11
The Diversity of Eye Optics

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Abstract: This chapter starts with a description of the optics of camera-type eyes, in which an image is projected upon a retina with cornea and lens as refracting elements. Ray tracing is explained with the human eye as an example of a terrestrial vertebrate's eye. Then the comparison is made to camera eyes of aquatic and amphibious animals, with an explanation of different kinds of aberrations, difficulties in accommodation to air and water as external media, and different solutions to these problems. A brief section deals with feedback regulation of eye development, and another one with eyes of particularly high light sensitivity. A section on compound eyes explains the difference between apposition and superposition eyes. It is pointed out that geometric optics (ray optics) is not adequate for analyzing the function of the small components of these eyes, and an introduction is given to waveguide and mode theory. This is followed by sections on antireflective nipple arrays, eyes with reflective optics, scanning eyes, and the chapter concludes with a treatise of the evolution of eyes.

11.1. Introduction

In this review of the different solutions of the optical problems of eye designs encountered in the animal kingdom, we shall not follow the course of evolution. Instead we shall start with our own eyes, as this is what the readers in general are likely to be most familiar with. The emphasis will thus first be on "camera-type" eyes, and later we will deal with compound and other types of eyes.

11.2. The Human Eye

We assume that the reader has a basic knowledge of the structure of the human eye. It is probably a common misconception that the refraction of light necessary for the projection of an image on the retina is mainly due to the lens. In fact, 80% of the refractive power is due to the curved external surface of the eye, at the outer surface of the cornea, because the difference in refractive index between

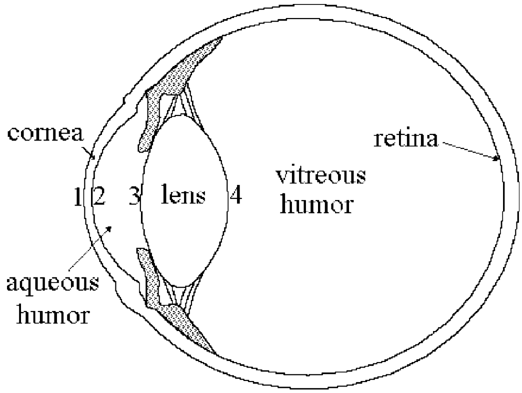

FIGURE 11.1. Longitudinal section of a human eye (schematic). The numbers indicate the numbering of interfaces used in the calculations in the text.

cornea and air is much greater than that between the lens and its surrounding media (aqueous humor in front, vitreous humor behind) (Fig. 11.1).

To understand how the optical components of the eye function, and why evolution of eye design in different environments has given the results it has, we shall start with how light is refracted in spherical interface.

From the formula derived in the legend of Fig. 11.2, we can see that:

1. For fixed n_1, n_2, and R, the smaller is a, the larger is b
2. For fixed a, n_1 and n_2, the smaller is R, the smaller is b
3. For fixed a and R, the larger is the difference between n_2 and n_1, the smaller is b.

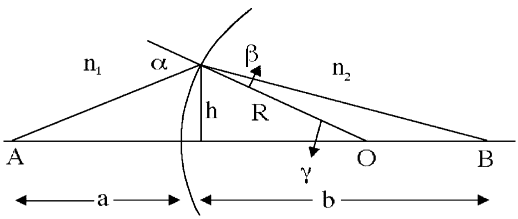

FIGURE 11.2. Refraction of light at a spherical interface between media with different refractive indices, n_1 and n_2. The radius of curvature is R, the center of the sphere O. A ray from A to B is refracted in the surface at a distance h from the line from A to B. The angle of incidence is α, the angle of refraction β. The shortest distance of A from the interface is α, that of B is b. For small values of h we have the following relations: $h/r = \tan(\gamma) \approx \gamma$; $h/a = \tan(\alpha - \gamma) \approx \alpha - \gamma$; $h/b = \tan(\gamma - \beta) \approx \gamma - \beta$. From this follows that $h/R + h/a \approx \alpha \approx \sin(\alpha)$ and $h/R + h/b \approx \beta \approx \sin(\beta)$. Since, according to Snell's law (see Chapter 1), $n_1 sin(\alpha) = n_2 sin(\beta)$, it follows that $n_1(h/R + h/a) = n_2(h/R + h/b)$, i.e., $n_1(1/R + 1/a) = n_2(1/R + 1/b)$ (independently of h as long as h is small compared to R), or $n_1/a + n_2/b = (n_2 - n_1)/R$.