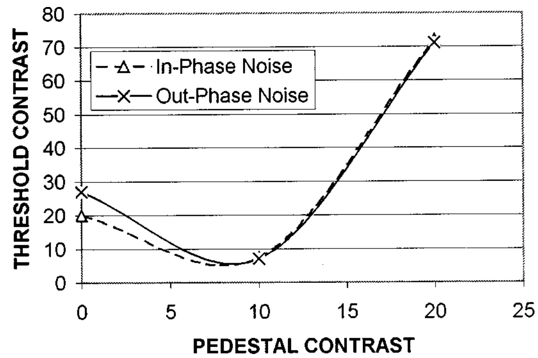

Fig. 3. Threshold (ordinate) versus pedestal contrast (abscissa). The no-noise threshold for this subject is approximately 10. A pedestal of 10 markedly lowers the threshold, while increasing it to 20 raises threshold from the no-noise condition. Subject, TC.

Table 1. Thresholds on a Pedestal at the Target Spot

		Noise Type		
Pedestal Amplitude	Subject	In Phase	Out Phase	No Noise
10	TC	7.5	7.1	3.3
10	SH	31.6	17.3	2.82
20	TC	72.3	70.6	51.4
20	SH	122.0	198.6	33.7
20	LP	45.1	59.5	30.4

Table 2. Thresholds for Subthreshold Summation at 1.5-arc min Separation

	Flank Stimulus on Background		
Subject	Increment–Increment	Decrement–Increment	None
SM	10.10	7.00	8.40
DM	8.80	6.60	8.60
TC	9.40	7.50	7.60
TC	30.50	17.10	—
SH	11.60	8.10	12.10
SH	11.50	11.20	12.10
Unweighted average	13.70[a]	9.60[a]	9.80

[a] $p < 0.02$, binomial test.

Table 3. Threshold for 3-arc min Separation

Subject	Runs	Noise Type: In Phase	Noise Type: Out Phase
SM	6	18.50	30.00
TC	9	16.60	23.70
DW	3	11.30	22.60
HS	2	10.20	12.20
TC	4	20.30	34.40
DM	4	34.40	55.00
Weighted average		19.10	30.10

causes more than a 50% threshold increase as compared with the in-phase noise. This set of results is incompatible with a large variety of single-element mechanisms; it also supplies intriguing clues as to what mechanism might be used by our subjects to detect these luminance increment stimuli.

4. DISCUSSION

We have shown that luminance noise placed symmetrically about and nearby a test spot raises the threshold for luminance change at that spot. The most striking results, however, are that out-phase noise is a better masker than in-phase noise (experiment 1) and that an opposite-phase helper is more effective than an in-phase helper (experiment 3). A pedestal test (experiment 2) rejects the possibility that uncertainty explains our finding of a noise effect. We can easily reject a number of other possible explanations for this effect because of several unique properties of the noise probe technique.

First, the noise stimulus, being zero mean, cannot contribute its effects by light-adaptation processes, so we can reject the notion that the class of sensitivity-lowering mechanisms based on light adaptation is responsible for the results that we observed.

Second, the noise probe must affect sensitivity by entering into the denominator of the effective signal-to-noise ratio for this task. To see this, consider the alternative. The noise might have led, by virtue of raising general contrast around the test spot, to an attenuation of the target, for example, by a compressive nonlinearity. There are several reasons to reject this idea: Thresholds with noise are as much as three times higher than those without noise. A pronounced compression would be necessary to produce this. Frequency-of-seen functions are shallower, which is indicative of greater noise. Compression would not be expected to affect this. Thresholds are more variable, which is also indicative of greater noise (and not of information loss). A simple contrast-gated compressive nonlinearity would not be expected to depend for its effect on the nature, in-phase or out-phase, of the noise, but the measured effect clearly does. Finally, the effect of the out-phase flanking pedestal (experiment 3), by its increase of general integrated contrast, should also have raised thresholds but instead lowered them.

In addition, the strategy of placing symmetrically positioned noise sources in antiphase near a target at once eliminates uninteresting possibilities such as stray light, defocus, or any of a host of spatial summation-equivalent operations. When noise effects persist in this regimen, the effects point to very meaningful possibilities.

In this discussion we describe the ways in which our results with the noise probe have helped to eliminate a number of other candidate mechanisms for the phenomena under test. We are left with the unexpected hypothesis that, if the detection is mediated by a single mechanism, a motion-sensitive mechanism underlies detection of foveal luminance change.

We considered the following range of additional possible single-mechanism elements in our investigation. Both even- and odd-symmetric receptive field profiles were entertained (reasons for rejecting linear versions of these have been advanced above). We allowed for half- or full-wave rectification either before or after the filter. We then asked qualitatively how in-phase and out-phase noise would be expected to affect threshold. The results of this exercise are shown in Table 4. As may be seen on inspection of the table, only two of these hypothetical mechanisms predict a noise effect with both in- and out-phase noise, and those are even symmetric filters with input rectification of either type. However, neither of these can predict the significant out-phase masking superiority of the sort that we observed (Fig. 2 and Table 2). This does not, of course, exhaust the range of possible models. It would be possible to entertain composite models that employ two or more such filters in parallel. Then one could achieve the result that was sought, by adoption of *ad hoc* assumptions concerning the relative sensitivity of such mechanisms.

Our hypothesis is simpler and deserves to be rejected before more-complex models are examined. It rests both on the surprising finding that out-phase noise is more potent than in-phase noise and on the subjective observation, shared by all our subjects, that the out-phase noise gives an unmistakable sensation of motion oscillating between the noise probe loci and across the target spot. Our out-phase flanking pedestal (helper) stimuli, which lower threshold, likewise give the sensation of directed motion[9] across the test spot. One can imagine a reason that this occurs (for which we are indebted to an anonymous reviewer): Each flanking spot and the target spot may be viewed as containing both leftward and rightward motion energy, balanced such that no net motion is normally visible. On occasion, though, motion energy in one

Table 4. Expected Threshold Effects in Candidate Mechanisms

Symmetry	Rectification: Site	Rectification: Wave Type	Noise Type: In Phase	Noise Type: Out Phase
Odd	Output	Full	None	Large
Odd	Output	Half	None	Large
Odd	Input	Full	None	None
Odd	Input	Half	None	None
Even	Output	Full	Large	None
Even	Output	Half	Some	None
Even	Input	Full	Large	Large
Even	Input	Half	Some	Some

flank will align with that of the test spot, leading to a motion percept, but only in the out-phase case. In the in-phase case those motion energies will go in opposite directions, and in a single-response mechanism they would tend to cancel.

If this is motion, these are apparent motion phenomena, for nothing in the field is moving. Furthermore, this is second-order motion,[10] because no motion energy is present in the out-phase noise mask. Possibly, the mechanism that detects our test spot is sensitive to motion. If so, this is not a mechanism tuned to the classical targets that we employed and which lie at the heart of clinical perimetry. This speculation may also provide a clue to the relatively poor measured quantum efficiency of the fovea to luminance change spot stimuli[11] and to the greater efficiency of the fovea to moving versus stationary stimuli,[12] regardless of whether the retinal image is stabilized[13] or not.[14] It is also consistent with the well-known dependence of vision on fixational eye movements that tend to sweep targets across small portions of the retina.

ACKNOWLEDGMENTS

We thank our subjects, S. Moore, D. Willen, and H. Smallman, for their participation. The study was supported in part by grants from the National Eye Institute to D. I. A. MacLeod (EY-01711) and to T. E. Cohn (EY-07606), by a Core Center grant to R. D. Freeman (EY-03176), and by a Tobacco Related Diseases Research Program grant to T. E. Cohn (6IT-0324).

This study was conducted while T. E. Cohn was a visiting scholar at the University of California, San Diego. He can be reached by e-mail at tecohn@spectacle.berkeley.edu.

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