4 VISUAL OPTICS

4.1 INTRODUCTION

4.1.1 Characteristics of the human eye. The design of an efficient optical instrument must include consideration for the use of the instrument. When the human eye is to be the translating instrument, the instrument must be designed for proper seeing. This section will call attention to some of the advantages and limitations of the human eye and seeing that are important for instrument design. The human eye is sensitive to radiant energy from 380 to about 740 mμ in wavelength. The limits of visibility for young eyes are about 313 - 900 mμ, but for practical purposes the narrower range is adequate and representative for average eyes. Light is defined as radiant energy evaluated according to its capacity to produce visual sensation. A few quanta can stimulate the retina and be seen as light. To see an object, light of suitable quality (color) and intensity from the object must form an image on the retina of adequate size, contrast, and duration for the retina to transform the light energy into nerve energy, and the nerve impulses must be conducted to the brain and integrated into consciousness. Age, glare, state of adaptation and visual acuity will modify vision.

4.1.2 Seeing. Seeing is a learned ability and training can improve the individuals seeing to limits set by the eye and nervous system. Seeing is a perceptual process that is affected by and incorporates other sensations, emotions, association mechanisms simultaneously active with vision, education, and past experience. It varies with the condition of the individual and the entities must be statistical probabilities of seeing rather than absolute values.

4.1.3 Loss of vision. The eye and vision are disturbed by many conditions and diseases. Emmetropia refers to an average normal eye, ametropia indicates a defective eye and amblyopia an eye with little or no vision that appears normal. Additional defects of the eye are covered in paragraph 4.3.3.

4.2 ANATOMY OF THE EYE

4.2.1 Physcial structure. The human eye, as illustrated in Figure 4.1, is a nearly spherical organ held in shape by a tough, outer, whitish-sclerotic coat and the pressure of its viscous content. The cornea, the transparent front part of the sclera, protrudes slightly as it has a greater curvature. Inside the sclera is the choroid containing the blood vessels, the opaque pigment and the ciliary process. The ciliary process includes the iris and the muscles which focus the lens of the eye. The pupil is the opening in the center of the iris. The retina covers the inside of the choroid to the ora serrata near the ciliary process. The space between the cornea and the iris is called the anterior chamber and between the iris and the lens is a posterior chamber. Both are filled with the aqueous humor. The space back of the lens and ciliary process is filled with the vitreous humor. The lens is attached to the ciliary muscle by many fibers or suspensory ligaments. Except for the opening in the iris the pigmentation of the sclera and iris normally makes the eye light tight. A lack of eye pigmentation is called albinism and vision is impaired by glare from light leakage onto the retina.

4.2.2 Intraocular pressure. The internal pressure of the eye is maintained quite constant by a balance of the formation of the aqueous humor at the back part of the ciliary process, from which it passes out through the pupil into the anterior chamber, and drains through the canal of Schlemm.

4.2.3 Metabolism. The transparent media, cornea, lens and vitreous do not have blood vessels and receive their nourishment from the fluids surrounding them. The transparency of the cornea depends on its relative hydration. The front part of the retina contains blood vessels which furnish nourishment to it and to the adjacent vitreous.

4.2.3.1 The retina is one region of the body where it is possible to see (with the ophthalmoscope) the condition of the blood vascular system and recognize changes from many systemic diseases. The focussing ability of the eye is altered by a change in the blood sugar concentration from inadequately controlled diabetes. Glaucoma is a disease characterized by an increase in the pressure within the eye ball and unless arrested promptly will lead to mechanical damage and loss of sight.

4.2.4 Development. The eye is developed early and is fairly well formed by six weeks after conception. An outgrowth from the front of the brain becomes the optic nerve and the retina of the eye. When this cup-shaped formation nearly reaches the skin of the embryo, that part of the skin sinks below the surface and becomes modified to form the lens of the eye. The skin closes over to form the cornea and the sclera. The choroid and the ciliary process form between the sclera and the retina. Like the brain, the eye is relatively large at birth al-

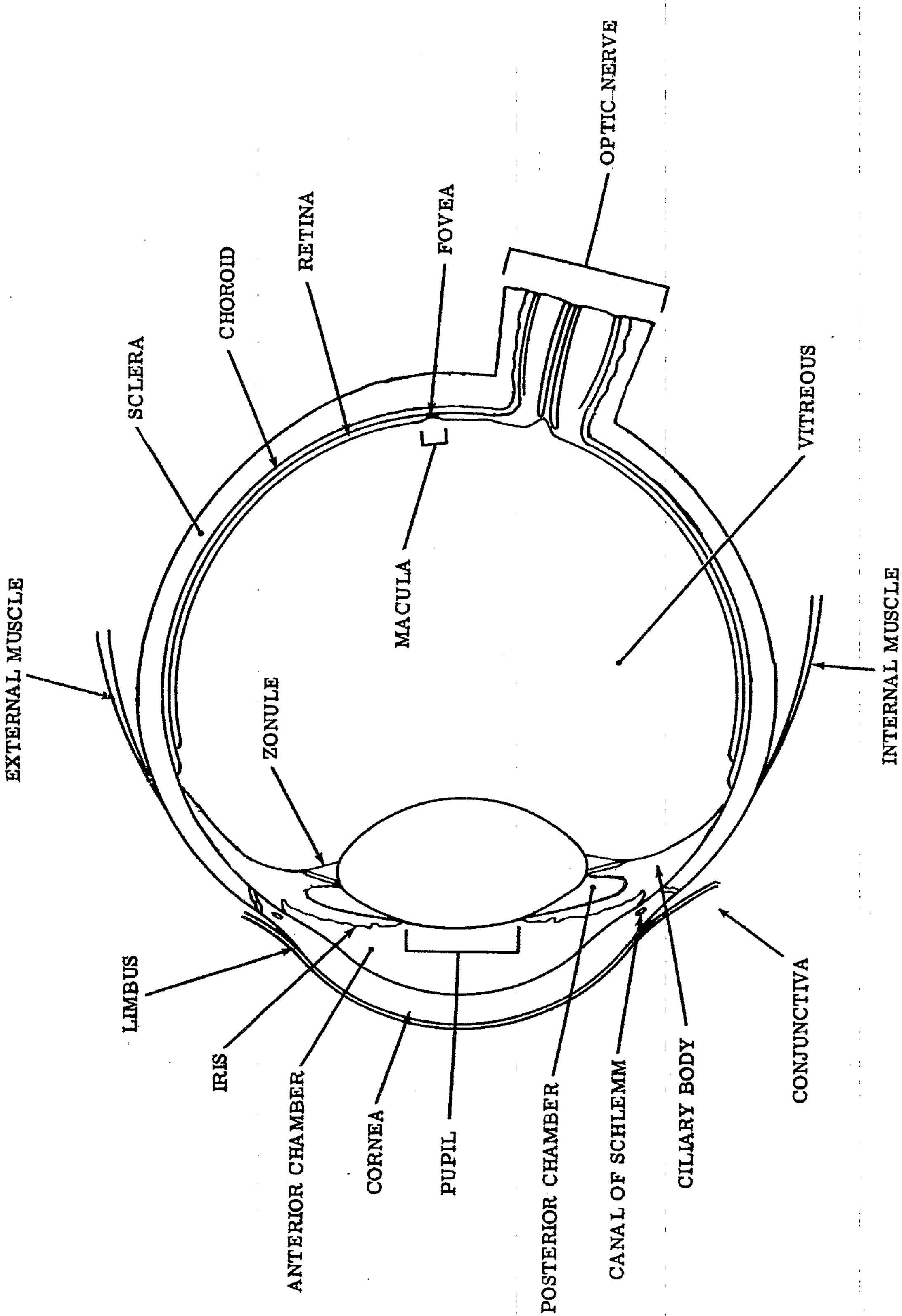

Figure 4.1. - Horizontal section of the right eye.

though vision then is imperfect and improves for several years. Color vision may not reach its greatest sensitivity until in the late teens. The various parts of the eye do not grow at the same rate and the eye and the body do not grow at the same rate. It is remarkable that the regulatory mechanisms tend to balance these different rates of growth to produce the emmetropic eye.

4.2.4.1 The muscles which control the eye will be described later. Briefly however, muscular action is usually a balance between opposing pairs of muscles which contain many contractile units and the resulting movement usually shows the action of the units in a stepwise progression, and fine oscillations when in equilibrium.

4.3 OPTICAL CONSTANTS OF THE EYE

4.3.1 Use of the "standard eye." As one would expect there are no universal dimensions for an eye, one finds instead, considerable variation in all dimensions. A good image formed on the retina may be the result of each part of the eye being perfect in form and refractive index, or the shapes and indices of the parts may have compensated for each others defects. Complete testing of each observer's eye would be time consuming and require special equipment. Instead a "standard" or typical eye is established and used as a standard observer for computational problems. Individual eyes can be examined to discover whether or not they correspond to the standard. There are several systems for "reduced" eyes, and a commonly used set of optical and mechanical characteristics for a typical eye is illustrated in Figure 4.2. Reduced is used here in the sense of an optically equivalent system.

4.3.2 Aberrations. Like other optical systems the eye is subject to the usual aberrations. The coordination of the focussing system and the retinal structure with sunlight over many years evolution has minimized some of the problems. Distortion and field curvature rarely bother in ordinary seeing, and chromatic aberration does not disturb vision. With the small pupils,of 3-4mm and average daylight, spherical aberration is minimal, although in dim light with large pupils it lessens vision.

4.3.3 Corrective lenses. The chief defects of the eye are myopia, hyperopia or hypermetropia, astigmatism, presbyopia and aniseikonia. The hyperopic eye focuses the image of a distant object behind the retina,and the myopic eye in front of the retina. In old age the focussing ability of the lens declines and this condition is termed presbyopia. Astigmatism results from asymmetry of the cornea. Aniseikonia will be discussed in paragraph 4.7 and aphakia will be discussed in paragraph 4.4.

4.3.3.1 Far sightedness, or hyperopia, can be due to the axial length of the eye being too short, or the focussing mechanism too weak, and is corrected by placing in front of the eye a plus lens of proper strength to replace the image on the retina. In near-sightedness, or myopia, the image is formed in the vitreous because the eye is too long, or the focussing mechanism is too strong, and the defect is corrected with a minus spectacle lens. Astigmatism due to irregular curvature of the cornea is corrected by a cylindrical spectacle lens.

4.3.3.2 Spectacles are usually fitted so that the back surface (vertex) of the lens is about 14 millimeters in front of the cornea although minus lenses for myopia may be set closer at 9 to 11 millimeters. Changing the position alters the effective power of the lens. Eyeglasses may be tilted slightly downward 4° to 12° for reading.

4.3.3.3 People with astigmatic corrections must wear their glasses for comfortable vision over long periods when using optical instruments. In recent years optical designers have made oculars with the eye point far enough from the lens so that the individual can see the whole field while wearing spectacles. The distance from the front of the spectacle lens to the cornea can vary from around 17 millimeters to 11 millimeters. If a substitute lens is mounted on the optical instrument to take the place of a spectacle lens, its power must be changed from that of the prescription when the substitute lens will be at a different position from the cornea than the spectacle lens. A substitute lens with cylindrical power must be mounted in proper orientation to the axis of the cylinder so it cannot rotate from the correct position.

4.3.3.4 People with only near or far sightedness (no astigmatism) usually remove their glasses when using optical instruments and refocus the instrument to correct for their defect. Therefore, focussing eyepieces should have sufficient range for the people intended to use them. A range of ± 1 diopter will include about 70 percent; ± 2 diopters will include about 85 percent; and ± 4 diopters about 98 percent of spectacle prescriptions.

4.3.3.5 Critical seeing can take place only when the image is located on the fovea at the center of the macula of the retina, as illustrated in Figures 4.1 and 4.2. This establishes a visual axis which is some 5-7° from the optical axis of the eye. The retina is blind over the area of the optic disc where the nerve fibers enter the eye to distribute over the retina, and this blind spot subtends some 7° vertically and 5° horizontally.

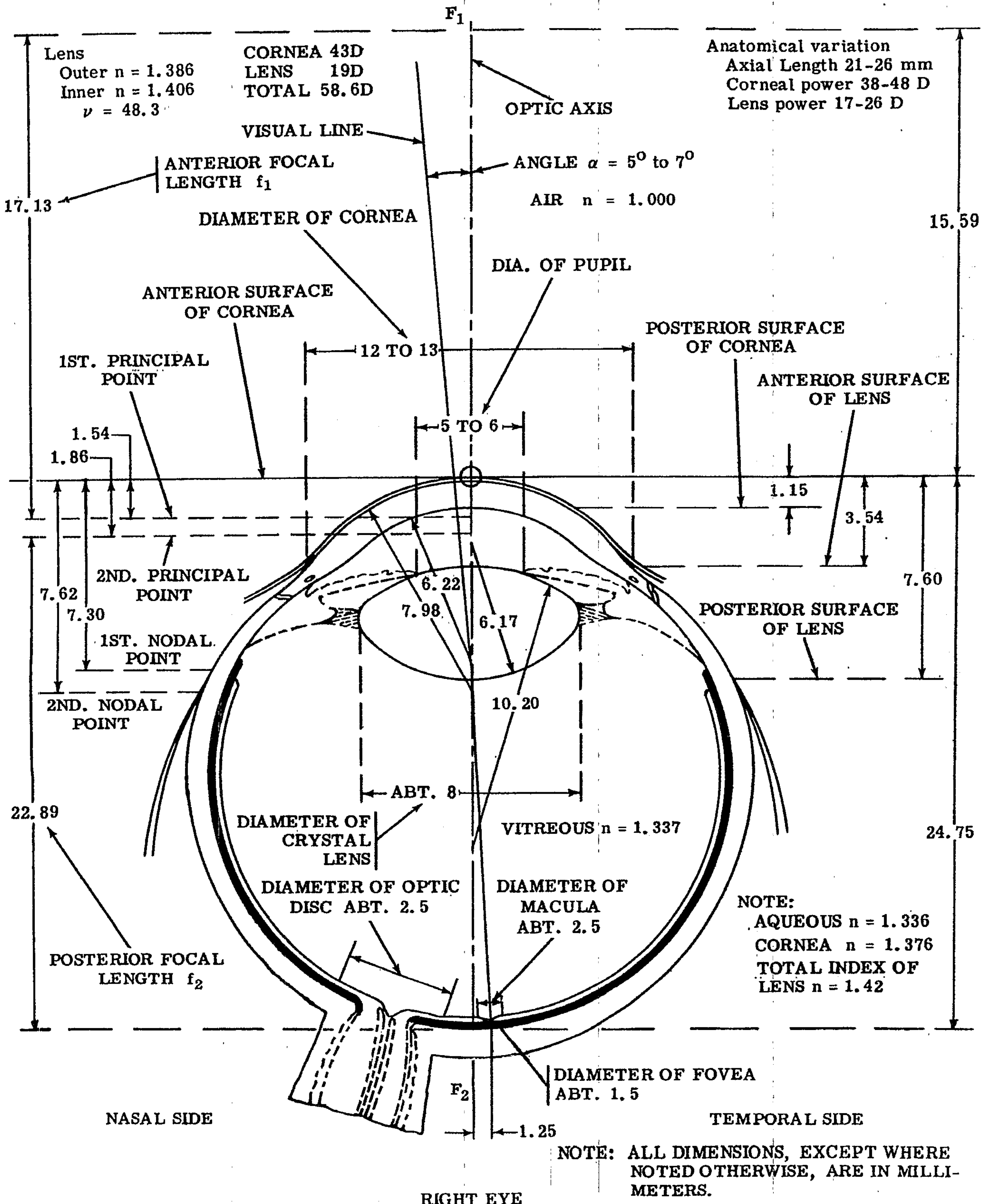

Figure 4.2 - Optical constants for a "standard eye."

4.4 IMAGE FORMATION AND THE RETINA

4.4.1 Cornea. The cornea is the first refracting surface for light entering the eye and is responsible for about 43 of a total of 58 diopters power of the eye. Normally the cornea is transparent and the refracting power is due to the curvature and refractive index difference between it and air on one side, and the aqueous humor on the other. The cornea in size averages 12 millimeters horizontally and 11 millimeters vertically.

4.4.1.1 A change in the hydration of the cornea can affect the light passing through it either by distortion or decreased transparency. The decrease caused by fluids and some early contact lenses, or from changes in old age, scatters light and haloes appear around light sources or small bright objects. Haloes from age changes are rarely reversible.

4.4.1.2 The two surfaces of the cornea usually are of similar curvature and have no lens effect on the entering light. Any deformity of the curvature of the cornea (astigmatism) distorts the image. Such changes are measured with a keratometer (ophthalmometer) and corrected by adding a corresponding cylinder of opposite sign into the spectacle lens for the eye. An extreme elongation of the center of the cornea (keratoconus) can be corrected by contact lenses. Astigmatism has some relation to the tension of the eye muscles and may change slowly from a vertical meridian to a horizontal meridian of greatest curvature during later life. There may be some residual astigmatism as well as that from the corneal surface.

4.4.1.3 Vision specialists sometimes refer to astigmatism with the rule (stronger power vertical) and against the rule (meridian of greatest curvature horizontal) based on the direction of movement of light reflected from the eye during skiascopic refraction.

4.4.1.4 Haidinger's Brushes are seen on looking at the blue sky (polarized), or at a uniform source of polarized blue light, as a diffuse cross. Some observers believe this phenomenon is due to the birefringence of the cornea. Other observers hold that it is due to neural structure or pigment arrangement in the retina. Attempts to use the Brushes for differential diagnosis of eye conditions has been unsuccessful so far.

4.4.2 Pupil. The pupil is the opening in the center of the iris as illustrated in Figures 4.1 and 4.2. In dim illumination the pupil opens to about 8 millimeters diameter in young eyes, and closes to about 2 millimeters diameter in intensely bright light. Under average conditions the pupil has a diameter of 3.5 to 4 millimeters. Resolution of the eye is decreased when the pupils are much larger or smaller than 3 to 4 millimeters. With ageing, the pupil remains smaller, and in extreme old age may not be more than 2 to 3 millimeters. The pupil is a stop, or diaphragm, in the dioptric system of the eye that affects image formation, illumination of the retina and the aberrations of the system. With small pupils (2 millimeters or less) diffraction becomes important.

4.4.2.1 The iris is composed of radial and circular muscle fibers and the size of the pupil is a resultant of these antagonistic muscles. Consequently the pupil shows continuous fine fluctuations in size, as well as opening and closing with changed luminance. The iris is not under voluntary control. Convergence of the eyes to a closer point in space also closes the pupil and this increases the depth of field.

4.4.2.2 Stimulation of the cornea, conjunctiva or eyelids, causes a slight dilation, followed by contraction of the pupil. Strong sensory stimulation, fear, and pain cause dilation via the psycho-sensory reflex. Many drugs effect the size of the pupil and some are used in the medical treatment of the eye to dilate (mydriasis) or contract (myosis) the pupil. Normally, both pupils respond together from the stimulation of either eye although the sizes may not be exactly the same. A marked difference in sizes indicates disease.

4.4.2.3 The pupil can decrease from 8 to 3 millimeters in 4 to 5 seconds. Dilation of the pupil from 3 to 6 millimeters takes 5 to 10 seconds and maximum dilation may take 5 to 10 minutes. Contraction at 5.5 to 7 millimeters per second and dilation at 3.0 to 4.5 millimeters per second is reported.

4.4.2.4 In designing optical instruments for visual use it should be kept in mind that the usable part of the exit pupil is no larger than the pupil of the eye. In order to decrease the precision with which the eye must be placed at the exit pupil in viewing, it is sometimes advisable to design the instrument so that the diameter of the exit pupil is considerably larger than any possible diameter of the pupil of the eye. In this case the portion of the exit pupil transmitting light to the observer's retina is limited to the size of the eye pupil, and the usable diameter of the entrance pupil (for axial bundles of rays) is equal to the diameter of the eye pupil multiplied by the magnification. However, if the exit pupil is smaller than the pupil of the eye the light entering the eye is limited by the exit pupil, and in instruments requiring maximum illumination on the retina every attempt should be made to provide an exit pupil diameter as large as the largest possible diameter of the pupil of the eye. Average pupil size for age and luminance are shown in Figure 4.3.

4.4.3 Lens. The lens of the eye changes curvature to focus light onto the retina. The lens is a transparent elastic body with an outer capsule, a less dense cortex, and a denser inside core. The lens is held in position

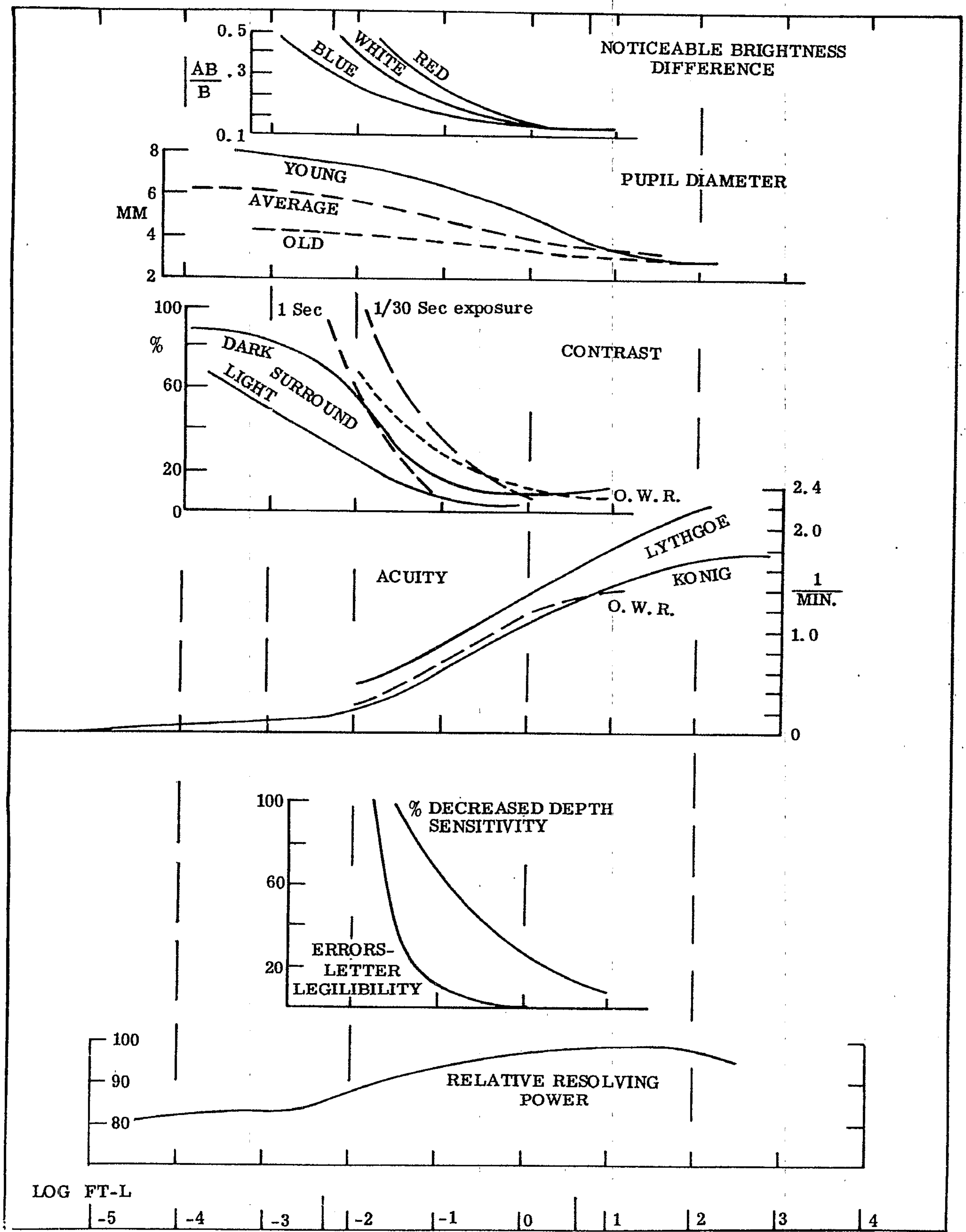

Figure 4.3. - Variation of some attributes of vision with Luminance.

by the suspensory ligaments, as shown in Figure 4.1. The ciliary process has circular, radial, and oblique muscle fibers which contract to pull on the fibers of the zonule and flatten the lens; or relax to lessen the tension and let the lens bulge to a more spherical form. Continuous fluctuations from muscle action take place producing amplitudes of 0.1 diopters focal change with a frequency of 4 to 8 cycles per second and smaller frequencies of 2 and 0.3 cycles per second. The lens has a total refracting power of some 19 diopters and the amplitude of accommodation of the lens varies from some 15 diopters in children to about 0.5 diopter in old age. The depth of field is about 0.5 diopter. However, to focus the eye from near to far requires 0.7 to 0.8 second, far to near 0.4 to 0.5 second, and near to far and back to near 1.15 to 1.25 seconds. When vision is less than 20/20, when exophoria exceeds 8 prism diopters at 33 centimeters, or when myopia, hyperphoria, or astigmatism are present, the time required to focus the eye will increase from that mentioned above.

4.4.4 Accommodation. The curvature of the front and back surfaces of the lens are different and the front surface is said to be hyperbolic in young people. The focussing of the lens is controlled by the sympathetic nervous system and cannot be altered voluntarily. There have been two theories advanced regarding accommodation. Helmholz thought that relaxation of the tension on the suspensory ligaments permitted the elastic lens substance, which had been deformed in the unaccommodated state, to return to its more convex form. E. F. Fincham's experiments indicate that such relaxation allows a highly elastic capsule to deform the lens substance from its unaccommodated state to the greater convexity required. The variations in thickness in different parts of the capsule favors the latter theory.

4.4.4.1 When the eye sees only an empty field lacking detail the lens tends to focus, not at the 20 foot "infinity" of the vision specialists, but at about 1 meter. This near-sightedness is called empty field myopia for a bright empty field, and night myopia when the empty field is due to darkness. In the latter case the change in spherical aberration from the dilated pupil and the Purkinje shift also contribute to the total myopia. Changes in the curvature of the lens can be measured objectively from changes in the Purkinje-Samson images reflected from the surfaces of the lens, or with an optometer from changes in the retinal image, using either light or invisible infrared radiation.

4.4.4.2 At about forty years of age the focussing mechanism begins to gradually fail (presbyopia) and additional plus lens correction becomes necessary to see details at the usual reading distance. The lens also tends to become yellowish, blues are seen less well in old age, and less light gets to the retina. In some eyes the lens becomes opaque (cataract) and must be removed to restore vision. The eye lacking a lens is said to be aphakic and the spectacle lens correction must be increased to substitute for the lens. As the spectacle lens has a fixed focus the aphakic eye will be corrected only at one distance. When one eye is aphakic and the other is not, the difference in the size of the images on the retina precludes binocular vision.

4.4.4.3 Optical instruments with focusable eyepieces must be designed to have an adequate adjustment in power to permit older people to use them, and to provide at least -2 diopters when designed for night use.

4.4.4.4 The vitreous humor is a transparent gel of slightly greater refractive index than water, that fills the space between the lens and ciliary process and the retina. Sometimes particles of tissue (muscae volitantes) tend to hang or float in the vitreous and are seen when one is observing through optical instruments. These may be fragments left over as the vitreous formed, or that have broken away during life. Nothing can be done to remove these fragments and they should be ignored. In some diseases, parts of the vitreous become opaque and vision is lost to a corresponding extent.

4.4.4.5 The retina, covering most of the area behind the ciliary process, translates light energy into nervous energy and contains the first coordinating nerve cells in the visual system. The front part facing the lens is composed of blood vessels, nerve cells and fibers and connective tissues, and at the back of the retina are the light sensitive rod and cone cells and protective pigment layer. The entrance of the optic nerve forms a disc (a blind spot where there are no light sensitive cells) and the visual angles subtended by this disc are about 7° and 5° as illustrated in Figure 4.2. The disc is about 3.5 millimeters (15.5° to center) on the nasal side of the optical pole of the eye and 1.5 degrees below the horizontal meridian of the eye.

4.4.4.6 The retina thins at the visual axis, some 5° temporal to the optical pole, as there are no blood vessels or nerve fibers over the fovea. The macula subtends about 12° and is 2.5 to 3 millimeters in diameter. The fovea includes about 1.5 millimeters of the center of the macula, or about 5° of subtended arc and is the most sensitive part of the retina. Some anatomists recognize an area of about 0.35 millimeters in the center of the fovea called the foveola.

4.4.4.7 The center of the fovea only contains cones and those at the central region are longer, thinner and more densely packed than cones elsewhere in the retina. This rod-free area is about 0.5 millimeter in diameter and subtends about 50 minutes of arc. From here to the edge of the retina the number of cones per unit area decreases, and the number of rods increases. At 20°, as illustrated in Figure 4.4, the rod population is densest.

4.4.4.8 The sensitivity of the retina to light varies with the area stimulated as shown in Figure 4.5. The fovea is most sensitive and used for seeing fine detail and color. Color sensitivity varies with position on the retina.

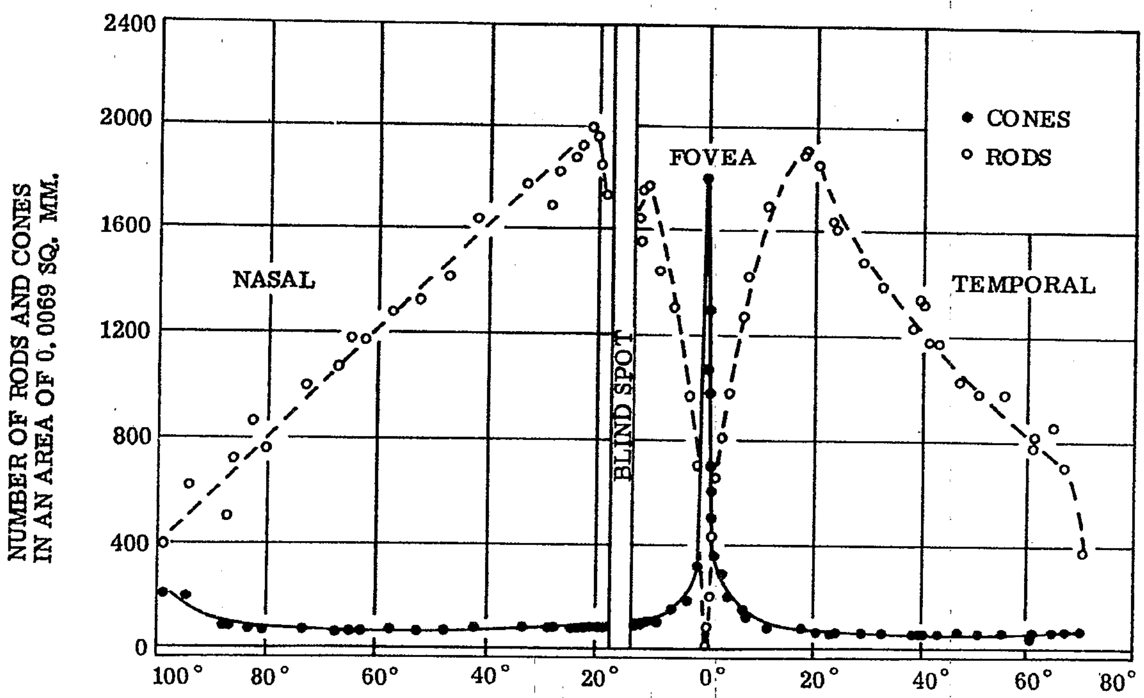

Figure 4.4 - The distribution of cones and rods across the retina (horizontal meridian).
(From National Research Council, A. Chapanis 1949)

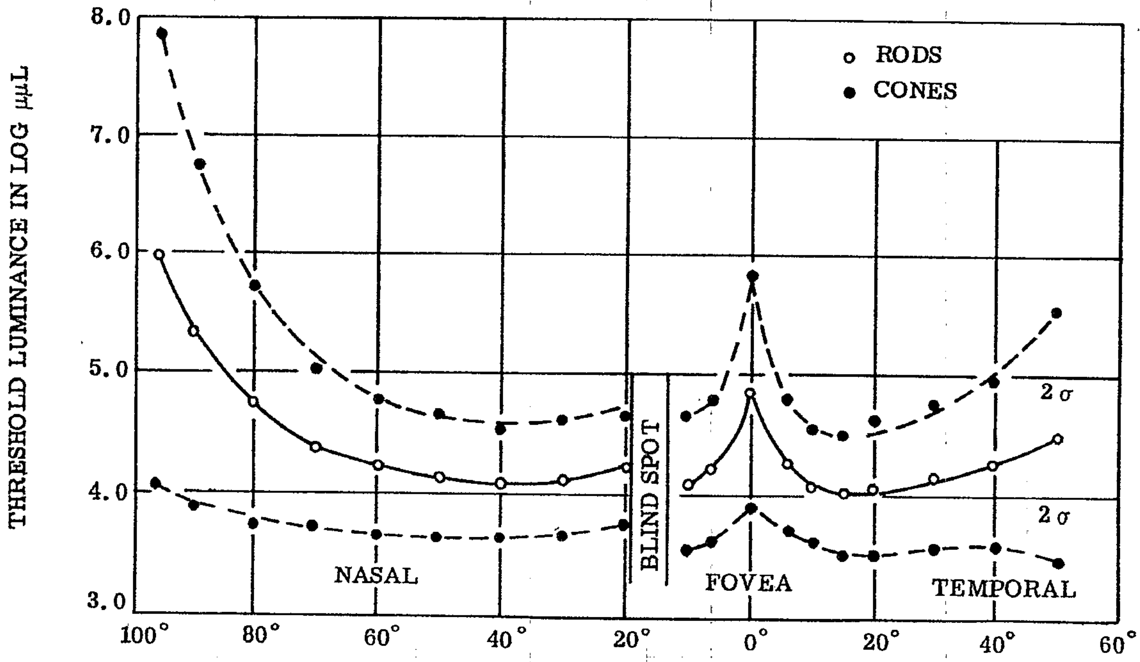

Figure 4.5 - Sensitivity to just perceptable luminance across the retina
(From National Research Council, A. Chapanis 1949)

4.4.4.9 The rods contain rhodopsin, which is bleached by light, and the products formed stimulate nerve conduction. Rods are sensitive to very small amounts of light and operate from a few quanta to a luminance of about that of moonlight (0.01 ft-L). The cones contain iodopsin and have a useful range from about 0.006 ft-L to 10,000 ft-L. Vision with the rod cells at low levels of light is called scotopic and cone cell vision at high levels is called photopic. The overlapping region (0.1-0.01 ft-L) is called mesoptic vision. The structure of the rods and cones is complex and the exact mechanism of vision is not fully known. A nerve fibre conducts or it does not. Nerve fibers respond to stimulation after a latent period and are insensitive during the refractive period following conduction. Chemical action and electrical potentials accompany the impulse. These factors and the light intensity establish the timing of the impulses. The frequency rate of conduction, and the interconnections of the nerve cells, codes the light from the image on the retina into the brain and consciousness. The cones of the fovea are individually connected to a single nerve fiber and have a direct path into the optic nerve. Beyond the fovea, the rods and some cones are connected in groups by the retinal nerve cells, thereby facilitating pattern vision.

4.4.4.10 The nerve fibers from the right half of each eye cross at the point where the optic nerves join, and go to the right hemispheres of the brain. Those from the left halves of each retina go to the left hemisphere. What is seen in the right half of each visual field is connected to the left hemisphere of the cerebrum and vice versa. Cutting one optic nerve would blind that eye while damage to an optic tract would blind the same half of both eyes.

4.4.5 Resolution. The rods and cones give the retina a mosaic structure that determines resolution. Minimum resolution depends on three factors: retinal location of the image as illustrated in Figure 4.6; the nature of the image and the criterion used; and adequate time for stimulation. A very small light (bright on dark) will be seen when its image has enough quanta (2-8) to stimulate the retina, and the smallness of the bright spot depends solely on its brightness. Two small dark objects can be recognized as two when their images spread over or involve two cones providing the diffraction patterns are sufficiently separated. The arc subtense of a cone is about 1 minute (49 to 73 seconds from a gradient of 4 to 6μ for the cones) and the average eye resolves details subtending 1 minute of arc at the eye (70μ at 250 millimeters). An extended image (rather than point) can be seen when much smaller. For example, a telephone wire can be seen against the sky when it subtends only 0.5 second. Horizontally or vertically oriented wires are seen about equally well, but when at 60° or 120° to the horizontal they are only about one-third as visible. A break in a line, or the misalignment of two lines, one above the other, (e.g. scale and vernier) of 4 seconds is visible. Grating objects have different

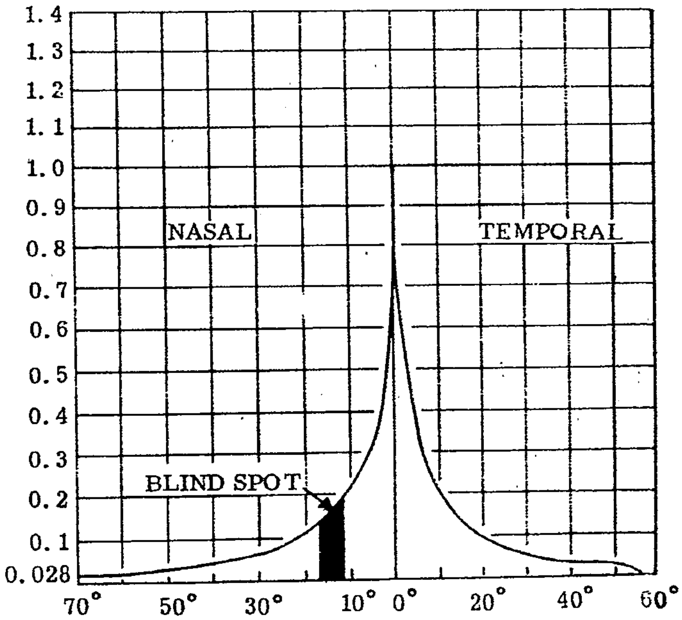

Figure 4.6 - Distribution of visual acuity across the retina expressed in degrees from the fovea

(From National Research Council, A. Chapanis 1949) thresholds. The minimum separable for a grating in motion is reported to be about 2 minutes for a visual acuity of 1.0 for a 2° retinal area and an optical nystagmus criterion. Resolving power decreases with distance from the fovea, to 25% at 5° and only 7% of foveal resolution at 10° from the fovea. Thresholds, as illustrated in Figure 4.7, decrease linearly as the distance from the fovea increases.

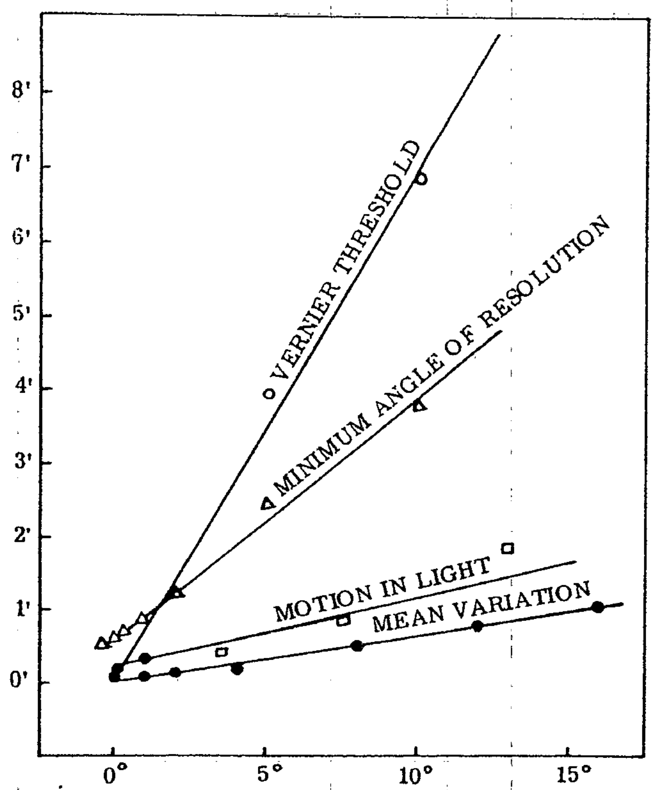

Figure 4.7 - Threshold decrease with distance (in degrees) from the fovea.
(From American Journal of Optometry No. 46, F.W. Weymouth, 1958)

4.4.5.1 Light entering the center of the pupil is more effective than light entering the edge of the pupil. This Stiles-Crawford effect is explained by the orientation of the cones within the retina since the effect occurs only in photopic vision (see paragraph 4.4.4.9). At about 1 millimeter from the center of the pupil there is a decrease to about 90%, at 2 millimeters 70%, 3 millimeters 40% and at 4 millimeters from the center of the pupil the effectiveness of the light is about 20% of that passing through the center of the pupil.

4.4.5.2 The light on the retina varies with the area of the pupil. The Troland (formerly called photon) is the unit of intensity of stimulus for $1mm^2$ of pupil area and a luminance of $1c/m^2$. Luminance (mL) times $5d^2/2$ = Trolands, when d is the pupil diameter in millimeters. Correction may be required for the Stiles-Crawford effect and for the transparency of the eye should a value other than 0.5 be preferred.

4.4.5.3 Optical instruments for visual use should be designed to provide the best image on the retina, of a size and intensity resolvable by the retina. When measurements or judgments can be made by vernier acuity they will be most sensitive, e.g. when a scale value can be aligned to the specimen, the measurement will be more accurate than if the scale is superimposed on the specimen. Small linear detail is more readily seen when imaged horizontally or vertically on the retina, rather than at oblique angles.

4.5 SEEING

4.5.1 Sensitivity. Light of equal energy from different parts of the spectrum does not appear equally bright to the eye as illustrated in Figure 4.8. The yellow-green at 555mμ is brightest and is ten times brighter than the blue of 470 or the red of 650mμ. The standard observer curve represents an internationally accepted sensitivity for use in calculations involving color and relative sensibility of the eye. Like the reduced eye discussed in paragraph 4.3.1, it is representative of average eyes and exact agreement is rarely found between it and an individual eye. Sensitivity curves for individual eyes reveal small departures from the standard observer curve that were averaged out of the standard.

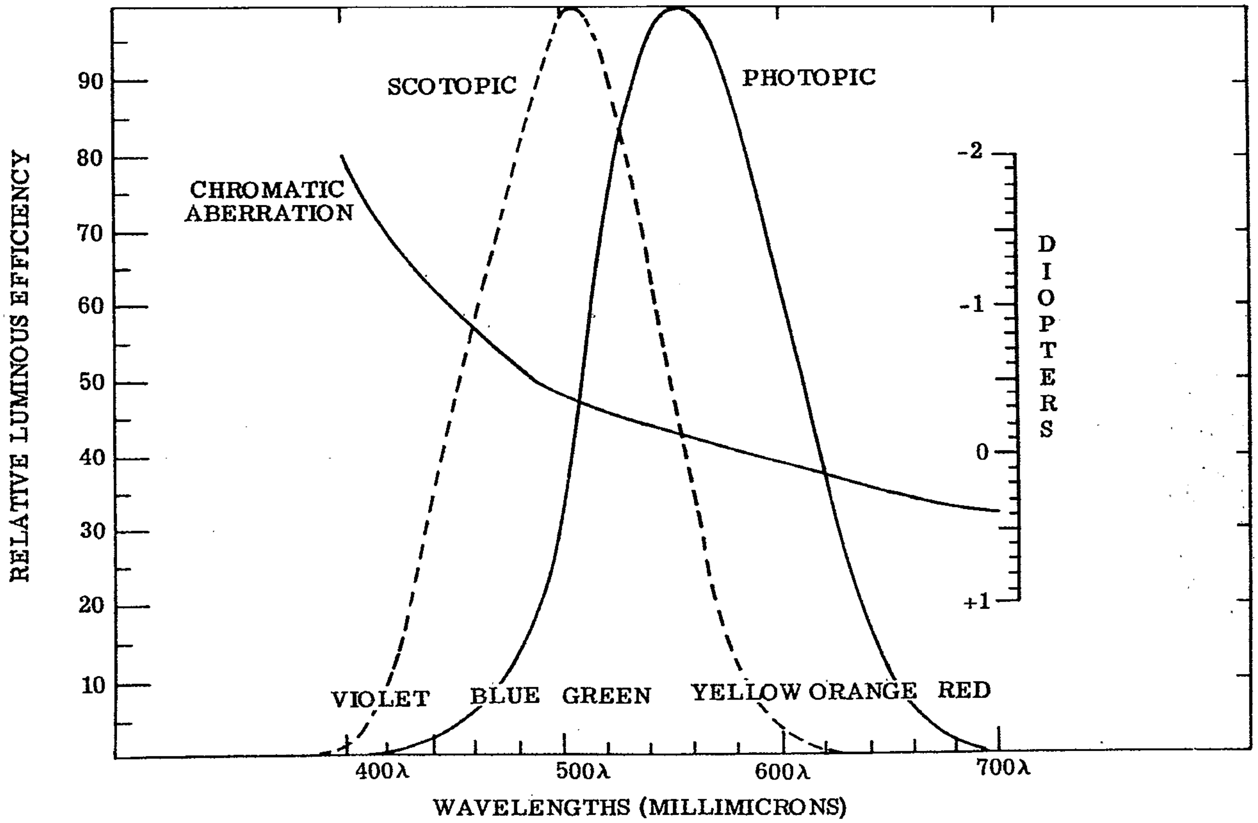

Figure 4.8. - Photopic and Scotopic standard observer curves and chromatic aberration of the eye.

4.5.2 Contrast and time. The eye can adapt itself to see over a wide range of light. The changes within the eye which make this possible involve the pigments of rods and cones and probably neural factors. The sensitivity of an eye in darkness increases rapidly for a few minutes, followed by a gradual increase for about ten minutes as illustrated in Figure 4.9. A further rapid increase of sensitivity (decrease of threshold) takes place until equilibrium is reached. While a further slow increase in sensitivity may take place for hours the amount is not large after one hour in the dark. The curve of Figure 4.9 is typical, and the change after ten minutes marks the end of the cone adaptation and the beginning of the dark adaptation of the rods. The shape of the curve depends on the adaptation state of the retina at the beginning of the dark period. The eye should be exposed for some minutes to a known light (12 log $\mu\mu$L) before measurement. This adaptation may be measured as the threshold at a given time, or as the time required to reach a known sensitivity. Wearing red glasses ($\lambda > 590$mμ) accomplishes some adaptation without being in total darkness.

4.5.2.1 After adaptation, the eye is more sensitive to blueish-green at 510mμ, and the scotopic standard observer curve applies as illustrated in Figure 4.8. The change in the brightest region of the spectrum, from 555 to 510mμ, is called the Purkinje shift. In the mesoptic range, as the eye becomes dark adapted, blues appear brighter and reds darker until color vision fails at about 0.04ft-C of illumination.

4.5.2.2 Dark adaptation is effected by the amount of previous exposure and the physical condition of the individual. It is facilitated to a limited extent by an increase in the available oxygen and is decreased by malnutrition (especially vitamin A deficiency), some drugs, and various diseases. Night-blind individuals cannot adapt to lower light intensities and are disqualified from night operations. When the luminance is too low for the sensitivity of the cones, one has to look to one side of an object so that its image is not on the fovea. The retina is more sensitive for scotopic vision at about 20^{o} from the fovea. This coincides with the greatest density of the rods.

4.5.3 Flicker. When the eye is illuminated by brief flashes of light, alternated with darkness, the eye sees a flickering until the rate reaches 10 to 30 cycles per second when the images fuse and appear continuous. This rate of fusion is called the critical flicker frequency (CFF) and slightly different values are obtained from increasing the rate than from decreasing the rate to fusion. The CFF increases with increased luminance. Talbot's law states that, "fluctuating and steady lights of the same energy content appear equally bright," although recent experimentation indicates that for brief exposures intermittent light is less efficient, while for long exposures fluctuations help. The difference is probably related to the small fluctuating movements of the eye. A great many factors affect the CFF and attempts to use it as a criterion of vision or health have not been very satisfactory.

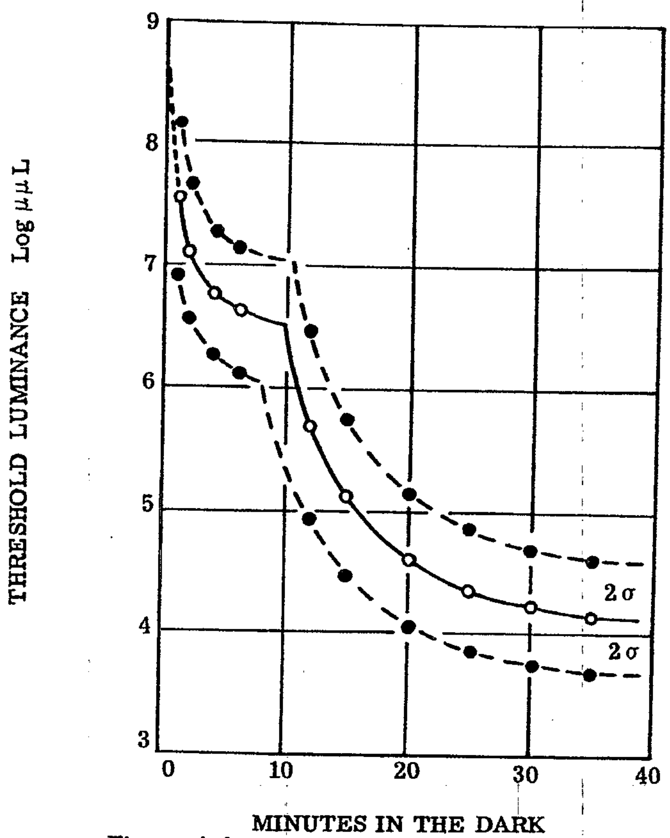

Figure 4.9. - A typical curve of dark adaption.

(From National Research Council, A. Chapanis 1949)

4.5.3.1 When the image is stabilized on the same exact part of the retina, vision gradually fades and disappears. Continuous small fluctuating movements (30-80 cps) and slow drifting of the eye prevents loss of vision. After the image drifts too far from its original position, a quick motion returns the image to the more sensitive part of the retina. To avoid the effect of eye movements in vision research, it is necessary that the stimulus be exposed no longer than 1/100th of a second. During steady fixation for 3 to 4 seconds the image may move over 25 to 50 receptors.

4.5.4 Measuring vision. For the practical purposes of measuring vision for the prescription of spectacle lenses various types of test charts are used, usually consisting of letters of different sizes. The standard is a 5 minute square letter, the individual details of the letter subtending at the observer's eye 1 minute of arc. The reference line on the chart is made with details of a size for the viewing distance to be used. Ordinary Snellen letter charts are designed for use at 20 feet from the observer. Other lines on the chart have graded sizes of letters, e.g. the line marked 40 ft. on the chart would subtend details of 2 minutes at the eye. Visual acuity (VA) is expressed as a fraction, the numerator of which is the design distance for the chart (usually 20 ft.) and the denominator is the line which can be read at that distance. With such a chart 20/20 vision would be normal, 20/15 would be better than normal, and 20/80 would be about 1/4 normal vision (observers only able to read at 20 feet, the line normal observers would read at 80 feet). These charts have high contrast black on a white background. In Europe similar charts are based on 6 meters distance (very nearly 20 feet) and the corresponding acuities are written as 6/6, etc. The Landolt C, a circle of 5 minutes diameter with a break of 1 minute (equal to the width of the line of the character) is used also as a test character. The break can be turned up, down, etc., to test its recognition.

4.5.4.1 Different letters have different thresholds for recognition and the few letters of about equal difficulty restricts chart construction and explains why different charts give slightly different results. The differences are not great enough to be of concern in ordinary clinical practice, but can be important in research work.

4.5.4.2 Visual acuity for moving objects is different from that measured with static tests and is called dynamic visual acuity (DVA) to distinguish it from ordinary or static visual acuity (SVA). Acuity varies with the contrast of the test target and illumination, Figure 4.3. Contrast is expressed as the difference between the luminance of the object and the luminance of its surround divided by the luminance of surround. At any given intensity there is a minimum contrast which is visible. Some relations between contrast and illumination are shown on Figure 4.3.

4.5.5 Lighting, comfort, and glare. For a given intensity of illumination, contrast, and size of object, there is also a minimum time for vision. At any luminance level less time is required to see at higher luminance levels. The time relations are different for scotopic vision at low luminance levels than for photopic vision. Except on rapidly moving vehicles the time factor is usually too small during daylight to limit vision. However, in the present jet age the seeing reaction time of an individual is too great to avoid collision at the distances at which very rapidly moving aircraft can be seen.

4.5.5.1 Adequate lighting is necessary for comfortable seeing. Too little light is inadequate, leads to strain and fatigue, and with too much light (sunlight on snow or ice) temporary blindness occurs. Outdoors, the eye can see well in the shade with 100 to 400 ft-L brightness. Indoors, considerably less luminance is available (6-20 ft-L). Because of the adaptation of the eye, the indoor room appears bright at night. The amount of illumination required for seeing depends on the size and reflectivity (contrast) of the object. Sewing with black thread on black cloth requires many times the illumination needed for black thread on white cloth. Lighting recommendations of the Illuminating Engineering Society are available and a recent revision considers contrast and time for adequate vision.

4.5.5.2 Light reaching the retina other than in a useful image is called glare. Glare reduces vision most when the glare source is close to the object or is between the object and the viewer. Small amounts of glare make seeing difficult and are uncomfortable. Excessive glare disturbs the adaptive state of the eye, can prevent seeing and should be avoided. Methods for measurement and computation of glare effects are available.

4.5.6 Color vision. Color vision depends on the spectral distribution of the illumination and the wavelength range reflected or transmitted to the eye, the state of adaptation of the eye and the part of the retina involved. For example, a red object would reflect wavelengths greater than 640mμ, a blue object from 410 to 480mμ. A monochromatic yellow light (589mμ) from a sodium lamp falling on a blue object could not be reflected and the object would appear dark. A yellow can also include yellow, orange and red light. Subtractive color appears when parts of the spectrum are removed; additive color when more than one color is combined, as by projecting onto a screen. The brightness of colors depends on the energy in the light and the sensitivity of the eye, Figure 4.8. The spectral distribution of energy from different sources can be quite different, e. g. ordinary tungsten lamps are deficient in blue and produce an excess of red light as compared with sunlight. The term daylight is meaningless unless specified with respect to, time, place and direction. Average noon sunlight is nearly an equal energy spectrum, but light from a north sky has an excess of blue and a higher color temperature than direct sunlight. To avoid these ambiguities in color measurement, standard sources have been defined and internationally accepted, and any work on color vision or color comparisons should be made with standardized conditions.

4.5.6.1 The normal human eye can match any color with a mixture of three primary colors: red, green, and blue. Color blindness, that is having only gray visual sensations, is extremely rare in humans and only a few such people (achromats) have been measured and described. More common is the condition of deficient color vision, and one in ten men and one in one hundred women have more or less color vision deficiency. The most common deficiency is poor red-green discrimination, and relatively rare are defects in blue-yellow vision. A mild deficiency, or anomalous color vision, is indicated when the person requires more or less green than red to match a standard yellow, but still must have all three primaries for color matching. When the deficiency is in green, the individual is said to be deuteranomalous; when the deficiency is in the red, protanomalous. A more severe type of color deficiency is dichromatic vision. The dichromat can match any color with only two primaries. Green deficient dichromats are called deuteranopes, and the red deficient dichromats are protanopes.

4.5.6.2 The color deficient individual is unable to distinguish certain colors, and the type of color confusion points to the kind of anomaly. There are appropriate tests to determine color deficiency and such tests must be done under proper illumination. A protan who is red deficient would see red, brown, dull green, and bluish green as the same color when they have the same brightness. A green deficient deutan would confuse purplish red, brown, olive, and a green. A tritan, the rare yellow-blue deficiency, would be unable to distinguish a purple from a tan or a yellow.

4.5.6.3 Color vision may improve and reach maximum towards the end of adolescence. Thereafter, there is little change until old age. Color defectiveness is inherited and no cure or remedy is known. A mild deficiency is only a small handicap and may not even be known by the person. Medium deficiency would exclude a person from working where medium color discrimination is important, and seriously deficient individuals should be excluded from all occupations where color recognition is important. Color codes should use colors which have a minimum confusion. A good example is a green traffic light with enough added blue that it is ordinarily not confused with the red light by most color defective people. The seeing of colors is more difficult when they are small and thereby require excellent color vision ability.

4.5.6.4 The very center of the retina is color deficient for yellow. A yellow object, sufficiently far away that its image is small enough to fall in this region, appears light grey or white. Yellow has not been a very satisfactory color for air-sea rescue, because of its confusion with the white caps on the ocean. The most conspicuous color depends on the background against which it is seen and the color vision of the observer. A golden yellow, or orange is usually readily seen. Reds appear dark and may not be seen by protans.

4.5.6.5 Looking at a colored object through a complementary colored filter makes the object appear dark; conversely, through a filter of the same color it may not be seen at all. Colored glasses reduces the overall amount of light to the eye, and vision is reduced in proportion to the loss of light. With the rare exception when complementary color contrast can be used, and there is sufficient light, colored glasses will reduce seeing. This reduction is increased as dusk approaches, and no colored glass improves seeing at night. A neutral glass can reduce the intensity of light and, if not too dark, maintain color discrimination.

4.5.6.6 The appearance of many colors will change with changes in the viewing conditions. Increasing, or decreasing, the intensity of light will de-saturate some colors, and change others to a different hue. As dusk falls, a lemon yellow gradually changes to light grey or white and may not be distinguishable from a white object. For the normal eye, red is seen as red when seen as a color, but other dim colors may not be recognizable. Some colors also change in hue after being fixated for some time.

4.5.7 Perception. Perception has been defined as a complex appearing in the field of consciousness and made of sense impressions supplemented by memory. Outside of experimental projects most seeing is done at the perceptual level. The recognition of objects depends on their form and shape, and is supplemented by learning or training. It is also possible to make psychological scales, as it is possible to adjust two lights so that one appears to be twice, or half as bright as the other. The scale of equal steps in brightness can then be related to the energies measured as photometric luminances. A brightness scale increases at an exponential rate with respect to the stimulating energy.

4.5.7.1 The appearance of objects depends on their immediate surrounds, due to retinal irradiation. A series of discs cut out of the same grey paper, but placed on brighter or darker greys will not appear to be the same, but lighter or darker depending on the contrast with the surround. The appearance of color depends on the surround and on the immediately previous color adaptation. White paper looks white in daylight and will also look white at night under tungsten illumination, even though the tungsten light has more red and yellow, and the paper is reflecting more red and yellow to the eye, as the eye has adapted to and interprets the new illumination. After exposure to an intense stimulation there is seen a series of after-images. These will be in complementary color when the object is colored and they are seen against a neutral background. The after-images gradually fade and may or may not affect seeing, depending on their intensity.

4.5.7.2 Much work, during and following World War II, has discovered better form, size and arrangement for visual displays to aid the designer when scales or indicators are needed. Vision through instruments involves the same principles discussed in this section. Unless the instrument produces a sharp image of proper size, intensity, and contrast on the retina it cannot be resolved and seen. Glare should be avoided. Reticles and scales that appear in the field of view require careful planning as to size, contrast, and lighting if they are to be seen with comfort. When half shade plates, or comparison fields are used in an optical instrument, the dividing lines should become invisible and the areas compared should have the same size, otherwise a slightly larger lighter area may be equated with a slightly smaller darker area.

4.6 MOVEMENT OF THE EYES

4.6.1 General. Six muscles move the eye. The conjunctiva, Tenon's capsule, and the fat pads within the orbital cavity of the skull aid in positioning the moving eye. The center of rotation is about 13-15.5 millimeters behind the cornea. Since there are no inflexible mechanical axes, the center of rotation may vary a millimeter or so depending on the resultant of the muscular action. The muscles which turn the eye are coordinated with those of the other eye, by the muscular movements within the eye, by the movements of the eye lids, and also by the neck muscles which move the head via the nervous system.

4.6.2 Muscular action. The superior and inferior rectus muscles as illustrated in Figure 4.10, raise and lower the eye in a plane 23° from the plane of the medial orbital wall. This is the wall of the skull seperating the nasal and orbital (eye) cavities. The medial (internal) and lateral rectus muscles rotate the eye toward or away from the nose in a horizontal plane, when the eye is in the primary position of looking straight ahead. The superior oblique muscle passes through tendon pulley and inserts into the upper, back side of the eye so that contraction of the muscle depresses the eye. The inferior oblique muscle is attached underneath the eye and on contraction raises the eye. The movement of the oblique muscles is in a plane through the center of rotation of the eye which slopes back about 129° from the medial orbital plane. The gaze must be directable to any place within its field of view, Figure 4.11, and maintain a horizontal reference on the retina corresponding with horizontal in the field of view. The superior oblique and the inferior rectus muscles working together

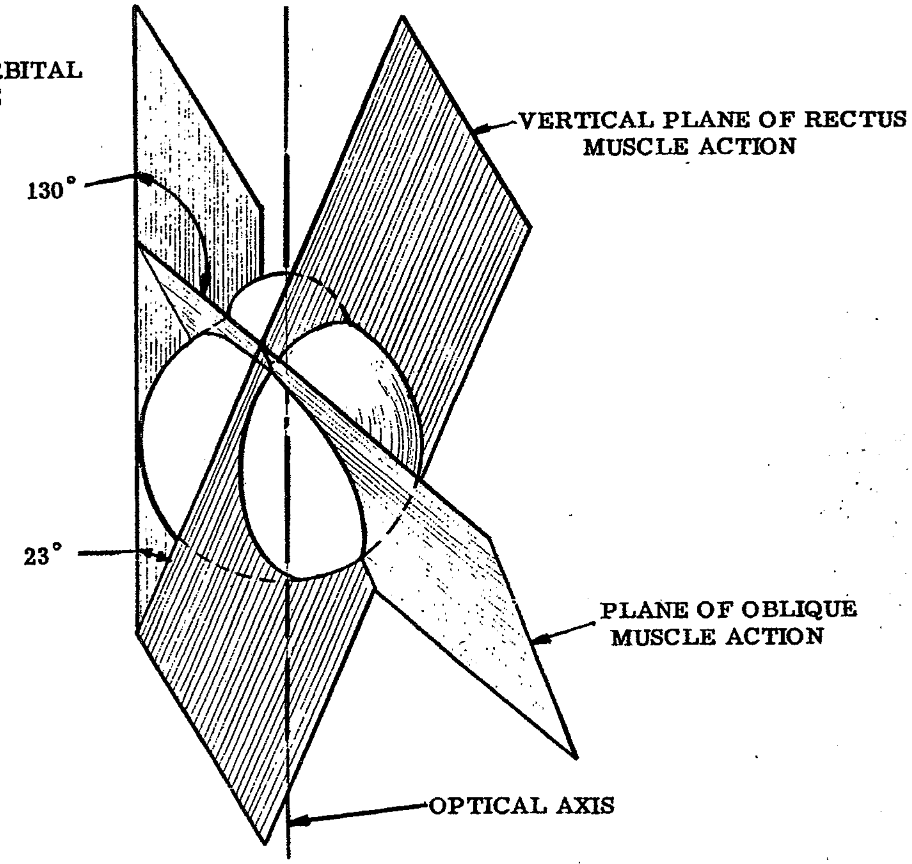

Figure 4. 10 - Planes of rotation of the external eye muscles.

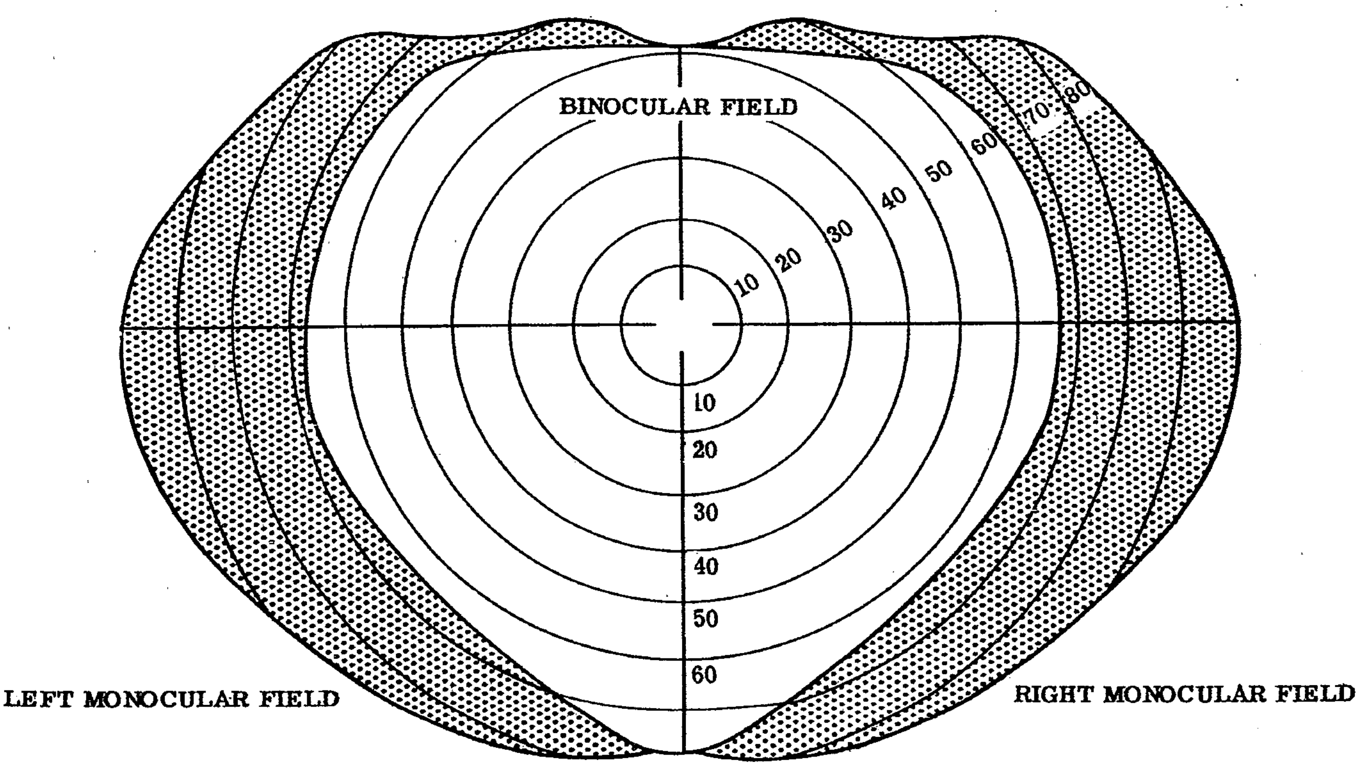

Figure 4. 11. - Monocular and binocular visual fields.

minimize a tendency for the eye to roll on an anterior posterior axis. Nevertheless, there is some torsion, or rolling, of the eye that can be mapped with the aid of after-images. Plotting the observations shows the visual field to have pincushion distortion.

4.6.3 Imbalance. The actual motions of the eye are complex. Adjustments of the eye to the left or right are made easily and up or down reasonably well, but the eye muscles are not arranged for movement of the eyes at oblique axes. Consequently, if the eyes are provided with more than slightly twisted images, they cannot adjust and fuse for single vision. The movement of the eye from one fixation to another is not smooth, and consists of movements of about 4 minutes subtended arc. The eye does not move directly to the point of fixation, but moves towards it and then approaches the fixation by a series of smaller movements. The following of a moving object by the eye also tends to go in small jumps rather than as a single smooth movement. The movements are the resultant of the contractions of one or more pairs of opposed muscles, and fluctuations are characteristic of neuromuscular mechanisms. Action potentials of the muscles can be recorded from electrodes placed around the eye, or within the muscles and their analysis is providing considerable new information on muscular movements. The eye follows a moving object as far as it can and then suddenly jumps back to a new fixation and this stepwise motion is called physiological nystagmus. Workers in mines under dim light develop a characteristic nystagmus.

4.6.4 Phorias and trophias. Two types of misalinement of the eyes have clinical importance. When one eye is covered and subsequently moves away from the fixation point, the condition is called a phoria. If the visual axes of the eyes are different when the eyes are open and uncovered, the condition is called strabismus or squint, and the direction is indicated by a tropia. Normal fixation is orthophoria or orthotropia and deviations would be heterophoria or heterotropia. The direction of the abnormal orientation is indicated by prefixes: eso- refers to movement toward the nose, exo- toward the temple, cyclo- a rotation, hyper- up, and hypo- down. Esotropia would indicate crossed eyes, while esophoria would indicate a moving toward the nose by a covered eye, or when the eye is dissociated from binocular vision.

4.7 BINOCULAR VISION

4.7.1 Advantages. The use of two eyes is a decided advantage in seeing. There is an apparent increase in brightness of about 20% when an object is seen with both eyes rather than with one eye alone. Normally the eye movements are equal and symmetrical and the sensory feed-back from the movements aids in balance and orientation of the organism.

4.7.2 Stereoscopy. A great advantage of two eye vision is the emergence of the experience of depth, or stereoscopic vision. Stereoscopic depth is a primary factor. Other factors which aid in the understanding of depth, such as superposition, are learned secondary factors. The basis of stereoscopic vision is horizontal dissimilarity of retinal images on corresponding points of the two retinas. In Figure 4.5, looking at the two points A and B which are at different distances from the eye, the images of the lines at A and B for the left eye are closer together than for the right eye. The fusion of these dissimilar images leads to the space perception that one is farther away from the other. Likewise, if one arranges drawings to give disparate images (within the physiological limits of the eye) when viewed through a stereoscope, the appearance of depth is produced. Stereopsis varies with the distance between the centers of the two eyes, the interpupillary distance (PD), and the spacing of the eyes alters the spatial visual geometry.

4.7.2.1 In designing binocular instruments, sufficient adjustment must be provided for the interpupillary distance of the intended observers. Formerly, 50 to 75 millimeters was considered adequate, but individuals are now growing larger and 76 millimeters maximum interpupillary distance have been used.

4.7.2.2 In stereoscopic depth the disparity between the retinal images for contours is probably more important than mere difference in size. There are limited areas on the retinas, within which objects can be placed on corresponding parts of the retinas, called Panum's areas. These areas are probably accounted for by the extent of the overlapping of the arborizations of the neurones from corresponding retinal points at the terminal areas of the cortex of the brain. The stereoscopic threshold is the smallest depth or disparity that can be experienced, and depends on the dimensions, contrast sensitivity of the retinal elements, and the sharpness of focus, i.e. the size of the blur circle on the retina. Stereoscopic acuity is less for individuals with less than 20/20 vision, but fails to increase with superior visual acuity. Stereoscopic vision is not limited to the macula and there is some evidence that it is maximal at an extra-foveal angle of 15-21 minutes. Useful stereoscopic depth is limited to about 1900 feet or a disparity angle of 24 seconds. For stereoscopic range finders the unit is about 12 seconds. The threshold for stereoscopic perception of depth increases with decreased illumination in dark adaptation, and shows a marked change which corresponds with the shift from photopic to scotopic vision.

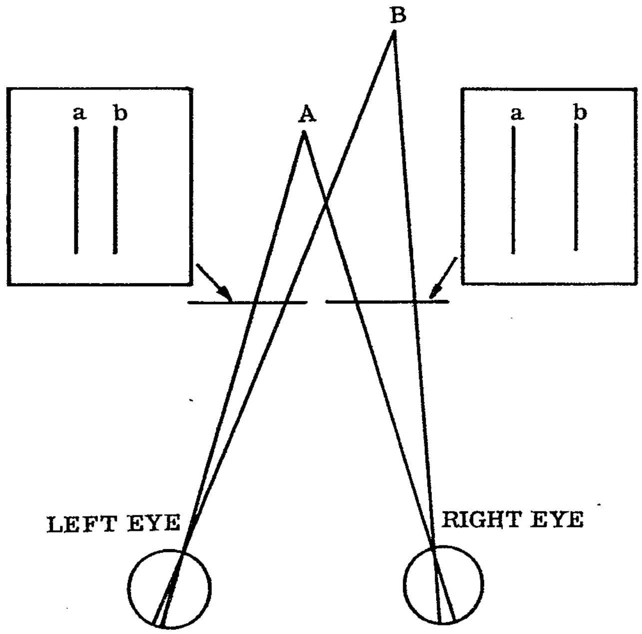

Figure 4. 12. - Stereoscopic vision with disparate images.
(From American Medical Association, Archives of Opthalmology, No. 60, K. N. Ogle, 1958)

4.7.2.3 One of the main problems in vision is the interpretation of the geometry of what we see. This involves the two eyes, their separation, and the connections within the brain. If we use a neutral filter to absorb some of the light to one eye, little change is noted in the stereoscopic effect for static objects, but if we look at a pendulum we find that the apparent movement is no longer in a single plane, but the bob tends to swing around an ellipse. This Pulfrich illusion is explained as a result of the different reaction times for the eye with and without the filter.

4.7.3 Psychological and physical space variations. Psychological visual space is different from Euclidean physical space. If five lights are arranged in a dark room to be in a straight line they will be found to be in a curved line after the lights are turned on. When aligned at right angles to straight ahead gaze, one plane is found where the lights would be set in a straight line. Nearer than that, the lights would be in an arc concave toward the eye and farther away in an arc convex to the eye. Such experiments provide evidence that psychological visual space is hyperbolic or elliptical rather than Euclidean. The transformation equations between physical and psychological space have not been fully worked out.

4.7.4 Limitations. There are practical applications for instrument design. If the images of an object are different in each eye either a depth sensation or distorted space perception will occur. When the differences are due to unequal magnification in size the appearance is that of a distorted space, and space distortion from size differences in the images is aniseikonia. The tolerance of individuals to such differences varies, but differences of 1 to 2% or more usually result in visual strain and discomfort. Differences of 5% usually preclude binocular vision. The differences are not always those of the actual size of the images on the retina but rather are an overall size effect which involves the central nervous system. An Eikonometer is used for clinical measurement and the aniseikonia can be corrected by a special size lens for one eye. Differences in size are innate in some eyes. In others they are produced artificially by a considerable difference in the spectacle prescription for the two eyes. A common problem arises from unilateral aphakia, when a strong, plus-spectacle lens is needed to take the place of the lens of the eye. It may not be possible under these conditions to restore stereoscopic binocular vision.

4.7.5 Design considerations. The design of binocular instruments is challenging since comfortable viewing with two eyes presents difficulties that do not occur with monocular instruments. The coordinated motion of the two eyes must not be disturbed. A pupillary adjustment of 50 to at least 76 millimeters should be provided. Magnification differences to the two eyes should not exceed 2%. Some people cannot tolerate more than 0.5% while others may tolerate a little more than 2%. Oculars must be paired so that increased size differences will not occur. Beam splitters should be neutral, otherwise the light to the two eyes will cause discomfort from the chromatic aberration of the eye. Should one eye receive a bluish light and the other eye a redish light the accommodation of each would have to be different, which would lead to strain and intolerable discomfort. The amount of light to the two eyes should be balanced, preferably within 10%. Vertical imbalance should not exceed 0.5 prism diopter. Horizontal imbalance need not be quite so small, but in excess of this value it would be fatiguing. Spectacle prescription practice holds to about 0.25 prism diopter. For low power instruments such as a bi-objective, binocular, microscope a 0.33 prism diopter difference may be tolerable. Any twist in the images should be kept to a minimum to avoid strain from complicated and difficult eye movements necessary to aline the images on the retinas. Since the light is divided to two eyes, more light will be required for binocular than for monocular instruments. In some types of binocular instruments, double mirrors or a large or diffusing mirror, may be necessary to direct the light to both eyes. When the objectives and the oculars of the instrument have different convergent angles, the appearance of depth can be made true (orthoscopic), or it can be increased or decreased (hyper- or hypostereoscopy), providing another variable for use by the instrument designer.

4.8 FATIGUE AND AGEING

4.8.1 Fatigue. Fatigue of the retinal processes is not likely at ordinary conditions. The usual "visual fatigue" (asthenopia) is muscular rather than retinal. Difficult seeing gradually involves 20 or more muscles, spreading to include those of the brow, cheek and lip. Greater mental effort is needed for getting and interpreting the visual information required. Uneven lighting results in one part of the retina needing more light and calling for pupil opening, while another is over stimulated and calling for a smaller pupil. The resultant conflict fatigues the ciliary process. Changes in illumination, too rapid for the accommodating ability of the eye, cause local and general fatigue. Continuous use of more than one-half of the available accommodative response, and close work necessitating strong convergence are fatiguing. Body tension increases during difficult seeing. An awareness of body sensation during difficult seeing, and the appearance of increasing hyper-reactivity, both increase general fatigue. A visual perceptual load, greater than can be assimilated, is also fatiguing. Visual fatigue is minimized with proper illumination, adequate contrast, form and time for seeing, proper arrangement for easy functioning of the eyes, and comfortable working conditions. An uncomfortable posture can cause eye strain and fatigue especially if seeing becomes difficult (dim light, fog, glare, etc.). An unpleasant task may make the eyes feel very tired, although instant recovery may occur on changing to an interesting visual task.

4.8.1.1 Any instrument that requires steady orientation of the eyes should be provided with a head rest, and heavy equipment should be properly supported in order to lessen fatigue. Instruments should be set up so that they are observed with a straight ahead position of the eyes, and when that is not feasible the instrument should be adjusted to the head for comfortable vision, not the whole body of the observer cramped into a viewing position. Image brightness and convergence should be adjustable and no adjustments of the eyes beyond normal functional ability should be required by an optical instrument (unless designed to test a visual function).

4.8.2 Age. Seeing is probably at its best towards the end of adolescence. Some of the age changes are summarized in Figure 4.13. At about age 40 the accommodative mechanism begins to fail and the individual is no longer able to focus the eye on near objects. This is due to a decrease in the elasticity of the lens of the eye, although the focussing muscles may also be involved. The condition is called presbyopia and is corrected by adding positive spherical power to the spectacles, usually in the form of a bifocal, or trifocal addition. The trifocal addition has the further advantage of providing an intermediate distance of clear vision just beyond that of the near correction. The pupil of the eye does not open as far in the elderly, which fortunately increases the depth of field. Although less light gets to the retina and greater illumination is necessary for equal visual efficiency. One experimenter has found that the illumination should be doubled for each 13 years increase in age.

4.8.2.1 The eye media lose transparency, particularly the lens, which becomes yellowish as age increases. These changes effect color vision, and in addition, lessen the light available for image formation. Accommodation is slower in old age than in youth. The efficiency of the retina declines and resistance to glare becomes less. The fibers of the lens may become opaque and form a cataract. With developing cataracts, asymmetrical screening may improve the vision slightly by reducing glare. The balance between enough light for adequate seeing, and excess light or glare, is difficult and more critical in later life. When instruments are to be designed for use both by young and old people the limitations of the older eye should be kept in mind.

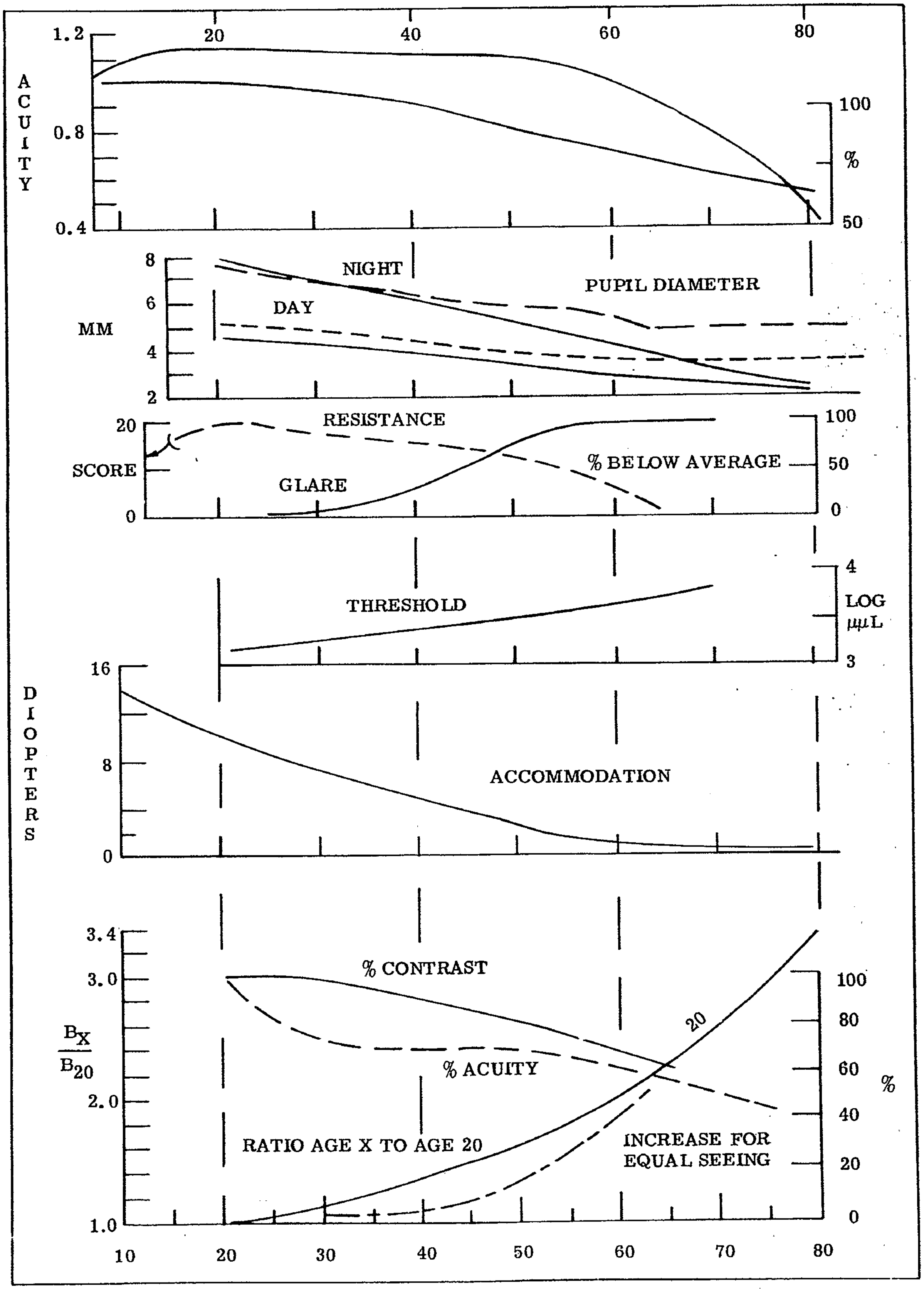

Figure 4. 13 - Some age changes in vision.
(From American Journal of Optometry, O. W. Richards, 1958)