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Brightness Induction from Uniform and Complex Surrounds: A General Model

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We studied the brightness induced from complex non-figural achromatic surrounds. A spatially uniform test field was surrounded by a random texture composed of two sets of dots. The luminance of each set of dots was modulated sinusoidally at 0.5 Hz. The mean luminance, phase and amplitude of modulation of each set were controlled independently so as to modulate the luminance and/or the contrast of the surround. Brightness induction was measured by a modulation nulling technique. The results were fit by a model in which the total brightness induced by a surround is equal to a weighted spatial summation of the induced effects from each point in the surround. The model incorporates local luminance gain controls in the test and surround fields and assumes that the magnitude of induction from each surround element is gain controlled by the difference between the mean luminance of the test and the individual surround elements. Copyright © 1996 Elsevier Science Ltd.

Brightness induction   Spatial integration   Simultaneous contrast   Lateral interactions   Gain control

INTRODUCTION

The perceived brightness of a spatially uniform achromatic test field of constant luminance can be increased or decreased in a straightforward manner by respectively decreasing or increasing the luminance of the area surrounding the test: classical brightness induction (Chevreul, 1839). If the luminance of the surround is modulated sinusoidally in time at a moderate frequency (around 1 Hz), the perceived brightness of the test modulates in opposite phase, and the induced effect can be measured by nulling with real luminance modulation inside the test field (Krauskopf *et al.*, 1986; Zaidi *et al.*, 1991), or by asymmetric matching (De Valois *et al.*, 1986). In the case of spatially uniform surrounds, within the luminance range provided by CRT monitors, the inducing and nulling modulations are related in a linear fashion (Krauskopf *et al.*, 1986).

When the surround is not spatially uniform, brightness induction can be more complicated. Some studies have shown that a spatially uniform surround and a spatially complex surround of the same space-averaged luminance have identical inducing effects on a central test (Valberg & Lange-Malecki, 1990). Zaidi *et al.* (1992) and Zaidi & Zipser (1993) examined spatially complex surrounds in terms of basis functions consisting of radially and concentrically varying spatial sinusoids. Experiments using individual and combined basis surrounds showed that brightness induction can be characterized as a linear spatial integration process in which the effects of parts of the surround at different distances from the test are weighted by a negative exponential as a function of distance from the test. Their data are consistent with the assumption that the total induced effect of the surround is simply the sum of the induced effects of individual surrounding points.

A number of other studies, however, have demonstrated failures of additivity of surround effects in brightness induction. In these studies, more complex attributes such as shape, transparency, or depth could be inferred in some of the stimuli used, and it is not clear whether the observed failures of additivity are due to spatial variations *per se* or to some higher cognitive mechanisms (e.g. Judd, 1966; Gilchrist, 1980; Zaidi, 1990; Adelson, 1990; Spehar *et al.*, 1995). There are also a few studies that used spatially variegated but non-figural surrounds and reported inducing effects that are more complex than could be explained by spatial additivity (Brown & MacLeod, 1991; Schirillo & Shevell, 1993). Zaidi *et al.* (1992) and Zaidi & Zipser (1993) had tried to isolate the properties of lateral combination processes by keeping the time and space-averaged mean luminance of all points in the stimulus equal. In the series of studies which exhibited a failure of additivity this was not true, thus making it imperative to explicitly consider spatially local and extended adaptation mechanisms.

The purpose of this study was to generate a general

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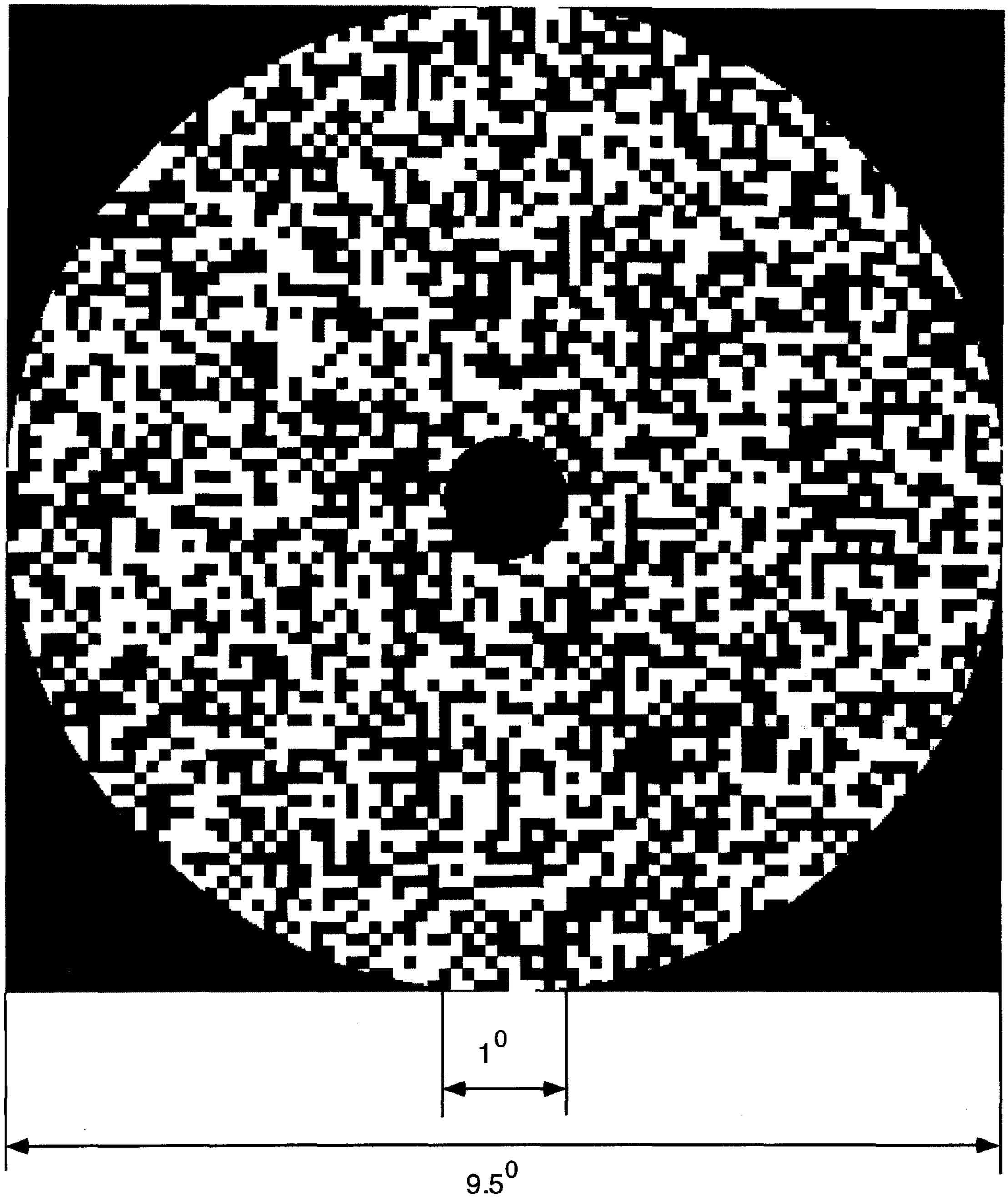

FIGURE 1. Stimulus configuration: spatially uniform 1 deg disk was surrounded by 9.5 deg annulus composed of binary random texture.

model for brightness induction from such variegated non-figural surrounds, to identify the conditions under which the induced effect can be described as spatially additive, and to delineate the processes that lead to failures of additivity. We present the results of four experiments that require progressively more complex qualitative explanations. We then present a quantitative model that accounts for these results.

EXPERIMENT 1. SPATIAL ADDITIVITY OF INDUCED EFFECTS FOR SURROUNDS AND TESTS AT EQUAL MEAN LUMINANCE

The purpose of this experiment was to extend the tests for spatial additivity done by Zaidi *et al.* (1992) and Zaidi & Zipser (1993). Zaidi *et al.* (1992) had shown linear spatial summation of brightness induction for surrounds consisting of concentric circles of uniform luminance which varied sinusoidally with increasing distance from the test. Using radially varying surrounds, Zaidi & Zipser (1993) extended this result to the case of radially varying surrounds, where the test was surrounded by areas varying in luminance, but only examined the case where the total induced effect was zero.

In Experiment 1 we used stimuli similar to Fig. 1, in which a foveally fixated spatially uniform disk was surrounded by an annulus filled with binary random texture, composed of equal numbers of two sets of

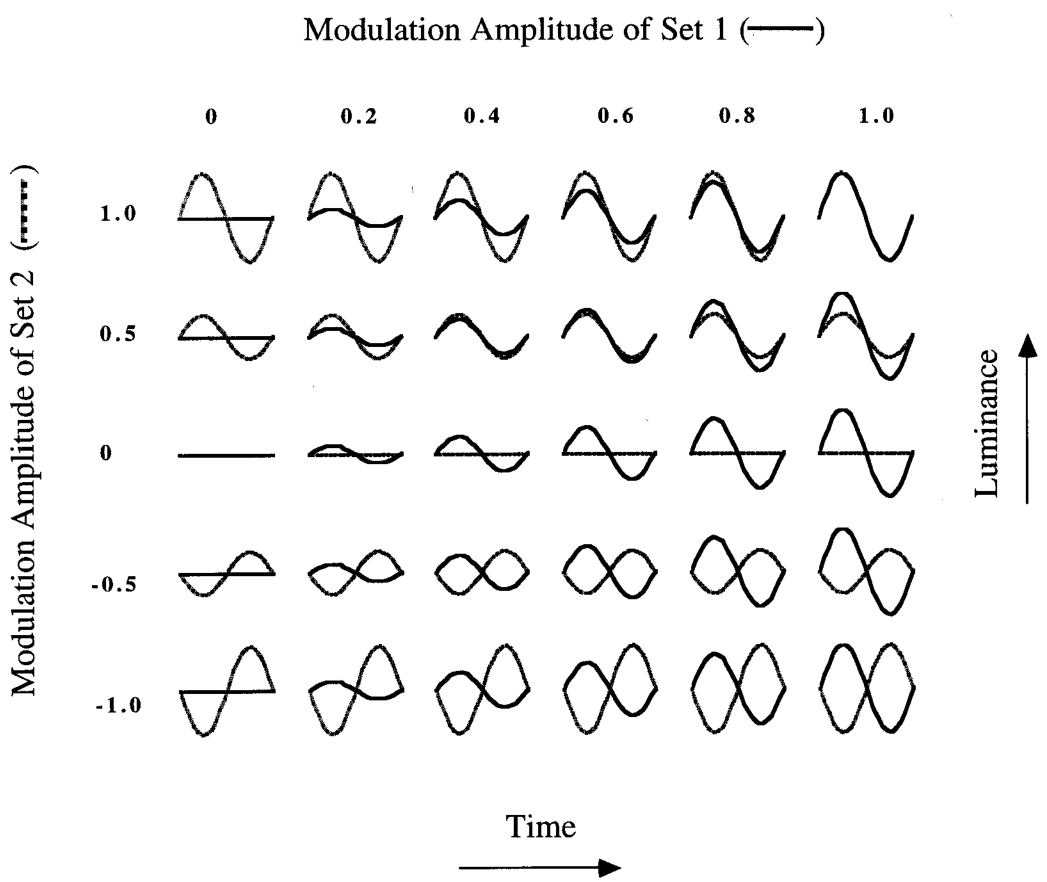

FIGURE 2. The luminance modulation of each set of the surround elements in Experiment 1. The luminance of both sets of texture elements was modulated sinusoidally at 0.5 Hz. The luminance modulation of one set was set at an amplitude of 0, 0.2, 0.4, 0.6, 0.8 or 1.0, paired with a modulation amplitude of the other set at 1.0, 0.5, 0, −0.5, −1.0, where a negative sign denotes modulation in the opposite phase.

randomly intermixed, equal sized, square elements. The luminance of each set of elements was modulated sinusoidally in time. The mean level, amplitude and phase of temporal modulation were independently controlled for each set. Temporal modulation of the luminance of the surround resulted in an induced modulation of the brightness of the test. The induced modulation was nulled by adding real luminance modulation inside the test field, and the amplitude of the nulling modulation was used as the measure of the induced effect.

In Experiment 1, the test and both surround sets had the same time-averaged mean luminance. We aimed to test whether the total induced effect was simply a sum of the effects induced by the modulation of each set separately, by varying the modulations of each of the sets independently over a wide range.

Methods

Stimulus parameters. The test was a spatially uniform achromatic disk (CIE chromaticity coordinates: $X = 0.311$, $Y = 0.335$) with a diameter subtending a visual angle of 1 deg, surrounded by a 9.5 deg annulus filled with achromatic random texture composed of two sets of elements. Each element was a square, 6 pixels wide on each side (equal to a visual angle of 0.1 deg). CRT monitors exhibit high spatial frequency non-linearities for small element sizes. The size of the elements was chosen to avoid these nonlinearities. There were approximately equal numbers of elements of the two sets along each concentric circle and radius of the surround. The time-average luminance of all the points in the test and the surround was 25 cd/m^2. The circular surround was enclosed within an achromatic, spatially uniform, steady, 10.67 × 10 deg rectangle whose mean luminance was also 25 cd/m^2.

For convenience, we normalized all luminance values by dividing by the screen mean luminance level, yielding a relative luminance scale ranging from 0 (dark) to 2 (maximum screen luminance of 50 cd/m^2). In all experiments, the amplitude of modulation was defined as $L_{max} - L_{mean}$.

In Experiment 1 we measured the total induction on the test when the luminance of both sets of texture elements was modulated sinusoidally at 0.5 Hz. The luminance modulation amplitudes of one set were 0.0, 0.2, 0.4, 0.6, 0.8 or 1.0, paired with modulation amplitudes of the other set of 1.0, 0.5, 0.0, −0.5, −1.0, where a positive or negative amplitude denotes modulation in phase or 180 deg out of phase with the paired modulation. One cycle of each of these combinations of luminance modulations are shown schematically in Fig. 2.

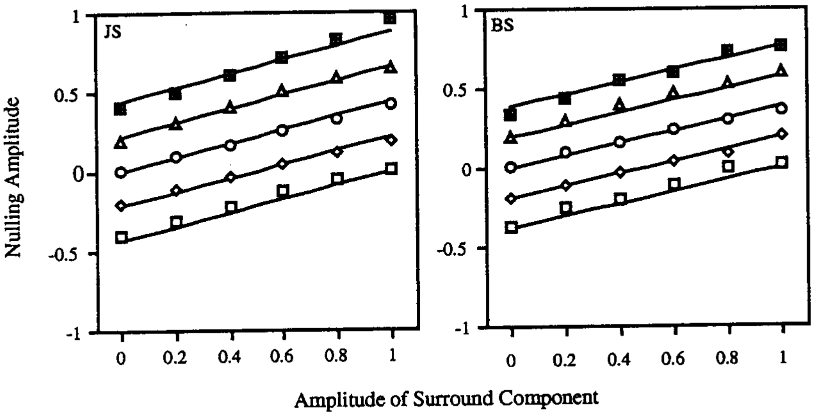

FIGURE 3. Results of observers JS and BS in Experiment 1. Test mean luminance equals 1.0. The amplitude of nulling modulation (ordinate) is plotted as a function of the magnitude of the modulation of one set of the surround elements (abscissa) with the amplitude of modulation of the paired set as a curve parameter: (□, −1.0; ◇, −0.5; ○, 0; △, 0.5; ⊞, 1). Each data point is the average of two 2AFC staircases (10 turns each). Error bars representing standard error of the mean were smaller than the symbols. The solid lines are given by equation (1) where m_0 is the slope of the best fitting line in Fig. 4 calculated separately for each observer.

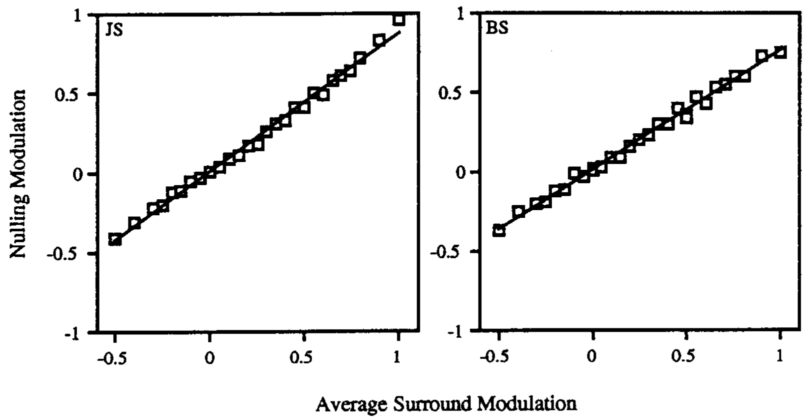

FIGURE 4. Results of Experiment 1 for observers JS and BS. The amplitude of nulling modulation (ordinate) is plotted as a function of the average magnitude of the modulation of the two sets of surround elements (abscissa). Solid lines show the best regression fit to the data sets, passing through the origin.

Measurement procedure. A 2AFC modification of the modulation nulling technique discussed by Krauskopf *et al.* (1986) and Zaidi *et al.* (1991, 1992), was used to measure the amount of induction within the central test. When the surround components were modulated at 0.5 Hz, a perceived modulation was induced in the test. To null the induced modulation, a real modulation was added to the test. During each trial, the observer fixated on the center of the test.

For each condition we initialized two 2AFC staircases, one above and one below the approximate null, found by allowing the observer to freely adjust the nulling modulation to minimize the perceived modulation in the test. Different tones were presented in coincidence with the positive and negative peaks of each sinusoidal cycle. The observer's task was to compare the test appearances at the two tones, and to respond whether the brightness of the test at the second tone was lighter or darker than its appearance at the first tone by pressing the appropriate buttons. From this response it was determined whether the nulling modulation was stronger or weaker than the induced modulation. When the observer's response indicated that the nulling modulation was stronger (or weaker) than the induced modulation, nulling modulation was reduced (or increased) by a fixed step of 12%. A turn in the staircase occurred when the observer's response indicated that the nulling modulation had changed from weaker to stronger than the nulling modulation (or vice versa). Each of these turns is a measurement of the observer's required nulling modulation, and the staircases continued until 10 such turns had been accumulated. To ensure the reliability of the measurements, we extracted several statistics. By examining the standard deviation we confirmed that each staircase converged; and by examining the *t*-test for the means, and F-ratio for the variances of the two staircases, we confirmed that they converged on the same value, despite having been initialized at different points. During each session the observer was presented with randomly interleaved conditions to ensure that no adaptation to a particular surround modulation would occur.

Equipment and stimulus generation. Stimuli were displayed on the screen of a BARCO 7651 color monitor with a refresh rate of 100 non-interlaced frames/sec. Images were generated using a Cambridge Research Systems Video Stimulus Generator (CRS VSG2/2), running in a 90 MHz Pentium based system. The VSG2/2, through the use of 12-bit DACs, is able to generate 2861 linear gray levels after gamma correction. By cycling though pre-computed look up tables (LUT) we were able to update the entire display each frame. All stimulus presentation, data collection, and the 2AFC staircase procedure were completely computer controlled.

Observers. One of the authors (BS) and another psychophysically experienced observer (JS) participated in all experiments. Both observers were corrected to normal for refractive errors.

Results

The main purpose of this experiment was to describe the function that relates the magnitude of induced modulation in the test to the amplitudes of modulation of the two sets of surround elements. The results are shown in Fig. 3. The amplitude of nulling modulation is plotted as a function of the amplitude of the modulation of one set with the amplitude of modulation of the other set as a curve parameter. For each modulation level of one set, the magnitude of nulling modulation was a linear function of the amplitude of the paired set. In addition, the five curves for each observer are parallel and equally spaced, indicating that the amplitude of nulling modulation is a linear function of the amplitude of each of the surround sets.

Simple additivity of the induced effects from the surround is also easily verified in Fig. 4. where the magnitude of the nulling modulation is shown as a function of the average modulation amplitude of the luminance of the two surround components. The best fitting line is shown for each observer. The R^2s were 0.994 and 0.993 for JS and BS, respectively, and the slopes were 0.874 and 0.766.

The data for each observer in Fig. 3 were fitted with the parallel lines given by the equation:

$$m_o(A_1 + A_2)/2 \qquad (1)$$

where m_o is a constant for each observer equal to the slope estimated in Fig. 4, and A_1 and A_2 are the modulation amplitudes of the two surround sets. The straight lines derived from equation (1) provide a good fit to all the slopes and spacing of the data in Fig. 3.

In Experiment 1, the method of independently controlled luminances of the two surround components leads to a variation of the space-averaged luminance and contrast in the surround. These results unambiguously support a spatial summation model over more general conditions than those examined by Zaidi *et al.* (1992) and Zaidi & Zipser (1993).

EXPERIMENT 2. SPATIAL ADDITIVITY OF INDUCED EFFECTS FOR SURROUNDS AND TESTS AT DIFFERENT MEAN LUMINANCE

By using stimuli in which all points in the test and the surround have the same time and space-averaged mean luminance level, the results of both Zaidi *et al.* (1992) and of Experiment 1 isolate lateral effects from other factors like variations in local adaptation level. Some of the claims for the failure of additivity have been made on the basis of experiments where the test and the complex surround were at different mean luminance levels. In Experiment 2 our purpose was to test spatial additivity of the inducing effects when the mean luminance level of the test differs from that of the surround.

The same equipment, surround stimuli and procedures were used as in Experiment 1. The time-averaged luminance of the surround was 25 cd/m^2, the time-averaged luminance of the test disk was set at either 0.5 or 1.5 times this value. Expressed in the relative luminance scale, the surround mean was 1.0 whereas the test values were 0.5 and 1.5.

Results

Figures 5 and 6 show the results of two observers for the conditions in which the time-averaged test luminance level was 0.5 and 1.5, respectively. The amplitude of nulling modulation is plotted as a function of the magnitude of the modulation of one set of the surround components, with the amplitude of modulation of the other set as a curve parameter. The results show that the magnitude of nulling modulation is a linear function of the modulation level of the surround components for tests at both luminance levels.

A comparison between Figures 5 and 6 shows that the amount of required nulling modulation increases as the mean luminance of the test increases. This is clearly reflected in the slopes of the best fitting lines in Fig. 7, where the magnitude of the nulling modulation is shown as a function of the average modulation amplitude of the two surround sets for each of the test mean levels. The slope of the linear relation increases with the mean luminance level of the test. The slopes for the tests of mean luminance levels of 0.5, or 1.5 are 0.406 and 0.919, respectively, for observer JS, and 0.465 and 0.890 for observer BS. R^2s were 0.993 and 0.996 for observer JS and 0.995 and 0.998 for observer BS. Results obtained in Experiment 1 (Fig. 4) can also be included in this comparison: the slope for the test of mean luminance level of 1.0 was 0.874 for observer JS and 0.766 for observer BS.

Figures 5 and 6 show the straight lines derived from equation (1) with m_o set to the corresponding slopes derived from Fig. 7. The lines reproduce the spacing and slopes of the data.

From the parallel and equally spaced straight lines in Figs 5 and 6 we can conclude that the inducing effects from individual surround components are combined in a simple additive fashion. However, tests with different mean luminance levels differ in required magnitudes of

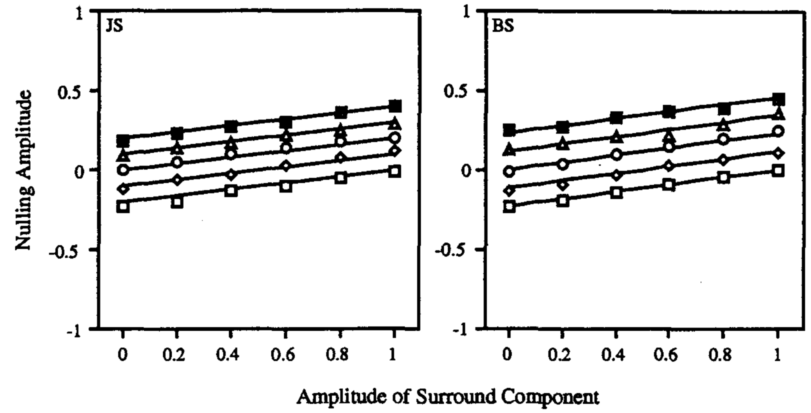

FIGURE 5. Results of Experiment 2 for observers JS and BS. Test mean luminance equals 0.5. The same graphical conventions are used as in Fig. 3.

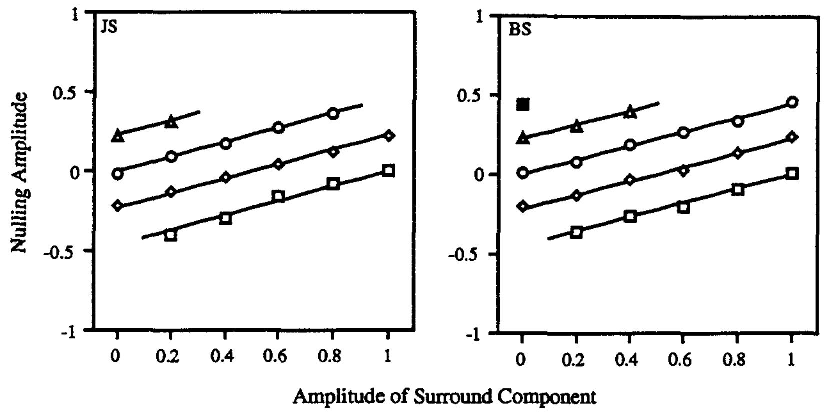

FIGURE 6. Results of Experiment 2 for observers JS and BS. Test mean luminance equals 1.5. All graphical conventions are identical to those in Fig. 3.

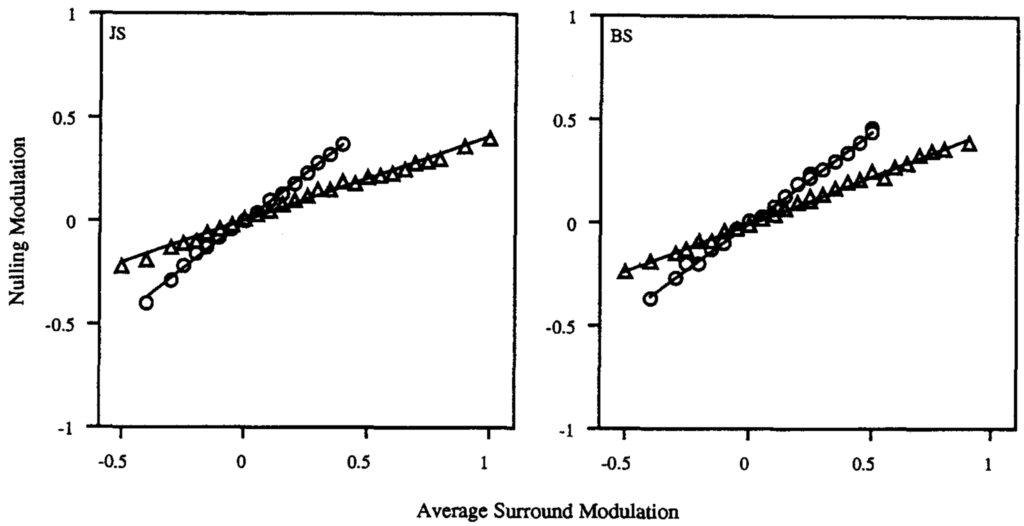

FIGURE 7. Results of Experiment 2 for observers JS and BS. The amplitude of nulling modulation (ordinate) is plotted as a function of the average magnitude of the modulation of the two sets of surround elements (abscissa) for two different test levels. Triangles represent data points for the test with mean luminance equal to 0.5. Circles represent data points for the test with luminance level equal to 1.5. All graphical conventions are identical to those in Fig. 4.

nulling modulation. It is important to note that in Figs 3–7 we have plotted the empirically measured *nulling* modulation amplitude, and not the amplitude of the *induced* modulation. It is well established (e.g., Watson, 1986) that the threshold for detection of temporal modulation at 0.5 Hz is an increasing function of the

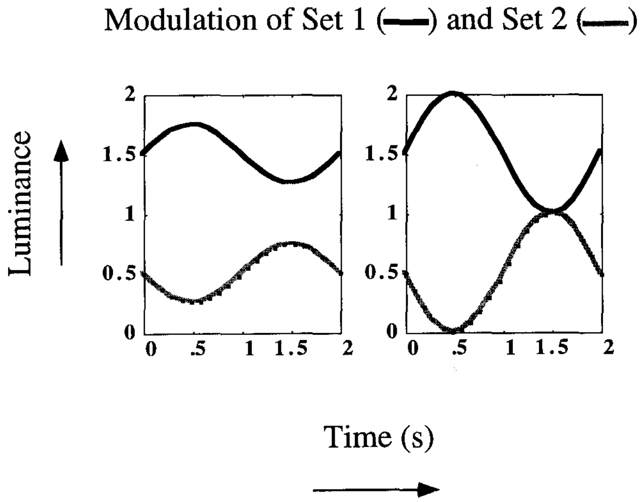

FIGURE 8. The luminance modulation of each set of the surround elements in time (sinusoidal modulation with frequency of 0.5 Hz) in Experiment 3. The two surround components were modulated with equal amplitudes in counterphase around different mean luminance levels. As a result, the space-averaged luminance of the surround was constant while the spatial contrast was modulated with amplitudes of 0.5 (left panel) or 1.0 (right panel).

mean luminance of the field. Craik (1938) conceptualized this fact in terms of a gain factor for the test modulation, set by the test mean luminance. In Experiments 1 and 2, even if the brightness induced from the surround were independent of the luminance level of the test, because of the gain set by the mean luminance of the test, the amount of real modulation needed to null the induced modulation should increase as a function of the test mean. The results of these experiments imply that local adaptation mechanisms in the test field should be incorporated into a general model of brightness induction.

EXPERIMENT 3. BRIGHTNESS INDUCTION FROM CONTRAST MODULATED SURROUNDS WITH CONSTANT SPACE-AVERAGED LUMINANCE

The results of Experiments 1 and 2 are consistent with additivity of the induced effects, resulting from time-varying changes in surround luminance. If the luminance of the surround set is modulated so that the spatially summed luminance along all circles concentric with the test, is constant at all instants of time, while only the spatial contrast between the two sets is varied, the spatial additivity model predicts zero brightness induction. However, some studies that compared the effects of textured or checkerboard surrounds to uniform surrounds of the same mean luminance at different levels of spatial contrast, have suggested that the space-average luminance of a non-uniform surround is not sufficient to predict the perceived brightness of a test patch (Brown & MacLeod, 1991; Schirillo & Shevell, 1993).

In Experiment 3 we used the same spatial configuration as Experiments 1 and 2 to examine whether modulation in spatial contrast of the surround could produce brightness induction in the test. This was achieved by modulating the luminances of the two surround components sinusoidally at 0.5 Hz, with equal amplitudes, in opposite phase, around different mean luminance levels, as depicted in Fig. 8.

At every time t, the Michelson contrast within the surround was defined as: $[L(t)_{max}-L(t)_{min}]/[L(t)_{max}+L(t)_{min}]$. Two different contrast modulation amplitudes were examined: 0.5 where the contrast of the surround varied sinusoidally in time from 0.25 to 0.75, and 1.0 where the contrast of the surround varied sinusoidally in time from 0 to 1. The space-averaged mean luminance of the surround was 1.0 (25 cd/m^2). Three mean luminance levels of the test were used: 0.5, 1.0, and 1.5 (12.5, 25, and 37.5 cd/m^2, respectively).

Results

Data for the two observers are shown in Fig. 9. The magnitude of nulling modulation is plotted as a function of the amplitude of contrast modulation. The three sets of symbols in each graph represent the data for the tests at the three different mean luminance levels. The symbols are connected by lines, extrapolated to the zero point, for the purpose of graphical clarity. The data of the two observers are similar. Contrast modulation of the surround does not produce any significant brightness induction for tests at the same mean luminance level as the surround (middle points). For tests at the other two mean luminance levels, the magnitude of the nulling modulation increases with the amplitude of the contrast modulation. The amplitude of nulling modulation required is small, but significantly greater than zero at both levels of contrast modulation ($P < 0.01$). The results for test luminance levels at 0.5 and 1.5 show nulling modulation of approximately equal amplitude but opposite sign. The brightness induced into the test at mean luminance 0.5, was in the same phase as the contrast modulation of the surround, whereas the brightness induced into the test at 1.5 was in the opposite phase. Phenomenally, this can be described in the following way: the test at mean luminance of 0.5 appears lighter on the higher contrast surround and darker on the lower contrast surround; the opposite happens for the test at mean luminance of 0.5.

The change in sign of the required nulling modulation as a function of test mean level, indicates that brightness induction is not a function of contrast modulation *per se*, and the results are better understood if the inducing effects of the two sets of surround elements are considered separately. A positive sign indicates that the nulling modulation was in the same phase as the modulation of the surround set with the higher mean luminance level in Fig. 8, and a negative sign indicates that the nulling modulation was in phase with a surround set of the lower mean luminance. The surround set whose mean luminance is closer to the mean level of the test seems to have a greater inducing effect. Mathematically, this is equivalent to the induced modulation being gain controlled by a decreasing function of the difference between the mean luminance level of the test and each set of the surround elements. In the case where the test level

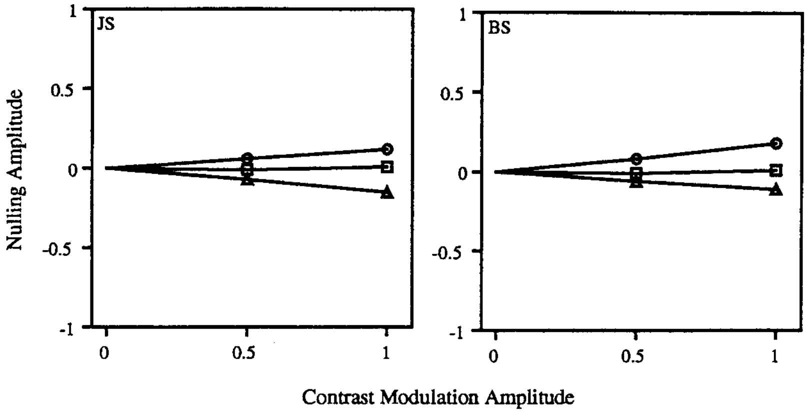

FIGURE 9. Results of Experiment 3 for observers JS and BS. The magnitude of nulling modulation (ordinate) is plotted as a function of the amplitude of contrast modulation (abscissa). Three curves in each graph represent the data for tests at three different mean luminance levels. Triangles represent data points for the test with mean luminance of 0.5. Squares represent data points for the test with a mean luminance of 1.0. Circles represent data points for the test with a luminance level of 1.5.

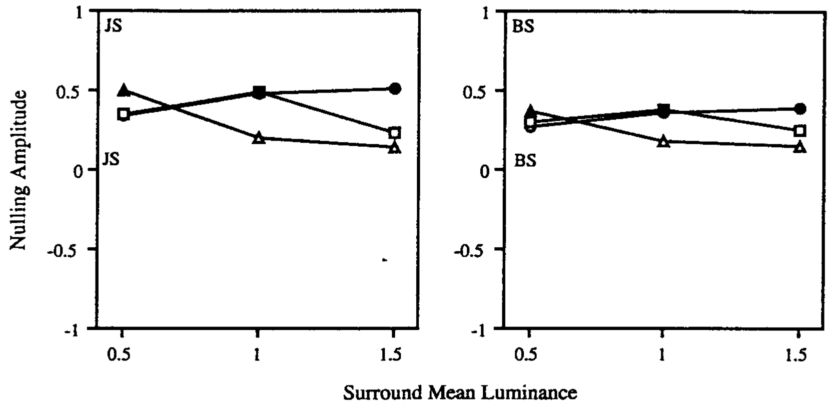

FIGURE 10. Results of Experiment 4 for observers JS and BS. The magnitude of nulling modulation is plotted as a function of the surround mean luminance level with test mean luminance level as a curve parameter. Triangles represent data points for the test with mean luminance equal to 0.5, squares test mean luminance 1.0 and circles test luminance level 1.5. Solid symbols indicate conditions where the time-averaged surround and test means were equal.

is equidistant from the mean levels of the two surround sets, the induced effects cancel out and there is roughly zero induced modulation.

More generally these results suggest that the magnitude of the difference between the luminance level of the test and the mean luminance level of each surround element should be considered in modeling the total induced effect from complex surrounds. We therefore postulate that there are pair-wise lateral connections between points in the test and the surround, and that the magnitude of the induction signal between them is a decreasing function of the mean luminance difference between them. To be consistent with the linear results of Experiments 1 and 2, the summation of induced effects has to occur posterior to this spatially extended gain control.

EXPERIMENT 4. INDUCED EFFECTS FROM SPATIALLY UNIFORM SURROUNDS AND TESTS AT DIFFERENT MEAN LUMINANCE LEVELS

In Experiments 1–3 we have shown the necessity of incorporating local and extended gain controls in induction models. If local gain controls function in the test field under these conditions, it is probable that they should also be active in the surround field. This would be revealed by measuring induction from surrounds at various mean levels. We did this in Experiment 4. In addition we tested whether spatially uniform surrounds had qualitatively different brightness induction effects than textured surrounds, or whether they shared similar mechanisms.

In Experiment 4 we used spatially uniform center and surround stimuli of the same size as in the earlier experiments. Three levels of the surround mean luminance (12.5, 25 and 37.5 cd/m^2) represented as 0.5, 1.0, and 1.5 were paired with three levels of the test mean luminance (also at 0.5, 1.0, and 1.5) for a total of nine conditions. In all conditions, the luminance of the surround was modulated sinusoidally in time at 0.5 Hz with an amplitude of 0.5. The best nulling modulation was estimated using the same 2AFC staircase procedure as Experiments 1–3.

Based on the results of Experiments 1–3, we expected that the magnitude of the induced effect would vary as a function of the difference between the test and surround mean luminance levels, i.e., when the surround and the test have the same mean luminance levels, the induced effect should be higher than when they are at different levels. In addition, we expected that as the surround mean level increases, the same inducing amplitude should produce less induction, through a mechanism similar to the one that causes the real nulling modulation to become less effective as the test mean level increases.

Results

Results for the two observers are plotted in Fig. 10. The magnitude of nulling modulation is plotted as a function of the surround mean luminance level with test luminance level as a curve parameter. For all three test levels, the magnitude of the nulling modulation was the highest when the surround modulation was at the same mean luminance as the test. The magnitude of the nulling modulation decreased monotonically as a function of the difference between the test and the surround mean luminance levels. When the mean luminance levels of the test and the surround were equal (i.e., the data points indicated by solid symbols) the magnitude of nulling modulation was approximately constant, indicating that the local gain control set by the surround mean luminance roughly balances the effect of the gain set by the test mean. The effect of the gain set by the test mean luminance is clearly evident in data for the surround luminance level of 1.0 (the three points in the middle of the abscissa), where the nulling modulation required for the test of the lowest luminance level is considerably lower than for the tests of higher luminance levels.

BRIGHTNESS INDUCTION MODEL

Zaidi *et al.* (1992) introduced a model of brightness induction in which total induction was the result of a spatially weighted summation of the individual induced effects from each point in the surround. This model was designed for the case in which the time-averaged mean luminance of each point in the test and in the surround was identical. To account for the results of this paper, we have generalized this model so that the induced effect from each point in the surround is proportional to its luminance attenuated by two gain controls and a spatial weighting function:

$$I(t) = -\int_0^{2\pi} \frac{\int_0^{\infty} W(s) \cdot \Gamma_D(\Omega, s) \cdot \Gamma_s(\Omega, s) \cdot L(\Omega, s, t) ds}{2\pi} d\Omega \tag{2}$$

I(t) is the total induced effect on the test patch at time *t*. (Ω,s) are the polar coordinates of a surround point, where Ω is the angular direction in radians, and *s* the spatial distance from the test in degrees of visual angle. $L(\Omega,s,t)$ is the luminance at that point at time *t*. $\Gamma s(\Omega,s)$ and $\Gamma_D(\Omega,s)$ are two gain control factors that affect the signals from (Ω,s). *W(s)* is a monotonically decreasing spatial weighting function of *s*, that Zaidi *et al.* (1992) showed can be well approximated by a negative exponential function with two parameters, κ and α:

$$W(s) = \kappa e^{-\alpha s} \tag{3}$$

We assume that the response of the visual system to a luminance signal at every point is gain controlled by a factor which depends solely on the mean luminance level at that point. Such local adaptation mechanisms exist early in the visual system (Shapley & Enroth-Cugell, 1985). Following tradition, we use hyperbolic gain control functions in our model. For each point in the surround, we calculate its gain factor by:

$$\Gamma_s(\Omega, s) = \frac{\gamma_s}{\gamma_s + \int L(\Omega, s, t) dt} \tag{4}$$

where the parameter γ is a constant for each observer. By incorporating this gain control, the induction model is able to predict that surround modulation about a low mean luminance level generates more induction than modulation of the same amplitude about a higher level.

We allow for the possibility that the local gain factor for the centered test field could be different from the surround gain. We calculate the factor, Γ_c, for the test by:

$$\Gamma_c = \frac{\gamma_c}{\gamma_c + \int L(0, 0, t) dt} \tag{5}$$

where $\int L(0,0,t)dt$ is the time-averaged luminance of the center of the test and γ_c is a constant parameter for each observer.

The experimental results show that induced modulation depends on the pair-wise differences between the mean levels of the test and individual surround points. We modeled this by attenuating the induction from each point by a gain factor set by the absolute difference between the time-averaged luminance at that point and the time-averaged luminance of the test:

$$\Gamma_D(\Omega, s) = \frac{\gamma_D}{\gamma_D + |\Gamma_s(\Omega, s) \cdot \int L(\Omega, s, t) dt - \Gamma_c \cdot \int L(0, 0, t) dt} \tag{6}$$

where the parameter γ_D is constant for each observer.

In the model presented by Zaidi *et al.* (1992), because the test mean was the same for all conditions, it was sufficient to assume that a real modulation in the test field would null the induced modulation when it was of an equal amplitude and in the opposite phase. For conditions that include different mean levels, the local adaptation mechanism operating on the test field will influence the effectiveness of the added nulling modulation. Therefore, the true null will be achieved when the real modulation, after being gain controlled by the test mean level, is equal and opposite to the induced modulation:

$$\Gamma_c N(t) = -I(t) \tag{7}$$

where $N(t)$ is the luminance modulation required to counteract the induction at time t. Thus the complete expression for the null is:

$$N(t) = \frac{1}{\Gamma_c}\int_0^{2\pi} \frac{\int_0^{\infty} W(s)\cdot\Gamma_D(\Omega,s)\cdot\Gamma_s(\Omega,s)\cdot L(\Omega,s,t)ds}{2\pi}d\Omega \quad (8)$$

For the spatial and temporal configuration used in the current experiments, the general model can be simplified. Because the spatial composition of the binary texture in the surround was a random distribution, it is sufficient to consider the effects of identical numbers and distribution of the two sets of surround elements, instead of considering each surround point individually. Therefore, instead of determining an observer's spatial weighting function, it is sufficient to estimate its aggregate effect on each of the two types of surround elements. In addition, the integrals in equation (8) can be replaced by the sum of the independent effects of the two surround sets. Further simplification can be achieved because of the nature of the temporal modulation. The luminances of the two surround components were always modulated sinusoidally with the same frequency, either in phase or in the opposite phase, the model predicts that the induced modulation should also be sinusoidal with the same frequency and in the opposite phase with either one or both of the surround components. Therefore, for these conditions, it is sufficient to describe the inducing and nulling stimuli by just their signed amplitudes of modulation instead of considering instants of the modulating waveform.

As a result, for all conditions in the present study, equation (8) can be simplified to predict the amplitude of the required nulling modulation N by the equation:

$$N = \frac{w}{\Gamma_c}\sum_{i=1}^{2}\frac{\Gamma_{D_i}\cdot\Gamma_{S_i}\cdot A_i}{2} \quad (9)$$

where w incorporates the effect of the integrated spatial weighting function over the surround; A_i is the signed amplitude of luminance modulation of the ith component, and Γ_{D_i} and Γ_{S_i} are the gain controls that apply to the set i. This simplified model has only four free parameters: γ_S, γ_D and γ_C, the three gain control constants, and w which scales the amplitude of induction for each observer.

The entire set of an observer's data was fit with equation (9) by using the MATLAB 'fmins' function (a standard simplex minimizing algorithm). The simulta-

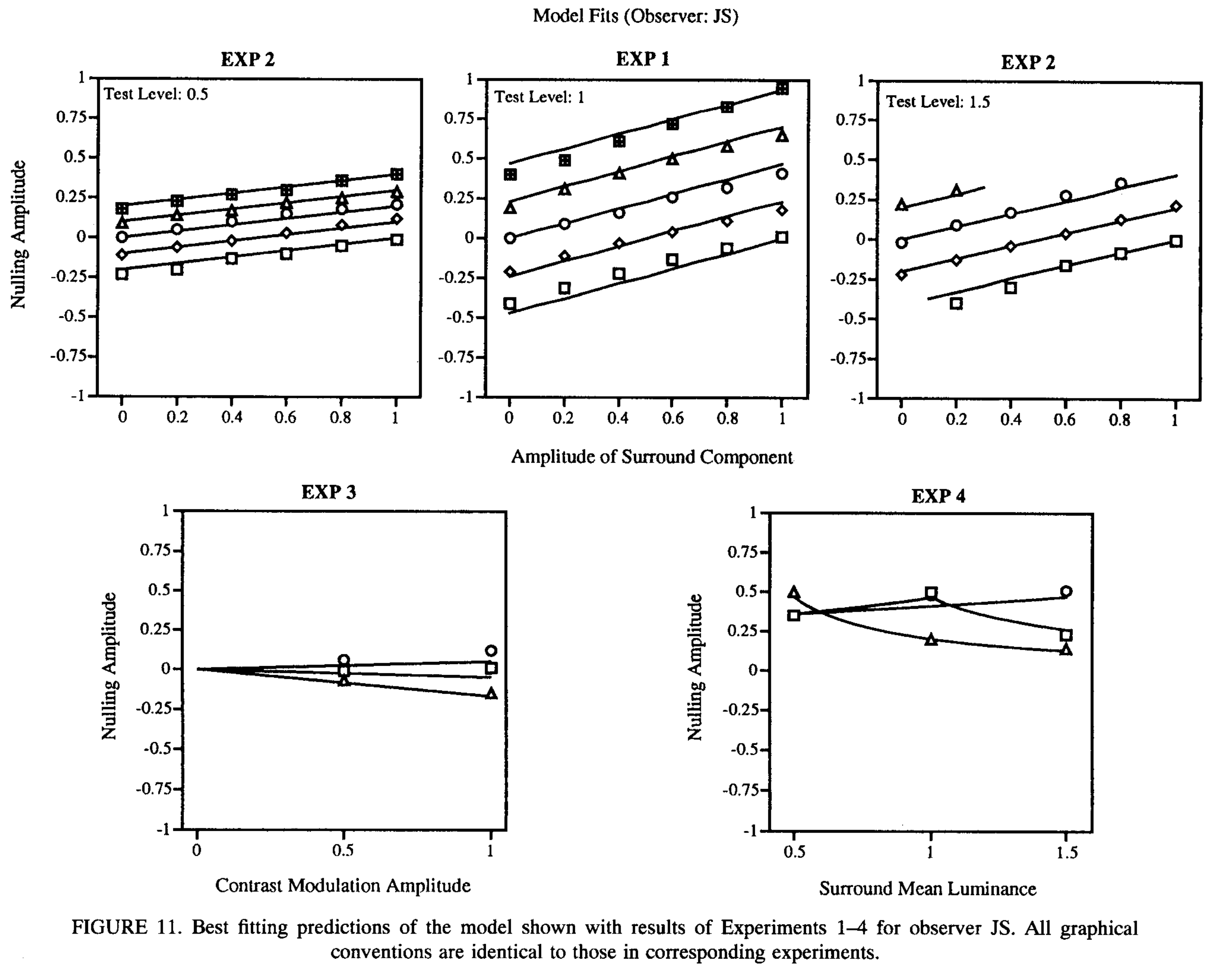

FIGURE 11. Best fitting predictions of the model shown with results of Experiments 1–4 for observer JS. All graphical conventions are identical to those in corresponding experiments.

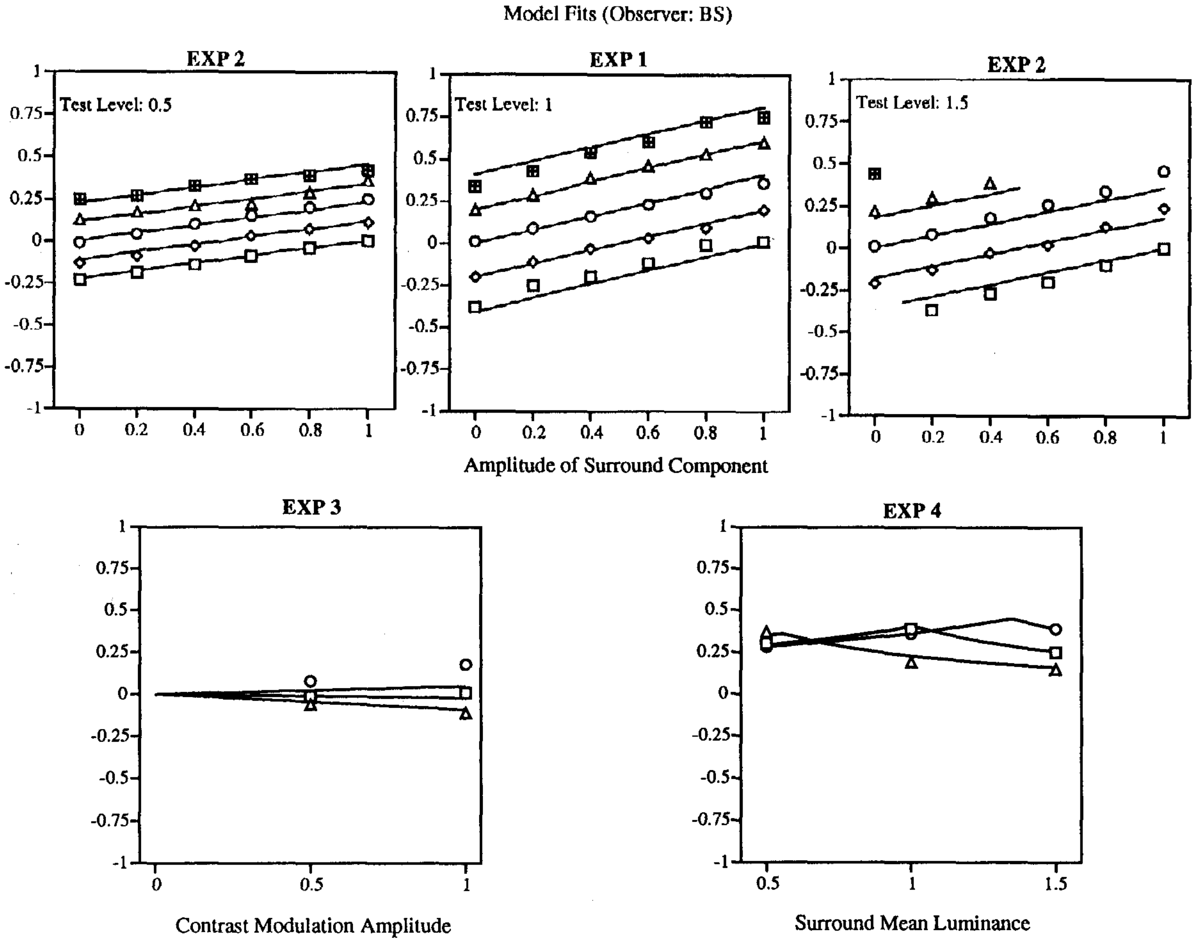

FIGURE 12. Best fitting predictions of the model shown with results of Experiments 1–4 for observer BS. All graphical conventions are identical to those in corresponding experiments.

TABLE 1. Parameter estimates for observers JS and BS

Observer	w	γ_S	γ_D	γ_C
JS	0.4908	1.087	0.1929	1.016
BS	0.4079	7.403	0.5671	3.762

The four parameters of the model were optimized to simultaneously fit all the data for each observer. Estimated parameters: w, scaling parameter; γ_S, local surround gain; γ_D, spatially extended surround-test difference gain; γ_T, local test gain.

neous fits of this model to the data from Experiments 1–4 are shown in Fig. 11 for observer JS and in Fig. 12 for BS. The values of the estimated parameters are presented in Table 1.

Figures 11 and 12 show that the model's predictions fit the data for both observers extremely well. The fit to data from Experiments 1 and 2 shows that at all fixed mean levels of test and surround, the model predicts a linear relationship between the amplitude of the modulation of the surround components and the nulling amplitude. It also accounts for the changes in the nulling modulation amplitude due to variations in the mean luminance level of the test.

The fit to the results of Experiment 3 is reasonably good. The model correctly predicts least brightness induction from changes in the spatial contrast of the surround when the test mean luminance level is equal to the surround. The relative amplitude and phase of brightness induction for tests whose mean luminance levels were higher or lower than the surround mean were also predicted by the model. However, the magnitude of brightness induction is somewhat underestimated for both observers.

The model's fits to the brightness induction data for different luminance levels of the uniform surround and test (Experiment 4), are also quite good. For all three test levels the model correctly predicts that the nulling modulation should have the greatest magnitude when the surround and text are at the same mean luminance. The model also predicts the monotonic decrease in the magnitude of the nulling modulation as the difference between the test and the surround mean luminance level increases.

It should be pointed out that the model can fit the data from each experiment almost perfectly if the parameters are estimated from just that set of data. We have required the model to simultaneously fit data that was collected over a 6 month period, with just a single set of parameters. We have also not tried to optimize the form

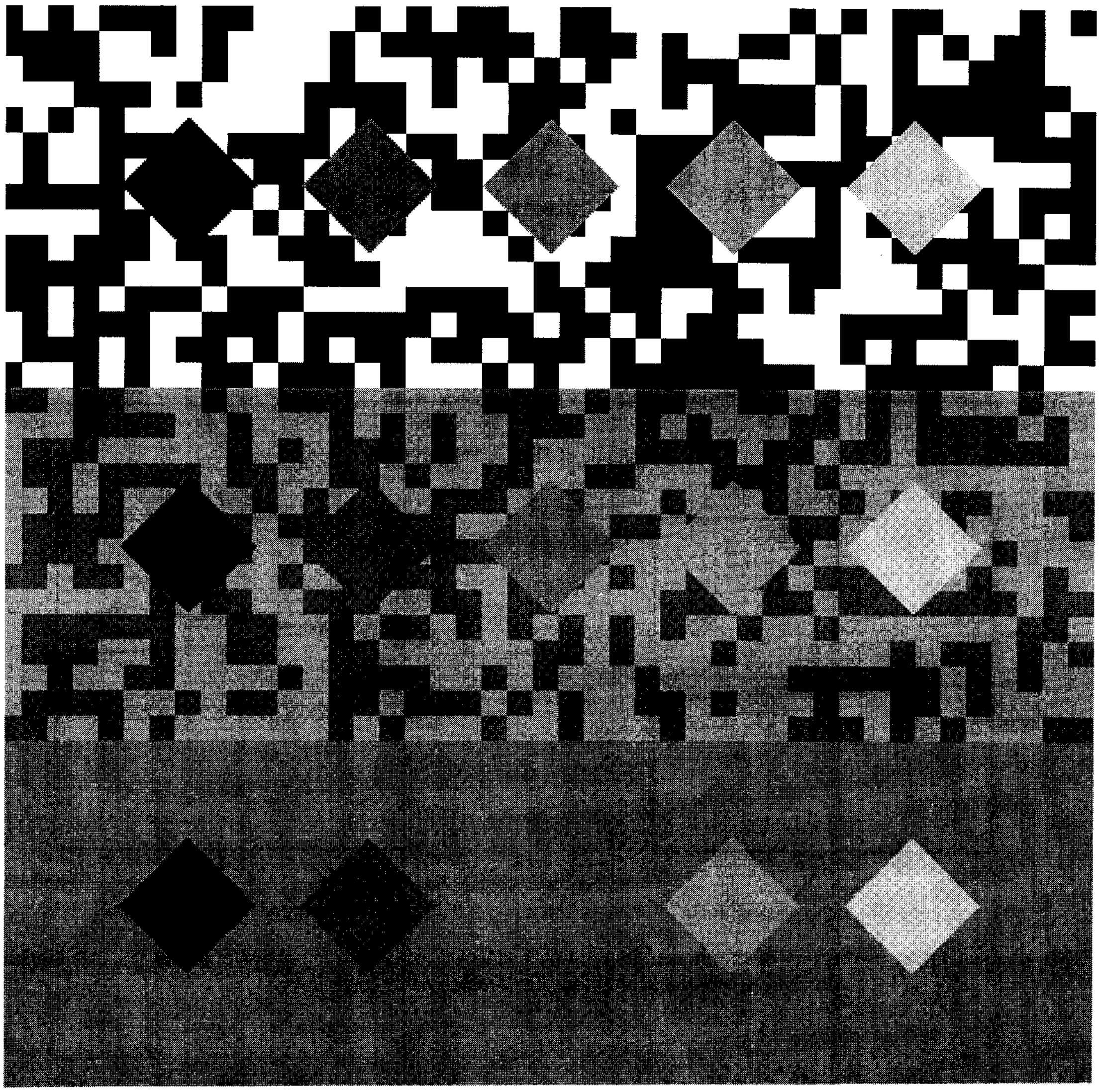

FIGURE 13. Brightness induction from random binary texture surrounds. The three vertical surround segments have equal spatially averaged luminance, while the spatial contrast progressively decreases from left to right (1.0, 0.33 and 0.0). Centered in each of the surround segments there are five spatially uniform diamonds with luminance decreasing from top to bottom. Diamonds across each row are of identical luminance. The luminance of the diamonds in the middle row is equal to the mean luminance of all the surround segments.

of the gain control function by adding extra parameters. The quantitative details of the model are not as important as the qualitative nature of the processes revealed by fitting the model to this set of data.

DISCUSSION

The results of the present study show that if local and spatially extended adaptation mechanisms are incorporated into a general model, brightness induction can be characterized as a linear summation of the induced effects of elements of complex surrounds. The present model incorporates separate local luminance gain controls in the test and the surround, and assumes that the magnitude of induction is gain controlled by the luminance difference between the test and each surround element. The fits of the model suggest that there are no fundamental differences between the mechanisms involved in brightness induced by complex or uniform surrounds.

There is a large amount of psychophysical and physiological evidence for the spatially local gain controls we have used (Chen *et al.*, 1987; Shapley & Enroth-Cugell, 1985). These adaptation mechanisms occur relatively early in the visual system. The novel suggestion in this model is the pair-wise spatially extended gain control on lateral interactions. Because the spatial weighting function for brightness induction falls off steeply as a function of distance from the test (Zaidi *et al.*, 1992), these pair-wise connections only have to straddle fairly short distances in retinal or cortical coordinates.

An alternative to this spatially extended gain control could be a static compressive non-linearity on these pair-wise connections. However, the predictions from a static non-linearity depart significantly from the straight lines required to fit the data from Experiments 1 and 2. The pair-wise gain control also makes different predictions than a pair-wise static non-linearity if the binary texture in Experiment 3 is replaced by dynamic random noise of the sort used by Chubb *et al.* (1989) to measure contrast-contrast. For a contrast modulated dynamic random noise surround, the time-averaged mean luminance is equal for all points in the surround, therefore, the gain control model predicts a marked reduction in brightness induction, whereas the static non-linearity predicts an induction level equal to that measured by Experiment 3. Measurements made by observer BS were in agreement with the predictions of the gain control mechanism.

Contrast-contrast has also been studied with spatially static noise patterns (Singer & D'Zmura, 1995; DeBonet & Zaidi, 1996). If the test disk in Fig. 1 was filled with spatially static noise of the same grain as the surround, then modulation of the contrast of the surround as in Fig. 8, would induce contrast modulation in the test. Our model incorporates point-by-point lateral interactions, and can be used to predict the brightness modulation induced into each element of the test. The model predicts that the brightness modulations induced into the lighter and darker elements of the test will be in opposite phase to the luminance modulations of the lighter and darker elements of the surround, respectively. Since the two luminance modulations are in opposite phase to one another, the induced modulations will also be in opposite phase, and the contrast inside the test will be seen to modulate in opposite phase to the surround. For our observers, the predicted amplitude of induced contrast-contrast was somewhat less than the measured amounts, indicating that in static noise patterns, induced brightness and induced contrast both play a role. It is clearly preferable to use dynamic random noise when studying the properties of contrast-contrast.

The time-varying methodology used in these experiments has enabled us to separate linear spatial summation from other effects due to luminance adaptation mechanisms. However, there is an important limitation to this methodology: the model predicts both time-varying and steady-state induction, but we were able only to measure time-varying induced effects. To judge how well our model would predict perceived gray levels in a static display, we used the demonstration shown in Fig. 13. The demonstration consists of three vertical surround segments of random binary texture with equal spatially averaged luminance and with spatial contrast progressively decreasing from left to right with values of 1.0, 0.3, and 0.0. Centered in each of the surround segments, there are five spatially uniform diamonds with luminance decreasing from the top to bottom. Diamonds across each row have identical luminance yet do not appear identical. Most observers see the diamonds as increasing in lightness from left to right in the top rows, and from right to left in the bottom rows. The relative rank of brightness for diamonds in each row can be predicted on the basis of the gain controls and linear summation embodied in this model. The induced brightness can then be added to the gain controlled physical luminance to generate a relative perceived gray level for each diamond. In the static case, our model predicts the perceived gray-level to be proportional to:

$$\Gamma_C \cdot C + I \tag{10}$$

where C is the luminance level of the test, Γ_C is given by equation (7) and I, which is constant for all t, is given by equation (6). Using the parameters estimated for observers JS and BS, we generated these predictions. The predicted rankings differed somewhat between observers, yet agreed almost perfectly with the actual rankings made by each observer (Zaidi *et al.*, 1995).

The success of the present model shows that in complex non-figural achromatic configurations, the perceived gray levels can be predicted by incorporating the effects of local and spatially extended adaptation mechanisms, and linear summation of the induced effects of individual elements of the surround. Even in configurations that allow figural interpretations, this model can be used to predict the effect of the non-figural gray-level variations. The effect of figural interpretations can then be isolated as departures from these predictions and studied independently.

REFERENCES

Adelson, E. H. (1990). Lightness judgments and perceptual organization. *Investigative Ophthalmology and Visual Science (Suppl.)*, *31*, 265.

Brown, R. O. & MacLeod, D. I. A. (1991). Induction and constancy for color saturation and achromatic contrast variance. *Investigative Ophthalmology and Visual Science (Suppl.)*, *32*, 1214.

Chen, B., MacLeod, D. I. A. & Stockman, A. (1987). Improvement in human vision under bright light: grain or gain? *Journal of Physiology, London*, *394*, 41–46.

Chevreul, M. E. (1839). *De la loi du contraste simultane des couleurs.* Paris: Pitois– Levreault.

Chubb, C., Sperling, G. & Solomon, J. A. (1989). Texture interactions determine perceived contrast. *Proceedings of the National Academy of Sciences*, *86*, 9631–9635.

Craik, K. J. W. (1938). The effect of adaptation on differential brightness discrimination. *Journal of Physiology*, *92*, 406–421.

DeBonet, J. S. & Zaidi, Q. (1996). Comparison between spatial interactions in perceived contrast and perceived brightness. *Vision Research*, in press.

De Valois, R. L., Webster, M. A. & De Valois, K. K. (1986). Temporal properties of brightness and color induction. *Vision Research*, *26*, 887–897.

Gilchrist, A. L. (1980). When does perceived lightness depend on perceived spatial arrangement? *Perception and Psychophysics*, *28*, 527–538.

Judd, D. B. (1966). Color appearance. *Proceedings international color meeting*, Lucerne, Switzerland, 1965 (Vol. 1, pp. 27–51). Gottingen: Musterschmidt.

Krauskopf, J., Zaidi, Q. & Mandler, M. B. (1986). Mechanisms of simultaneous color induction. *Journal of the Optical Society of America, A3*, 1752–1757.

Schirillo, J. A. & Shevell, S. K. (1993). Brightness contrast from a complex surround requires a complex description. *Investigative Ophthalmology and Visual Science*, *34*, 219.

Shapley, R. & Enroth-Cugell, C. (1985). Visual adaptation and retinal gain controls. *Progress in Retinal Research*, *3*, 263–346.

Singer, B. & D'Zmura, M. (1995). Contrast gain control: a bilinear model for chromatic selectivity. *Journal of the Optical Society of America, A12*, 667–674.

Spehar, B., Gilchrist, A. L. & Arend, L. A. (1995). White's illusion and brightness induction: The critical role of luminance relations. *Vision Research, 35,* 2603–2614.

Valberg, A. & Lange-Malecki, B. (1990). 'Colour constancy' in Mondrian patterns: a partial cancellation of physical chromaticity shifts by simultaneous contrast. *Vision Research, 30,* 371–380.

Watson, A. B. (1986). Temporal sensitivity. In Boff, K. R., Kaufman, L. & Thomas, J. P. (Eds), *Handbook of perception and human performance. Vol. 1.* New York: John Wiley.

Zaidi, Q. (1990). Apparent brightness in complex displays. *Vision Research, 30,* 1253–1255.

Zaidi, Q., DeBonet, J. & Spehar, B. (1995). Perceived grey-levels in complex configurations. *Proceedings of the IS and T/SID's Third Color Imaging Conference,* 39–42.

Zaidi, Q., Yoshimi, B. & Flanigan, N. (1991). The influence of shape and perimeter length on induced color contrast. *Journal of the Optical Society of America, A8,* 1810–1817.

Zaidi, Q., Yoshimi, B., Flanigan, N. & Canova, A. (1992). Lateral interactions within color mechanisms in simultaneous induced contrast. *Vision Research, 32,* 1695–1707.

Zaidi, Q. & Zipser, N. (1993). Induced contrast from radial patterns. *Vision Research, 33,* 1281–1286.

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