

accommodation dual-mode characteristics, adaptation model of accommodation and vergence, nearwork-induced transient myopia (NITM) model, refractive error development model and emmetropization, and model of saccade-vergence interactions.

Basic Anatomy and Physiology of Eye Movements

The goal of the accommodation, or focusing, system is to provide a clear and sharp image of an object on the retina. Figure 1A shows a cross-sectional view of the interior of the human eyeball. Light rays enter the eye first through the transparent cornea, which comprises about $2/3$ of the fixed refractive power of the eye. The rays then pass through the opening in the iris, called the pupil, and is refracted by the transparent lens, which comprises the remaining $1/3$ of the fixed optical power. The lens has, in addition, a variable component that is controlled by the ciliary muscle (which is part of the ciliary body) through its action via the zonular fibers located between the ciliary body and the lens. In this way, the light rays of a target at different distances can be focused by the variable-powered lens onto the fovea, which is a small high-acuity region on the retina. The act of focusing from a far (F) to a near (N) target is called accommodation (Fig. 1B). Moreover, the image can be focused within a certain range either in front of or behind the retina, thus providing a small amount of retinal-defocus, and still be perceived as clear and sharp. This is called the depth-of-focus or DOF (not explicitly shown in Fig. 1B). However, if the retinal-defocus is outside the DOF, the image is perceived to be blurred, and accommodative feedback is used to change the lens power and reduce this blur to a minimum. In general, for viewing of objects closer than about 1 m, the resultant image is focused behind the retina and the accommodative response is said to “lag” the stimulus. Although retinal-defocus, and hence the perceived blur, is an even-error signal (for stimuli given in diopters rather than linear displacement units)⁴ that does not provide a direction sense of the error, other optical cues such as chromatic aberration, where light rays of shorter wavelength (e.g. blue) are refracted more than those of longer wavelength (e.g. red), and spherical aberration, where peripheral rays impinging on a lens are refracted more than central rays, as well as

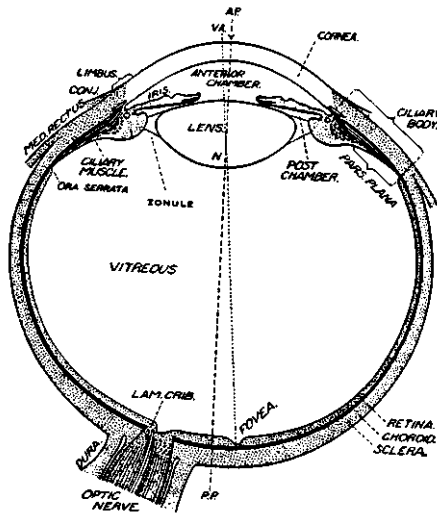


Fig. 1A Cut-out section of the interior of the eyeball showing the transparent cornea and lens, which provide $2/3$ and $1/3$, respectively, of the refractive power of the eye. The ciliary muscle controls the front surface curvature of the lens to provide variable focusing. The light-sensitive retina contains a small region, called the fovea, for acute vision (adapted from Last,⁹⁷ p. 30, with permission).

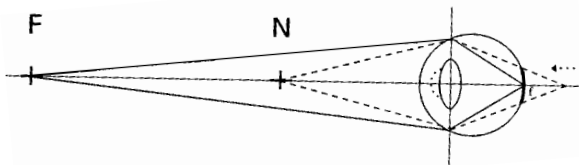


Fig. 1B Schematic diagram of light rays for initially far target (F; solid lines) that is focused on the fovea (f) and the sudden introduction of a near target (N; dashed lines). Accommodation to the near target changes the curvature of the front of lens and moves the under-converged light rays forward to bring the rays into focus at f (see dashed arrow).

perceptual cues (such as size, perspective and overlap) all contribute to accurate direction sense of accommodation in normal daily life. Thus, the initiation of the accommodative response is almost invariably in the correct direction under real-life conditions.

The goal of the binocular eye movement system is to provide a single (rather than double) percept by bringing the images of a target onto corresponding retinal points in the two eyes. Hence, when the target moves in depth, the eyeball in each eye must be rotated by the muscles outside the eyeball, called extraocular muscles (Fig. 2A), to once again bring the images in register on the retinas. There are three pairs of extraocular muscles that are concerned with horizontal, vertical and oblique rotations of the eye. The very efficient pulley actions of these extraocular muscles and their multidimensional control of eye rotations can be fully appreciated by the mechanical engineer. In this monograph, we will be concerned primarily with the horizontal muscles, called the medial rectus and lateral rectus, that are reciprocally innervated and rotate the eye in the horizontal plane. The neural pathways for the control of horizontal eye movements are shown in Fig. 2B. The neural signals are formed in the higher neural centers and then sent to the oculomotor (3rd nerve) and abducens (6th nerve) nuclei, which in turn send signals to the horizontal recti muscles. These signals drive the two eyes in a coordinated fashion so that the lines of sight intersect at the target. The resulting images in the two retinas are combined by the brain to form a single percept. When a target is displaced in depth (e.g. between far (F) and near (N) positions in Fig. 3A), an angular difference between the near and far targets, $\alpha - \beta$ (called disparity), is created and causes the muscles to rotate the two eyes in opposite directions to track it in a disjunctive manner. A disjunctive or vergence response for a target displacement from far to near is called convergence, and that from near to far is called divergence. On the other hand, when a target is moved laterally from side to side (e.g. between positions T1 and T2 in Fig. 3B), the two eyes rotate in the same direction to track it in a conjunctive or conjugate manner. There are two types of conjugate eye movements — saccades that jump to follow rapid target displacements and pursuit eye movements that smoothly follow relatively slowly moving targets.

Basic Measurement Terms

The basic unit of measurement for the focusing or accommodation system is the diopter (D). A diopter is a unit of optical power that is equal to the reciprocal of the distance of the target from the corneal plane (or more