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The psychophysics of detecting binocular discrepancies of luminance

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ABSTRACT

In the natural world, a binocular discrepancy of luminance can signal a glossy surface. Using a spatial forced choice task, we have measured the ability of subjects to detect binocular luminance disparities. We show that the detection of binocular luminance disparity shares several basic psychophysical features with the detection of surface properties such as lightness and chromaticity: an approximation to Weber's Law, spatial summation, temporal summation, and a deterioration with increasing eccentricity. We also discuss whether color-deficient subjects could derive reliable information about chromaticity from the binocular disparities of luminance induced by a monocularly worn color filter.

1. Introduction

When the cyclopean visual system is presented with monocular stimuli of discrepant luminances, the two stimuli may be combined so that the fused percept has an intermediate brightness. The rules that govern this binocular summation of brightness have been investigated (e.g. Anstis & Ho, 1998; Curtis & Rule, 1978; Dawson, 1913; De Weert & Levelt, 1974; Engel, 1969; Levelt, 1965a; Sherrington, 1904; Teller & Galanter, 1967). However, the discrepant monocular images may also result in a number of other binocular percepts, such as binocular luster (e.g. Helmholtz, 1909; Pieper & Ludwig, 2002; Sheedy & Stocker, 1984; Yoonessi & Kingdom, 2009), binocular rivalry (Ludwig, Pieper, & Lachnit, 2007; Wolfe & Franzel, 1988), the sieve effect, the floating effect (Howard, 1995) or the Venetian blinds effect (Cibis & Harris, 1951). The exact nature of the percept is determined by the spatial and luminance profiles of the monocular images. Although these several effects have usually been studied by deliberately creating different dichopic images in a laboratory, it could be argued in each case that a particular three-dimensional arrangement in the real world would give rise to the corresponding percept.

1.1. Role of binocular luminance disparity in the perception of gloss

The reflectance properties of a surface can be represented as a sum of diffuse and specular reflections. Specular reflections are associated with glossy surfaces, and judgments of surface gloss are affected by the fraction of light that is reflected in the specular direction and by the spread of light to either side of the specular direction (Hunter, 1937; Hunter & Harold, 1987). The rating of the glossiness of a surface increases with an increase in the specular component (e.g. Wendt, Faul, & Mausfeld, 2008). The specular component is reflected at the same angle as the angle of incidence or is distributed around that angle. If the illuminant is directional, the intensity of the light reflected from glossy surfaces will therefore be different for different viewpoints, with the difference determined by the specular component (Bhat & Nayar, 1998). In other words, a given point on a glossy surface will usually present discrepant luminances to the two retinas: Since the surface reflects more light in one direction than another and since the two eyes are laterally separated, the light reaching one eye will be greater than that reaching the other (Ludwig et al., 2007; McCamy, 1998; Oppel, 1854). The visual system may therefore be exposed to discrepant levels of monocular luminances when viewing glossy surfaces. This discrepancy, which may subjectively be seen as luster, is potentially a cue to the smoothness or shininess of the surface (McCamy, 1998; Tyler, 1983, 2004). However, the percept of gloss has been shown to be multidimensional (e.g. Billmeyer & O'Donnell, 1987; Ferwerda, Pellacini, & Greenberg, 2001; Harrison & Poulter, 1951) and the binocular disparity of luminance would be only one of several cues that determine this complex percept.

Many of the classical studies of binocular luster studied monocular stimuli that are not just of different luminances but are of reversed contrast polarity. Dove (1851) viewed a stereoscopic pair of images, one of which had a white outline drawing of a geometrical figure on a black background and the other a black outline on a white background: When the images were fused, the solid appeared lustrous (see also Helmholtz (1909) and Whittle (1994)).

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Rated binocular luster peaks when the monocular spots have opposite contrast polarities in the two eyes (Anstis, 2000), but some level of luster may also be perceived when the contrast polarity of the dichoptic spots is the same (but their contrasts or luminances differ) (Anstis, 2000; Pieper & Ludwig, 2002; Sheedy & Stocker, 1984). In the natural world a local highlight visible to one eye will rarely be matched by an actual decrement in the other eye; and in the present paper we confine ourselves to the case where the dichoptic stimuli have the same contrast polarity. Without inquiring into the exact nature of the subjective percept that is being used, we measure the observer's ability to detect the binocular luminance disparity.

1.2. Binocular luminance disparity as a cue for the daltonian

Monocularly worn tinted filters have been proposed as a treatment for color deficiency (Cornsweet, 1970; Harris, 1998; Zeltzer, 1971). These could improve color discrimination by increasing the gamut of chromatic or luminance variation within a visual scene. However, monocular filters could also introduce a discrepancy in the intensity and chromaticity of light reaching the two eyes from a given surface. It has been suggested that the induced discrepancy of luminance, perceived subjectively as luster, could be used by color-deficient individuals to improve their color discrimination (Heath, 1974; Schmidt, 1976; Sheedy & Stocker, 1984). The amount of discrepancy between the monocular luminances produced by a given filter will depend on the spectral reflectance of the object, the spectral power distribution of the illuminant and the transmission spectrum of the monocular filter (see Fig. 1). The degree of this discrepancy will affect the probability of an object looking lustrous (Pieper & Ludwig, 2002), and so the probability of seeing luster will vary according to the spectral power distributions of different stimuli. The daltonian could learn to use this new sensory cue to discriminate colors that would normally be confused. The daltonian would be able to distinguish between true gloss and the luster produced by the colored lens, because there is usually a spatial binocular disparity of highlights in the former case but would not be in the second case. Whether the subjective percept was actually luster or rivalry (or indeed – after training – a chromatic one), the objective luminance discrepancy between the eyes could provide the daltonian with a cue to real-world spectral differences to which he was otherwise blind.

1.3. Aims of the present study

In the experiments below, we examine the rules that govern the detection of the binocular disparity in the intensity of light reaching the eyes from a given point in the scene. This cue potentially indicates the surface property of gloss in the real world and we ask whether the rules governing its detection are comparable to those that govern the detection of other surface properties such as lightness and chromaticity. We ask some of the basic questions that a psychophysicist might ask when first approaching lightness or chromaticity: Does the detection of binocular luminance disparity obey Weber's Law? Does it exhibit spatial summation comparable to that described by Riccó's Law? Does it exhibit temporal summation comparable to that described by Bloch's Law?

Our secondary purpose was to discover whether the rules that govern the detection of binocular luminance disparity would allow the luminance discrepancy induced by colored monocular filters to be used by daltonians to discriminate spectral power distributions that they were unable to discriminate under normal circumstances. If we know the typical human thresholds for detecting binocular luminance disparity, we can in principle estimate the number of detectable disparities that would be introduced into a natural scene by a monocular filter worn by a daltonian.

Our measurements were of psychophysical performance rather than phenomenological judgment. An analogy could be made here with another surface property, color: Some experiments on color vision are concerned with the observer's subjective judgment of hue whereas others strictly measure the ability to discriminate chromaticity. In studies of gloss and luster, the dependent measures have most often been phenomenological. Our limited aim in the present study is to apply performance psychophysics to the detection of binocular luminance disparity. Another example of the use of performance measures to establish dichoptic thresholds is seen in a recent study of natural images by Yoonessi and Kingdom (2009).

Operationally, we required our subjects to detect a target that had discrepant monocular luminances in a four-alternative spatial forced choice. It was therefore critical to ensure that only this cue could be used to solve the task. In the Methods we describe how the distractor stimuli were chosen to guarantee that the subject could not identify the target either by using monocular luminance or by using the binocular sum of the monocular luminances.

2. Experiment 1A: discrepant incremental contrasts

2.1. Method

2.1.1. Apparatus and stimuli

Stimuli were presented dichoptically on a Sony Trinitron monitor driven by a Visual Stimulus Generator (VSG 2/5; Cambridge Research Systems Ltd.), with a frame rate of 100 Hz and resolution 800×600 pixels. The monitor was calibrated using a CRS Ltd. ColorCal colorimeter. The stimuli were fused by means of a

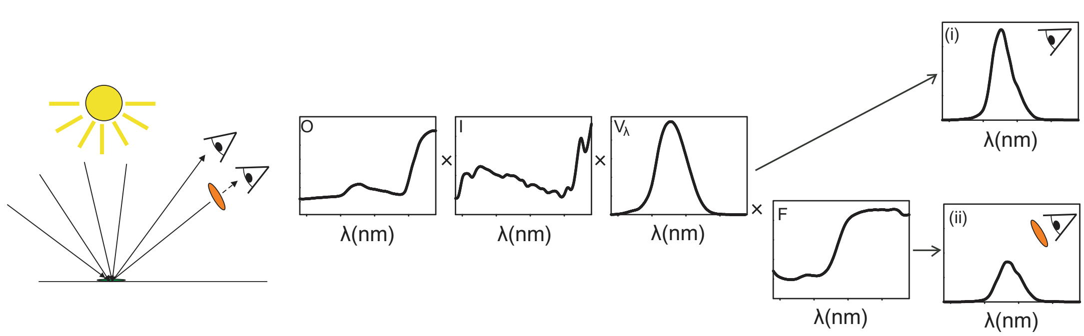

Fig. 1. Discrepant monocular luminances can be introduced by a monocularly worn filter. The luminance of the object seen by the eye without the filter is calculated by multiplying the spectral reflectance of the object (O) by the spectral radiance of the illuminant (I) and by the spectral luminosity function (V_λ). To calculate the luminance seen by the eye wearing the filter, this product is also multiplied by the transmission spectrum of filter (F). Each result ((i) and (ii)) is then integrated across wavelength to obtain the luminance as seen by each eye.