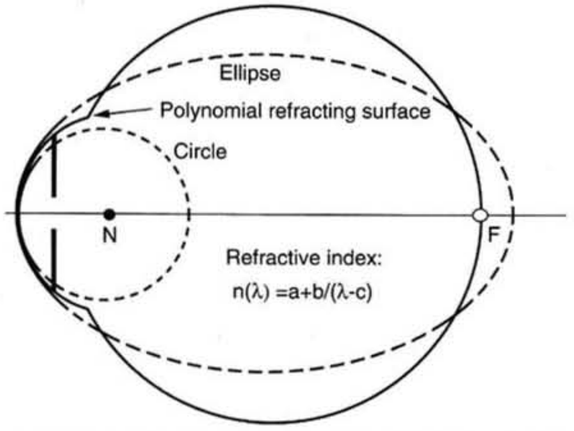
A New Optical Model of the Human Eye

BY LARRY N. THIBOS, MING YE, XIAOXIAO ZHANG, AND ARTHUR BRADLEY, SCHOOL OF OPTOMETRY, INDIANA UNIVERSITY, BLOOMINGTON, IND.

Optical imperfections of the eye are a potential limiting factor for any information system that is optically coupled to the eye. Myriad systems of this kind currently exist: from microscopes to telescopes, from night-vision goggles to medical instruments, from heads-up displays in the cockpit to virtual-reality headsets in the amusement arcade. In all of these cases, as well as for normal unaided vision, the optical apparatus of the eye represents a low-pass spatial filter at the front end of the visual system that is a potential limiting factor for any visual task. Apart from defocus, which the eye automatically corrects by a reflexive change in optical power of its internal lens, the major optical factors limiting visual performance are chromatic aberration, spherical aberration, and diffraction at the pupil.[1] To help gauge the potential magnitude and significance of these optical factors, and to provide a useful design element for optical engineers, we have developed an accurate, mathematically tractable model of the human eye that takes account of these three primary factors.

Since the 19th century, the eye's chromatic aberration has been described by an extremely simple model consisting of a single, spherical, refracting surface separating air and water. Since the refractive index of water varies with wavelength, this model has a degree of longitudinal chromatic aberration that is only slightly less than that present in the typical human eye. Our first modification of the traditional model, therefore, was to improve its accuracy by replacing water with a medium that is more dispersive at short wavelengths.[2] Next, by including a pupil, the model eye also accounts for diffraction and two forms of transverse aberration: chromatic difference of magnification[3] and chromatic difference of position.[4] To account for residual amounts of transverse chromatic aberration at the fovea, the pupil may be displaced slightly from the optical axis in the model, if necessary. Another useful variant of the model is obtained by changing the refracting interface to a surface of revolution of an ellipse (*i.e.*, a prolate spheroid). This model, which we dubbed the "chromatic eye," is free of spherical aberration for distant, in-focus objects and has only minor amounts at other wavelengths.

Although mathematically simple, a spherical refracting surface has considerably more spherical aberration than is found in human eyes, whereas the elliptical model has less. Therefore, to match the average spherical aberration of human eyes we chose a fourth-order polynomial refracting surface that lies in between.[5] This final model (see Figure), which might be called the "Indiana Eye," thus accounts for the three major factors (diffraction, chromatic dispersion, and spherical aberration) that limit image quality in the average human eye. Because of its simple form, the model is suitable for analytical as well as numerical solution to optical design problems in which the final imaging device is the human eye. It is also useful for computing retinal image quality under normal, free-viewing conditions.



The Indiana model eye has a single refracting surface separating air from a medium that is slightly more dispersive than water. Two reference surfaces (a circle and an ellipse) are drawn with dotted curves. The pupil lies between the refracting surface and the nodal point N, and may be decentered from the visual axis to model transverse chromatic aberration at the fovea F. Further details of the model may be found in Refs. 2 and 5.

REFERENCES

1. L.N. Thibos *et al.*, "The effect of ocular chromatic aberration on monocular visual performance," Optom. Vis. Sci. **68,** 1991, 599-607.
2. L.N. Thibos *et al.*, "The chromatic eye: A new model of ocular chromatic aberration," Appl. Opt. **31,** 1992, 3594-3600.
3. X. Zhang *et al.*, "Experimental determination of the chromatic difference of magnification of the human eye and the location of the anterior nodal point," J. Opt. Soc. Am. A **10,** 1992, 213-220.
4. L.N. Thibos *et al.*, "Theory and measurement of ocular chromatic aberration," Vision Res. **30,** 1990, 33-49.
5. M. Ye *et al.*, "A new single-surface model eye that accurately predicts chromatic and spherical aberrations of the human eye," Invest. Ophthal. Vis. Sci. **34** (supp.), 1993, 777.