CHAPTER TWO

Anatomy of the visual system

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The diagrams in this chapter are designed to illustrate the essential structural features of the visual system of Primates. Since most of the experimental work has been done on macaque monkeys, many of the diagrams are based on the monkey rather than on man. The systems are, however, believed to be basically similar.

In all the diagrams of the eye the light is deemed to be entering from the top of the diagram (arrow). It is focussed by the refracting cornea and lens so that after passing through the vitreous body and inner layers of the retina it is absorbed by the visual pigments in the outer segments of the rods and cones. Light unabsorbed by the retina is absorbed by the melanin of the pigment epithelium and choroid. The apparent inversion of the cell layers in the retina results from its embryological development (see Fig. 2.5*c*) and probably depends on the evolutionary history of the eye in early vertebrates.

Fig. 2.1. (*a*) Equatorial section through the eye, in diagrammatic form to illustrate main features. The thickness of all the layers has been greatly exaggerated.

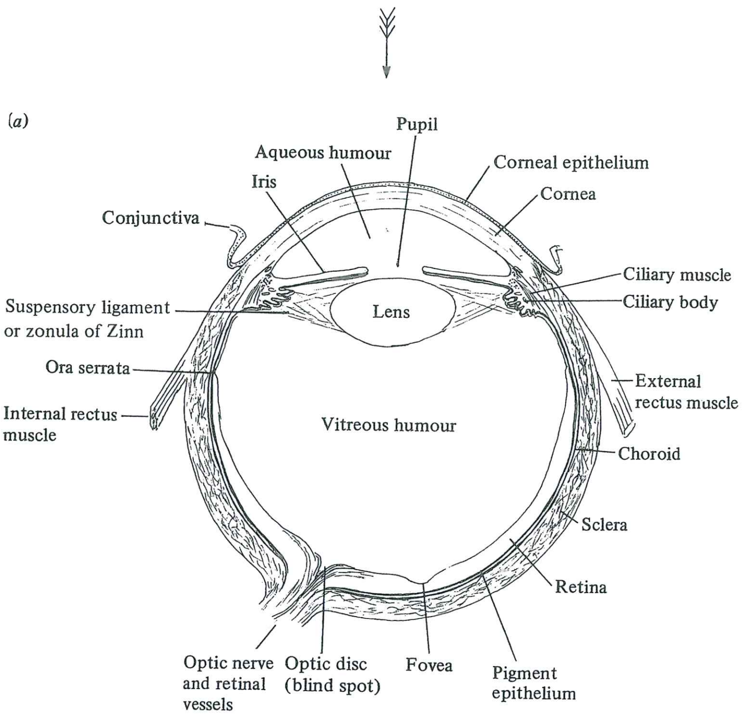
b, *c*) Extrinsic muscles of the right eye: (*b*) from above, (*c*) from below. The superior ectus, inferior rectus, medial rectus and inferior oblique are supplied by branches of he third (oculomotor) nerve. The superior oblique is supplied by the fourth (trochlear) nerve. Note that the tendon passes through the trochlea. The lateral rectus is supplied by the sixth (abducens) nerve. The levator palpebrae receives fibres from the 3rd nerve and the sympathetic system.

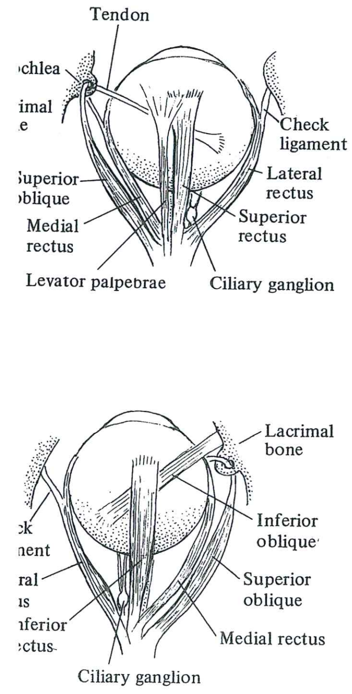
d) Enlarged diagram of a section through the anterior part of the eye. The cellular ens is slung in a hammock of fine collagen fibres (zonula of Zinn) between which the queous humour, produced from the epithelium over the ciliary processes, percolates before it passes through the pupil into the anterior chamber (arrows), from which it rains away into the canal of Schlemm through the trabecular meshwork, and thence nto the veins. The optical properties of the lens are caused by special intracellular roteins (crystallins) and the presence of hyaluronic acid, probably between the cells.

The ciliary muscles reduce the focal length of the lens by causing the ciliary processes o approach the pectinate ligament and so reduce the tension on the fibres of the onula. This allows the elasticity of the lens to cause it to become more spherical. Some f the muscles run radially to the pupil, others circumferentially. When both sets ontract the perimeter of the ciliary processes is reduced. (See Chapter 4.)

The collagen fibres of the cornea are arranged in alternating layers. In each layer he fibres run parallel to each other but at right angles to the fibres in the layers above nd below. The fibres are embedded in a medium rich in special mucopolysaccharides keratosulphate, chondroitin sulphate and hyaluronic acid). This medium normally as the same refractive index as the fibres, but is sensitive to its water and ionic content. All these factors contribute to its transparency or otherwise.

The vitreous humour owes its transparent and gelatinous character to hyaluronic cid.





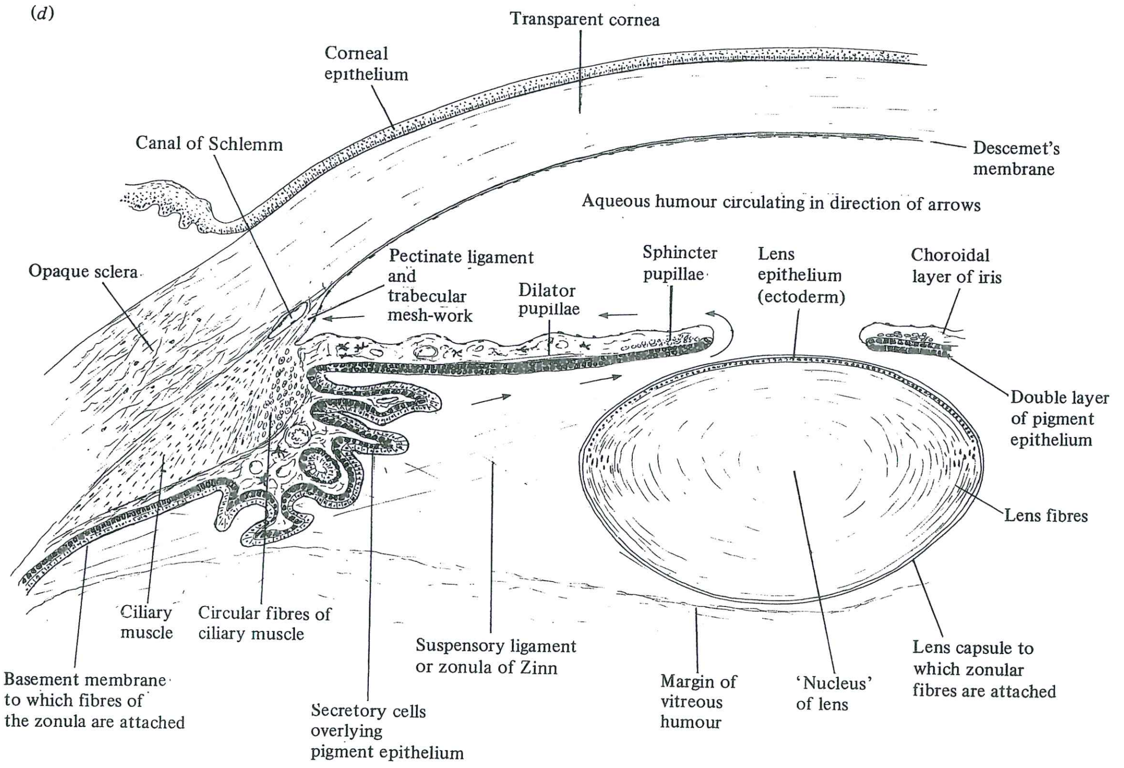


Fig. 2.2. Histological features of the retina.

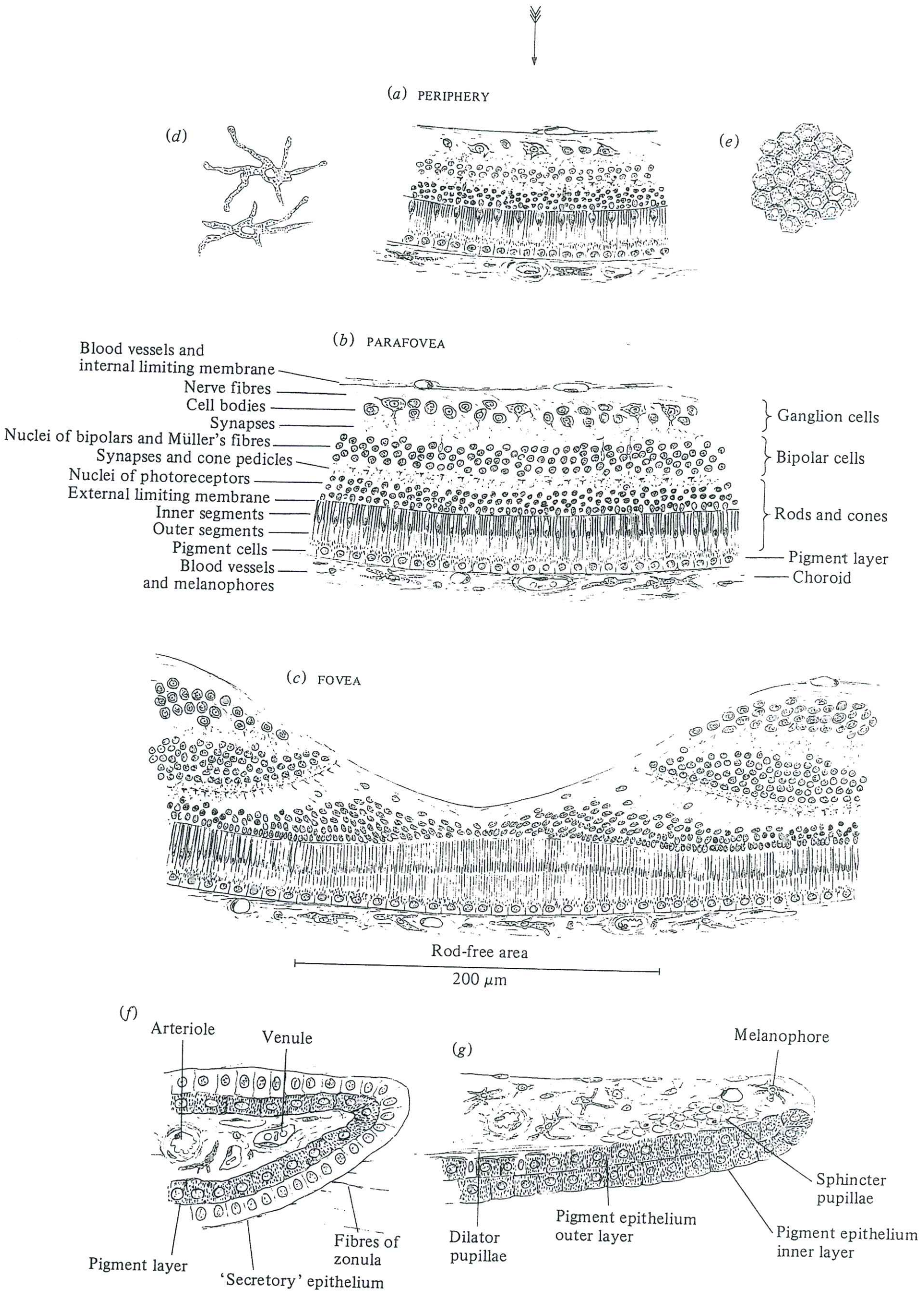
(*a*, *b*, *c*) Radial sections of the retina in three regions as seen in fixed and stained preparations, schematised. The following points should be noted. (i) Lengthening and narrowing of the cones from periphery to fovea, and their increasing concentration. (ii) Corresponding decrease in the number of rods and their complete absence from the centre of the fovea. (iii) Progressive changes in the character and numbers of ganglion cells and bipolar cells from the periphery to the foveal slope. The fovea ('pit') is actually the central depression from which these cells are pushed aside. (iv) The cone pedicles near the fovea form an almost continuous line. (v) The outer processes of the rods and cones interdigitate with the processes of the pigment cells of the retina. (vi) The pigment layer of the retina rests on the choroid coat which is very vascular and contains pigment cells of a different type (cf. *d*, *e*). (vii) Blood vessels that enter the eye with the optic nerve at the 'blind spot' ramify over the inner surface of the retina and they also extend between the ganglion cells and bipolar cells. (viii) The elongated nuclei of the fibrous supporting cells (Müller's fibres) can be seen among the nuclei of the bipolars.

(*d*) Two mesenchymal pigment cells (melanophores) from the choroid (or the anterior layers of the iris). These cells occur as isolated mobile units.

(*e*) Surface view of the pigment epithelium of the retina. These cells are fully adherent to each other in a single layer. Both types of pigmented cells contain melanin, a black pigment that is not photosensitive.

(*f*) The tip of a ciliary process is shown. Note that the pigment epithelium rests on vascular connective tissue closely akin to the choroid and containing melanophores. Over the pigmented epithelium there is another layer of unpigmented epithelium. This is believed to produce the aqueous humour by controlled filtration from the tissue fluid and the blood. The superposition of these two epithelia has an embryological explanation (see Fig. 2.5). The collagen fibres of the zonula are attached to a basement membrane on the surface facing the zonula.

(*g*) The tip of the iris is shown. The anterior portion is again composed of tissue akin to that of the choroid. The combination of its fibrous character and differing numbers and distribution of melanophores gives the iris its characteristic colour, for it is backed by the same double epithelium as the ciliary processes but behind the iris both layers are pigmented. The sphincter pupillae muscle, activated by the short ciliary nerve (parasympathetic) is derived from the epithelial layer; so too are the fibres of the dilator pupillae, whose cell bodies may remain in the epithelium and which are activated by sympathetic fibres running in the long ciliary nerve from the superior cervical ganglion.



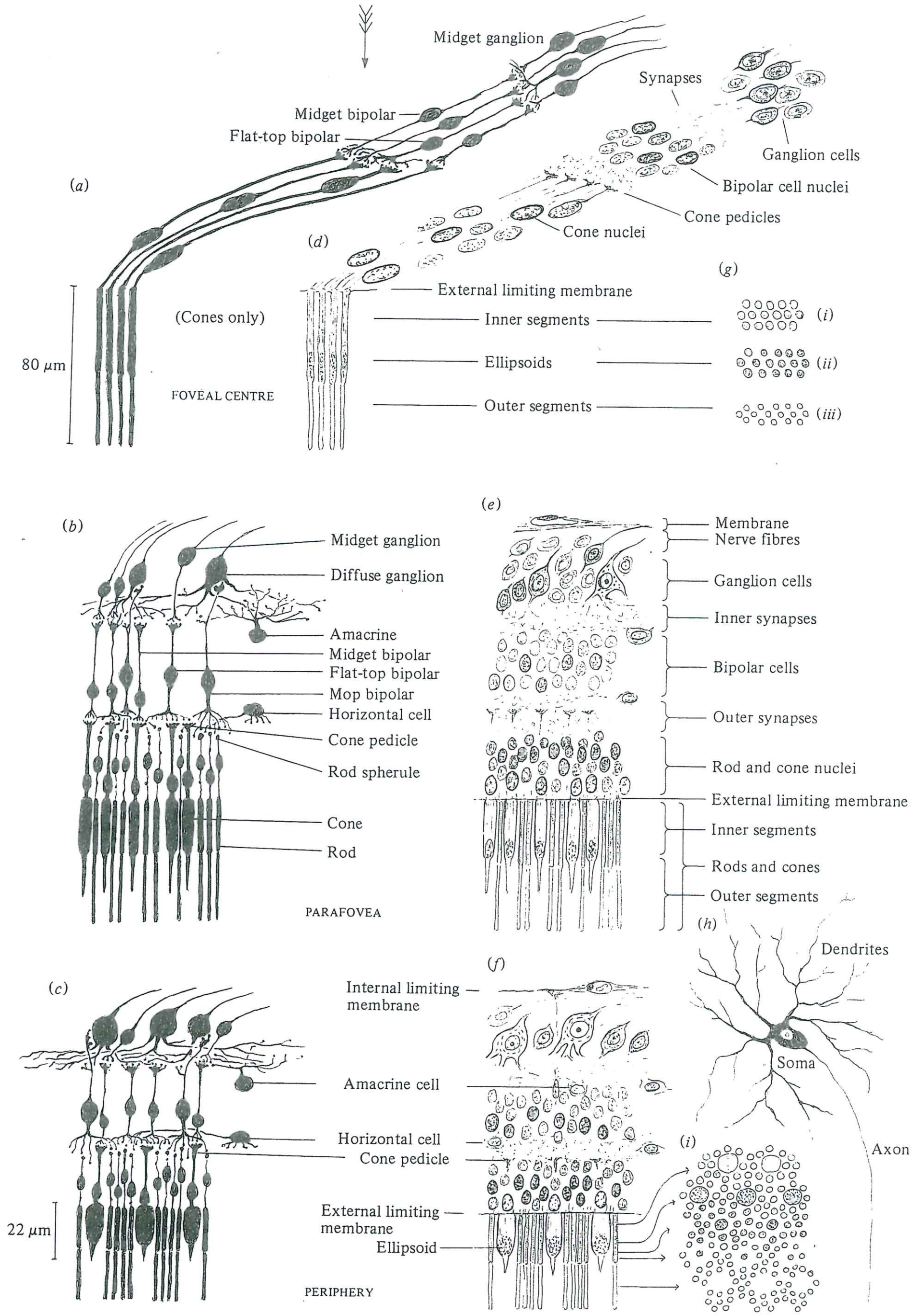


Fig. 2.3. Cytological features of the retina.
(*a*, *b*, *c*) Schematic diagrams of the supposed arrangements of cells based on observations on sections of the fixed retina treated by the Golgi technique of silver impregnation. This technique, of which there are several modifications, usually impregnates completely those cells that take the silver at all, though occasionally the axons may remain unimpregnated.
(*a*) Foveal centre; (*b*) parafovea; (*c*) periphery.
(*d*, *e*, *f*) Sections of the same parts of the retina as they would appear if fixed and stained by standard histological methods, (e.g. Susa fixation and iron haematoxylin). For the sake of clarity the cells that correspond to those depicted in the Golgi preparations have been drawn more heavily. Shrinkage during the various processes makes precise measurements on histological preparations of dubious value.
(*g*) The arrangement of the foveal cones as seen in transverse sections at three different levels: (i) through the inner segments which probably contain the macular pigment; (ii) through the ellipsoids, which are concentrations of mitochondria; and (iii) through the outer segments, which contain the photo-sensitive pigments (see Chapters 5 and 9). The long central processes of the foveal cones probably also contain the macular pigment.
(*h*) A ganglion cell, impregnated with silver, as it would appear in a retina spread out flat on a slide and subjected to a Golgi technique.
(*i*) Transverse sections of the peripheral rods and cones at different levels. Such a gradation is frequently seen in sections that are not absolutely transverse to the rods and cones.

Note that rods terminate centrally in end-knobs or 'spherules', while cones end at a slightly deeper level in end-feet or 'pedicles'.

Horizontal cells and amacrine cells do not show typical axons though the former may have one much longer process than the rest. S. L. Polyak, who made extensive studies of retinae impregnated by the Golgi technique suggested that ganglion cells could be classified into several different groups according to the pattern and extent of their dendritic trees. In these diagrams, midget ganglion cells and two other types of ganglion cell can be distinguished by the single or multiple origin of their dendrites, the 'receptive field' of the dendrites and also by the distribution and size of the Nissl's granules (ribosomal particles) in their cell bodies.

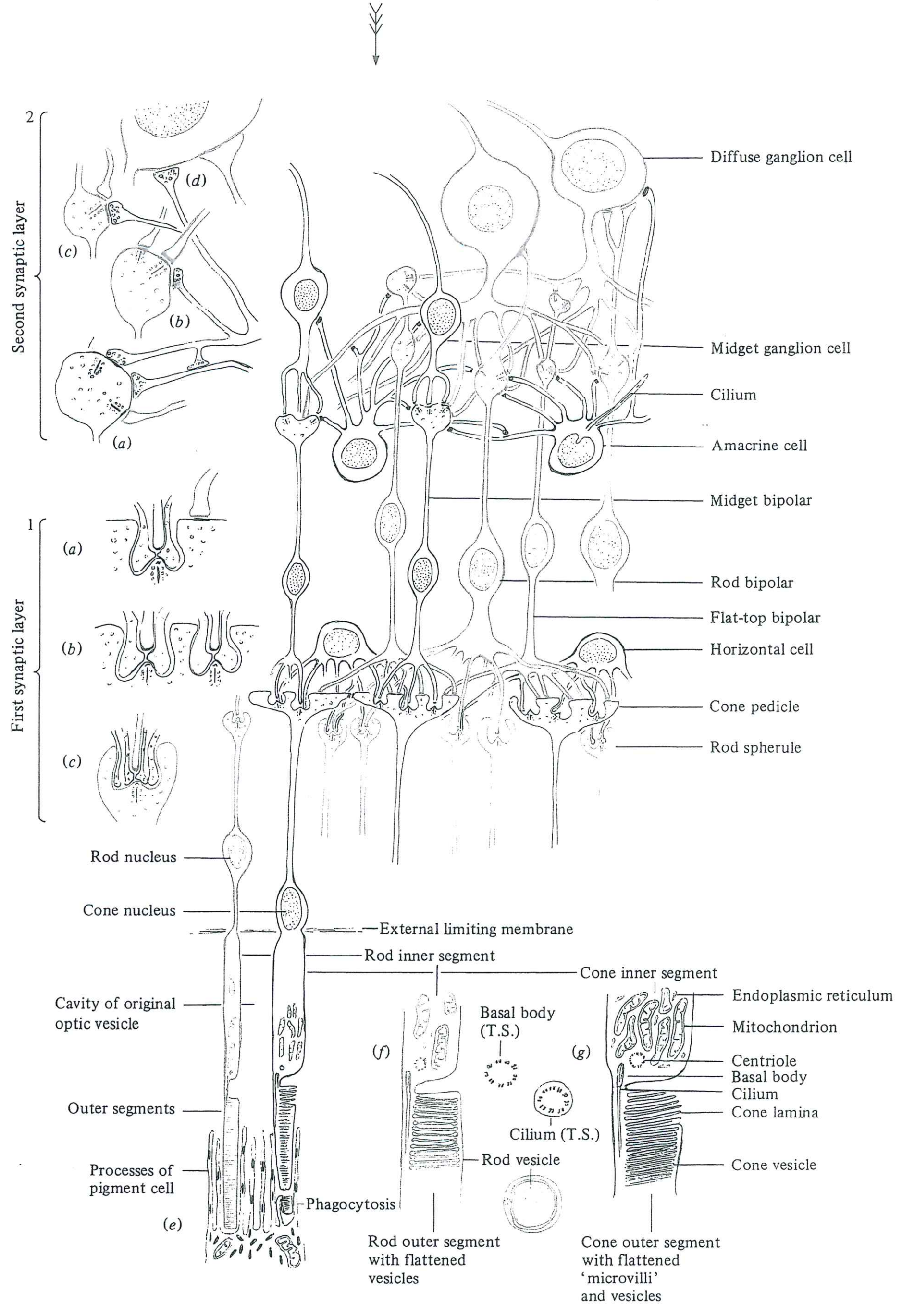


Fig. 2.4. Retinal structure reconstructed from studies with the electron microscope (largely derived from the observations of J. E. Dowling & B. B. Boycott, (1966). *Proceedings of the Royal Society Series B*, **166**, 80–111). Colour coding is used throughout this figure to differentiate cells as follows:

Blue: Rods, rod bipolar cells, diffuse ganglion cells.

Red: Cones, midget bipolar cells, midget ganglion cells.

Green: Flat-top bipolar cells.

Black: Processes of pigment epithelium cells, horizontal cells, amacrine cells.

In the main diagram, which shows a general plan of the retina, the colour coding serves to draw attention to the apparently direct pathways suggested by the anatomy: (i) numerous rods → rod bipolar → diffuse ganglion (all blue in the diagram); (ii) single cone → midget bipolar → midget ganglion (all red); (iii) several cones → flat-top bipolar → diffuse ganglion.

On the left are enlarged diagrams of the main types of synapse so far recognised.

(1) Synapses in the outer (first) synaptic layer.

(*a*) Cone pedicle with process from midget bipolar and horizontal cell and also a process from a flat-top bipolar. (Note that there is no synaptic ribbon nor any aggregation of vesicles in this type of synapse.)

(*b*) Cone pedicle with processes from midget bipolar and horizontal cells.

(*c*) Rod spherule with process from rod bipolar and processes from horizontal cells.

(2) Synapses in the inner (second) synaptic layer.

(*a*) Midget bipolar with process from midget ganglion and process from diffuse ganglion (both with synaptic ribbons) and with processes from amacrine cells. Note the position of vesicles in the last.

(*b*) Flat-top bipolar with diffuse ganglion cell and with amacrine cell processes. Note positions of synaptic ribbons and vesicles.

(*c*) Rod-bipolar knob with processes from diffuse ganglion cell and amacrine cell.

(*d*) Terminal process of rod bipolar and process of amacrine cell on cell body of diffuse ganglion cell.

In the main diagram note also the following points.

(*e*) Processes of the pigment epithelium cell (with pigment granules) interdigitating with the outer processes of rods and cones, for the phagocytosis of the tips of which they are believed to be responsible.

(*f*) The junction between the inner and outer segments of a rod. Note that the outer segment is composed of a stack of flattened vesicles.

(*g*) The junction between the inner and outer segments of a cone. Note that the more basal part of the outer segment is composed of flat processes resembling flattened and laterally extended microvilli. In both rods and cones note the centrioles and the basal bodies from which ciliary fibres project into the outer segment, suggesting that the outer segments are modified flagella, or cilia, comparable with those on ependymal cells which are embryologically related to rods and cones (see Fig. 2.5*c*).

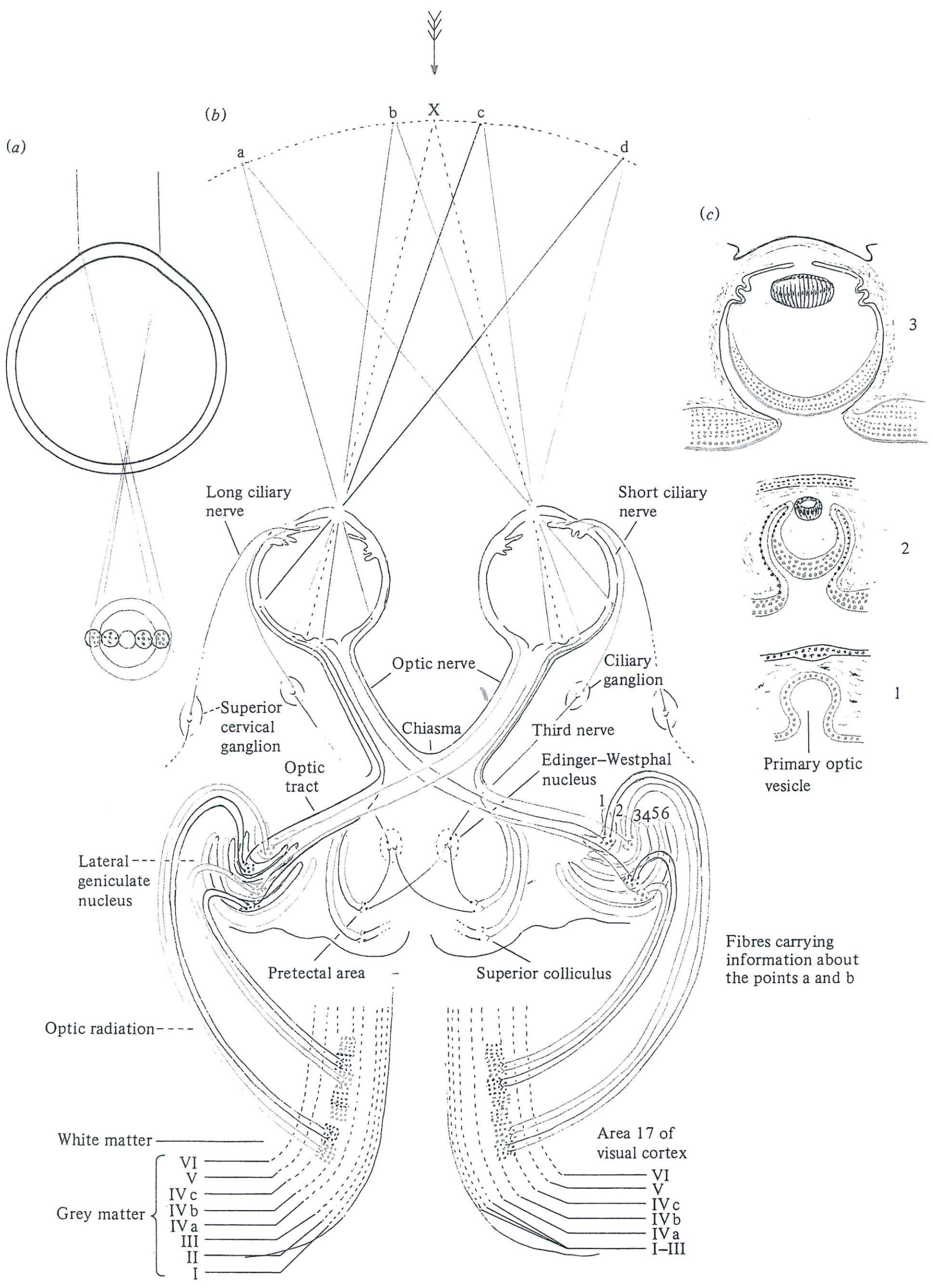


Fig. 2.5. Neural pathways; chromatic aberration; embryology.

(*a*) Diagram to illustrate the effects of chromatic aberration. When yellow-green rays are focussed on the retina, blue rays come to a focus in front of it and red rays behind it. In consequence, a point of white light, if nominally focussed on a cone, would spread out at the level of the receptor processes as a 'blur circle' with a diameter of about five cone diameters, the outside receiving only blue and violet rays.

(*b*) A schematic diagram of the main neural pathways involved in vision. The eyes are deemed to be directed towards the point X of the object abcd. The images of the points a, b, c and d fall as indicated on different parts of the retinae. If the neural paths (appropriately coloured) are followed from the stimulated points along the optic nerves, optic tracts, lateral geniculate nuclei and optic radiations it will be seen that information from the left visual field ends up in the right visual cortex and from the right field goes to the left cortex. Synapses are made in the lateral geniculate nucleus with cells in specific layers (ipsilateral in layers 2, 3 and 5, contralateral in layers 1, 4 and 6). The fibres from the cells in the geniculate nuclei terminate in layer IV of the cortex.

Other fibres from the retina travel to the superior colliculus and the pretectal area. From the latter, neurons lead to the Edinger–Westphal nucleus, from which the third nerve takes origin to supply some of the extrinsic eye muscles (see Fig. 2.1) and to relay in the ciliary ganglion to activate the ciliary muscles and the dilator pupillae, by way of the short ciliary nerve (parasympathetic). The dilator pupillae is supplied by the long ciliary nerve (sympathetic) from the superior cervical ganglion.

(*c*) Schematic and simplified diagrams to illustrate the main features of three stages in the embryogenesis of the eye.

Black: ectoderm and its derivatives, the lens and conjunctiva. The pigment epithelium, derived from the neural ectoderm.

Blue: neural ectoderm and neural tissue, including that of the retina.

Green: ependyma and the rod and cone layer of the retina.

Red: 'secretory' epithelium over the ciliary processes, derived from neural ectoderm. The mesenchyme which gives rise to the cornea, the sclera, the ciliary muscles, the choroid, the anterior part of the iris and the vitreous body.

1. Outgrowing optic vesicle inducing thickening of the ectoderm.
2. Invagination of the optic vesicle (simplified); separation of the lens 'vesicle'; beginning of the differentiation of the neural ectoderm.
3. Main features of the maturing eye and neural tissue. The conjunctival epithelium overlies the developing cornea. The lens fibres (epithelial cells) obliterate the cavity of the lens vesicle. The iris and ciliary processes are formed and the layers of the retina are beginning to differentiate.

Note that the pigment layer lies on one side of the occluding optic vesicle and the rod and cone layer on the other. It is the processes of the cells on the apposing walls of the vesicle that interdigitate, so that the rods and cones and the processes of the pigment cells are bathed in fluid that was originally cerebrospinal fluid.

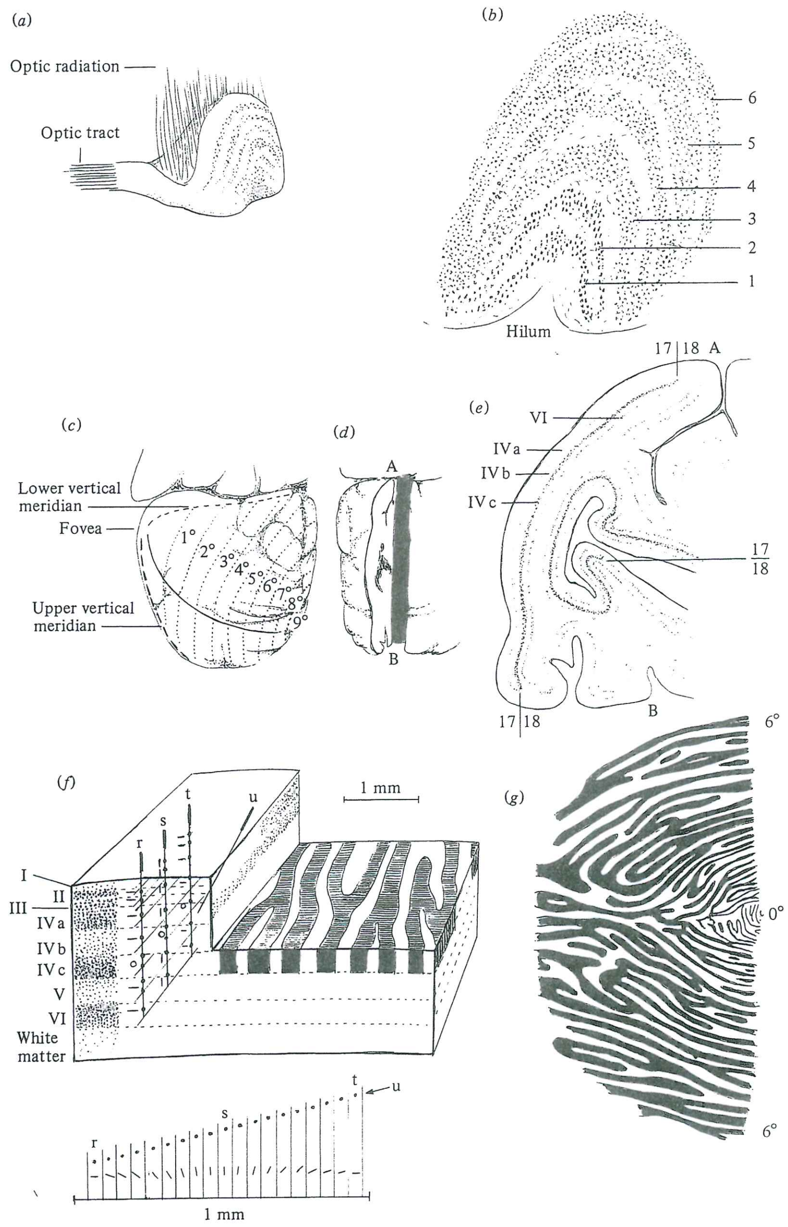


Fig. 2.6. The lateral geniculate nucleus and the striate cortex.

(*a*) Model of the lateral geniculate nucleus, showing the relationship between the fibres of the optic tract and those of the optic radiation.

(*b*) The laminated structure of the lateral geniculate nucleus as seen when a section is stained to show the Nissl's granules in the cells. The cells in layers 1 and 2 are noticeably larger than the rest. Fibres from the fovea end predominantly in the central portions of layers 6, 5, 4 and 3 and very rarely if at all in 1 and 2. From the parafovea they end in all layers, and from the periphery the fibres end on the lower margin of the body where the layers tend to be much less distinct.

(*c*) A superficial view of the left visual cortex of the monkey as seen from behind indicating the regions where fibres from different parts of the visual field terminate.

(*d*) A similar view of the right visual cortex with a segment removed. If the wall on the left of the space so formed were then removed and sectioned it would have the structure shown in (*e*).

(*e*) Vertical sagittal section of visual cortex of monkey (see *d*) showing cell layers IV and VI of the grey matter both in the outer portion and in the infolded portion. In area 17 of Brodmann layer IV is divided into IVa, IVb and IVc. In area 18 it is united into one. The optic radiation ends in layer IVc of area 17.

(*f*) The cell layers in area 17 of the visual cortex are indicated on the left of the diagram. On the right of the diagram layers I to IVb are deemed to have been removed. The shaded areas in layer IVc show how each eye is represented. Fibres from the left eye (say) end in the cells in the black zones, those from the right eye in the colourless zones (see Fig. 2.5(*b*)). The cells in this part of the cortex are arranged in vertical columns and the columns have very specific functions. For example, in one set of observations, electrodes were inserted progressively, and records taken from the cells at different depths. If the positions of the electrodes were as indicated by r, s and t the cells were found only to respond when the eye was stimulated by an illuminated bar having the orientation in the visual field indicated by the direction of the short lines opposite the positions of hypothetical cells. The sign o indicates that the cells in that layer IVc showed no such specificity. If an electrode u was inserted almost parallel to the surface and passing through layers II to IVa in a direction parallel to r, s, t the cells were found to respond only to stimuli having orientations in the visual field as indicated in the diagram below. In other words there seem to be columns of cells in the visual cortex, each one of which specialises in some oriented feature of the visual image.

(*g*) If the parts of the visual field corresponding to the cells encompassed by the grey stripes in (*f*) were also shaded black in the visual field, it would appear with a pattern essentially similar to that shown here. The fovea monopolises a disproportionately large part of the visual cortex and the periphery has only a very small representation among the cells of the cortex. Expressed differently, only a small area of cortex is involved in registering quite large peripheral fields, but small central fields occupy large areas of cortex.

In making the diagrams for this figure heavy reliance has been placed on the work of W. E. Le Gros Clark and also on the observations of D. H. Hubel & T. N. Wiesel and their Ferrier Lecture (*Proceedings of the Royal Society, Series B*, **198**, 1–59). The debt is willingly and gratefully acknowledged.

CHAPTER THREE

Image formation in the eye

M. MILLODOT

3.1. OPTICAL CONSTANTS OF THE EYE

Just like those of other bodily structures, the dimensions of the human eye vary greatly among individuals. Thus average values have to be adopted, which are ironically called 'constants' of the eye. However, most of the dimensions of the various parts of the eye are normally distributed, at least in healthy eyes.

The determination of these dimensions is difficult as they must be measured *in vivo* as far as possible. Formerly, enucleated eyes were used, but because they were usually diseased and because the circulation of the blood had ceased, these eyes may have been distorted. More recently, however, most constants of the eye have been obtained on living eyes, with the exception of the refractive indices of the media.

Index of refraction

Refraction is the change in the direction of propagation when light passes from one transparent medium to another. The refractive index (n) of a medium is defined:

$$n = \frac{\text{velocity of light in vacuum}}{\text{velocity of light in the medium}} = \frac{\sin i}{\sin r}$$

where i is the angle of an incident ray (in the vacuum) and r is the angle of the refracted ray (in the medium), both angles being measured from a line perpendicular to the surface.

When light passes from one transparent medium to another, $(\sin i/\sin r) = (n'/n)$, where n and n' are the refractive indices of the first and second medium respectively. Since the refractive index of air is close to unity and that of the cornea is 1.38, substantial refraction ocurs at the outer surface of the cornea. However, when a person is swimming under water, without a mask, the cornea is bathed in water of approximately the same refractive index ($n = 1.333$) and its effective power is almost eliminated. This produces

a retinal image that is vastly out of focus and vision is hazy (the eye is in fact rendered artificially hyperopic). The indices of the different media of the eye are given in Table 3.1. Since the lens is heterogeneous, its index is nominal and is based on its optical effect.

Curvature of the optical surfaces

An optical surface is defined as a boundary between two media of different refractive indices. The eye consists of four optical surfaces: the anterior and posterior surfaces of the cornea and the anterior and posterior surfaces of the crystalline lens.

The method of measuring these curvatures *in vivo* depends upon the reflection of light from objects by these surfaces. Such reflected images are called catoptric or *Purkinje–Sanson images*. In contrast, the images that are formed on the retina and give rise to vision are called dioptric images. All optical surfaces refract and reflect light but the amount reflected is only of the order of 3–4% depending on the indices of the media. You can observe this reflection from the cornea of the eye. Looking at someone else's eye you can see reflected images, of fluorescent tubes, for instance, and perhaps even of your own profile.

The sizes of these catoptric images can be measured and then the radius of curvature of the surface (r) can be assessed using a relationship between the size (y) of an object placed at a given distance (x) from the surface and the size of the image (y') formed by reflection: $r = -2\,xy'/y$. (For the derivation of this relation see Bennett & Francis (1962) in *The Eye 4*, p. 115, ed. H. Davson.) Instruments based on this principle such as ophthalmometers or keratometers, which measure the radius of curvature of the anterior surface of the cornea, have been used reliably for a century. These instruments are also used routinely to assess the astigmatism (see below) of the cornea.

The problem becomes more difficult when measuring the curvature of the other optical surfaces of the eye. Considerable ingenuity has gone into doing this using catoptric images reflected by the posterior corneal surface and the two surfaces of the lens. Modern methods of investigation have made use of photography of these images and have yielded very accurate results. Average findings are given in Table 3.1.

The four images reflected by the optical surfaces of the eye are referred to as Purkinje–Sanson images I, II, III, and IV, starting from the front surface of the cornea (I). Images I, II and III are erect

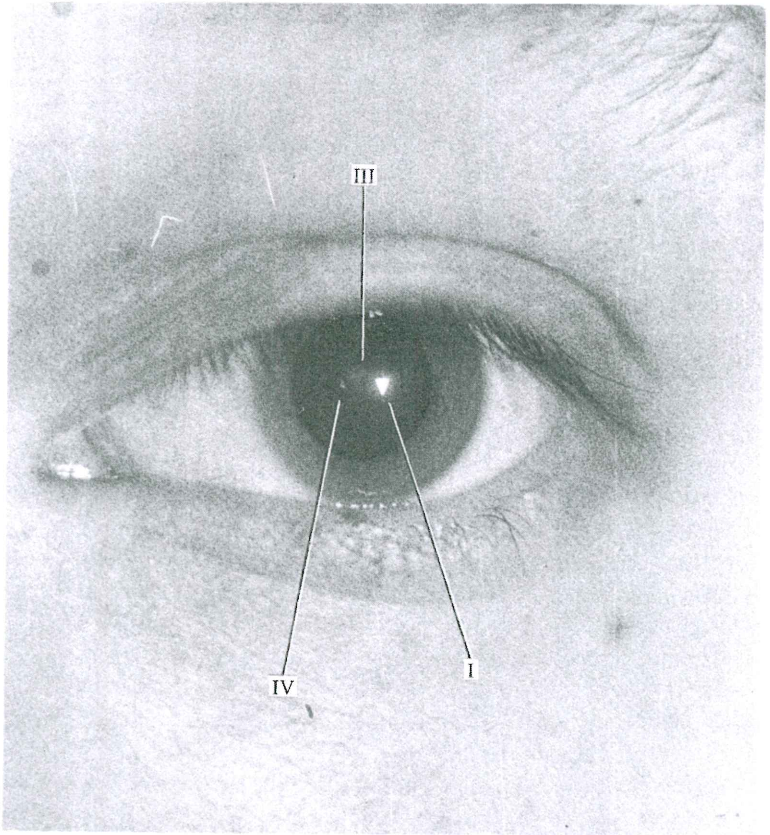


Fig. 3.1. Photographs of three of the Purkinje–Sanson images. A triangular source (point down) is seen reflected by the anterior corneal surface (I), the anterior lens surface (III), and the posterior lens surface (IV). The reflection from the posterior corneal surface (II) is very dim and is masked by I. The size of the images is related to the curvature of the surfaces, so III and IV can be used to follow the changes during accommodation. Note that IV is inverted because a real, inverted, image is formed by the concave posterior lens surface. The other images are erect.

because the surfaces upon which they are formed are convex towards the light path. Image IV is inverted (see Fig. 3.1) because the posterior surface of the lens is concave. Image I is bright but the others are very dim, especially II since the cornea and the aqueous humour have very similar refractive indices. A good deal of our knowledge of the mechanism of accommodation has been gained by measuring the III and IV Purkinje–Sanson images, since their changes show how the lens changes in shape (see p. 64).

Besides the catoptric and dioptric images there exist *entoptic images*, which are visual sensations arising from images of objects located within the eye itself. The best known of these are the 'muscae volitantes', which appear as floating specks in the field of view. They are due to shadows cast upon the retina by small particles in the vitreous body. An entoptic phenomenon that you can easily observe under special circumstances is that induced by the retinal blood vessels, which lie outside the retinal layers. Close your eye and use a small torch to throw light through the sclera by placing the torch against the eye near the outer angle of the orbit. The shadows of the vessels will now fall on the retina and, perhaps because it is an unaccustomed stimulation, they will be visible for a short period of time. If you move the torch the shadows become visible again. You will see an intricate branching pattern known as the *Purkinje tree* which corresponds to the branches of the retinal arteries and veins radiating from the optic disc. Some people have difficulty at first in seeing this effect, but once seen it is unforgettable.

Position of the optical surfaces

The separation between the various optical surfaces is also important to the dioptrics of the eye. Formerly this was determined by focussing a microscope on one surface, then the next, and so on, and recording the distance each time.

More recently, ultrasonographic techniques have been introduced to assess the relative positions of the surfaces: very high frequency sonic energy (5 to 10 megacycles) is reflected at the various optical surfaces. Knowing the speed of sound in a given medium, and the time taken, it is possible to deduce the distance. The results thus obtained are in good accord with the other methods. The locations of the various surfaces are given in Table 3.1.

Length of the eye

The length of the eye from the anterior corneal surface to the retina can also be assessed by ultrasonography. This is possible because the interface between the vitreous humour and the retina and that between the retina and the pigment epithelium reflect ultrasound as well as light. (The slight optical reflection at the former interface allows the concave surface of the fovea to be seen with the ophthalmoscope.) Another way of determining the position of the retina

Table 3.1. *Optical constants of an average adult human eye*

Structure or surface	Refractive index	Radius of curvature (mm)	Distance from anterior surface of cornea (mm)
Cornea	1.376	—	—
Aqueous humour	1.336	—	—
Lens (total)	1.41	—	—
Vitreous humour	1.336	—	—
Anterior corneal surface	—	7.8	0
Posterior corneal surface	—	6.8	0.5
Anterior lens surface	—	10.0[a]	3.6[a]
Posterior lens surface	—	−6.0	7.2
Retina	1.363	—	24.0

[a] When the eye accommodates at its maximum the anterior surface of the lens alters its curvature to about 6 mm and that surface moves forward to be approximately 3.2 mm away from the anterior surface of the cornea.

relative to the cornea is by X-rays. The retina is slightly sensitive to X-ray stimulation. A sheet of X-rays aimed at right angles to the optical axis of the eye will intersect the retina in a circle. The subject reports seeing a light circle. As the X-ray device is moved posteriorly it will eventually stimulate one small point at the posterior pole of the eye. Then the subject will report seeing a small luminous point. In this case the distance between the X-ray device and a microscope aimed at the front surface of the cornea represents the length of the eye. Ultra-sonographic and X-ray methods yield results that are in good agreement but they involve some risks of injury to the eye. The average length of the eye is shown in Table 3.1.

Dioptrics of the eye

The power of a spherical refracting surface such as those in the eye is equal to $P = (n' - n)/r$, where n and n' are the refractive indices of the object (first medium) and image (second medium) spaces respectively and r the radius of curvature in metres. The converging or diverging power (P) of a lens is expressed in a unit called the dioptre (abbrev: D), which is equal to the reciprocal of the focal length in metres. Thus the strength of a lens with a focal length (f) of 1 m is 1 D; of one with focal length of $\frac{1}{2}$ m, 2 D, and so on.

Table 3.2. *Refractive power (in* D) *of the optical surfaces of an average adult human eye*

Anterior surface of cornea	48.2
Posterior surface of cornea	−5.9
Anterior surface of lens	8.4
Posterior surface of lens	14.0

For example the refractive power of the anterior surface of the cornea, which is against air ($n = 1.0$), is equal to $P = (1.376 - 1.0)/(7.8 \times 10^{-3}) = 48.2\ D$. The power of the other optical surfaces of the eye can be calculated in the same fashion and the results are given in Table 3.2.

It is obvious from Table 3.2 that the major refracting surface of the eye is the anterior surface of the cornea, since it separates two media (air and cornea) differing widely in refractive indices. Thus any irregularities on this surface will have major consequences for the image formation of the eye. Oedema, which is a sequel of any lesion of the cornea and of some other ocular and systemic conditions, will alter the configuration of the cornea as well as reducing its transparency. All of these effects cause blurred vision.

The total refracting power of the eye is not equal to the simple addition of the four refractive surfaces. This is because the separation of the surfaces tends to diminish the cumulative refractive effect. Indeed the power of two refractive surfaces is $P = P_1 + P_2 - (d/n)\, P_1 P_2$ where P_1, P_2 are the powers of the two refractive surfaces, d their separation and n the refractive index of the medium separating them. If all four surfaces of the eye were against one another ($d = 0$), the total power would be 64.7 D (adding the values in Table 3.2). In reality the total power of the human eye is approximately 60 D.

There are considerable individual differences in human eyes, yet it is useful to have an optical model of a typical eye to help in understanding the dioptrics of the eye and for convenience in calculations. These optical models are called *schematic eyes* and the most widely used model was devised by the Swedish ophthalmologist, Gullstrand (1862–1930).

A simple yet often sufficiently accurate model is the *reduced eye*. It consists of a simple spherical surface assigned the average power of the eye ($P = 60\ D$) and separating air outside from a medium of refractive index $n = 1.333$ (the same as for water) inside the eye (see Fig. 3.2). The radius of curvature of this simple surface is

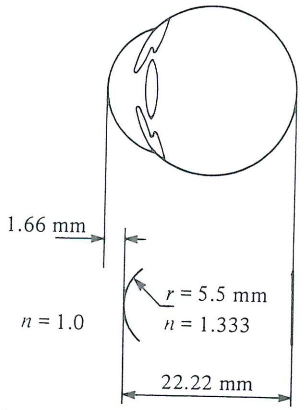


Fig. 3.2. The reduced eye (lower) consists of a single spherical refracting surface of 5.5 mm radius of curvature separating air ($n = 1.0$) and a medium with the refractive index of water ($n = 1.333$). It produces an image the same size as the average real eye with its multiple refracting surfaces, but is slightly shorter.

$r = (1.333 - 1.0)/60 = 0.0055$ m or 5.5 mm. The focal lengths (the distance between the surface and the focal points) of this eye are

anterior focal length, $f = -n/P = -1.0/60 = -0.0167$ m or -16.7 mm

posterior focal length, $f' = n'/P = 1.333/60 = 0.02222$ m or 22.22 mm.

This hypothetical simple surface is not coincident with the cornea of the eye. It occupies a place at which a simple surface has the same effect as that of the whole optical system of the eye. Therefore it is situated 1.66 mm behind the real cornea (see Fig. 3.2). It must be noted though that the refractive surface of the reduced eye has a greater curvature (and thus greater power) than the real cornea, so that it compensates for the absence of the lens.

The posterior focal point (that is where the image of an object placed at infinity is formed by the optical system) lies within the plane of the retina in the normal or *emmetropic* eye. As we shall see later (p. 70) if the retina lies either in front or behind the posterior focal point, the eye is said to be *ametropic*.

Axes of the eye

Although specialists have defined several axes of the eye (five, in fact) it is at first sufficient to consider two of them. Firstly the *optical axis*. This is the line that joins the centres of curvature of the four optical surfaces of the eye. It is a somewhat theoretical line since the eye is a biological structure and its optical surfaces are not necessarily truly spherical and their centres of curvature are not necessarily colinear. Nonetheless, the optical axis can be approximately defined as a line close to the several centres of curvature. The optical axis cuts the retina at the posterior pole of the eyeball, that is, a point somewhere between the optic disc or blind spot (where the optic nerve enters the eye and there are no photoreceptors) and the fovea (see Fig. 3.3).

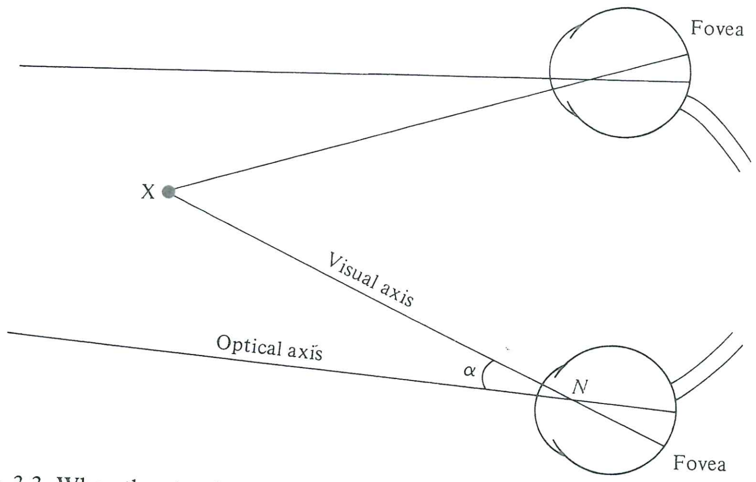


Fig. 3.3. When the *visual* axes of the eyes are converged on a fixation point X the *optical axes* (see text) are less convergent. The angle between the visual and optical axes (α) is about 5° in adults.

The other axis is the *visual axis*. It is the line joining the fixation point (X in Fig. 3.3) to the fovea of the eye, where vision is sharpest (see Chapter 8). This line passes through the equivalent centre of curvature of all the optical surfaces of the eye called the nodal point (N) which lies on the optical axis. A light beam passing through the nodal point is undeflected.

In the reduced eye the optical and visual axes are assumed to coincide and this is convenient for the purpose of simple object–image calculations. But the real eye is such that the fovea does not lie upon the approximate optical axis of the eye. The optical axis forms an angle with the visual axis, *angle alpha* (α) which is equal, on average, to 5° in the adult. In the child this angle is greater because the retinal distance between the fovea and the posterior pole of the eye is almost the same as in an adult but the length of the eye is much smaller (about 18 mm).

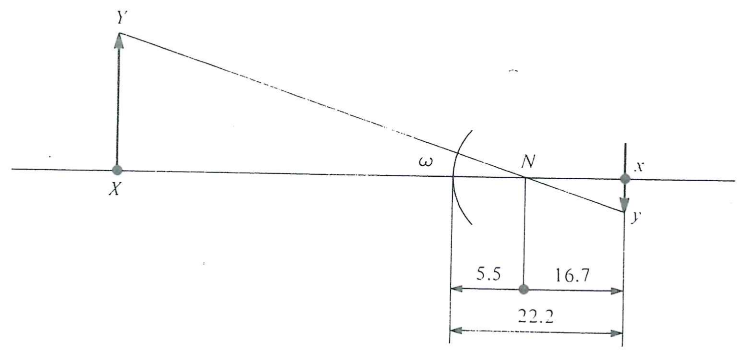


Fig. 3.4. Image formation in the reduced eye. In this simple case the ray through the nodal point N is undeviated, and the ratio of image size to object size is the ratio of *posterior nodal distance* xN to object distance XN. The construction is more complex for optical systems with multiple refracting surfaces, but the posterior nodal distance is still the main factor determining image size; it has an average value close to 16.7 mm in the human eye.

There is a clinical consequence of this fact. When a child is examined and asked to look at you, his eyes may appear to diverge, as the pupil will probably be slightly turned outwards, since it is more or less symmetrical about the optical axis (see Fig. 3.3). The child appears to be affected by a divergent squint and the uninitiated practitioner may regard this condition as abnormal.

Retinal image size

The reduced eye offers a simple model with which to show how the retinal image is constructed. Suppose we are fixating an object XY (see Fig. 3.4) at a given distance. Draw straight lines from the extremities of that object through the centre of curvature or nodal point (N) (which is defined as the point through which light rays pass undeflected) of the simple surface of the reduced eye to the retina, where an image xy is formed. It is clear from Fig. 3.4 that the image thus obtained is inverted and smaller.

The two lines crossing at N form an angle ω called the *visual angle*, which is defined as the angle subtended by the object at the nodal point. It is obviously equal to the angle xNy which is subtended by the retinal image. The size of the retinal image can be deduced from $xy/XY = xN/XN$. Since the distance between the nodal point and the retina is 16.7 mm $xy = 16.7\ XY/XN$.

For small angles, the following approximation is often adequate:

$$\text{retinal image size (mm)} = 17 \times \tan\text{(visual angle)}$$

A few examples may be useful.

1. *What is the visual angle subtended by an object 5.24 mm high at a distance of 6 m and what is the size of the corresponding retinal image?*

$$\begin{aligned}\tan \text{visual angle} &= 5.24/(6 \times 10^3) = 873 \times 10^{-6}\\ \text{visual angle} &= 3'\\ \text{retinal image} &= 17 \times \tan 3' = 0.015 \text{ mm or } 15\ \mu\text{m}\end{aligned}$$

2. *Assuming that a foveal cone has a diameter of 2.5 μm, what is the angle subtended at the nodal point?*

$$\begin{aligned}\tan \text{angle} &= 0.0025/17 = 147 \times 10^{-6}\\ \text{angle} &= 30 \text{ s of arc}\end{aligned}$$

It is interesting to note that from this result it follows that an angle of 1 min corresponds approximately to 5 μm on the retina; that is a distance covering about two photoreceptors.

The pupil

The image-forming mechanism of the eye consists not only of the optical surfaces but also of a diaphragm, the pupil, which dilates in darkness and contracts in bright light. Typical limits for pupil diameter are 8 and 2 mm, and the sixteen-fold change in retinal illumination thereby allowed cannot alone account for the eye's ability to cope with a range of 10^{10} in average illumination (for a full account of this ability we must consider neural processes of adaptation, the bleaching of photopigment, and retinal duplexity – the presence of partially independent rod and cone systems; see Chapter 7). However, it has been shown that the rapid dilation of the pupil when the observer passes from bright illumination to dimmer does yield a substantially improved sensitivity during the early minutes of dark adaptation when the slower processes of neural adaptation are still incomplete. A second advantage of a mobile pupil is that it can act to optimise spatial resolution: when the visual scene is dimly lit, visual acuity is limited by the number of photons available and it is better to have a large pupil, whereas at higher levels of illumination the optical aberrations of the eye set a limit to resolution and then, as will become clear in later sections, it is better to have a smaller pupil.

When only one eye is exposed to light, both pupils contract; this is the consensual reflex, an important diagnostic clue in neuro-ophthalmology. The pupil also contracts when the subject is looking

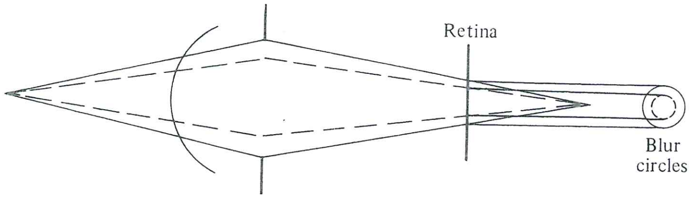


Fig. 3.5. The effect of pupil size on the blur circle formed by an out-of-focus image on the retina. For a small pupil size the blur circle is reduced and objects over a larger range of distances can be seen sharply; depth of focus is increased.

at new objects and is smaller in old age. Being under sympathetic control, it is additionally influenced by emotions such as fear (dilation) or aversion (contraction). Pupil size can be altered by the instillation of drugs: mydriatics such as homatropine dilate the pupil and miotics such as pilocarpine contract it.

Out-of-focus images

If, for some reason (e.g. error of accommodation, ametropia) the image of a point source viewed by the eye is not focussed on the retina it will form on the latter a patch of light called a *blur circle* (or diffusion circle) (see Fig. 3.5). A blur circle may result whether the image is formed in front of or behind the retina, but in the latter case the image can be moved back on to the retina, if the eye accommodates.

The size of the blur circle depends on two factors. It is clear from Fig. 3.5 that it is proportional to the diameter of the pupil. And it can be easily realised by simple drawings that it is also proportional to the distance by which the stimulus is out of focus.

If you normally wear glasses you can strikingly demonstrate for yourself the role played by the diameter of the pupil. Remove your glasses and place an object at a distance such that it appears blurred. Now view the object through a small pinhole aperture pierced in a card. The blur circle is diminished and vision is thereby much improved. In the clinic it is often necessary to assess whether the poor visual acuity of a patient is to be attributed to a need for an optical correction or to *amblyopia* (a reduced visual acuity that cannot be corrected by optical means). If when the pinhole (of about 1 mm diameter) is placed in front of the eye the patient's vision improves, it indicates that his eye is not amblyopic and an optical correction is warranted.

Depth of field of the eye

The depth of field of the eye is the distance through which a point object can be moved without appearing blurred, whilst the eye is fixating a point, and without changing accommodation. This depth of field extends in front and behind the fixation point and depends on the fact that the retina and brain cannot discern any blur until it exceeds a certain threshold value (about 0.15 D). Strictly speaking the *depth of focus* is the dioptric distance corresponding to the depth of field.

Pupil size is also critical and the smaller it is, the larger the depth of field. With an average pupil size of 4 mm the depth of field at infinity extends to about 3.5 m in front of the eye and the depth of field at 1 m varies from about 1.4 to about 0.8 m. With a pupil diameter of 2 mm, the depth of field at infinity extends to about 2.3 m and at 1 m it varies from about 1.8 to about 0.7 m. Thus one can understand why reading is easier with increased illumination as the pupil contracts affording a larger depth of field: the need for precise accommodation is reduced.

3.2. ABERRATIONS

The image formed by the optical system of the eye is not perfect because the eye, like most optical systems, suffers from diffraction and various aberrations. But, unlike other optical images, the image formed by the eye on the retina is not destined to be viewed by an observer. The image is information supplied to the retina for coding and transmission to the visual centres of the brain.

This concept was not understood until the nineteenth century and scientists were baffled by the fact that the retinal image is inverted. In this century scientists have been baffled by the aberrations of the eye. These are of small magnitude (for small or average sized pupils). In fact we are beginning to discover that the aberrations that Nature has not corrected may play a useful role in the visual process.

Diffraction

The image of a point object formed by a perfect optical system cannot be a point, owing to the wave nature of light. The image of a circular point of light is a pattern consisting of a central bright disc surrounded by alternate dark and bright rings of diminishing intensity. Therefore the edges of an image are never sharp. The central bright zone is called the Airy disc and its radius (r) is equal to $1.22\lambda x'/d$ where λ is the wavelength of light, x' the posterior focal length and d the diameter of the pupil. Thus even in an optically perfect eye (with 2.5 mm pupil) the Airy disc strays over several cones, although the bulk of the illumination ($> 80\%$) of the central disc falls on a single cone. For a pupil size twice as large, the Airy disc is half the size, and so on. Large pupils give rise to less diffraction, a factor beneficial to the resolving power of the eye. However, as we shall see, the other aberrations act in the reverse fashion, that is the larger the pupil the more degraded is the retinal image.

Chromatic aberration

The velocity of light in a medium varies with its wavelength; and consequently the refractive index, the power and the focal length vary accordingly. Thus the image of a source of white light consisting of a wide range of wavelengths is extended along the optical axis, as each wavelength has a corresponding focal point. As only the image of one wavelength at a time is in focus on the retina, the images belonging to the other wavelengths form blurred patches on the retina.

Fig. 2.5*a* illustrates the axial chromatic aberration of the eye. Short wavelengths (blue) are more refracted than long wavelengths (red). Actually when the eye is at rest, that is, looking at infinity, blue light is focussed well in front of the retina whilst red light is focussed just behind the retina. The dioptric extent of this elongated retinal image is about 1.5 *D*, that is, a clinically significant error. Yet this aberration goes unnoticed and does not hinder visual perception, probably because the extremes of the spectrum where the refractive error is large have poor luminous efficiency (see Fig. 5.8).

To demonstrate to oneself the existence of chromatic aberration one needs to look at a white source of light through a filter that transmits only the blue and red ends of the spectrum, such as a Kodak Wratten filter No. 35. One then sees a red point surrounded by a blue halo.

Spherical aberration

Optical surfaces of constant radius refract light rays to the same extent only if the rays are incident near the optical axis (paraxial optics). Light rays penetrating into the eye near the edge of the pupil are refracted more than the paraxial rays. Consequently the retinal image formed by such a system is a blurred patch and is said to be affected by spherical aberration.

Actual measurements have shown that the human eye is very little affected by spherical aberration. Even for large pupil diameters spherical aberration of the retinal image rarely exceeds 1 *D*. The main reason for this is the fact that the cornea is not spherical but flatter in the periphery than in the centre. Therefore peripheral rays are less refracted than they would be if the cornea were spherical.

3.3. THE OVERALL QUALITY OF THE RETINAL IMAGE

The optical aberrations of the eye and diffraction at the pupil result in an image that is not perfect. Objective measurements of its quality in the living eye can be made by the following technique. The subject looks at a special lamp that has a single straight wire as its filament. The eye forms an image of this filament on the retina, and care is taken to ensure that the image can be accurately focussed there. The retina absorbs most of the light in the image, but a small fraction is scattered and passes backwards through the lens and out of the pupil. If the optics were perfect, this light would be focussed back on to the original filament but the imperfect optics cause it to form a blurred image centred on the filament. It is actually this light scattered from the retina and refocussed by the lens that is responsible for the bright green reflection from a cat's eye when it is caught in a headlight beam; the optics of the cat's eye are poor enough for the image reformed around the headlight to spread as far as the observer's pupil, and the reflecting tapetum behind the cat's retina causes the reflected image to be much brighter than in man.

To determine image quality one inserts a semi-silvered mirror at an angle between the lamp and the eye, thus reflecting the returning light to one side where it can be scanned by a very sensitive photocell. The intensity of the light at each point in the scan is the *line-spread function* resulting from a double passage through the eye's optics. At this point use has to be made of the Fourier transform (see Chapter 1.2); one considers the line filament lamp as a source of spatial sinusoids which are demodulated by being passed *twice* through the optics of the eye; this results in the measured line spread function. Now these measurements can be expressed as a set of spatial sinusoids by performing a Fourier transform on them; knowing the composition of both input and output in terms of spatial sinusoids one can calculate the attenuation at each frequency resulting from the double passage through the optics, and the attenuation at each frequency from a single passage is simply the square root of that resulting from the double passage. This is the way the MTF (Chapter

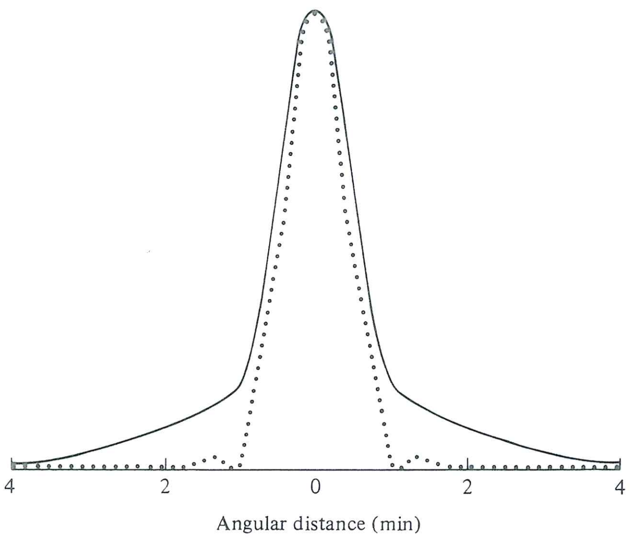


Fig. 3.6. The continuous line shows the *line spread function* of the human eye in perfect focus with a 2 mm pupil (from Campbell & Gubisch, 1966). The subject looked through an aperture at a thin, straight, electric filament and the light reflected back from the retinal image through the pupil was analysed as described in the text. Distances from the centre of the image are given in min of arc; 4.9 μm on the retina are equivalent to 1 min. Notice that although the image spreads more than 3 min (15 μm) on either side of the centre, and is more than 1 min (5 μm) wide at half height, it is not very much broader than the best possible image that can be formed with a 2 mm pupil and light of wavelength 560 nm. The dotted line shows the line spread function for such a diffraction-limited image.

1, § 1.2) was calculated. To obtain the line spread function for a single passage one simply retransforms this MTF, and the results of doing so are shown in Fig. 3.6.

The line spread function is narrowest, corresponding to optimum resolution, for pupil diameters between 1.5 and 2.5 mm. For smaller diameters the image is not only dimmer but also worse because diffraction broadens the line spread function. For larger diameters it is also broader as a result of optical aberrations, though there is an effect (the Stiles–Crawford effect) that alleviates this degradation. Measurements of effectiveness of light entering the pupil at different points show that it is less effective at the edge than at the centre, so the badly focussed light entering at the edges will be less effective.

This effect works for cones, which subserve high acuity, but for rods light entering the pupil at any point is equally effective. Thus rods reap the full benefit of the brighter image that results from pupil dilation, whereas cones 'see' a less blurred image than might be expected.

3.4. SUGGESTIONS FOR FURTHER READING

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CHAPTER FOUR

Accommodation and Refraction of the eye

M. MILLODOT

4.1. ACCOMMODATION

The phenomenon of accommodation is best illustrated by making the following observations. Draw a small mark on a window with a chinagraph pencil or felt pen. Then look at a distant object through the window straight through that mark with one eye (cover the other eye with your hand to avoid confounding the experiment with double images). You will notice that the mark is blurred; then look at the mark and the distant object becomes blurred. You cannot be in focus at both distances simultaneously. In fact to view the mark on the window you must make a conspicuous ocular effort, whereas the eye seems to return naturally to focussing on the distant object. These simple observations demonstrate that the eye needs to adjust itself to see near objects clearly. This mechanism is called accommodation.

Brief history

This phenomenon has, of course, been known since ancient times although it was not always recognised to be a peripheral process. It was even attributed to a shift of attention. Scheiner in 1619 was the first to show that it depended on actual changes taking place in the eye. He made two small pinholes in a card, some 3–4 mm apart. Looking through them at say, a needle, you see it singly. If now you look at the distance or at some point closer to you than the needle, the needle will appear double. The explanation of this phenomenon is given in Fig. 4.1. However, if Scheiner's experiment proves that the eye accommodates to focus at different distances, one important question remains, that is, what structure in the eye is responsible for these changes in accommodation?

It was thought that perhaps the shape of the cornea altered with accommodation, as is in fact the case in some birds. Indeed very small changes would be significant since the cornea makes the greatest contribution to the optical power of the eye (see Table 3.2). Alternatively it was thought that perhaps the length of the eye varied with accommodation. These hypotheses were disproved by the audacious experiments of Thomas Young at the turn of the nineteenth century. Firstly Young immersed his eye in water, so eliminating the corneal power, since water and cornea have similar refractive indices. In these circumstances, the power of accommodation remains unaffected. Secondly, to prove that the length of the eye did not change during accommodation, Young inserted a metal hook at the outer angle of his orbit (he took advantage of his rather prominent eyes) whilst looking towards his nose, and rested it against the posterior pole of the eyeball. If the hook presses against the retina one sees a bright spot in the field of vision called a *phosphene*. However, even when the eye was maximally accommodated the hook was not displaced nor was there any difference in the appearance of the phosphene, demonstrating that no elongation of the eye had occurred. Thus the business of accommodation was attributed to the crystalline lens. It is conceivable that accommodation could take place by forward and backward movements of the lens, as is the case in some fish, but this is not the case in man.

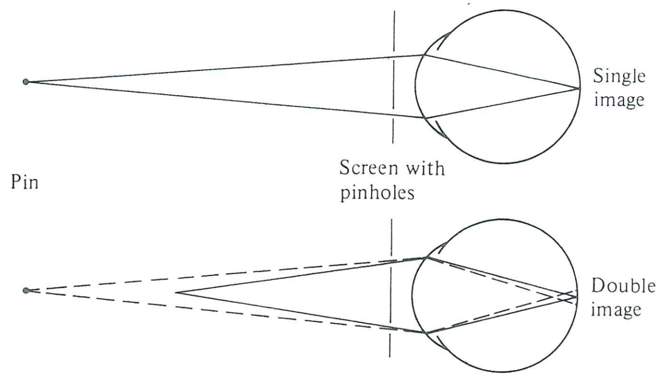

Fig. 4.1. Scheiner's experiment. A pin is viewed through two pinholes in a card held immediately in front of the cornea. An image is formed by each pinhole, but these are coincident when the eye is focussed at the distance of the pin (upper diagram), and the pin is seen clear and single. If the eye's dioptric power is increased by focussing at a closer distance (continuous lines in lower diagram) the two images coincide at a point in front of the retina and have separated again at the retina, as shown by the dashed lines, so a double image of the pin is seen.

Modifications of the eye during accommodation

The changes that occur in the eye during accommodation are revealed in various ways. Firstly by observing the eye using, for example, a biomicroscope. Secondly by observing and measuring the Purkinje–Sanson image (see Chapter 3). Thirdly by histological examination of an eye in which accommodation was induced either chemically or electrically prior to death of the animal.

The most obvious change that presents itself during accommodation is a contraction of the pupil. This contributes to the accommodative effort by reducing the diameter of the diffusion circle on the retina and thereby extending the depth of field. However, the most important modification is an increase in curvature of the front surface of the lens. This is clearly seen by merely observing the Purkinje–Sanson image corresponding to this surface (III). It becomes conspicuously smaller since the radius of curvature of the surface varies from 10.2 to 6 mm for an accommodation of 7 *D*.

At the same time the thickness of the lens increases by nearly 0.5 mm. Consequently the depth of the anterior chamber diminishes with accommodation and the edge of the iris moves slightly forward. Moreover the equatorial diameter (that is, the diameter of the lens in the vertical plane) also decreases. This has been evinced by observing people in whom part of the iris is missing. Finally the radius of curvature of the back surface of the lens varies very slightly (from 6 to 5.5 mm). All these changes are shown diagrammatically in Fig. 4.2. They take place rapidly, some 300 ms (±80) from the time the retina has received the stimulus, although the system takes somewhat longer to adjust for a change in stimulus from near to far.

Theory of accommodation

Helmholtz, in 1855, was probably the first person to suggest that the ciliary body played an active role in accommodation. This is corroborated by examination of histological sections: myopic eyes have thinner ciliary muscle than hyperopic eyes as the latter usually exert more accommodation. It is also confirmed in observations of freshly enucleated eyes where drugs that either stimulate or paralyse accommodation had been injected prior to the death of the animal.

But if the role of the ciliary body was unquestioned, controversies developed over the manner in which this muscle contraction was supposed to induce a change in the shape of the crystalline lens. We shall not describe the numerous theories that have been suggested in the last hundred years. We shall merely relate the presently established view, which is in fact more-or-less a confirmation of the century-old theory of Helmholtz.

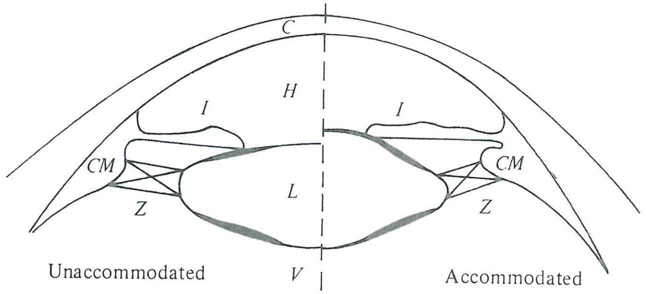

Fig. 4.2. Schematic diagram of the anterior part of the human eye unaccommodated (left half) and accommodated (right half). *C*, cornea; *H*, aqueous humour; *I*, iris; *L*, lens; *CM*, ciliary muscle; *V*, vitreous body; *Z*, zonule. See also Fig. 2.1.

When the eye is relaxed the zonule (Fig. 2.1) is tense and pulls the crystalline lens which flattens, particularly in its front surface. When the eye accommodates, the zonule is relaxed and the lens assumes a more spherical shape owing to the elasticity of the capsule and of the lens. However, it was difficult to understand how the front surface of the lens adopted its particular shape until Fincham in 1925 suggested that this peculiar form taken by the lens was due to the structure of the capsule. Indeed the capsule is not evenly thick: it is thickest and strongest near the equator and therefore the lens flattens in this area whilst it becomes more spherical near the optical axis where the capsule is thinnest and weakest. This theory is consistent with all the changes occurring during accommodation.

Stimulus to accommodation

Although some people can exercise voluntary control over their accommodation, the act of accommodating is commonly believed to be reflex in nature. Somehow the eye manages to take up the correct accommodative stance for any distance, so minimising the blur in the parts of the image falling in the central region of the fovea. In a normal environment, accommodation may be controlled by the several perceptual cues to distance (Chapter 12). Thus it is known that the mechanism controlling accommodation, like that determining our phenomenal experience, can be tricked into mistaking a change in apparent size for a change in distance. A particularly important stimulus to accommodation is an increase in convergence, the inward rotation of the eyes that serves to maintain single vision when an object is brought close to the observer (Chapter 11). However, when a single monocularly-viewed point of light is optically changed in depth, the accommodative mechanism continues to respond – and usually responds unhesitatingly in the direction required to bring the newly blurred image back into focus. In these reduced circumstances, most cues to distance are eliminated and accommodation must be controlled by properties of the blurred image itself. Chromatic aberration (Chapter 3) may provide one cue, since in over-accommodation it will be the short wavelengths that are most out of focus (see Fig. 2.5) and in under-accommodation it will be the long wavelengths. However, when chromatic aberration is eliminated by illuminating the target with monochromatic light, many subjects still respond correctly, or can learn to do so. Residual sources of information may then be spherical aberration and the direction of changes in blur during microfluctuations of accommodation. The latter are about 0.1 *D* in amplitude and 0.5 Hz in frequency with average pupil size. They are analogous to the motor tremor existing in all muscles.

Night and space myopia

When the eye is confronted by some visual stimulation situated at some distance it adjusts its focus correctly. In the absence of any objects or contours in the visual field (as when one looks into empty space or in the dark), the accommodative mechanism of the eye adopts a stance that corresponds to a certain amount of accommodation (from 0.5 to 1.5 *D*). In other words the eye becomes more powerful and its second focal point no longer coincides with the retina but is displaced towards the lens. The eye is then said to be affected by space myopia or night myopia. Actually, night myopia is not due only to accommodation: it also depends on spherical aberration and the shift in spectral sensitivity (the 'Purkinje-shift') that occurs when illumination is lowered. Clinically this condition must be kept in mind. Correction may be attempted but it is cumbersome as another pair of glasses must be substituted as soon as illumination increases. Space myopia is well known by fighter pilots and is taken into account in their training.

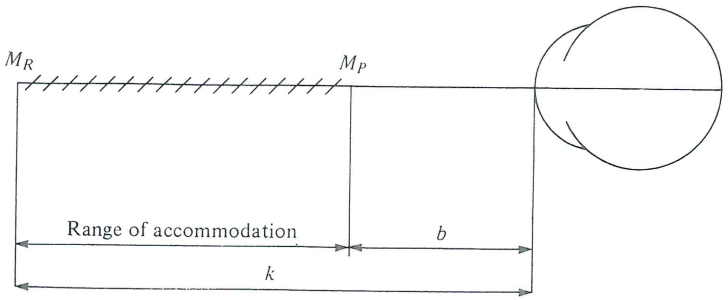

Fig. 4.3. Range of accommodation of an eye. M_R is the far point (punctum remotum) at a distance k metres; it would be at infinity in an emmetropic eye. M_p is the near point (punctum proximum) at a distance b; this recedes with age. The distance between them is the range of accommodation, and is best expressed as the amplitude of accommodation in dioptres, namely $1/k - 1/b$ (note that k and b are, by convention, both negative since they are in front of the cornea). This is simply the additional power in dioptres required to change focus from far to near point. It is plotted as a function of age in Fig. 4.4. A similar diagram would be applicable to short or far-sighted individuals wearing lenses to correct their ametropia.

Amplitude and range of accommodation

The furthest distance away at which an object can be seen clearly is called the *far point* of the eye (or *punctum remotum*). This point is represented as M_R in Fig. 4.3. To see at such distance the eye must be fully relaxed. And the fact that this object is seen clearly means that its image is formed exactly on the retina. If the far point of the eye is situated at infinity, the eye is said to be *emmetropic*. Otherwise it is *ametropic*. We shall return to this point later (see §4.2).

When maximum accommodation is exerted (i.e. the refracting power of the eye is increased to its maximum), the nearest point at which an object can be seen clearly is called the *near point* of the eye (or *punctum proximum*). This point is represented as M_P in Fig. 4.3.

The distance between the far point and the near point is called the *range of accommodation*. The maximum amount of accommodation that can be exerted is called *amplitude of accommodation* (A). It is always positive and equal to A (in dioptres) $= K - B$ where $K = 1/k$ and $B = 1/b$. k and b are the distances between the eye and the far and near point, respectively (see Fig. 4.3). K and B represent the amount of dioptres corresponding to objects situated at M_R and at M_P. If the far point is at infinity (emmetropic eye), $K = 1/\infty = 0$.

If M_R is at 1 m, $K = 1/1 = 1\ D$; at 0.25 m, $K = 4\ D$, etc. A problem might be helpful here.

1. *Suppose the far point of an eye is at 1 m (we shall see that this is the case of a myope) and the near point 0.12 m away. What is the range and amplitude of accommodation of this eye?*

The range of accommodation is $100 - 12 = 88$ cm or 0.88 m.

The amplitude of accommodation is (the distances are negative because they are anterior relative to the cornea)

$A = 1/(-1) - 1/(-0.12) = -1 + 8.33 = 7.33\ D$

The far point of an emmetropic eye (or corrected ametrope) is at infinity. Thus the main clinical measurement of accommodation consists of measuring the near point of the eye. The most common technique is the 'push-up' method. A card made up of small print is brought towards the patient's eye whilst he fixates the smallest letter that he can see distinctly. The distance at which the letter gets blurred is the near point. So if a person wearing his spectacles sees the test-type blurred at a distance of 25 cm his amplitude of accommodation is 4 *D*.

Age factors

As we grow older our eyes inevitably change. Our crystalline lenses become harder and less elastic. This leads to a loss of the amplitude of accommodation since the lens has a lesser tendency to become more convex. Consequently the near point of the eye recedes. This is illustrated in Fig. 4.4.

It is interesting to note in Fig. 4.4 that in fact we lose our accommodation from a very early stage in life. This fact may give some credence to J. J. Rousseau's view that we start dying the moment we are born.

When the accommodative ability of the eye is so reduced that the near point of the eye retreats further than the normal required distance (e.g. that required for reading a book), the eye is said to have become *presbyopic*. This condition occurs in most people between the ages of 42 and 48 years. Young people whose amplitude of accommodation is inordinately low for their age ought to be suspected of some systemic condition.

Cataract

With age the lens usually loses some of its transparency and becomes somewhat yellowish. If the loss of transparency is such that vision is noticeably impaired the eye is said to have a cataract. Other circumstances may also give rise to cataract: trauma to the eye, excess radiation such as infra-red, ultra-violet or X-rays, some diet deficiencies or uncontrolled diabetes. The principal treatment of cataract is to remove the crystalline lens, thus making the eye *aphakic*. We shall come back later to the optical correction of this condition (see §4.2).

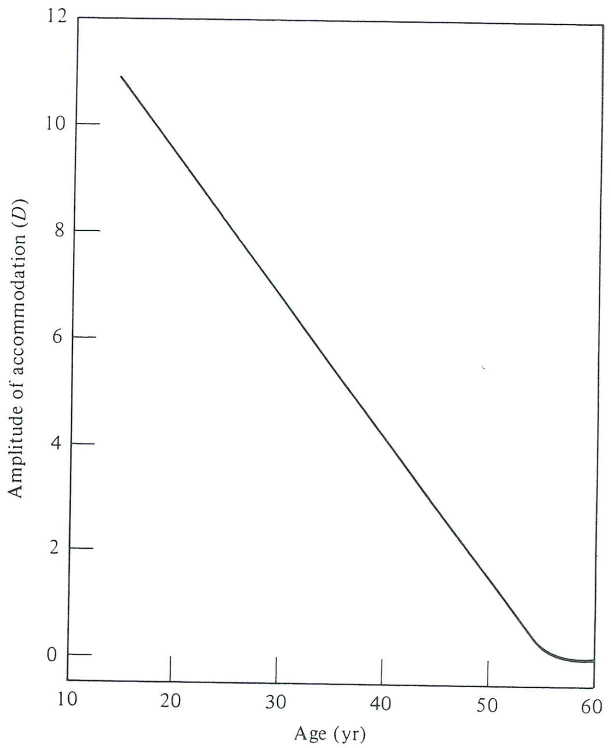

Fig. 4.4. Relationship between age and the range of accommodation. (After R. F. Fisher.) The function shown is based both on subjective measurements and on physical measurements of lenses taken from cadavers.

4.2. REFRACTION OF THE EYE

Classification

An eye that, with its accommodation relaxed, produces an image on its retina of an object situated at infinity, is said to be *emmetropic*. It must be kept in mind, though, that emmetropia is a necessary but not sufficient condition for clear vision. Whether the patient sees distinctly depends upon the integrity of the retina and of the neurophysiological stages of the visual process, the subject of subsequent chapters.

However, if the retina is not situated in the plane of the eye's focal point (the focal point is the point of convergence of light rays emerging from an optical system when the incident rays are parallel) we have a condition called *ametropia*. In this condition the far point of the eye does not lie at infinity.

There exist two types of spherical ametropia, depending on whether the retina is situated in front of or behind the focal point of the eye. These are *myopia* (or short-sightedness) and *hyperopia* or hypermetropia (or long-sightedness). Later we shall discuss another ametropia called *astigmatism*. In passing, it is worth noting that the lack of harmony of the various components of the optics of the eye needs to be only very slight to cause an ametropia. Indeed an error of 0.3 mm in the length of the eye or a variation of 0.2 mm in the radius of curvature of the cornea gives rise to 1 D of ametropia. It is surprising, therefore, that about half of the population is emmetropic.

Myopia

Myopia is a condition in which the image of a distant object is formed, not on the retina, but in front of it (see Fig. 4.5). This may occur for either of two reasons. (1) The eye is too long whilst the focal length is normal (axial type of ametropia). This is the more common case. (2) The power of the eye is too great (refractive type of ametropia), a condition that gives rise to a shorter focal length whilst the length of the eye is normal. Some cataracts provide examples of the latter: the refractive index of the lens increases and thus the power of the eye increases and the patient becomes myopic (or less hypermetropic if that were the case).

As illustrated in Fig. 4.5 the image of a distant point on the retina of a myope is blurred. As the object is moved closer to the eye its image moves closer to the retina: the point in space where the object first has an image sharply formed on the retina is the *far point* of the eye. Myopes may spontaneously complain of blurred vision, but usually they are discovered at school when they have difficulty in reading the blackboard.

The reciprocal of the distance in metres between the cornea and the far point represents the amount of myopia in dioptres. This is called the *ocular refraction* or *refractive error* of the eye given as $K = 1/k$ where k (in metres) is the distance from the cornea to the far point. For example, if the far point of a myope is situated 25 cm in front of the eye, his ocular refraction $K = 1/-0.25 = -4\ D$.

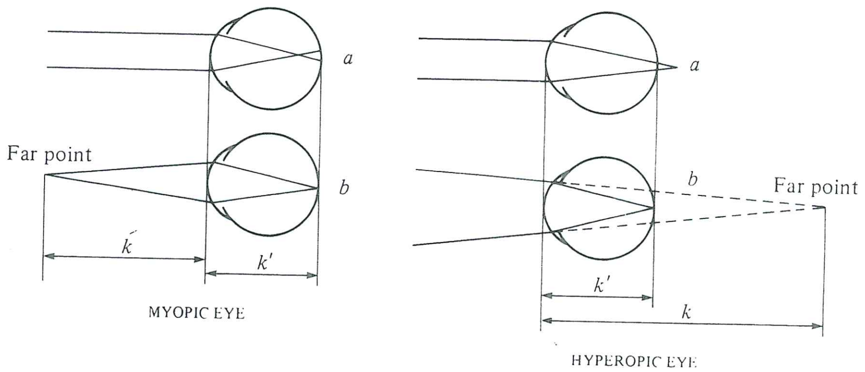

Fig. 4.5. Left: a myopic eye with relaxed accommodation; (*a*) looking at infinity; (*b*) looking at its far point.
Right: a hyperopic eye with relaxed accommodation; (*a*) looking at infinity; (*b*) with a convergent beam of light focussed at its far point.

Myopia usually develops around puberty and increases somewhat with further growth. It stays more or less constant thereafter. There is a strong hereditary influence in the development of myopia. Environmental factors may also contribute but the evidence supporting this hypothesis is uncertain. The incidence of myopia in the general population varies according to age, race and geography. We can consider that about one person in five is myopic (of over 0.5 D) but this number doubles among Chinese and Japanese. There also exists a type of myopia called progressive myopia, which is considered pathological since it is accompanied by some damage to the eye structures.

Hyperopia

In this condition the image of a distant object is focussed behind the retina, as illustrated in Fig. 4.5. This can be attributed either to an eye that is too short compared to the normal, or to an abnormally low refractive power of the eye (as occurs when there is a decrease in sugar concentration of the blood).

The far point of a hyperope is located behind the eye (see Fig. 4.5). In other words an object ought to be placed there so that its image be formed on the retina. This is obviously impossible (anatomically, all that is behind the eye is orbital fat!) and the far point of a hyperope is not real, it is virtual.

However, to compensate for this unlucky optical situation hyperopes accommodate continuously thereby increasing the refracting power of the eye and bringing the focal point back on to the retina. Therefore uncorrected hyperopes, unlike myopes, see objects at all distances clearly (provided they have enough accommodation) but at the expense of eye-strain and sometimes headaches. This is especially so after prolonged close work because of the constant high demand on accommodation.

The ocular refraction (K) of a hyperope is equal to $1/k$, where k (in metres) is the distance from the cornea to the far point. For example, if the far point of a hyperope is situated 50 cm behind the cornea $K = 1/50 \times 10^{-2} = 2\ D$.

Hyperopia usually develops soon after birth and strong evidence seems to indicate that genetic factors play an important role in determining this ametropia. One may consider that about one person in three is hyperopic in Western countries.

Correction of ametropia

The fundamental principle of the correction of ametropia is simple. It suffices to find an ophthalmic lens or a contact lens of a power such that its focal point coincides with the far point of the eye. An object at infinity will thus be focussed ultimately on the retina after passing through the correcting lens.

The power of the required correcting lens is $P = 1/SM_R$, where SM_R is the distance from the lens to the far point (see Fig. 4.6). P is called the *spectacle refraction*. It differs from the ocular refraction (which is relative to the cornea) by an amount dependent upon the separation between the eye and the spectacle which is about 12 to 14 mm. If the eye is corrected by a contact lens placed against the cornea the spectacle refraction is equal to the ocular refraction.

The optical correction of a myope consists of a negative lens since this lens has a virtual focal point in front of the eye (SM_R is negative). This is illustrated in Fig. 4.6. The optical correction of a hyperope consists of a positive lens since such a lens has its focal point behind the eye (SM_R is positive) as shown in Fig. 4.6.

The difference between spectacle and ocular refraction is usually small but it becomes quite significant in cases of large ametropias. For example, suppose an eye has a far point situated 10 cm behind the cornea; the ocular refraction is $K = 1/k = 1/0.10 = 10\ D$. Assuming that this patient wears spectacles 14 mm from his corneas his spectacle refraction is $P = 1/SM_R = 1/114 \times 10^{-3} = 8.77\ D$. In this case the difference is equal to 1.23 D. This fact is important in optical correction by contact lenses: hyperopes need contact lenses with more power (1.23 D in this case) than glasses; it is the reverse for myopes. Similarly the power of the correction changes as the spectacles are moved away from the eye. You sometimes see people getting some temporary relief by moving their spectacles further down their nose, an indication that the correction has become incorrect.

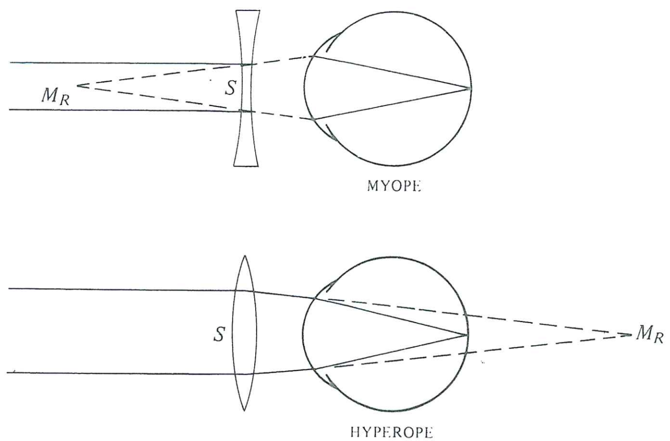

Fig. 4.6. A myope (top) requires a diverging, concave lens ($-^{\text{ve}}$ power) in order to provide the diverging beam that is focussed on his retina when accommodation is relaxed (see Fig. 4.5, left, *b*). Similarly a hyperope (lower) requires a converging, convex lens ($+^{\text{ve}}$ power) to provide a converging beam (see Fig. 4.5, right, *b*).

For most purposes an ametropic eye with an appropriate correction (either in the form of spectacles or contact lenses) functions more or less like an emmetropic eye. However, corrected ametropes do not exert exactly the same amount of accommodation and the size of their retinal image is slightly different.

Astigmatism

In the ideal eye the refractive surfaces are spherical with equal curvatures along all meridians. However, most human eyes do not fulfil these criteria, and the cornea in particular may have slightly

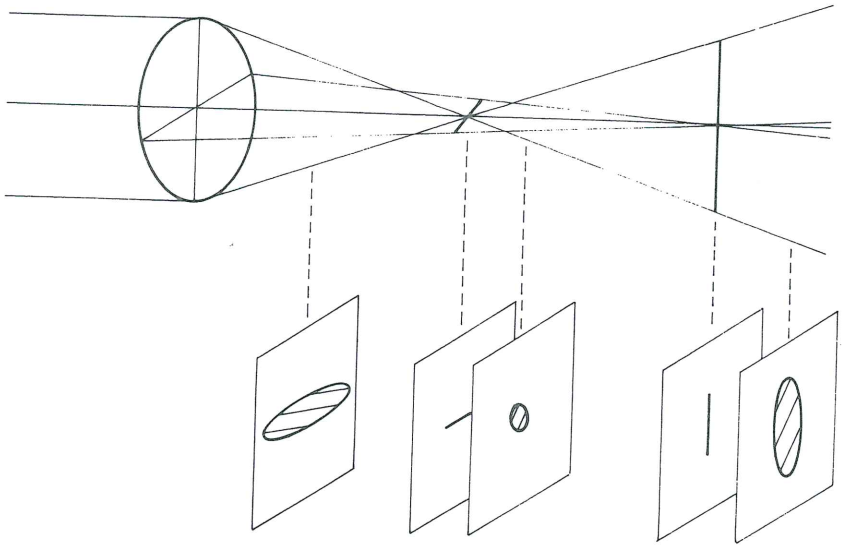

Fig. 4.7. Astigmatic pencil of light emerging from a toric lens. In planes at successively greater distances from the lens the beam forms a line, then a disc, then a line at right angles to the first. The aberration is corrected by a cylindrical lens of appropriate power and orientation.

different curvatures in the various meridians. As a result, light rays will be refracted more in one meridian (that of the greatest curvature) than in the other at right angles to it (that of least curvature). The image of a distant object will no longer be simple. This defect is called *astigmatism*, a term derived from the Greek roots *a* ('without') and *stigma* ('a point') and meaning the condition in which an optical system does not form a single point focus. Fig. 4.7 shows how an astigmatic lens refracts the light from a distant point source, the lens being assumed to have its greatest power in the vertical meridian. The bundle of transmitted rays does not have a disc-shaped cross-section converging to a point, as is the normal case. At one point the cross-section of the bundle forms a horizontal line (corresponding to one focus) and at a greater distance from the lens it forms a vertical line (corresponding to the other focus); at one intermediate point the cross-section is disc-shaped and at all others it is elliptical, the long axis depending on the nearest focal line. The amount of astigmatism is defined in terms of the dioptric distance between the two focal lines.

Astigmatism is an optical anomaly that is superimposed on the spherical ametropia, which may be present. Yet, it is usually only half as bad as an equal amount of spherical ametropia. Indeed the eye can see relatively clearly the contours in an object parallel to the focal line focussed on (or near) the retina. If, for example, the vertical focal line is focussed on the retina the eye will discern clearly all vertical features of an object and thereby recognition will be easier than if the whole object were blurred uniformly. It is for this reason that the standard subjective test for astigmatism is a chart composed of black lines orientated in different directions (see Fig. 4.8). A patient who has astigmatism will see some lines more sharply and others, at right angles, more blurred. The directions thus found indicate the two meridians of astigmatism. In clinical practice corneal astigmatism is measured accurately with a keratometer or ophthalmometer which give either the radii of curvature or the powers in the two meridians.

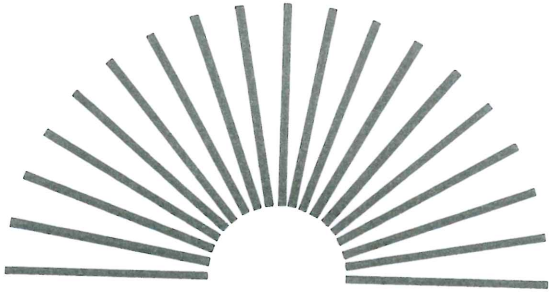

Fig. 4.8. Chart for testing astigmatism. If the eye is astigmatic, some lines will be out of focus whatever the state of accommodation.

Correction of Astigmatism

To correct astigmatism we must secure a lens such that it forms the image of a distant object at the two far points of the astigmatic eye, one for each principal meridian. Such an optical correction will have different curvatures in different meridians, but its astigmatism will, of course, be complementary to that of the eye. A lens with different powers in its two principal meridians is a spherocylindrical lens or toric lens and a lens with power in only one meridian is called a cylindrical lens.

Since the cornea is the main site of astigmatism in the eye, hard contact lenses offer a valuable means for such corrections, besides being inconspicuous. As the tears fill the space between the lens and the cornea the contact lens effectively eliminates the natural cornea.

The main refracting surface becomes that formed by the front surface of the contact lens which needs to be spherical only and of an appropriate curvature needed to correct the remaining spherical ametropia, if any.

Astigmatism that can be corrected by a spherocylindrical lens of appropriate power and angle is called *regular astigmatism*, but sometimes the distortion of the cornea is more complex and its optical aberrations cannot be remedied by any spherocylindrical lens. This condition is called *irregular astigmatism* and is typically the result of trauma or of keratoconus or of distortion following a cataract operation. In such cases, contact lenses are especially valuable.

It is absolutely essential that spherical ametropia and astigmatism be corrected as early in life as possible. Failure to do so may lead to irreversible amblyopia (see Chapter 20).

Aphakia

When the crystalline lens is absent, the eye is said to be *aphakic*. This usually occurs as a result of the operation for cataract (see §4.2). Extremely rare are cases in which the lens was dislocated in such a way that it is no longer situated in the optical path of light. Aphakes cannot see clearly at any distance, and are of course, unable to accommodate. Therefore they require two corrections, one for distance and one for near.

The power of an aphakic eye is reduced by about a third and its optical characteristics are those of the remaining cornea (see Chapter 3). As a result the aphakic eye is hyperopic, or is less myopic if it was highly myopic before the operation. In fact it could be emmetropic if it were between $-13\ D$ and $-11.5\ D$ prior to the operation. The correcting lens consists of a strong positive lens with very curved surfaces. The visual acuity of a corrected aphake is usually quite good, about 6/6 (or 20/20). Correction by contact lenses provides increased visual field, improved cosmetic appearance and slightly better vision, since the cornea is usually quite astigmatic as a result of the operation, a condition that is corrected more adequately with hard contact lenses.

Furthermore, contact lenses produce a smaller retinal image than spectacles and this is a distinct advantage in unilateral aphakia. In this case the image size in the normal eye is different from that in the corrected aphakic eye (a condition called *aniseikonia*) and the brain cannot fuse the two images. This difference can amount to 25% in a pair of eyes in which the aphakic eye (which was originally emmetropic) is now corrected by a $+11\ D$ lens placed 12.5 mm in front of the cornea and the other eye is emmetropic. If the aphakic eye is corrected with a contact lens the aniseikonia would amount only to 6%. Binocular vision might not be easy but is, in these circumstances, possible.

4.3. MEASUREMENT OF THE REFRACTION OF THE EYE

The clinical measurement of the eye's refractive error is often referred to elliptically as simply 'refraction'. Clinical refraction was codified by Donders in the middle of the last century. The importance of refraction need not be stressed, as clear and comfortable vision is certainly one of the prerequisites of a better and more useful life in the modern world.

Refraction is determined in two ways, called subjective and objective according to whether or not the patient is required to judge what he sees. The objective method is considered to be only a guide to the subjective measurement, which is regarded as the last court of appeal.

The subjective measurement of visual performance is a psychophysical procedure of the type discussed in Chapter 7. However, the psychophysics employed in the clinic is a far cry from that used with trained observers in the laboratory. Indeed it is an art to extract the desired information out of patients with the minimum amount of testing under variable conditions and fluctuating attention. This is one of the main reasons why refraction is almost always assessed objectively as well as subjectively. Besides, objective methods are sometimes the only possible means of refracting the eye, particularly when dealing with malingering, illiterate or psychotic patients.

Retinoscopy

Although Sir William Bowman in 1859 noted it without appreciating its clinical value, this method of objective refraction is credited to a French ophthalmologist Cuignet who rediscovered it, almost inadvertently, in 1873.

Retinoscopy utilises the light reflected by the interior back surface of the eye. The retina plays the role of an object (R) the image of which is formed at the far point (M_R) by the dioptrics of the subject's eye (*see* Fig. 4.9). One is merely left with finding this far point. The illumination of the retina is very simple (*see* Fig. 4.9*a*). It consists

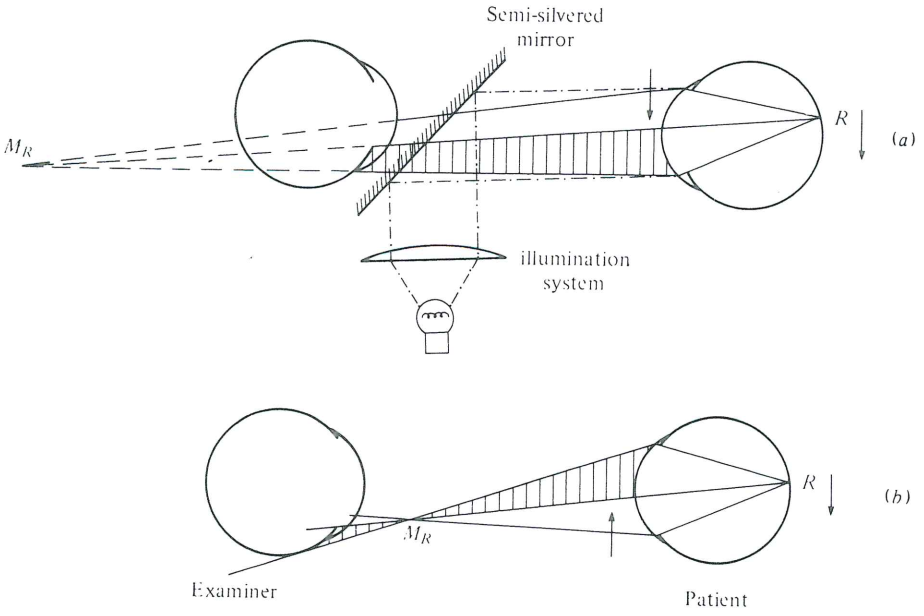

Fig. 4.9. Basic principle of retinoscopy. The illumination system is shown only in (*a*) so as to retain simplicity in diagram (*b*). The hatched areas appear dark to the examiner and the vertical arrows represent movement of the light beam.

of a source of light (usually a small battery-operated bulb), a condensing lens, which gathers light emanating from the bulb, and a semi-silvered mirror (or a mirror with a small aperture) which reflects light into the patient's eye. The mirror arrangement lets the examiner view the patient's pupil along the same axis as the path of light to and from the fundus.

If the examiner views the subject's pupil other than from the far point, he will see more or less of it illuminated depending upon the fraction of the reflected beam of light that penetrates his own pupil; but if the patient's far point happens to be situated in the plane of the examiner's pupil (this is called the neutral point), the latter will see the patient's pupil as either completely bright or completely dark because the nearly punctate image will either lie within the examiner's pupil or outside it. Therefore, to use the retinoscope the examiner tilts it to and fro, so moving the position of R on the retina, and he observes the change in the illuminated area of the pupil (called the reflex). If the patient's far point is as drawn in Fig. 4.9*a*, as R moves downwards, the examiner will see the reflex gradually extend over the pupil from top to bottom. Thus, when the far point lies behind the examiner's eye the reflex moves in the same direction as R and consequently in the same direction as the tilt of the retinoscope. Positive lenses can be placed in front of the patient's eye until the examiner reaches the neutral point. The patient's refractive state can then be calculated as described below. If the patient's far point is as drawn in Fig. 4.9*b*, as R moves downwards, the examiner will see the reflex gradually extend over the pupil from bottom to top. Thus when the far point lies between the examiner and the patient the reflex moves in the direction opposite to the tilt of the retinoscope. Negative lenses are placed in front of the patient's eye until the examiner reaches the neutral point.

The final estimate of the patient's ametropia takes into account the lens that was placed in front of the patient and the distance separating the patient and examiner. If, for example, the examiner is 50 cm from the patient, $-2\ D$ is added to whatever lens is in front of the patient. If there is no such lens the patient is simply $-2\ D$ myopic. If a $+5\ D$ was needed to reach the neutral point the patient is $+3\ D$ hyperopic, etc.

Ophthalmoscopy

Although Charles Babbage had devised a method of observing the fundus of human eyes, it is to Helmholtz in 1851 that the ophthalmoscope is attributed, as he improved and thoroughly described the technique and its application. Being able to view the internal structures of the living human eye was rightly hailed as a revolution in medical science in the nineteenth century. The ophthalmoscope has never ceased to be the most invaluable companion of the eye practitioner and even of the general practitioner. It is used to assess the state of health of the eye as well as some other systemic conditions (e.g. diabetes, arteriosclerosis or intra-cranial pressure). However, we describe this instrument here as it can be used to assess, grossly, the refraction of the eye.

Like retinoscopy, ophthalmoscopy makes use of the minute amount of light reflected by the fundus of the eye (about 1/10000 of the light that enters the eye). Thus one must illuminate the fundus in such a way that the examiner's eye is located along the path of the incoming light without being in its way. This is achieved by the use of a semi-silvered mirror (or by reflecting the ingoing light from the tip of a small prism), as shown in Fig. 4.10. If the patient is

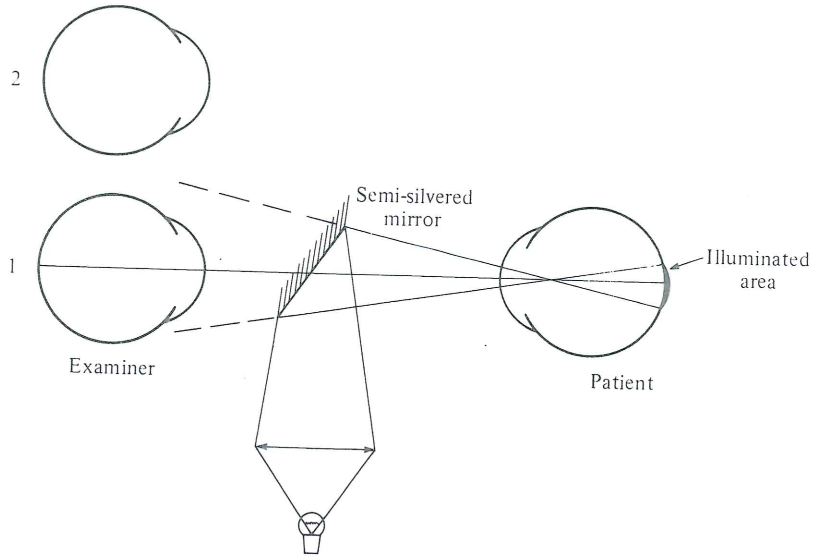

Fig. 4.10. Principle of the ophthalmoscope. In position 1 the examiner views the illuminated retina, but this is not possible in position 2.

emmetropic his retina will be imaged at infinity and will appear clearly to the examiner (assuming the latter is emmetropic and unaccommodated). If, on the other hand the patient's retina appears blurred, the examiner will place lenses in front of his own eye until he sees it clearly, that is when the image of the patient's retina will be formed at infinity through his eyes' optics plus the correcting lens.

As the ophthalmoscopic examination is carried out with the examiner's eye situated as close as possible to the patient's eye the correcting lens is almost situated in the spectacle plane of the patient. The dioptric power of that lens gives an approximate indication of the patient's spectacle refraction. This method of objective refraction is far simpler than retinoscopy but it is much less accurate. It depends on the examiner's ability to relax his accommodation and his appraisal of the sharpness of the patient's fundus, both of which are difficult to achieve consistently and accurately.

4.4. SUGGESTIONS FOR FURTHER READING

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