A neural model of surface perception: Lightness, anchoring, and filling-in

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Abstract—A neural model is proposed of how the visual system processes natural images under variable illumination conditions to generate surface lightness percepts. Previous models clarify how the brain can compute relative contrast. The anchored Filling-In Lightness Model (aFILM) clarifies how the brain ‘anchors’ lightness percepts to determine an absolute lightness scale that uses the full dynamic range of neurons. The model quantitatively simulates lightness anchoring properties (Articulation, Insulation, Configuration, Area Effect) and other lightness data (discounting the illuminant, the double brilliant illusion, lightness constancy and contrast, Mondrian contrast constancy, Craik-O’Brien-Cornsweet illusion). The model clarifies how retinal processing stages achieve light adaptation and spatial contrast adaptation, and how cortical processing stages fill-in surface lightness using long-range horizontal connections that are gated by boundary signals. The new filling-in mechanism runs 1000 times faster than diffusion mechanisms of previous filling-in models.

Keywords: Surface perception; lightness; anchoring; filling-in; retinal adaptation; long-range horizontal connections; visual cortex.

1. INTRODUCTION

1.1. From luminance to anchored lightness

The retina receives luminance signals, which are a product of reflectances and illumination levels (Hurlbert, 1986; Lambert, 1760; Wyszecki and Stiles, 1982), from objects in the world. Surface reflectances, or the percentages of light reflected by a surface in each wavelength (also known as albedo), provide information about the material properties of objects. From these luminance signals, the visual system is able to estimate object reflectances by compensating for an immense dynamic

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range of mean illuminations across time, and for a wide dynamic range across a single scene. This process of ‘discounting the illuminant’ is not sufficient, however, to efficiently see the world because illuminant-discounted signals may represent only the relative amounts of light that each object surface reflects to the eyes. For effective perception, the brain also needs to compute an absolute lightness scale that can represent the full-range of experience from dim moonlight to dazzling sunlight.

Early neural models of surface lightness perception simulated many classical psychophysical data based upon estimates of relative light levels, including brightness constancy, contrast, and assimilation; Craik-O’Brien-Cornsweet effect; Koffka-Benussi ring; Kanizsa-Minguzzi anomalous brightness differentiation; Hermann grid; Land Mondrians viewed under constant and gradient illumination conditions that could not be explained by Land’s Retinex theory; Bergström brightness percepts of step-like and smoothly modulated luminance profiles; Hamada brightness percepts of luminance increments and decrements; Mach bands; low-contrast and high-contrast missing fundamental and nonlinear contrast effects associated with sinusoidal luminance waves; and Ehrenstein brightness enhancement (Cohen and Grossberg, 1984; Gove et al., 1995; Grossberg and Todorovic, 1988; Neumann et al., 1998). Consistent extensions of these models simulated 3D figure–ground brightness percepts, such as Fechner’s paradox; binocular brightness summation; Bregman-Kanizsa figure–ground separation; Kanizsa stratification; Munker-White effect; Benary cross; checkerboard percepts; McCollough effect; Necker cube; transparency, and 3D neon color spreading (Grossberg et al., 2002; Grossberg and Kelly, 1999; Grossberg and Swaminathan, 2004; Grossberg and Yazdanbakhsh, 2003, 2005; Kelly and Grossberg, 2000; Ross and Pessoa, 2000).

Given the large amount of already simulated data, the present article developed a model that is consistent with these earlier explanations, while also proposing how an absolute lightness scale may be constructed by the brain. To realize this goal, the new anchored Filling-In Lightness Model (aFILM) provides a more sophisticated account of early visual filtering, lightness filling-in, and lightness anchoring. The model quantitatively simulates, for the first time, key psychophysical data about lightness anchoring, as well as other lightness data to show that it is consistent with earlier model explanations. Neurophysiological and anatomical data that support model hypotheses are also summarized (see Table 1). aFILM can also process complex natural scenes under difficult lighting conditions. Although the present work focuses on achromatic images, a variant of the model has been shown capable of processing chromatic natural images as well (Hong and Grossberg, 2004). The model was briefly reported in Hong and Grossberg (2003).

1.2. Discounting the illuminant by early visual preprocessing

Retinal preprocessing of visual signals contributes to discounting the illuminant and creating a relative lightness scale. These processes include two mechanisms of gain control: light adaptation and contrast adaptation. Human vision adapts to ten orders of magnitude of daily variations of ambient illumination (Cornsweet, 1970;