Perceived Grey-Levels in Complex Configurations

Qasim Zaidi, Jeremy S. DeBonet and Branka Spehar
SUNY College of Optometry, New York, New York

Abstract

We present a non-recursive integral-equation model that predicts perceived grey levels in complex achromatic displays as a function of the physical luminances of individual pixels in the display. The model incorporates spatially local luminance adaptation mechanisms, contrast gain controls and spatial distance dependent weights on lateral connections, and linear summation of the induced effects of individual surrounding pixels.

Introduction

Empirical measurements made by Chevreul[4] showed that in a complex display, the perceived brightness of a patch depends not only on its physical luminance, but also on simultaneously induced brightness from surrounding patches. Since this work, extensive empirical research has been conducted on induced brightness from variegated surrounds. Figure 1 demonstrates a particularly interesting case. This figure consists of three vertical surround segments filled with random binary texture. The space-averaged luminance of the three segments is equal and the spatial contrast progressively decreases from left to right with values of 1.0, 0.3 and 0.0 Michelson contrast. Centered in each of the surround segments are five spatially uniform diamonds decreasing in luminance from top to bottom. Diamonds across each row have identical luminances yet they 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, indicating that the magnitude of induced brightness from a surround varies as a function of the relative luminance of the test. The purpose of this study was to identify the different factors involved in brightness induction from such achromatic, variegated, and non-figural surrounds, and to generate a tractable model for computing perceived grey-levels.

Zaidi, Yoshimi, Flannigan and Canova[14] and Zaidi and Zipser[15] used basis functions consisting of radially and concentrically varying spatial sinusoids to examine the effects of spatially complex surrounds. They showed that brightness induction can be characterized as a linear spatial integration process in which the effects of different parts of the surround are weighted by a negative exponential function of distance from the test. Their results were consistent with the assumption that the total induced effect of the surround is simply the sum of the induced effects of individual surrounding points. Similarly, Valberg and Lange-Malecki (1990) showed that in certain conditions, a spatially uniform surround and a spatially complex surround of the same space-averaged luminance have identical inducing effects on a central test .

Other studies, however, have demonstrated failures of additivity of surround effects in brightness induction[7,5,13,1,11]. In the stimuli used in some of these studies, more complex attributes such as shape, transparency, or depth could be inferred, and higher cognitive mechanisms may be responsible for the observed failures of additivity. The complex effects reported by Brown and MacLeod[2] and Schirillo and Shevell[10], however, were based on spatially variegated but non-figural surrounds. Zaidi et. al.[14] and Zaidi and Zipser[15] had provided evidence for additive lateral combination by equating the time-averaged luminance of all points in the stimulus. This was not true in the series of studies which exhibited failures of additivity, thus making it imperative to explicitly consider spatially local and extended adaptation mechanisms.

Model

We have found that the perceived relative grey-levels of test patches in this display and other complex (but non-figural) achromatic spatial configurations can be predicted by the expression:

$$P_T = \Gamma_T \cdot T + I_T \tag{1}$$

i.e. P_T the predicted perceived grey-level is equal to T the luminance of the test multiplied by the gain factor for that luminance level, Γ_T (Equation 2), plus I_T the total induced brightness on the test (Equation 3).

Γ_T is set by local adaptation mechanisms that affect the perceived brightness of the test. We assume that this gain is set only by the luminance level of the test, and is independent of the brightness induction mechanism. We model this gain by the hyperbolic function:

$$\Gamma_T = \frac{\gamma_T}{\gamma_T + T} \tag{2}$$

where γ_T is a constant parameter for each observer.

The total induced brightness is equal to the sum of the individual induced effects from all of the points in the surround. The induced effect from each point in the surround is proportional to its luminance attenuated by two gain controls and a spatial weighting function:

$$I_T = -\int_0^{2\pi} \frac{\int_0^{\infty} W(s) \cdot \Gamma_D(\Omega,s) \cdot \Gamma_S(\Omega,s) \cdot A(\Omega,s)\ ds}{2\pi} d\Omega \tag{3}$$

where I_T is the total induced effect on the test patch; (Ω, s) are the polar coordinates of a surround point, Ω is the angular direction in radians and s the spatial distance from the test in degrees of visual angle; $A(\Omega, s)$ is the luminance at that point. $W(s)$ is a monotonically decreasing spatial weighting function of s, that can be well approximated by a negative exponential function with two parameters[14]:

$$W(s) = \kappa e^{-\alpha s} \tag{4}$$

We assume that the response of the visual system at a given point to a luminance $A(\Omega, s)$, is gain controlled by the luminance level at that point, as a hyperbolic function:

$$\Gamma_S(\Omega,s) = \frac{\gamma_S}{\gamma_S + A(\Omega,s)} \tag{5}$$

where γ_s is a constant parameter for each observer. We found that in complex displays, the magnitude of induction also depends on the pair-wise differences between the luminance levels of the test and individual surround points. We modeled this by attenuating the induction signal by a hyperbolic function of the absolute difference between the luminance at each point and the luminance of the test:

$$\Gamma_D(\Omega,s) = \frac{\gamma_D}{\gamma_D + \left|\Gamma_S(\Omega,s).A(\Omega,s) - \Gamma_T T\right|} \tag{6}$$

where γ_D is another constant parameter for each observer.

Tests

We have tested a temporal version of this model with an extensive set of psychophysical[12]. In these experiments, 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 was controlled independently so as to modulate the luminance and/or the contrast of the surround. Brightness induction was measured using a modulation nulling technique[8]. The time varying methodology used in these experiments enabled us to separate linear spatial summation from the effects of brightness adaptation mechanisms. For each observer, using a standard simplex minimizing algorithm, we estimated a single set of parameters for the model that produced a good fit to the data from all the experiments.

In this paper we tested predictions from the static version of the model for the display shown in Figure 1. Two observers were asked to rank the perceived lightness of the diamonds in each row (1 = lightest). Using the parameters estimated for each observer by Spehar, De Bonet and Zaidi[12], the relative perceived grey-levels for diamonds in each row were predicted from the model. As the tables at the bottom of Figure 1 show, the predicted rankings differed somewhat between observers, yet agreed almost perfectly with the actual rankings made by each observer.

Discussion

There is a large amount of psychophysical and physiological evidence for the spatially local gain controls we have used [3,9]. These adaptation mechanisms are known to occur relatively early in the visual system. The novel suggestion in this model is the pair-wise spatially extended gain control on lateral interactions. Since the spatial weighting function for brightness induction falls off steeply as a function of distance from the test, these pair-wise connections can be restricted to fairly short distances in retinal or cortical coordinates.

This model decouples the inducing signal from the induced signal. There is no psychophysical or physiological evidence that the out-going inducing signal from a point is affected by in-coming induced signals. The decoupling removes the need to make a recursive model like Grossberg and Todorovic's[6], and results in computational simplicity.

The success of the present model shows that perceived grey levels can be predicted in complex achromatic configurations by incorporating the effects of local and spatially extended adaptation mechanisms, and linear summation of the induced effects of individual elements of the surround. The model consists of a simple non-recursive integral equation with the only independent variables being the physical luminances of individual pixels, making it easy to implement for arbitrary, non-figural, achromatic displays.

References

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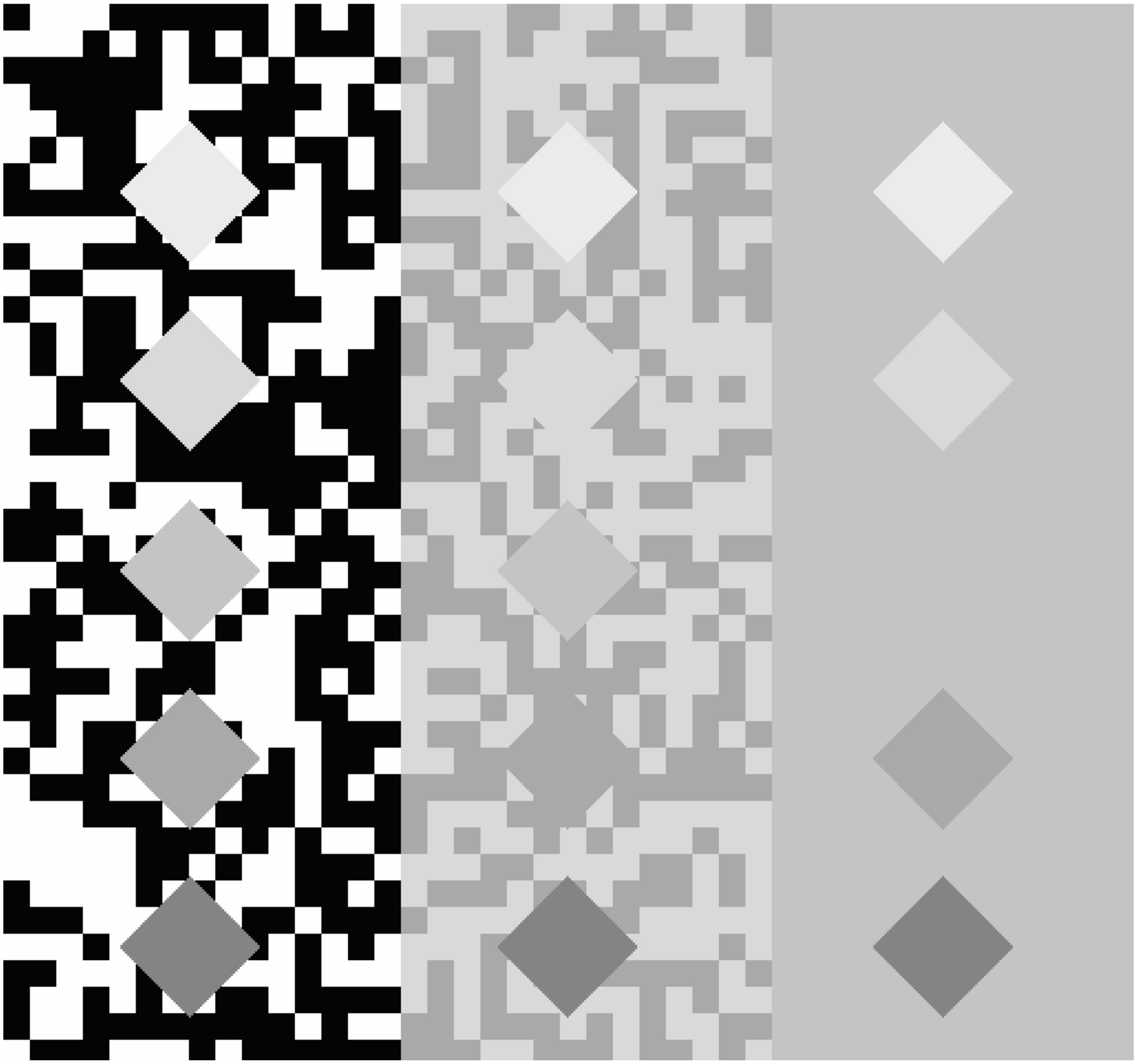

Observer JS			**Observer BS**		
3 (3)	**2 (2)**	**1 (1)**	**3 (3)**	**2 (2)**	**1 (1)**
1 (1)	**2 (3)**	**3 (2)**	**3 (2)**	**2 (3)**	**1 (1)**
1 (1)	**2 (2)**	**3 (3)**	**1 (1)**	**2 (2)**	**3 (3)**
1 (1)	**2 (2)**	**3 (3)**	**1 (1)**	**2 (2)**	**3 (3)**
1 (1)	**2 (2)**	**3 (3)**	**1 (1)**	**2 (2)**	**3 (3)**

Figure 1. Brightness induction from random-binary-textured 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 columns are five spatially uniform diamonds with luminance decreasing from top to bottom. The luminance of the diamonds in the middle row is equal to the mean luminance of the surround segments. Diamonds across each row are of identical luminance but their perceived lightnesses differ. For two observers the ***empirical*** *and* ***(predicted)*** *ranked lightness of diamonds within each row are presented in a similar configuration as the display.*

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