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Chromatic and wavefront aberrations: L-, M- and S-cone stimulation with typical and extreme retinal image quality

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ABSTRACT

The first physiological process influencing visual perception is the optics of the eye. The retinal image is affected by diffraction at the pupil and several kinds of optical imperfections. A model of the eye (Thibos & Bradley, 1999), which takes account of pupil aperture, chromatic aberration and wavefront aberrations, was used to determine wavelength-dependent point-spread functions, which can be convolved with any stimulus specified by its spectral distribution of light at each point. The resulting retinal spectral distribution of light was used to determine the spatial distribution of stimulation for each cone type (S, M and L). In addition, individual differences in retinal-image quality were assessed using a statistical model (Thibos, Bradley, & Hong, 2002) for population values of Zernike coefficients, which characterize imperfections of the eye's optics. The median and relatively extreme (5th and 95th percentile) modulation transfer functions (MTFs) for the S, M and L cones were determined for equal-energy-spectrum (EES) 'white' light. The typical MTF for S cones was more similar to the MTF for L and M cones after taking wavefront aberrations into account but even with aberrations the S-cone MTF typically was below the M- or L-cone MTF by a factor of at least 10 (one log unit). More generally, the model presented here provides a technique for estimating retinal image quality for the S, M and L cones for any stimulus presented to the eye. The model is applied to some informative examples.

1. Introduction

A single point of monochromatic light that enters the eye has a two-dimensional retinal image due to diffraction and imperfections of the eye's optics. The retinal image can be characterized by a point spread function (PSF), which varies with the wavelength of light. With broadband light, the retinal image is determined by decomposing the point of light into its spectral components; the PSF is applied separately at each wavelength (Barnden, 1974; Ravikumar, Thibos, & Bradley, 2008). The distribution of light on the retina is the superposition of the light distributions for each of the wavelengths. When an observer views a complete scene rather than a single point, each point in the scene is independently affected by the eye's optics; conceptually, the resulting retinal image at each wavelength is the superposition of the distribution of light from each point in the scene. Retinal image quality depends on both the PSF for each wavelength and the spatial and spectral distribution of the light in view.

Optical models of the eye have been sought for centuries for a variety of applications (Emsley, 1952; Smith, 1995). A relatively recent model (Thibos & Bradley, 1999) was used here to determine the spatial and spectral distribution of light on the retina; this distribution then was used to find the spatial distribution of light for each receptoral cone class, L, M and S. This model has two advantages in comparison to Marimont and Wandell's (1994) well known model of retinal image quality. First, higher-order wavefront aberrations were considered explicitly here rather than as an implicit property of a wavelength-independent point spread function (Marimont & Wandell, 1994, p. 3116). Second, the Thibos and Bradley model-eye depends on specific parameters (Zernike coefficients) that characterize an individual eye, and these parameters have a known multivariate population distribution. The population distribution allowed estimates of individual differences in retinal image quality among people with normal corrected vision (Thibos, Bradley, & Hong, 2002). While a general comparison of the retinal image quality given by the Marimont and Wandell model versus the one used here is not possible because the models depend on different assumptions, results from the two models are compared in Section 5 using a typical eye from the population distribution given by Thibos, Bradley, and Hong (2002). The two models agree well in this special case (as discussed later).

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The first part of this paper focuses on retinal image formation. The optical model is described and the calculated photoreceptor absorptions are explained. In the second part, the model is applied to broadband 'white' spectral stimuli to assess typical and extreme retinal contrast sensitivity in a normal population of human observers. The third part considers some specific cases to show how retinal image quality depends on particular features of a visual stimulus, and to demonstrate how the model may be applied to particular types of images.

2. Part 1: Retinal image model

The retinal image is determined by characterizing the eye's optics. Any optical system can be fully described mathematically over an isoplanatic area by its optical transfer function (Williams & Becklund, 1989) so calculating the retinal image involves determining the eye's optical transfer function (OTF) or the closely related point spread function (PSF). The PSF gives the retinal image of a monochromatic point source, taking account of the optics of the eye. The OTF is the Fourier transform of the intensity PSF.

A precise model of the eye includes various optical factors that affect the PSF at each wavelength. This section covers the main properties of the model eye used to determine the PSFs. Recall that the external stimulus pattern entering the eye is decomposed into multiple monochromatic stimulus patterns, and then the stimulus pattern at each wavelength is convolved with its wavelength-dependent PSF. This gives the retinal image $I(x,y,\lambda)$ at each wavelength λ. Superposition of these monochromatic retinal patterns yields the retinal spectral distribution of light for each spatial location (x,y). These spectral distributions allow calculation of the spatial distribution $I_C(x,y)$ of cone excitation for each cone type C (C = L, M or S) by applying the appropriate cone spectral sensitivity function $S_C(\lambda)$ as a weighting factor:

$$I_C(x,y) = \int S_C(\lambda) I(x,y,\lambda) d\lambda. \quad (1)$$

2.1. Optics of the human eye

The human eye has three main optical components that affect retinal image quality: the pupil, the cornea and the lens. The pupil diffracts light entering the eye, resulting in a PSF with a central point surrounded by concentric rings (Roorda, 2002; Williams & Hofer, 2004). The cornea accounts for most of the eye's refraction (about 43 diopters) while the lens, which refracts light after passing through the pupil, adds more than 20 diopters in a young adult (Roorda, 2002). The cornea and lens are the primary contributors to wave aberrations, which degrade retinal image quality. In the study here, all of these factors were combined into a reduced-eye optical model containing a pupil and a single refracting surface that is distorted from an optically perfect ellipse to exactly mimic the monochromatic aberrations of the whole eye (Ravikumar, Thibos, & Bradley, 2008). To account for individual variation, numerous such models were constructed using a statistical distribution of aberrations in a normal population of healthy adult eyes, as elaborated below. The monochromatic imaging capability of each model eye is summarized by its PSF.

Longitudinal chromatic aberration (LCA) is a consequence of refraction by a dispersive medium: light of different wavelengths is brought into focus at different distances. The focal distance increases with wavelength. LCA was included in the model by allowing the Zernike coefficient C_2^0 for defocus to vary with wavelength as prescribed by the Indiana Eye model of chromatic aberration (Thibos, Ye, Zhang, & Bradley, 1992). Transverse chromatic aberration was ignored because of its weak marginal influence on image quality when LCA and wave aberrations are considered (Ravikumar, Thibos, & Bradley, 2008). Similarly, the slight effect of higher-order chromatic aberrations on image quality was not included (Nam, Rubinstein, & Thibos, 2010).

Retinal image quality depends on pupil size and the wavelength of light. The greatest loss of image quality from diffraction occurs with a small pupil and long wavelengths. On the other hand, the greatest loss from refractive elements occurs with a large pupil and short wavelengths. The sharpest retinal image, therefore, typically is at an intermediate pupil size near 3 mm, which balances the tradeoff between diffraction (worse at smaller pupil diameters) and the deleterious effects of wave aberrations (worse at larger diameters).

The best known wave aberrations caused by the eye's optics are defocus and astigmatism, which are ameliorated by standard corrective lenses. Higher-order wave aberrations (trefoil, coma, spherical, as well as other still higher-order aberrations) also reduce image quality (Packer & Williams, 2003). The imperfections captured by the higher-order wave aberrations include the irregularities in optical elements within the eye. The eye's lower- and higher-order wave aberrations can be modeled accurately using Zernike polynomials; the first 15 Zernike mode numbers were used here for the polynomials (Thibos & Bradley, 1999; Thibos, Hong, Bradley, & Cheng, 2002). Statistical sampling of Zernike aberration coefficients produced a random sample of 100 model eyes for analysis, each of which yielded monochromatic PSFs that were representative of human eyes (Thibos, 2009).

As mentioned above, each wavelength of light is affected differently by the optics of the eye so each wavelength has its own distinct PSF; we refer to the set of PSFs for all wavelengths in the visible spectrum as a hyperspectral PSF. Spectral sampling here was every 10 nm, a choice supported by the analysis of Ravikumar, Thibos, and Bradley (2008). A hyperspectral PSF captures two important aspects of retinal image quality. First, an object with a single broadband chromaticity, such as equal-energy-spectrum 'white', does not necessarily produce on the retina an image at only that chromaticity because some wavelengths are more strongly dispersed than others. Second, spectral mixtures that are visually indistinguishable in color as large homogenous patches (color metamers) may not match at other spatial frequencies because the wavelengths composing each metamer are unequally affected by optics (Marimont & Wandell, 1994; Poirson & Wandell, 1993).

An implication of the second point is that the influence of optics on the retinal image can be determined only from the full spectral distribution of light entering the eye. In general, a trichromatic description of the light – for example CIE X,Y,Z tristimulus values or the excitations of the three types of cones – is not sufficient. While some special cases can reduce the computational burden of multiple convolutions (for example, spectral homogeneity where every point in the image emits the same relative radiance spectrum, or when the full spectral distribution is uniquely determined by the trichromatic specification; Barnden, 1974; Ravikumar, Thibos, & Bradley, 2008), these conditions rarely occur in the natural world.

2.2. Cone quantal absorptions

Transduction of light at the photoreceptors establishes the neural responses that mediate vision. There are three classes of cone photoreceptor, labeled S, M and L, with peak sensitivity in the short-, middle- or long-wave part of the visible spectrum, respectively. The response of each cone type depends on the rate of quantal absorption. The relative spectral sensitivity of each type of cone is known (Smith & Pokorny, 1975) so the rate of quantal absorption for S, M or L cones can be calculated directly from the spectral energy distribution of light at each point on the retina. (The spacing