Surround effects on the shape of the temporal contrast-sensitivity function

Branka Spehar

School of Psychology, University of New South Wales, Sydney, NSW 2052, Australia

Qasim Zaidi

State University of New York, The State College of Optometry, 100 East 24th Street, New York, NY 10010

Received October 23, 1996; revised manuscript received February 10, 1997; accepted February 13, 1997

The shape of the temporal contrast-sensitivity function at low temporal frequencies is sensitive to the relative luminance of the test and the surround. We show that this effect is due to greater sensitivity, in different conditions, either to the internal luminance modulation in the test or to temporal changes in the spatial contrast at the edge of the test. We measured temporal contrast sensitivity in tests at various luminance levels combined with surrounds at levels of higher, lower, or equal luminance as the test; compared the sensitivity for contrast modulation to luminance modulation at different temporal frequencies; and compared temporal contrast sensitivity in uniform and textured surrounds of equal mean luminance. Temporal contrast sensitivity was similar on equiluminant steady and out-of-phase modulating surrounds, indicating that the measured sensitivity for small tests in equiluminant surrounds is based on the detection of the temporal modulation of the spatial contrast at the edge of the test field. For all temporal frequencies, contrast sensitivity decreased as a monotonic function of the absolute magnitude of the Michelson contrast between test and surround. When small test fields of moderate to high intensities are embedded in dark surrounds, the sensitivity at lower spatial frequencies is similar to the sensitivities measured for a large test and may reflect sensitivity for luminance modulation within the test. © 1997 Optical Society of America [S0740-3232(97)00209-3]

Key words: Temporal vision, contrast sensitivity, adaptation, surround effects, crispening effect

1. INTRODUCTION

The temporal contrast-sensitivity function for human observers has been measured with a number of spatial and temporal configurations.[1–5] The shape of this function is affected by the conditions of measurement. In particular, temporal contrast sensitivity at low temporal frequencies is affected by the relative luminance difference between the test and the surround: Temporal contrast sensitivity is low pass on equally luminant surrounds but bandpass on dark surrounds.[3–5] In other words, for low-frequency modulations, the addition of a surround equal in luminance to the average luminance of the test field enhances flicker sensitivity relative to the dark surround condition. In this paper we investigate the cause of this phenomenon.

A number of different explanations have been proposed for this phenomenon. Kelly[6–8] suggested that the sensitivity at low temporal frequencies for small fields might be influenced by the presence of an edge between the flickering field and its surround. He hypothesized that sensitivity to lower frequencies is altered by the high-frequency transient-edge responses resulting from eye movements. However, a number of studies have found no difference in the temporal frequency sensitivity curves obtained under normal and stabilized viewing conditions,[5,9–10] thus refuting Kelly's hypothesis.

Keesey[5] proposed that the sensitivity to low-frequency flicker is mainly determined by the difference of the state of activity of two sets of receptors, those stimulated by the flickering field and those stimulated by the immediate surrounding field. When the two sets of receptors are at the same level of activity, the visual system responds to smaller variations of illuminance than when the activity levels of the two sets of receptors are different. When the activity levels of neighboring receptors are different, an inhibitory interaction develops with a time constant slow enough to modify only the low-frequency response. The magnitude of the inhibitory interactions depends on variables like the magnitude of the illuminance difference.

Taking a different approach, we reasoned as follows: In a center–surround configuration, temporal modulation of the luminance in the central test field also produces temporal changes in the spatial contrast at the edge between the test and the surround. In a particular condition, the measured threshold will reflect either the sensitivity to the luminance modulation inside the test or the sensitivity to the modulation in the edge contrast, whichever is greater. In four experiments we examined various factors that affect these sensitivities. In experiments 1 and 2 we measured temporal contrast sensitivity at various luminance levels combined with surrounds having luminance levels higher than, lower than, or equal to that of the test. In experiment 3 we compared the sensitivity for contrast modulation with luminance modulation at different temporal frequencies. In experiment 4 uniform and textured surrounds were used to determine

0740-3232/97/0902517-09$10.00

whether the pedestal contrast of the test field is based on local contrast or on the average luminance of the surround.

2. EXPERIMENT 1

A. Effect of Surrounding Luminance Levels on Temporal Contrast Sensitivity

In experiment 1 our purpose was to investigate the relationship between temporal contrast sensitivity and the relative luminance of the surround. We measured temporal contrast-sensitivity functions for uniform foveally fixated targets of constant average luminance over a range of surround luminances.

1. *Stimuli*

The test field was a uniform 1° centrally fixated disk with average mean luminance of 25 candelas per square meter (cd/m^2), sinusoidally flickering at 0.25, 0.5, 1.0, or 2.0 Hz. The test field was embedded in three steady spatially uniform surrounds: dark, equiluminant, and light, with luminances of 0, 25.0, and 50 cd/m^2, respectively. The outer radius of the circular surround field subtended 5.5°. For all the conditions in this study, the border of the display was dark.

2. *Equipment*

All stimulus presentation and data collection was computer controlled. Stimuli were displayed on the 14.14° × 10.67° screen of a BARCO 7651 color monitor with a refresh rate of 100 frames/s. Images were generated with a Cambridge Research Systems Video Stimulus Generator 2/3 running in a 90-MHz Pentium-based system. Through the use of 12-bit digital-to-analog converters, after gamma correction the Video Stimulus Generator 2/3 is able to generate 2861 linear levels for each gun. Any 256 combinations of levels of the three guns can be displayed during a single frame. By cycling though precomputed lookup tables we were able to update the entire display each frame. Phosphor chromaticity specifications supplied by BARCO and gamma-corrected linearities of the guns were verified with a Spectra Research Spectra-Scan PR-650 photospectroradiometer. The mean luminance of the screen was equal to 25 cd/m^2.

3. *Procedure*

Observers viewed the display binocularly from a distance of 1.5 m and fixated the center of the monitor. A chin rest was used to stabilize the position of the observer's head. Within a session, between trials, the observers viewed steady time-averaged surround and test configurations. Temporal contrast-sensitivity thresholds were measured with a two-interval forced-choice procedure: In each trial the observer indicated in which of two intervals a test appeared to flicker by pressing buttons. The temporal sequence and the spatial configuration of the stimuli are illustrated in Fig. 1. A double-random staircase procedure was used to estimate threshold contrast sensitivity. Thresholds were taken as the average of 16 transitions. To keep the state of adaptation constant, thresholds for each surround condition were determined in separate experimental sessions. Measurements were made on two color-normal observers, including one of the authors (BS). Observers adapted to the steady time-averaged surround and test configuration for 2 min at the initiation of each session followed by 2 s of readaptation before each trial.

B. Results

Results for two observers are shown in Fig. 2. Sensitivity defined as the inverse of the threshold amplitude is plotted as a function of temporal frequency for different surround conditions. Temporal contrast sensitivity in the dark surround condition falls off at low frequencies, consistent with a bandpass function of the temporal frequency, similar to the earlier results obtained by Kelly[2] and Roufs.[3] In the equal surround condition, temporal contrast sensitivity is higher for almost all the frequencies tested, and there is no drop-off at lower temporal frequencies, similar to the results obtained by Harvey[4] and Keesey.[5] The results of this experiment thus replicate the basic phenomenon reported by other investigators. However, temporal contrast sensitivity in the light surround condition also falls off at low temporal frequencies. This falloff in sensitivity in the light surround condition shows that temporal contrast sensitivity is not a monotonic function of the intensity of the surround, thus clearly ruling out an overall adaptation level hypothesis. The drop-off at low frequencies is greater for the dark surround than for the light surround, even though the absolute luminance difference is equal in the two conditions.

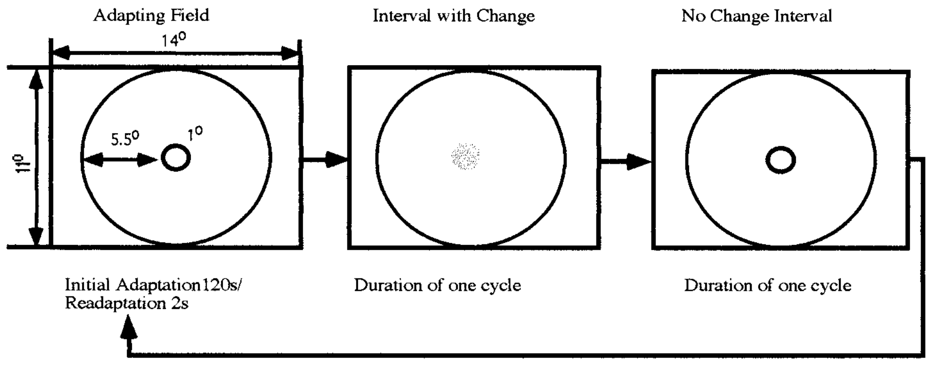

Fig. 1. Schematic representation of the temporal sequence and the spatial configuration of the stimuli used in experiments 1–4.

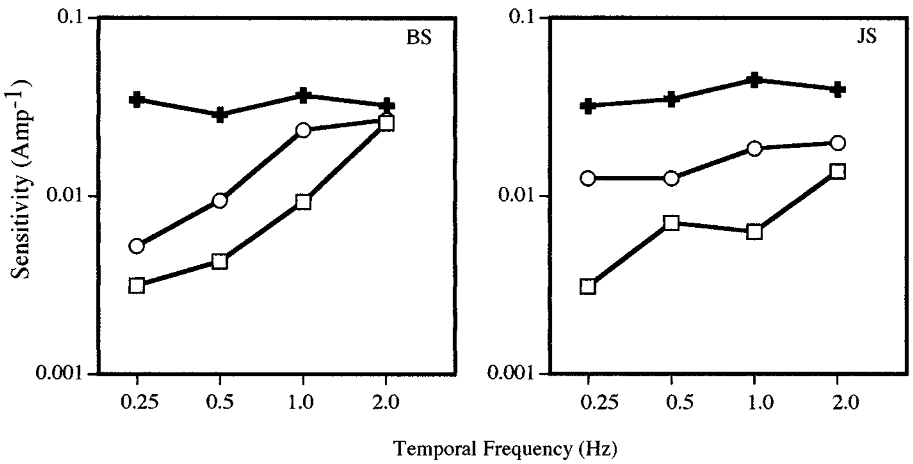

Fig. 2. Results from two observers (BS and JS) in experiment 1. Amplitude sensitivity is plotted as a function of temporal frequency with different surround conditions as curve parameters: squares, 0 cd/m^2 (dark surround); crosses, 25.0 cd/m^2 (equiluminant surround); and circles, 50 cd/m^2 (light surround).

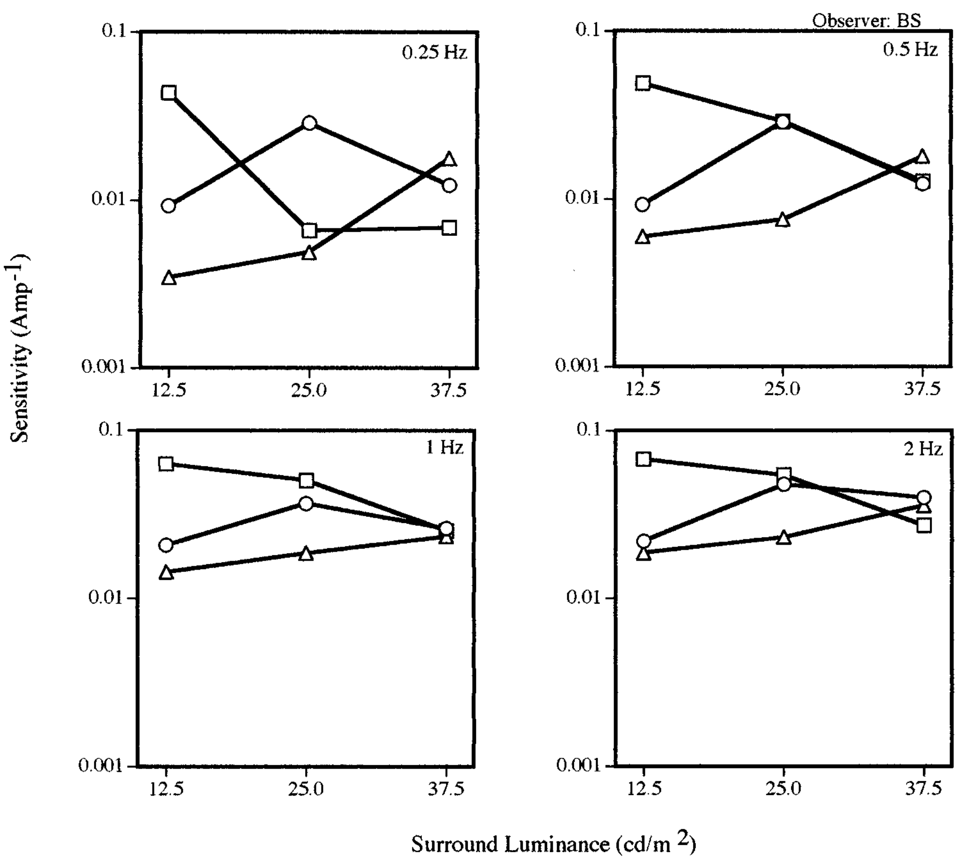

Fig. 3. Results from observer BS in experiment 2. Amplitude sensitivity is plotted as a function of the surround luminance level with the luminance level of the test as a curve parameter: squares, 12.5 cd/m^2; circles, 25.0 cd/m^2, and triangles, 37.5 cd/m^2. Four different panels show amplitude sensitivities at different temporal frequencies.

However, the Michelson contrast between the test and the surround is greater for the dark surround.

3. EXPERIMENT 2

A. Effects of Relative Luminance Levels of Test and Surrounds

To investigate more thoroughly the effects of relative luminance difference between the test and the surround on temporal contrast sensitivity, we performed the following experiment. Test fields of three different mean luminance levels (12.5, 25.0, and 37.5 cd/m^2) were paired with three similar levels of the surround luminance (12.5, 25.0, and 37.5 cd/m^2), respectively. The 3 $\times$ 3 design was repeated at each temporal frequency (0.25, 0.5, 1.0, and 2.0 Hz). The equipment, the experimental procedures, and the other stimuli characteristics were the same as in experiment 1.

B. Results

Results for two observers are shown in Figs. 3 and 4. Sensitivity as the reciprocal of the threshold amplitude is plotted as a function of the surround luminance level with the luminance level of the test as the curve parameter. Four panels show amplitude sensitivities at different temporal frequencies. For both observers and across all the temporal frequencies, temporal contrast sensitivity at each luminance level of the test is the highest when the test and the surround are of equal mean luminance and falls off monotonically with the absolute difference in the average luminance levels between the test and the surround. The one exception out of 72 conditions is one of JS's 2-Hz data points. In conditions in which test average luminance was identical to the surround luminance (i.e., the highest point for each surround luminance), the highest sensitivity was obtained with the test at the lowest luminance level with a monotonic decrease as a function of increasing luminance level of the test. This pattern replicates the finding that the threshold for detecting the temporal modulation in the test increases with the mean luminance level of the test field.[1–3] The novel result, reported here, is the monotonic decrease in the sensitivity at each measured luminance level of test with an increase in the difference between the average luminance level of the test and the surround.

In Figs. 5 and 6 these data are replotted as contrast sensitivity (amplitude sensitivity times test mean) versus the Michelson contrast between the test and the surround. The Michelson contrast between the average test luminance (L_T) and the surround luminance (L_S) was calculated as

$$C = (L_T - L_S)/(L_T + L_S). \qquad (1)$$

This metric enabled us to make direct comparisons of the temporal contrast sensitivities for tests and surrounds of different mean luminance levels at each of the temporal frequencies measured. The luminance level of the test is used as the curve parameter. The squares, circles, and triangles represent the tests whose luminance levels were 12.5, 25.0, and 37.5 cd/m^2, respectively. For the test luminance level of 25.0 cd/m^2, two additional data points corresponding to the dark (0 cd/m^2) and the light (50 cd/m^2) surround condition from experiment 1 were included in the analysis. For all the temporal frequencies, contrast sensitivity decreases as a monotonic function of the magnitude of the Michelson contrast between test and surround. In each panel, the points from the three separate curves shown in Figs. 3 and 4 are superimposed. Temporal contrast sensitivity is impaired by the presence of a pedestal contrast at the edge of the test. This result indicates that sensitivity to contrast modulation at the edge of the test may determine threshold. However, before this assertion can be made, a direct test of sensitivity to luminance modulation and sensitivity to contrast modulation must be performed.

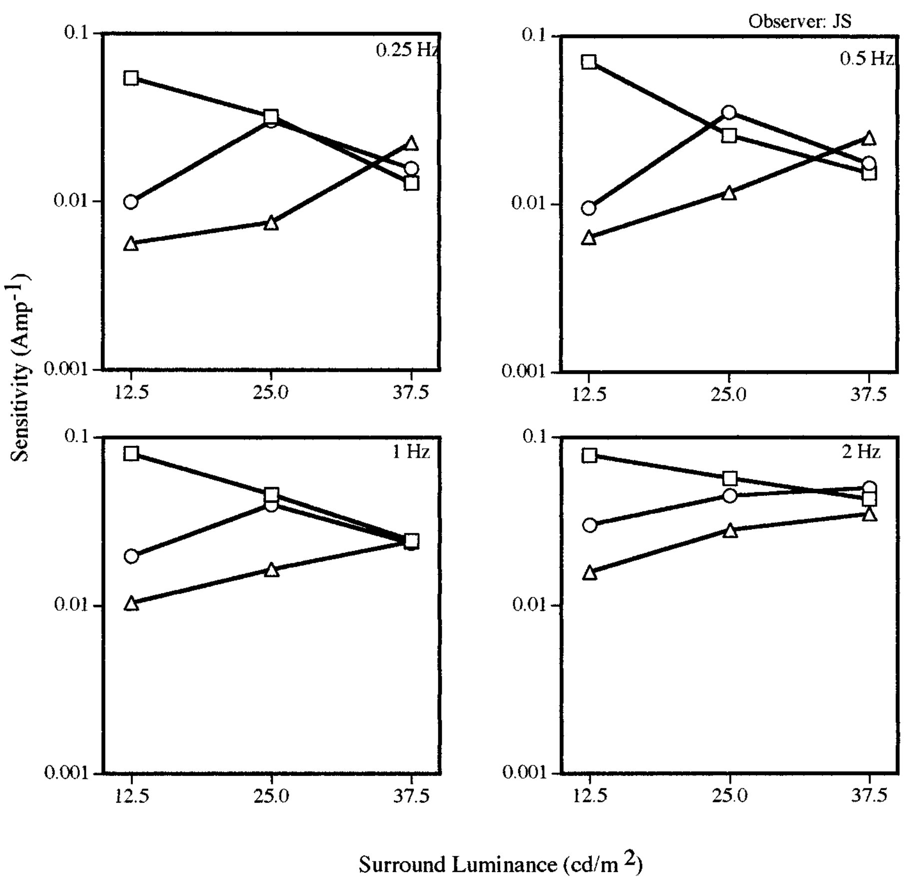

Fig. 4. Results from observer JS in experiment 2. Amplitude sensitivity is plotted as a function of the surround luminance level with the luminance level of the test as a curve parameter: squares, 12.5 cd/m^2; circles, 25.0 cd/m^2; and triangles, 37.5 cd/m^2. Four different panels show amplitude sensitivities at different temporal frequencies.

4. EXPERIMENT 3

A. Sensitivity to Contrast Versus Luminance Modulation

To verify that temporal contrast sensitivity in center–surround configurations is determined by sensitivity to temporal contrast modulation at the edge of the test, we measured temporal contrast sensitivity in conditions in which the surround was modulated with the same amplitude and frequency as the test, either in the same phase or in the opposite phase.

The mean luminance level of the test was 25.0 cd/m^2. The surround was modulated with the same amplitude and frequency as the center, either in phase or opposite phase at two different mean luminance levels: 25.0 and 37.5 cd/m^2 (equiluminant and lighter surround conditions, respectively). Thus the temporal contrast sensitivity for the test was determined in four conditions: equiluminant in phase, equiluminant opposite phase, lighter in phase, and lighter opposite phase. In all the conditions the local temporal luminance modulations were identical, but in the counterphase modulation condition the temporal variation of the spatial contrast at the edge of the test field was available as an additional cue. The equiluminant in-phase condition was identical to luminance modulation of a large spatially uniform field. The equipment, the experimental procedures, and the other stimuli characteristics were the same as in experiments 1 and 2.

B. Results

Results for the two observers are shown in Fig. 7. Amplitude sensitivity is plotted as a function of the temporal frequency, with the condition type as a curve parameter. The filled symbols represent results in the opposite-phase-modulation conditions, and the open symbols represent results for the in-phase-modulation conditions. The circles represent results for the conditions in which the test and the surround were modulated at the same mean luminance levels, and the triangles represent results for the conditions in which the surround was modulated around a higher mean luminance level than the test.

For both observers and for both surround mean luminance levels, amplitude sensitivity was higher in the opposite-phase conditions than in the in-phase conditions. The opposite-phase surround modulation conditions (filled symbols) yielded results qualitatively similar to those of experiment 1 (Fig. 2). For the detection of con-

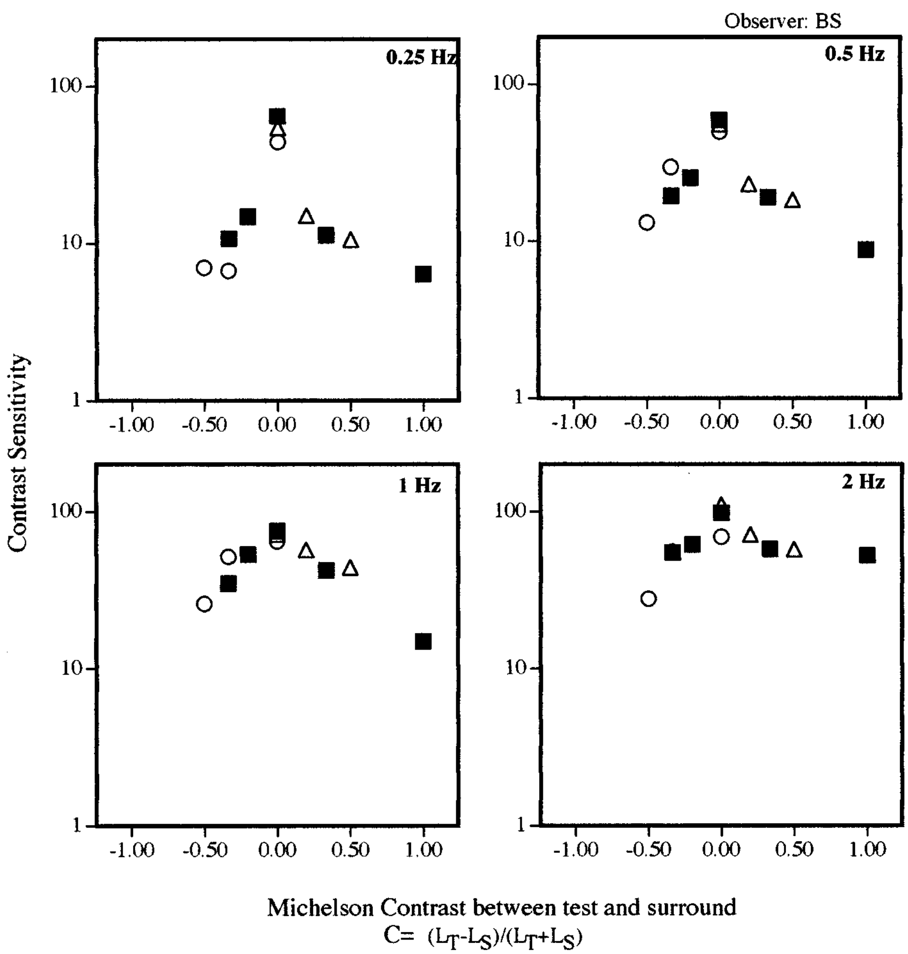

Fig. 5. Replot of results from observer BS in experiment 2. Contrast sensitivity is plotted as a function of the Michelson contrast between the mean luminance level of the test and that of the surround, with the luminance level of the test being used as a curve parameter: squares, 12.5 cd/m^2; circles, 25.0 cd/m^2; and triangles, 37.5 cd/m^2. Four different panels show contrast sensitivities at different temporal frequencies.

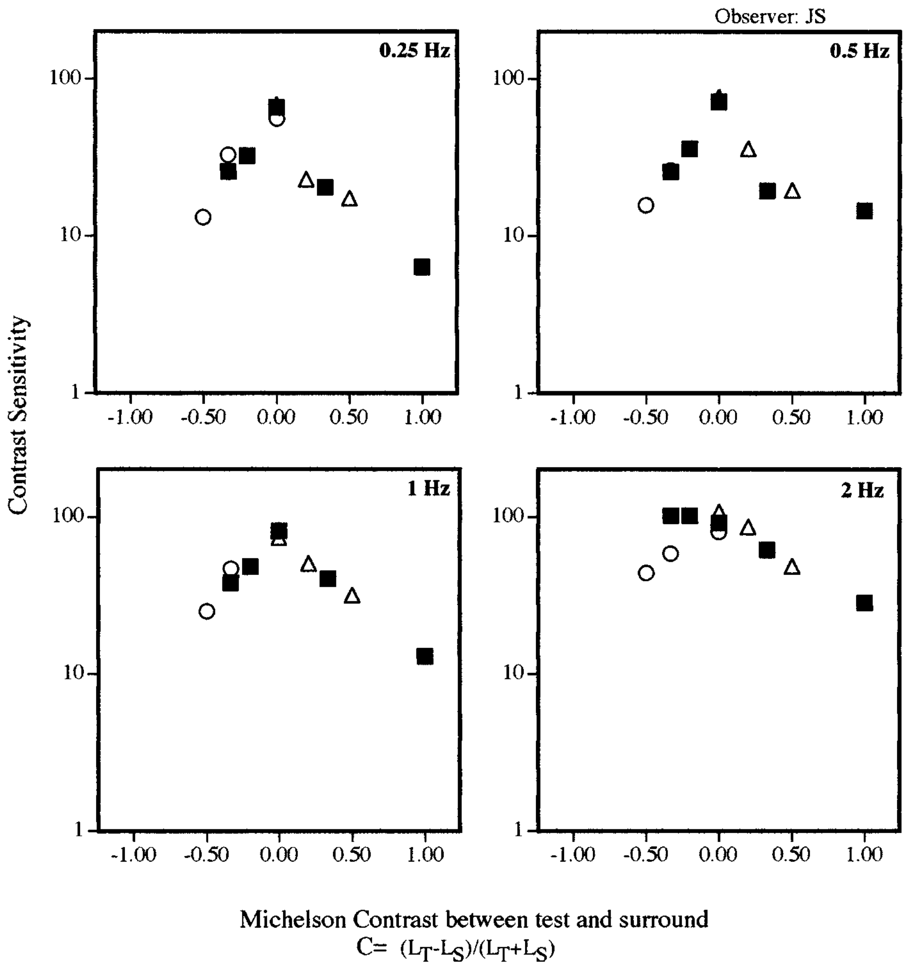

Fig. 6. Replot of results from observer JS in experiment 2. Contrast sensitivity is plotted as a function of the Michelson contrast between the mean luminance level of the test and that of the surround, with the luminance level of the test being used as a curve parameter: squares, 12.5 cd/m^2; circles, 25.0 cd/m^2; and triangles, 37.5 cd/m^2. Four different panels show contrast sensitivities at different temporal frequencies.

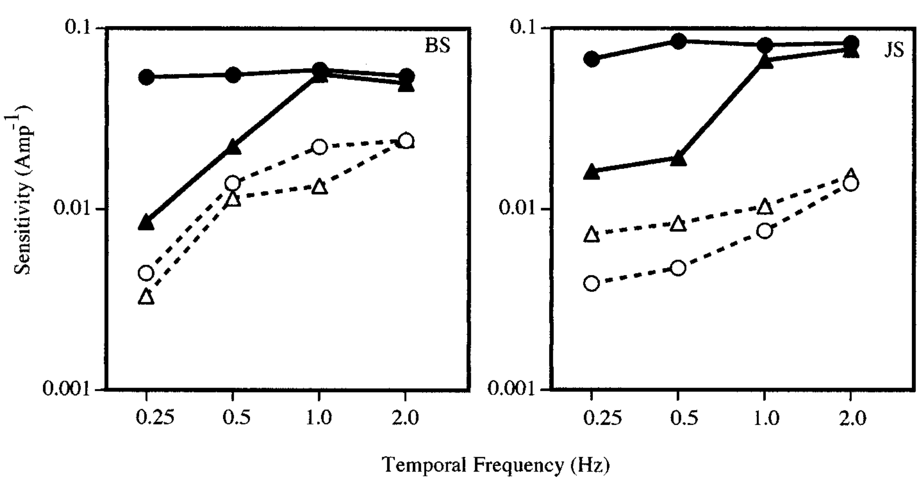

Fig. 7. Results from two observers (BS and JS) from experiment 3. Amplitude sensitivity is plotted as a function of the temporal frequency, with the condition type being used as a curve parameter. The filled symbols represent results in the opposite-phase-modulation conditions, and the open symbols represent results for the in-phase-modulation conditions. The circles represent results for the conditions in which the test and the surround were modulated at the same mean luminance levels, and the triangles represent results for the conditions in which the surround was modulated at a higher mean luminance level than the test.

trast modulation in the condition in which the test and the surround were modulated around equal mean luminance levels (filled circles), there was no drop-off of sensitivity at lower temporal frequencies. The results for the lighter opposite-phase surround condition (filled triangles) show the drop-off in sensitivity at lower temporal frequencies, just like the drop-off in sensitivity observed in experiment 1 with the steady lighter surround (Fig. 2). These results indicate that the detection of contrast modulation is hampered by the presence of a steady pedestal contrast at the edge of the test, selectively, for lower frequencies.

Temporal contrast sensitivity in the in-phase surround modulation conditions (open symbols) was a monotonically increasing function of temporal frequency for both surround mean luminance levels and was not affected substantially by the surround mean level. Thresholds in these conditions could be set by sensitivity to luminance modulation in the darkest part of the field, i.e., the test, or by sensitivity in the periphery to contrast modulation at the edge of the surround. The similarity between the two sets of curves indicates that in both cases the observer is most sensitive to luminance modulation inside the test.

Comparison of the results for the in-phase and the opposite-phase conditions for the same surround mean luminance reveals that the contrast modulation was a more useful cue at lower temporal frequencies and in the absence of any pedestal contrast between test and surround. In other words, in the conditions in which the center and the surround were not of identical mean luminance, the steady pedestal contrast between the center and the surround made the use of this cue less effective.

5. EXPERIMENT 4

A. Textured Surrounds

Experiments 1–3 demonstrate that temporal contrast sensitivity at low temporal frequencies is dependent on the contrast between the mean luminances of the test and the surround. We wanted to determine whether this contrast effect between the test luminance level and the surround is determined by the surround average luminance or on the basis of the local contrast between the center and each surround element. In experiment 4 we compared temporal contrast sensitivity in uniform centers when they were embedded in nonuniform surrounds of the same average luminance but varying spatial contrast. Uniform test field at 25.0 cd/m^2 was embedded in random binary textured surrounds of the same mean luminance but with Michelson contrast values of 0.0, 0.5, and 1.0.

The equipment, the experimental procedures, and the other stimuli characteristics were the same as those used in experiments 1–3.

B. Results

Figure 8 shows the results of experiment 4 for the two observers. Amplitude sensitivity is plotted as a function of temporal frequency, and the three curves correspond to three surrounds, respectively, of equal average luminance but different contrasts. The top curve (open squares) corresponds to the surround with Michelson contrast equal to 0.0, i.e., uniform equiluminant surround identical to the one from experiment 1. The asterisks and the circles correspond to surrounds of 0.5 and 1.0 internal contrast, respectively. The results show that temporal contrast sensitivity decreases as a monotonic function of the internal spatial contrast in the surround. The loss of sensitivity is proportional to the magnitudes of local contrast at the edge of the test, and not to the space-averaged contrast between test and surround. The effect is more pronounced at lower temporal frequencies, similar to the counterphase results shown in Fig. 7.

6. DISCUSSION

To understand whether sensitivity to luminance or to contrast modulation was responsible for the results in equiluminant and dark surround conditions in Fig. 2, we performed two additional comparisons, which are shown in Fig. 9. We compared the results of the two observers for the static equiluminant (filled crosses) and the dark surrounds (filled squares) from experiment 1, with the equiluminant out-of-phase modulating surround (open crosses) and equiluminant in-phase modulating surround

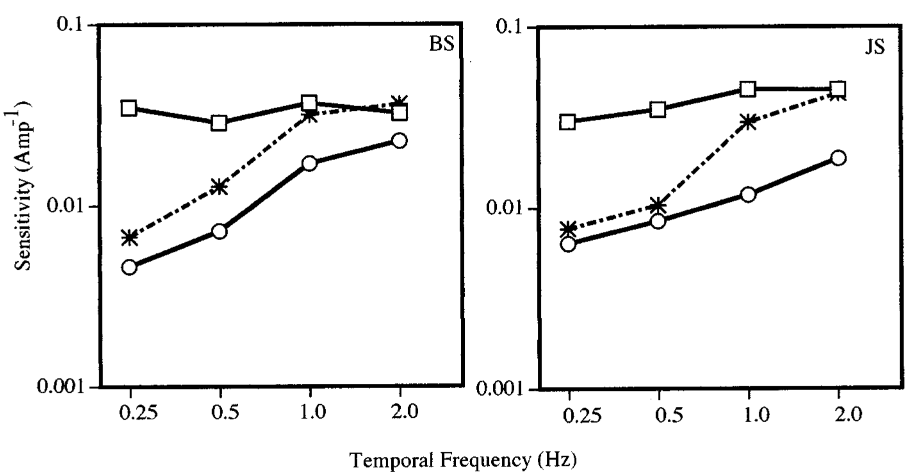

Fig. 8. Results from two observers (BS and JS) from experiment 4. Amplitude sensitivity is plotted as a function of the temporal frequency, with the internal spatial contrast of the surround being used as a curve parameter: squares, 0.0; asterisks, 0.5; and circles, 1.0.

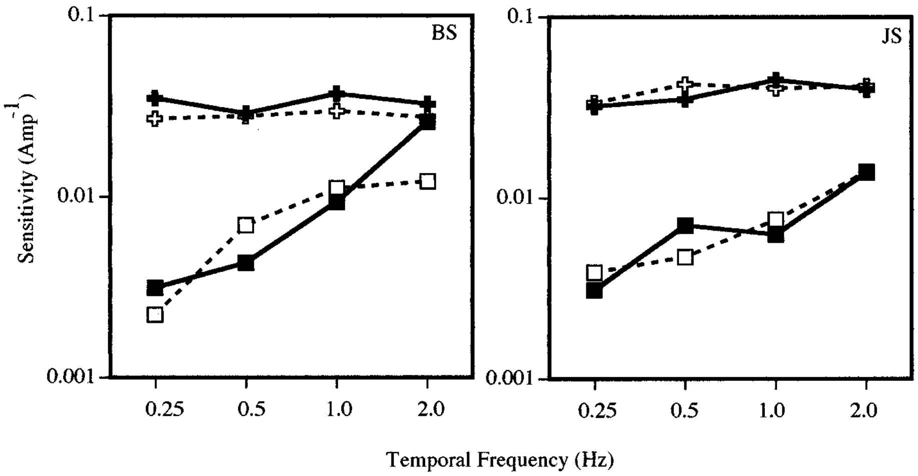

Fig. 9. Comparison of the results from two observers (BS and JS) from experiments 1 and 3. Amplitude sensitivity is plotted as a function of the temporal frequency, with the condition type being used as a curve parameter. The filled symbols represent results with the equiluminant (filled crosses) and the dark surrounds (filled squares) from experiment 1. The open symbols represent results in the equiluminant opposite-phase-modulation condition (open crosses) and in the equiluminant in-phase-modulation condition (open squares) from experiment 4.

(open squares) from experiment 3. For all the test intensities temporal contrast sensitivity is similarly low pass on equiluminant steady and out-of-phase modulating surrounds, indicating that the measured sensitivity in equiluminant surrounds is based on the detection of the temporal modulation of the spatial contrast at the edge of the test field. When small test fields of moderate intensity are embedded in dark surrounds (filled squares), the sensitivity at lower spatial frequencies is similar to the sensitivities measured for large test fields (open squares) and may reflect sensitivity for luminance modulation within the test.

For all the temporal frequencies, contrast sensitivity decreases as a monotonic function of the magnitude of the Michelson contrast between test and surround. The decrease is roughly symmetric around zero contrast, i.e., the absolute magnitude of the contrast is the important variable. Since the steady surround can make the perceived brightness of the test appear darker or lighter through simultaneous induction, this result indicates that induced steady brightness does not affect thresholds. A similar conclusion was reached by Cornsweet and Teller[11] on the basis of increment threshold measurements.

Our results are relevant to the phenomenon known as the crispening effect[12,13] which refers to enhanced luminance discrimination when the test luminance is near the background luminance. On the basis of scaling and increment threshold measurements, Whittle has shown that, when the difference between the luminance of the center and the luminance of the background is small, discriminability is related to the difference in luminance between the center and the surround rather than to the luminance of the center but that it is related to the luminance level of the test alone when the difference between the center and the surround is large. The results of this study provide more direct evidence that discrimination is based on the contrast between test and surround when the two are at the same luminance level. As the steady pedestal contrast between the test and the surround is increased, the sensitivity to the contrast difference declines, and, beyond some pedestal contrast, sensitivity to luminance modulation of the test itself determines threshold.

Our results and possibly even the crispening effect can be discussed in terms of contrast-sensitive neural mechanisms of the kind reviewed by Graham.[14] Psychophysical and physiological evidence points to early processing of visual images by classes of spatial pattern analyzers that are sensitive to different bands of spatial and temporal frequencies. In general, units that are more sensitive to higher spatial frequencies respond better at lower temporal frequencies. These units are most likely to determine sensitivity to small flickering tests on equiluminant surrounds at low temporal frequencies by detecting modulation of the high-spatial-frequency edge between the test and the surround. In the presence of a substantial contrast pedestal at the edge, these mechanisms would be desensitized,[15] and sensitivity may be determined by units more sensitive to lower spatial frequencies that are less sensitive to lower temporal frequencies.

ACKNOWLEDGMENTS

We thank Jonathan E. Szura for participating as an observer. A portion of this research was presented at the 1996 annual meeting of the Association for Research in Vision and Ophthalmology, Inc., held in Fort Lauderdale, Florida. This study was supported by National Institutes of Health National Eye Institute grant EY07556 to Q. Zaidi.

REFERENCES

1. H. de Lange, "Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light. I. Attenuation characteristics with white and colored light," J. Opt. Soc. Am. **48**, 777–784 (1958).
2. D. H. Kelly, "Visual responses to time-dependent stimuli. I. Amplitude sensitivity measurements," J. Opt. Soc. Am. **51**, 422–429 (1961).

3. J. A. J. Roufs, "Dynamic properties of vision. I. Experimental relationships between flicker and flash thresholds," Vision Res. **12**, 261–278 (1972).
4. L. O. Harvey, "Flicker sensitivity and apparent brightness as a function of surround luminance," J. Opt. Soc. Am. **60**, 860–864 (1970).
5. U. T. Keesey, "Variables determining flicker sensitivity in small fields," J. Opt. Soc. Am. **60**, 390–398 (1970).
6. D. H. Kelly, "Flickering patterns and lateral inhibition," J. Opt. Soc. Am. **59**, 1361–1370 (1969).
7. D. H. Kelly, "Theory of flicker and transient responses. I. Uniform fields," J. Opt. Soc. Am. **61**, 537–546 (1971).
8. D. H. Kelly, "Adaptation effects on spatio-temporal sinewave thresholds," Vision Res. **12**, 89–101 (1972).
9. L. H. van der Tweel, "Some problems in vision with respect to linearity and frequency response," Ann. (N.Y.) Acad. Sci. **89**, 829–856 (1961).
10. L. H. van der Tweel, "Relation between psychophysics and electrophysiology of flicker," Doc. Ophthalmol. **18**, 287–304 (1964).
11. T. N. Cornsweet and D. Teller, "Relation of increment thresholds to brightness and luminance," J. Opt. Soc. Am. **55**, 1303–1308 (1965).
12. H. Takasaki, "Lightness change of grays induced by change in reflectance of gray background," J. Opt. Soc. Am. **56**, 504–509 (1966).
13. P. Whittle, "Brightness, discriminability and the 'crispening effect,'" Vision Res. **32**, 1493–1507 (1992).
14. N. Graham, *Visual Pattern Analysers* (Oxford U. Press, Oxford, 1989).
15. A. B. Watson, "Temporal sensitivity," in *Handbook of Perception and Human Performance*, K. R. Boff, L. Kaufman, and J. P. Thomas, eds. (Wiley, New York, 1986), Vol. 1, Chap. 6, pp. 1–43.