**The eye : its elementary anatomy, physiology, and optical constants / by Lionel Laurance ; revised by George Lindsay Johnson.**

# THE EYE

## ITS ELEMENTARY ANATOMY, PHYSIOLOGY, AND OPTICAL CONSTANTS

BY

LIONEL LAURANCE

Nov/198

To my old friend
G. E. Ellis Esq
with the joint authors
Compliments
G. Johnson

# THE EYE

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BY

LIONEL LAURANCE

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# PREFACE

THE proofs of this little work, which I have written for students in optics, have been read through and revised by Mr. George Lindsay Johnson, M.D., F.R.C.S., to whom I acknowledge my deep indebtedness. That Mr. Johnson has passed the proofs is sufficient guarantee of the precision of the facts herein contained.

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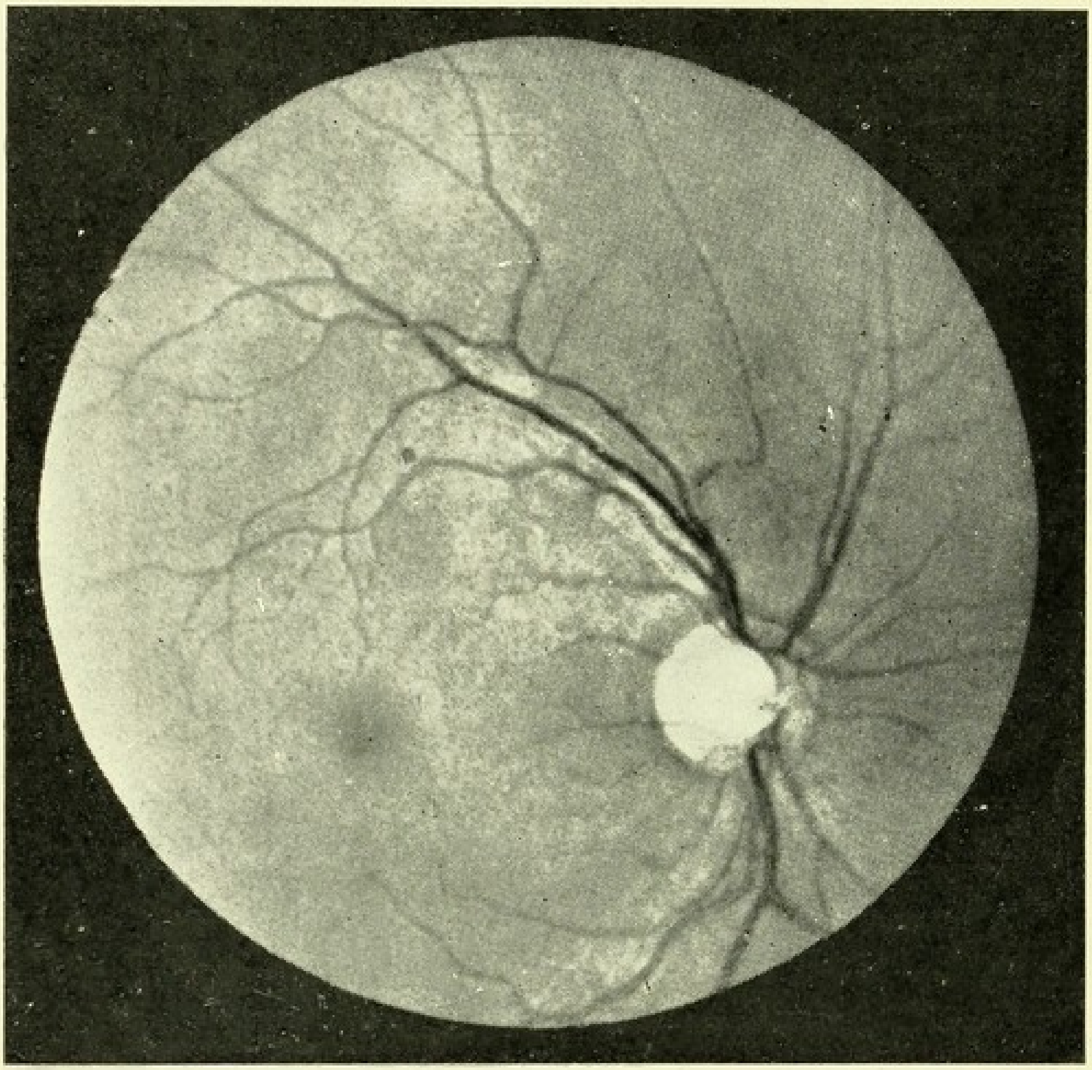

Fig. A.—**Photograph of the Fundus of a Normal Eye.**
(Enlarged 2 diameters.)

Taken from life by Professor Dimmer, of Graz.

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# THE EYE

## CHAPTER I

## THE ANATOMY OF THE EYE

**The Eyeball.**—The eyeball is an elastic sphere, approximately an inch in diameter, having the segment of a smaller sphere projecting from the front. It resembles a plum in shape, the stalk corresponding to the optic nerve.

There are three coats—the sclerotic, the choroid, and the retina, which surround and enclose two transparent chambers—the anterior, or aqueous, and the posterior, or vitreous, which are partitioned off from each other by the transparent crystalline lens and its suspensory ligament.

**The Sclerotic.**—*The first coat* is the *sclerotic*, which is a tough, opaque, fibrous covering surrounding about five-sixths of the globe; the remaining portion projects in front, and its tissue is modified to form the *cornea*, which is transparent and elastic, and resembles a hemisphere of transparent celluloid. The junction of the sclerotic with the cornea is termed the sclero-corneal margin. The sclerotic may be regarded as the protective envelope of the eye, its functions being to preserve the contents from injury and to maintain its shape,

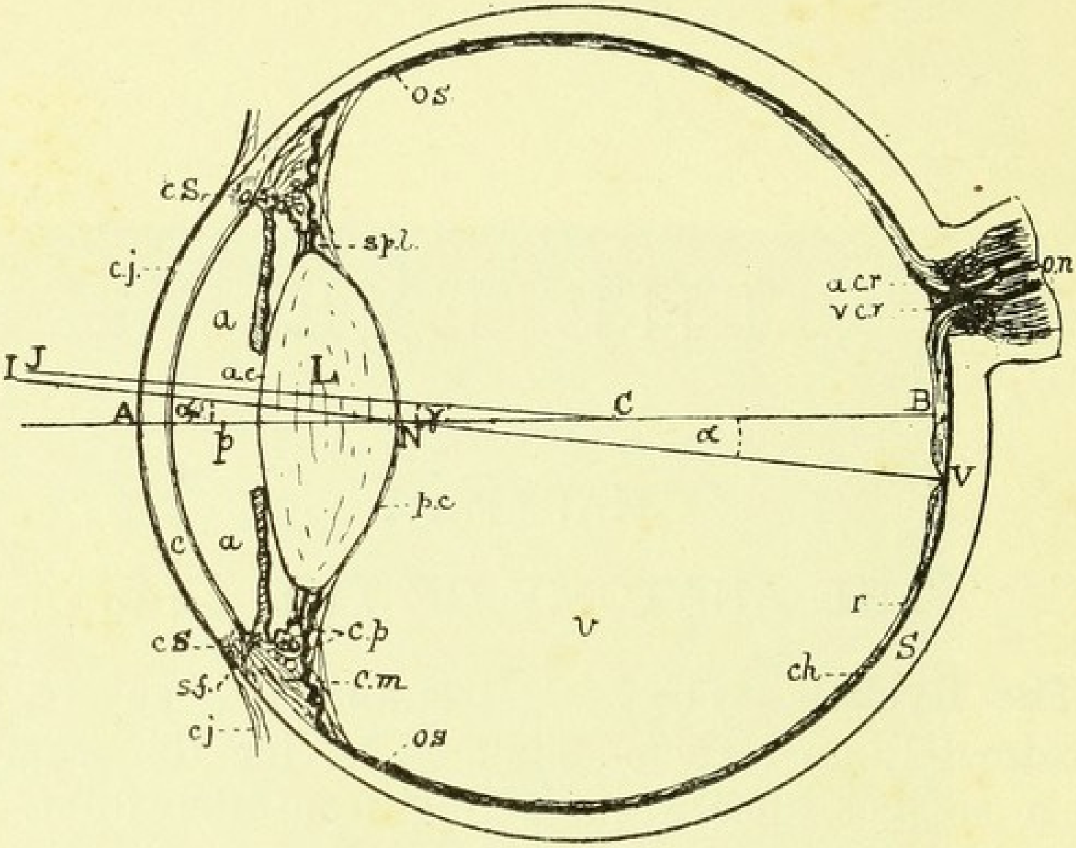

Fig. 1.—**Horizontal Section of the Eye.**
(Magnified about 3 diameters.)

*A*, Anterior pole.
*B*, Posterior pole.
*C*, Centre of rotation.
*P*, Principal point.
*N*, Nodal point.
*V*, Fovea centralis.
*AB*, Optic axis.
*IV*, Visual axis.

*JC*, Line of fixation.
Angle $\alpha = ANI$, the angle between the optic and visual axes at the nodal point.
Angle $\gamma = ACJ$, the angle between the optic axis and line of fixation at the centre of rotation.

---

*aa*, Aqueous.
*v*, Vitreous.
*L*, Crystalline.
*c*, Cornea.
*S*, Sclerotic.
*ch*, Choroid.
*r*, Retina.
*cm*, Ciliary muscle.
*cp*, Ciliary processes.
*i*, Iris.

*spl*, Suspensory ligament.
*sf*, Spaces of Fontana and pectinate ligament.
*cs*, Canal of Schlemm.
*ac*, Anterior capsule of lens.
*pc*, Posterior capsule of lens.
*cj*, Conjunctiva.
*on*, Optic nerve.
*os*, Ora serrata.
*vcr*, Central vein of the retina.
*acr*, Central artery of the retina.

while the cornea forms the window, and is the first and principal refractive medium in the dioptric system of the eye.

The cornea is about 1 millimetre thick, the sclerotic becoming much thicker towards the optic nerve.

**The Cornea.**—The cornea has three layers:

1. The outer or *epithelial layer* is continuous with the conjunctiva of the eyeball, and consists of several rows of cells, between which are fine nerve ends which render it exceedingly sensitive to foreign bodies.
2. The *middle layer* consists of the true corneal tissue, and occupies the greater part of this coat. It possesses numerous layers of connective tissue, which lie in planes at right angles to each other, and are nourished by lymph which flows between them.
3. The *internal layer* (membrane of Descemet) is a highly elastic layer which curls up when divided. It is lined internally by a single row of cells, which are continued around the angle of the chamber, forming the external layer of the iris as far as its pupillary margin.

**The Choroid.**—The *second coat* consists of the *choroid* proper, the *ciliary body*, and the *iris*. The choroid is composed of connective tissue, bloodvessels, and dark brown pigment cells. The use of the latter is not understood, but in the presence of light they undergo curious amœboid movements—that is to say, the tiny processes of the cells elongate and contract similar to those of an amœba. The cells are evidently connected with vision, since they exist to a greater or lesser degree in all animals which have light-perceiving organs. Even the so-called pigment spots found in shell-fish, which constitute the most primitive eye of all, consist of brown pigmented cells, similar to those of the choroid, and evidently allow of light and darkness being distinguished.

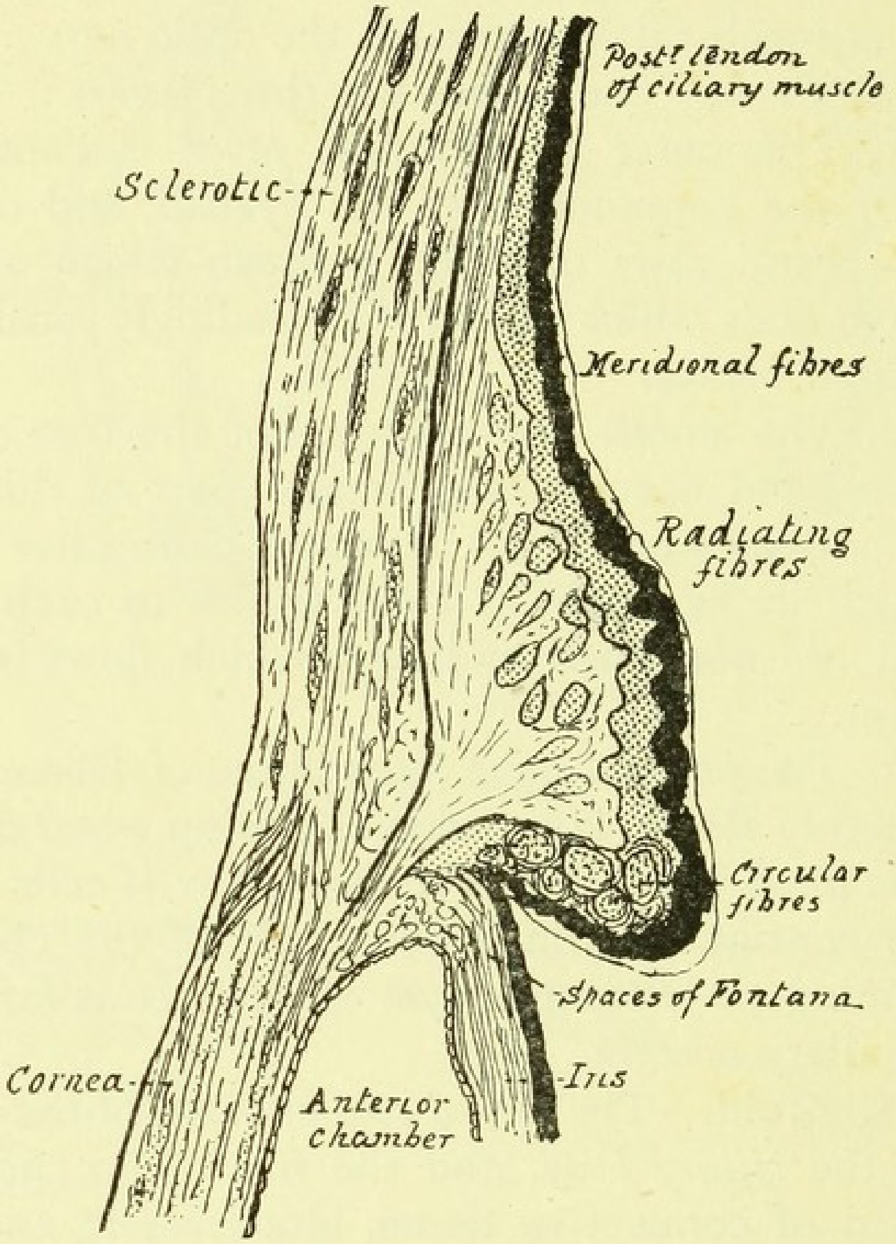

Fig. 2.—**Vertical Section through the Eye at the Sclero-corneal Junction, showing the Attachments of the Ciliary Muscle and Iris.**

**The Ciliary Body.**—The ciliary body is composed of connective tissue, lymphatic vessels, a well-defined muscle, the processes, and the suspensory ligament.

The *ciliary muscle* consists of two parts. First, *the radiator* which arises from the base of the iris, and inner wall of the canal of Schlemm (situated at the junction of cornea and sclerotic), and, passing backwards, is inserted into the connective tissue of the choroid. Second, *the sphincter* (Müller's ring), which forms a ring of muscular fibres, running at right angles to the straight fibres round the periphery of the lens, but unconnected with it, being 2 or 3 millimetres outside the edge of the latter. The ciliary muscle lies between the ciliary processes and the sclerotic, and immediately behind the base of the iris.

The *ciliary processes* are a direct prolongation of the choroid, forming a convoluted gland, richly supplied with bloodvessels and covered with secreting cells and dense black pigment. The function of these cells is to secrete a fluid to nourish the crystalline and vitreous humour, and, together with the pigment cells of the iris, to replenish the aqueous.

**The Iris.**—The *iris* lies behind the cornea, and is a thin, highly pigmented membrane, having a central round aperture called the *pupil*. Its posterior surface is thickly covered with black pigment cells, which are continuous with those lining the ciliary processes. Its pupillary margin rests against the front surface of the lens, while its anterior surface is visible from the outside of the eye through the cornea, and is separated from the latter by a space, filled with a watery fluid—the aqueous humour.

The iris corresponds in shape and function to the iris diaphragm of a photographic lens, regulating by its contractility the amount of light admitted to the interior, and serving as a means of correcting spherical aberration and radial astigmatism.

The pigment of the iris gives to the eye its distinctive colour; if deficient, the iris appears grey or blue, running through all shades of hazel and brown as the pigment increases. European infants usually possess blue or steel-grey irides, the colour becoming darker or brown as the child gets older. Nearly all mammals have yellowish brown or dark brown irides, but birds have brilliantly coloured ones—scarlet, green, golden-yellow, blue, etc.—which often harmonize with the colour of their feathers.

The iris contains straight elastic fibres radiating towards the centre, which are called *dilator*, because they dilate the pupil when the opposing circular muscle is inactive. This latter muscle consists of a circular band of contractile fibres, called the *sphincter pupillæ*, which lies close to the free edge of the iris. When stimulated by light it contracts, thereby tending to close the pupil, overcoming the elasticity of the radiating fibres and stretching them towards the centre. The circular fibres are undoubtedly muscular (unstriped muscular fibres), but it has never been clearly proved that the radiating fibres are muscular; they probably consist of elastic tissue, and are kept slightly on the stretch by the circular ones. According to Lindsay Johnson, in some mammals, such as the seal and sea-lion, the iris contains striped (voluntary) fibres, which enable the animal to open or close the pupil at pleasure, so as to enable it to see clearly both in and out of water, but in man the iris cannot be altered voluntarily. In fishes the iris is quite immovable, and the pupil therefore is fixed. In a bright light, in man, the pupil contracts immediately, and it becomes dilated as the light is reduced; in total darkness it is widely dilated. When the muscles are at rest the pupil is of medium size—*i.e.*, 3 or 4 millimetres in diameter. Also, when the eyes converge to fix a near object, the pupil contracts in proportion to the amount of convergence and accommodation exerted, and the reverse happens when the accommodation is relaxed, as when looking at a distant object.

Certain drugs likewise affect the pupil; thus a weak solution of eserine or pilocarpin, when dropped on to the conjunctiva, contracts the pupil to the size of a pin-head. Large doses of opium or some of its derivatives do the same. Such drugs are termed myotics. On the other hand, weak solutions of belladonna or its alkaloids, atropine, homatropine, etc., dilate the pupil even more widely than is the case in total darkness, as also do cocaine and some other drugs, but not to the same extent as the former. Such drugs are termed mydriatics.

The pupil appears black because light issuing from it tends to follow the direction of the entering rays, and therefore fails to enter an observer's eye, unless his eye is situated in the line of direction of the reflected rays. This can be effected by looking through a hole in the centre of a mirror adjusted to reflect a beam of rays into the eye, which constitutes the principle of the ophthalmoscope. If, however, the eye is widely dilated, a position can generally be found in which the observer can receive a sufficient amount of reflected light, without an ophthalmoscope, to perceive the colour of the fundus of an observed eye. This is quite easy in the case of the eye of a dog or cat, especially in a partially darkened room.

**The Retina.**—*The third coat* is the *retina*, which is an expansion of the optic nerve adapted to receive the impressions of light. It contains various layers, the most important being the *bacillary* layer, or the layer of *rods and cones;* this is situated next to the hexagonal pigment cell layer, which latter lies in contact with the choroid. These two layers may be considered the percipient portions of the retina, since they are specially influenced by the action of incident light. The rods and cones are packed close together with their free ends touching the hexagonal pigment layer, and are thus turned away from the cornea (see Fig. 3) so as to be in the most favourable position for receiving light reflected from the choroid.

In a vertical section under the microscope they appear like a field of corn, while in a transverse section they appear like a mosaic of round discs, each having a dot in the middle, which is the cut end of an ultimate nerve fibril (see Fig. B). The fibrils pass to the ganglion cells, from which nerve filaments proceed to the optic nerve which they form by their collection.

**The Optic Disc.**—The *optic disc,* where the optic nerve enters the eye, is the most conspicuous part of the fundus. When seen with the ophthalmoscope, it appears as a pink disc, from which bloodvessels radiate over the red fundus field (see Fig. A). Surrounding it a white ring of bare sclerotic is sometimes seen, or a crescent of black pigment.

**The Macula and Fovea.**—At the back of the eye, in the line of the visual axis, about 1·5 millimetres to the temporal side of the posterior pole, is a highly sensitive area termed the *yellow spot,* or *macula lutea.* In children and most hypermetropes its boundary may be seen, with the ophthalmoscope, as a bright reflex ring, a little larger than the circumference of the disc.

This area (see Fig. C) is about 2·5 millimetres in diameter, and is called the sensitive area, because all clear vision lies within it. The true macula is only about 1 millimetre in diameter, and this is the area of most distinct vision ; for instance, letters of the alphabet forming words cannot be read if their images fall on any part of the retina lying outside this *true macular region.* In its centre there is a minute pit or depression about 0·25 millimetre in diameter, called from its position the *fovea centralis.* This part consists

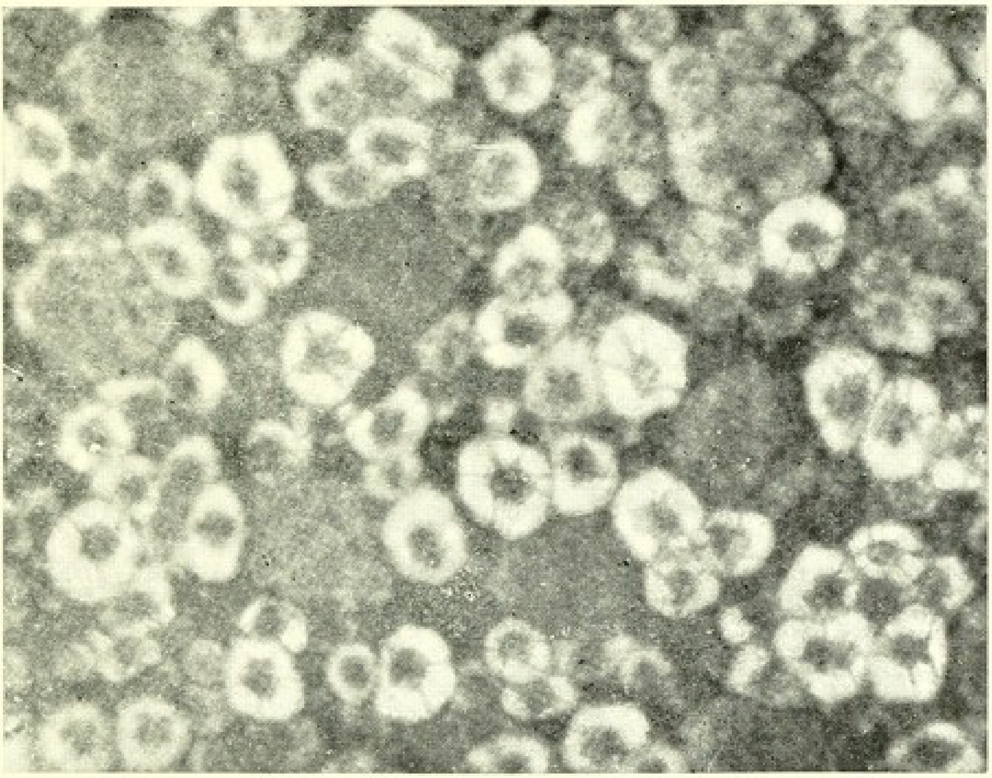

Fig. B.—**Transverse Section through the Base of the Rods and Cones.**

Photographed from nature by Lindsay Johnson, showing the dark cones surrounded by numerous lighter and smaller rods. The black spot in the centre of each rod section is the ultimate nerve fibril which conveys the visual sensation to the brain. The white substance (of Schwann) is the insulating matter. The nerve fibril is kept in a central position by numerous radiating bands, as shown in the figure. Each cone contains one or more nerve fibrils, which are insulated and supported in a similar manner to those of the rods.

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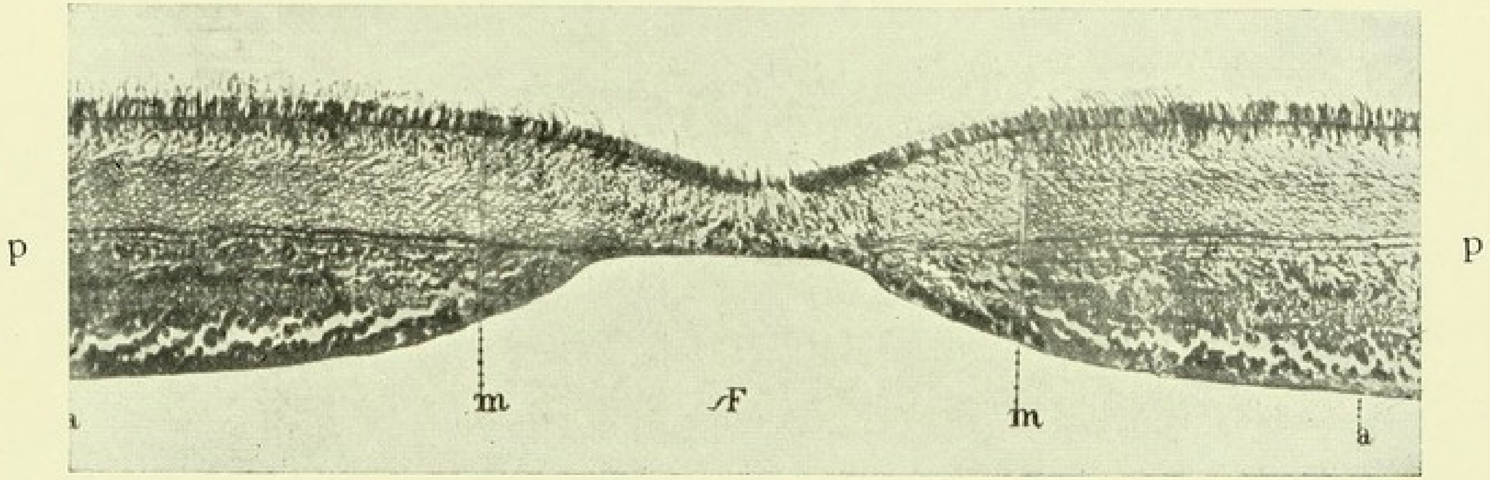

Fig. C.—**Vertical Section through the Centre of the Macula**.

From a photograph by Lindsay Johnson, showing:

F, The foveal pit.
mm, The true macula.
aa, The macular area.
pp, The retinal plexus border layer.

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entirely of narrow cone fibres packed very closely together, and here vision is most acute. The sensibility of the retina to light diminishes rapidly from the macula ring to the *ora serrata*. This is the peripheral termination of the retina, which lies a little anterior to the equator of the eye and near to where the choroid proper merges into the ciliary processes.

The retina is transparent and invisible in health, the red colour of the *fundus*, as the back of the interior of the eye is called, being chiefly derived from the reflected light of the choroidal pigment, and to some extent also from the colour of its bloodvessels. Its thickness varies from 0·1 millimetre to 0·3 millimetre approximately, the general thickness being 0·15 millimetre.

### The Layers of the Retina and Choroid.

These are, from the vitreous backwards, as follows:

1. *Internal Limiting Membrane.*—A thin, almost structureless, membrane without nerve fibres. Its inner surface lies in contact with the vitreous humour, or, according to some anatomists, the hyaloid membrane, but it is open to question whether this latter membrane really exists.

2. *Nerve-Fibre Layer.*—This is made up of a sheet of nerve fibres which unite to form the optic nerve.

3. *Nerve Cells (Ganglionic) Layer.*—Supposed to be a kind of relay battery of nervous (electric?) energy. These cells are very large, having long processes which unite with those of other cells and with the nerve fibres. The retinal bloodvessels run in this layer. They are the branches of the central artery and vein, and are very conspicuous when seen by the ophthalmoscope.

4. *Internal Molecular Layer*, consisting of a fine network of fibres, which shut off the large bloodvessels from the posterior layers.

5. *Internal Granular Layer.*—This layer carries the capillaries, but its functions are unknown.

6. *External Molecular Layer.*—Is similar to No. 4; it shuts off communication with the capillaries. All layers external to this are nourished by lymph (by osmosis).

6A. *The Retinal Plexus Border Layer.*—A narrow, well-defined, and strongly marked layer of interlacing fibres, which extend from the fovea to the optic nerve on the one side, and to an equal distance on the outer side of the fovea. It has been discovered in the retinæ of man and most monkeys, and has been so named by Mr. Lindsay Johnson. Its use is unknown, but it is evidently connected with acute vision, since it only occurs over and around the macular area. It is clearly seen in Fig. B in a line with the front of the fovea.

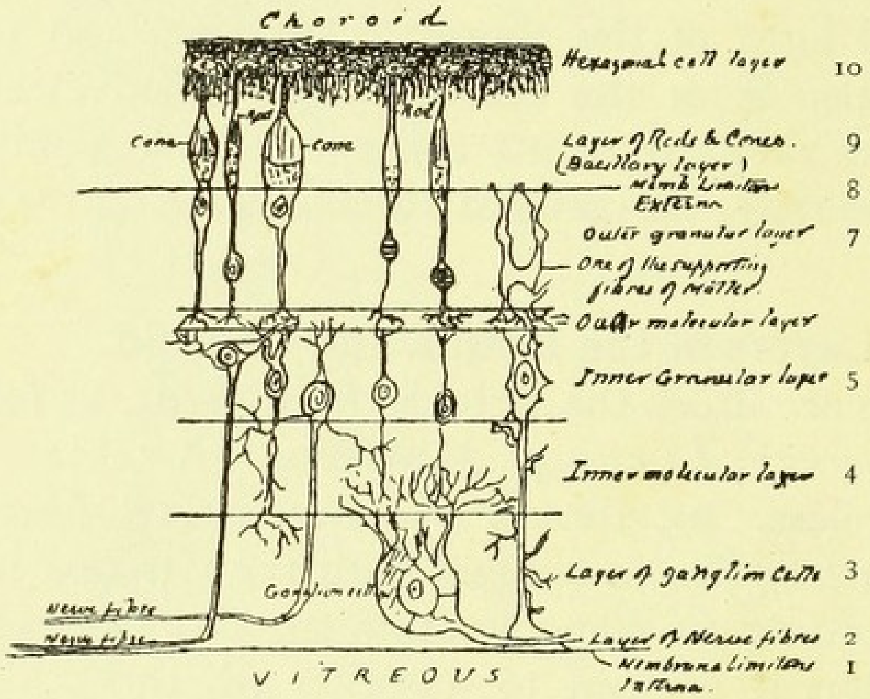

Fig. 3.—**Drawing made from a Microscopic Section of the Retina.**

1, Membrana limitans interna.
2, Nerve-fibre layer.
3, Layer of ganglion cells.
4, Internal molecular layer.
5, Internal nuclear layer.
6, External molecular layer.
7, External nuclear layer.
8, Membrana limitans externa.
9, Bacillary layer (rods and cones)
10, Hexagonal pigment layer.

7. *External Granular Layer.*—The function of this layer is also unknown.

8. *External Limiting Membrane.*—A thin membrane having perforations through which the rods and cones pass and are held in position, thereby securing their insulation.

9. *Bacillary Layer, or Layer of Rods and Cones.*—These are the perceptive terminals of the optic nerve, on the ends of which the image of external object is supposed to be formed. The ends of the rods (and cones ?) lie in close contact with the hexagonal layer.

10. *Hexagonal Pigment Layer.*—A glandular layer which secretes the visual purple—a colouring matter connected with vision which surrounds the outer halves of the rods and the tips of the cones.

The *layers of the choroid* are:

11. *Limiting Membrane* (*Membrane of Bruch*).—A transparent, colourless, and structureless layer destitute of nervous elements. It resembles Descemet's membrane at the back of the cornea.

12. *Capillary Layer,* which with No. 13 nourishes the hexagonal pigment layer.

13. *Layer of Large Bloodvessels.*

14. *External Pigment* (*Fusca*) *Layer,* containing a great number of cells, each having a nucleus pigment granule, and irregularly shaped processes capable of amœboid movements in the presence of light. The function of these cells is unknown.

Layers 1 and 8 are supporting membranes connected together by an immense number of vertical connective tissue fibres (Müller's fibres) which run at right angles to them, thus supporting the intermediate layers. Layers 2, 3, 5, and 7 form the conducting apparatus. As Lindsay Johnson first pointed out, one of the functions of layer No. 4 (internal molecular layer) is to separate the bloodvessels from the capillaries, while that of the external molecular layer (No. 6) is to separate the capillaries from the lymphatic and the visual purple secretions. Nos. 9 and 10 are perceptive layers, while No. 10 has a secreting function as well.

**The Optic Nerve.**—The *optic nerve* passes through the sclerotic, at the back of the globe, about 2 millimetres to the nasal side of the posterior pole. The end of the nerve where the retina begins can be seen with the ophthalmoscope (see Fig. A), or in the eye, when it is cut in two and opened, as a round or vertically oval disc, from 2 to 2·5 millimetres in diameter, hence its name the *disc,* or *papilla.* It is also sometimes called the *blind spot* because, the retina being absent there, it is insensitive to light. The sheath of the optic nerve is continuous with the sclerotic.

**The Visual Purple.**—This is a colouring matter, first discovered by Boll, of Vienna, in the eyes of frogs, and which has been found to exist in man and many other animals' eyes. It plays an important part in vision, although apparently not essential for sight. If a piece of retina be removed from an eye in the dark and spread out on a glass slip, it appears a reddish yellow-violet (chamois) colour when brought into the light. In a few minutes the colour fades away. If, however, the rod and cone side of the bleached retina be laid on a piece of the choroid carrying the hexagonal layer of the retina (which must be quite fresh), the colour will return again, thus showing that it is secreted by this layer. If a piece of retina be laid on a glass slip, and covered over with a small design cut out of black paper, or a small negative, and then taken into the light, all the parts exposed to the light become bleached, while the part covered by the negative or paper remains reddish purple. This will likewise fade away, but it may be fixed in a 4 per cent. solution of alum in the dark, and thus a natural print, called an *optogram*, may be obtained. Under the action of light not only is the visual purple bleached in direct proportion to its intensity, but the hexagonal cells send out processes which pass down between the rods, carrying with them bunches of purple-brown crystals. On the eye being removed to the dark, the processes withdraw, and leave the rods free, while at the same time the visual purple accumulates. If one goes from brilliant sunlight into a dimly lighted room, it takes some minutes before one can see anything, but gradually the objects become more and more clear. The probable explanation of this is that in bright sunlight the visual purple is used up as fast as it is formed, so that if one goes into a dark room the visual purple, which is quite sufficient to enable one to see in bright sunshine, is altogether inadequate to see in a dim light. It is found that this purple surrounds the rods, but not the cones, and none is found at the fovea. The function, therefore, of the purple appears to be to enable one to see better in a dim light. The back of the eye in most animals has a brilliant yellow, green, orange, or purple colouring matter, called the tapetum, but whatever the colour may be it rapidly fades under the action of light.

**The Humours of the Eye.**—The interior of the globe contains the *crystalline lens*, which separates the *aqueous* and *vitreous* humours, all three being transparent.

**The Aqueous.**—The aqueous, which lies between the cornea and iris, is, as its name implies, a watery fluid, which is saline. The aqueous, with the cornea, constitute a concavo-convex lens. It is contained in a cavity about 3·6 millimetres deep at the central line. At the angle of the chamber between the iris and cornea the boundary wall consists of connective tissue, termed the *pectinate ligament*, having coarse meshes (*spaces of Fontana*), through which the aqueous waste secretions are carried off to the lymphatics of the eye. One of these spaces is unusually large, and is known as the *canal of Schlemm*. It is thought by some anatomists to be a small vein.

The iris divides the aqueous into two portions, an anterior (above described) and a posterior, which occupies a small triangular space between the iris and the periphery of the lens. As far as is known, it is without importance. The aqueous is termed the *anterior chamber*, and some anatomists refer to its posterior portion as the *posterior chamber*, while others give this name to the vitreous.

**The Crystalline Lens.**—The *crystalline lens* is an unequally curved bi-convex lens, about 8 millimetres wide and 3·6 millimetres thick. It lies immediately behind the iris, and is formed of a series of tape-like fibres, which are arranged in consecutive layers, like an onion. The ends of these fibres unite to form three lines in front and three behind. The lines radiate from the centre of the crystalline to the circumference, each forming an angle with the next of 120°, so that they form in front an inverted **⅄** and behind an upright **Y**. They probably give rise to the star-shaped appearance of any bright light, which is distinctly seen by an uncorrected myope. The lines are visible to the naked eye when the crystalline is removed, and are rendered very conspicuous by boiling.

The *nucleus* is denser than the *cortex*, so that the crystalline may be regarded as a bi-convex lens of high refracting power, enclosed between two convexo-concave menisci of lower power. The advantages of this construction are, first, by having the nucleus of greater density than the two menisci, which form the coverings,

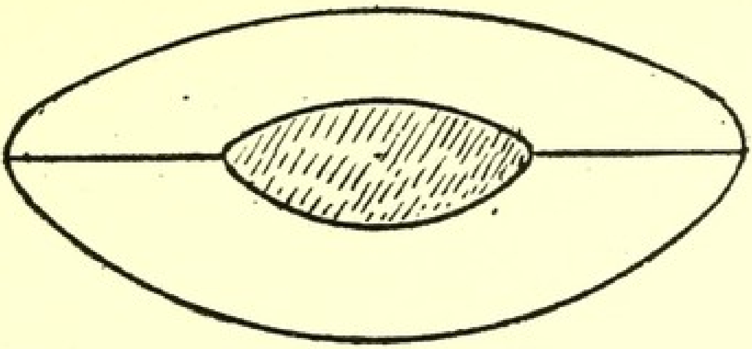

Fig. 4.—**Diagram showing the Component Parts of the Crystalline producing a Compound Lens.**

or cortex, the refractive power of the whole lens is greater than if it had been of the same density as the nucleus throughout ; second, it renders possible the alteration in curvature of the lens in accommodation ; third, its form tends to diminish the confusion images of
caused by imperfections in the media ; fourth, it reduces spherical aberrations by approximating the foci produced by the several zones of the lens.

The crystalline is contained in a *capsule*, and lies in a cup-like recess of the vitreous. It is retained in place by the *suspensory ligament* (zonule of Zinn), which is attached to the circumference of the lens. The ligament consists of various filaments which arise from the membrana limitans interna (or hyaloid membrane) at the ora serrata, and from the ciliary processes. The triangular space formed at the margin of the crystalline is called the *canal of Petit*.

**The Vitreous.**—The *vitreous humour* lies behind the crystalline. It occupies about four-fifths of the interior of the globe; it is of a jelly-like nature, resembling the white of a fresh egg. It is bounded behind by the membrana interna, and in front by the ligament and lens capsule.

**Accommodation.**—According to Helmholtz, when the ciliary muscle, and consequently the eye, is at rest, the straight fibres of the muscle retract the folds of the processes, so that the ligament, pulling on every part of the front surface of the crystalline, causes it to become flattened. On the other hand, when the muscle contracts, the processes are bulged forward and inwards

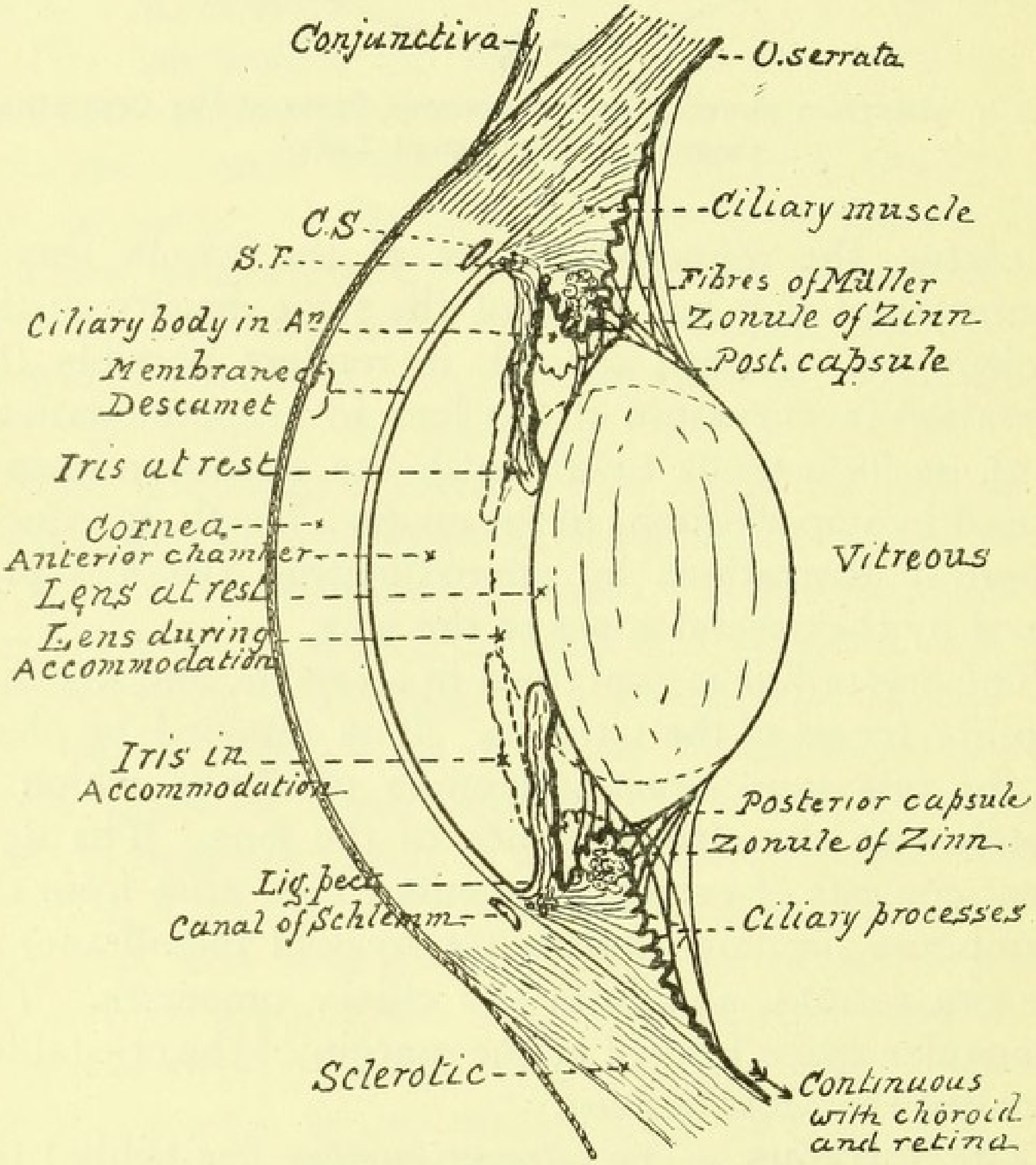

Fig. 5.—**Horizontal Section through the Middle of the Cornea, showing the Parts of Eye connected with Accommodation.**

The dotted line shows the form of the crystalline and the position of the iris during accommodation.

towards the lens margin, thus releasing the tension of the ligament on the crystalline, the front surface of which, by its natural resiliency, becomes advanced and more convex, while the back surface remains stationary and practically unaltered as to curvature.

This action of the ciliary muscle, by altering the shape of the crystalline lens, increases the refractive power of the eye, and is termed *accommodation*, and is demonstrated by the catoptric test (*q.v.*). Some authorities, however (Tscherning, for instance), state that accommodation results from direct tension of the circular fibres on the crystalline, causing this body to become flattened at the periphery and more convex at the centre. Either action produces the same result—viz., increased curvature of the front surface of the lens.

Certain drugs, termed cycloplegics, such as homatropine and atropine, relax or paralyse the accommodation, while others, such as eserine and pilocarpine, have the contrary effect. Most drugs which dilate the pupil also paralyse the accommodation, exceptions to this being cocaine and its derivatives—eucaine, etc. All the cocaine group produce local insensibility to pain.

The power of accommodation, owing to the reduced elasticity of the crystalline, becomes smaller with age, so that reading-glasses become necessary to supplement the loss of accommodation after middle life.

**The Internal Muscles.**—The *internal muscular systems* of the eye are (1) the iris, which controls the amount of light admitted to the eye; and (2) the ciliary, which supplies additional refractive power when needed.

**The External Muscles.**—The *external muscular system* of the eye, by which the globe is rotated in all directions, consists of six muscles—the four *recti* and the two *obliques*. The recti are so termed because they run straight from their origin to their attachment on the sclerotic, while the obliques do not. These six muscles may be considered as constituting three pairs, of which the one acts as antagonist to the other of each

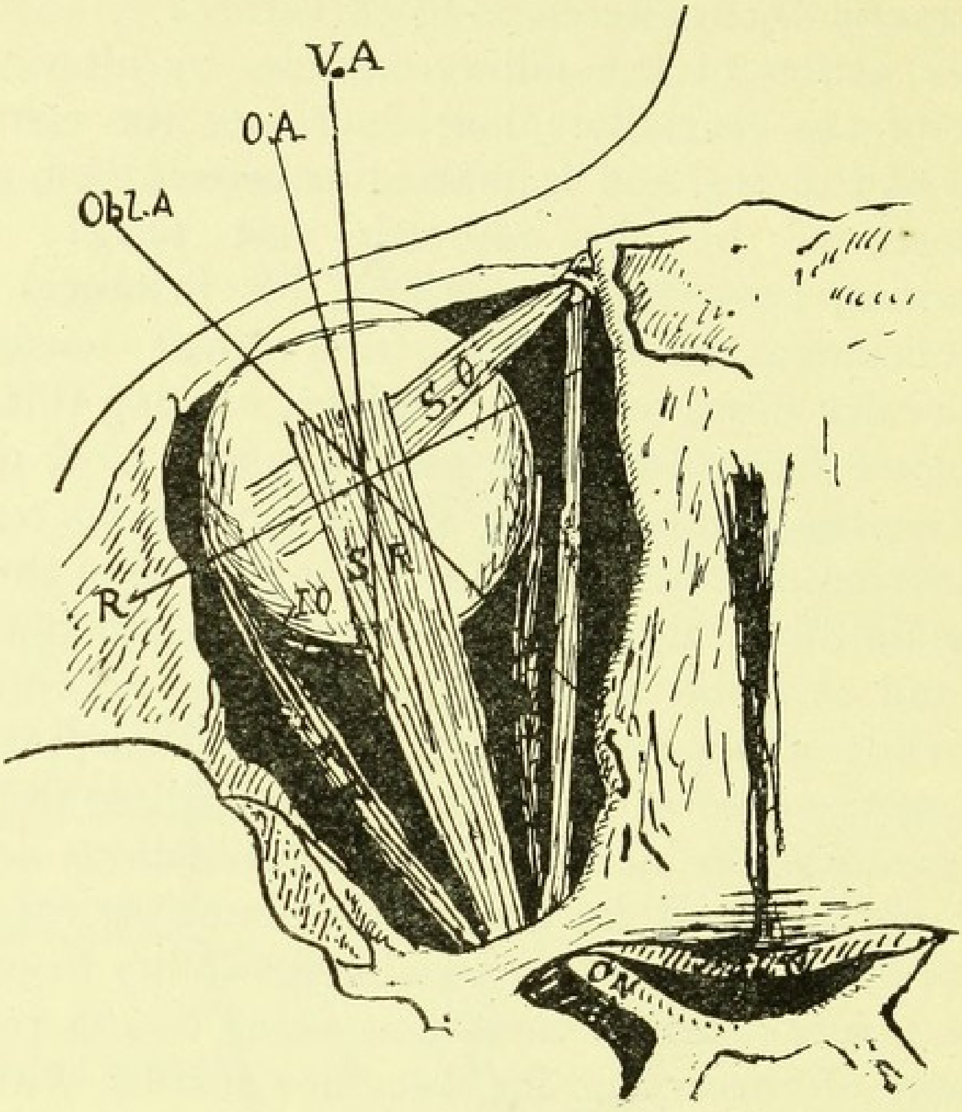

Fig. 6.—**The Orbit, opened from above, showing the Eye in situ with the Superior Internal and External Recti and the Superior Oblique Muscles.**

The attachment of the inferior oblique muscle can just be seen. Part of the optic nerve, the chiasma, and the cut end of the optic tract are shown—

*VA*, Visual axis.
*OA*, Optic axis.
*Obl.A*, Axis of rotation of the oblique muscles, making an angle of about 30° with *OA*.
*R*, Axis of rotation of the superior and inferior recti, making an angle of about 60° with *OA*.

*IR*, Internal rectus.
*ER*, External rectus.
*SR*, Superior rectus.
*SO*, Superior oblique.
*IO*, Inferior oblique.
*ON*, Optic nerve.

pair. The first pair is completely, and the second and third pairs are partially, antagonistic.

The *first* pair consist of the *external rectus*, which turns the eye *out*, and the *internal rectus*, which turns the eye *in*, the motion being on a *vertical axis*. Thus, for example, if the eye is directed outwards, the external rectus contracts, and at the same time the internal rectus relaxes.

The *second* pair consist of the *superior rectus*, which turns the eye *up* and slightly *in*, and the *inferior rectus*, which turns the eye *down* and slightly *in;* the rotations are on a *horizontal axis*, inclined forward on the nasal side *about* 30°.

The *third* pair consists of the *superior oblique*, which turns the eye *down* and *out*, and the *inferior oblique*, which turns the eye *up* and *out*. The axis of rotation is *oblique*, inclined outwards on the nasal side *about* 60°, in the horizontal plane.

**Rotation of the Globe.**—The above directions refer to the front of the eye, or the outer end of the visual axis, for the back of the globe, with the macula, rotates in each case in the opposite direction. The *three axes of rotation* cross each other at a point situated in the centre of the vitreous, termed the *centre of rotation*, which lies about 9 millimetres in front of the retina, or 13 millimetres behind the pole of the cornea. When the eyes are adjusted for infinity, they are said to be in their *primary position*, and any deviation from it is a *secondary position*.

The muscles of the eye are capable of moving the globe round a vertical, a horizontal, and an oblique axis, but they do not normally rotate the eye around the optic or visual axis, at least not more than 1° or 2°. The law of Listing is based on this fact. Torsion of the eye—*i.e.*, rotation around the optic axis—is only apparent, and does not really exist. It appears to occur when the eye is moved from its primary to an oblique secondary position.

The intermediate positions of the eye result from combined action of two or more muscles. The superior rectus turns the eye up and in, the inferior oblique turns the eye up and out, so that for the eye to be directed upwards these two muscles would act, the outward tending of the inferior oblique being counteracted by the inward tending of the superior rectus. The eye is turned, say, down and in by the combined action of the internal and inferior recti and superior oblique muscles.

**Yoked Muscular Actions.**—Combined action of muscles of the two eyes is termed *yoked*, or *conjugate*. Thus, if the two eyes are turned to the right, the external rectus of the right eye acts with the internal rectus of the left.

**Convergence.**—The most important of the yoked actions is that of *convergence*, which also is independent of any of the others, and may be exerted simultaneously with them. When the two internal recti are contracted convergence of the visual lines occurs, in order to see a near object. The two eyes cannot simultaneously be turned outwards by the external recti beyond a very limited angle of 2° or 3° for the two eyes together, and that only by some people.

**Attachments of the Muscles.**—The four recti and the superior oblique have their origin at the apex of the orbit in a fibrous ring surrounding the *optic foramen*, the latter being the aperture where the optic nerve enters the orbit. The inferior oblique has its origin at the nasal side of the globe.

The four recti are attached to the sclerotic, in front of the equator of the globe, about 5 or 6 millimetres behind the edge of the cornea; the two obliques are attached behind the equator; the superior oblique, after passing through a pulley and then slightly forwards, becomes attached to the sclerotic at the temporal side of the top of the globe. The inferior oblique, arising at the nasal side of the orbit, passes backwards and outwards, and becomes attached to the sclerotic at the temporal side of the bottom of the globe. Hence, when a rectus contracts, the front of the globe turns with it; but when an oblique contracts, it is the back of the eye which is primarily acted on. Thus, if the superior oblique contracts, it rolls the back of the eye up and in, while the front of the globe rotates in the contrary direction—viz., down and out.

The four recti slightly retract the globe, while the obliques advance it, in its socket, thus helping to keep it in position, which is also maintained by the optic nerve, Tenon's capsule, the conjunctiva, and eyelids. Many mammals are provided with a special muscle, by which the eye can be withdrawn into the socket; but this muscle is quite wanting in man.

**The Axis and Poles.**—The imaginary line which passes through the apex of the cornea and the centre of the crystalline to a point near the inner margin of the macula lutea is termed the *optic axis*. The front end of this line, at the centre of the cornea, is the *anterior pole*, and the other end, at the centre of the fundus, is the *posterior pole*.

**The Equator and Meridians.**—The *equator* is an imaginary plane cutting the globe, vertical to the optic axis, and dividing the eye into the anterior and posterior hemispheres. The various planes which cut the eye through the poles are called *meridians*.

**The Nodal and Principal Points.**—The optical centre of the eye is known as the *nodal point*. It may be said to coincide with the apex of the posterior surface of the crystalline, but the focal distances of the eye are measured from an imaginary point, called the *principal* *point*, which marks the *combined refracting plane* of the eye, and is situated in the aqueous, between the cornea and the anterior surface of the crystalline. The nodal and principal points lie on the optic axis.

**The Visual Axis.**—If the eye were constructed on mathematical instead of physiological principles, the centre of direct vision—*i.e.*, the fovea—would lie at the posterior pole. But the *visual axis* or *line of vision*, which connects the fovea with the centre of the object looked at, does not coincide with the optic axis.

**Angle $a$.**—In the normal eye the optic and visual axes cross and form at the nodal point the *angle* $a$ (Alpha), which is variable as to size.

The cornea is, however, not part of a sphere, but forms one end of an ellipse, whose long axis is directed outwards in front and towards the optic disc behind. It makes an angle with the visual axis, and the angle which the corneal axis makes with the visual axis is slightly greater than the angle $a$, but for practical purposes the corneal axis may be considered identical with the optic axis, so that the angle Alpha is that angle which the visual line makes with the optic axis or the corneal axis indifferently.

When the fovea lies to the outer (temporal) side of the posterior pole, as it usually does, the visual line cuts the cornea to the inner (nasal) side of the optic axis, and the *angle Alpha is positive.* When the fovea lies exactly at the posterior pole, the visual line and optic axis coincide, and the *angle Alpha vanishes.* When the fovea lies to the inner (nasal) side of the posterior pole, the visual line cuts the cornea to the outer (temporal) side of the optic axis, and the *angle Alpha is negative.*

**The Line of Fixation.**—This is the direction of vision from the centre of rotation, and it forms with the optic axis the angle $\gamma$ (Gamma). But the line of fixation being almost identical with the line of vision, the angle Gamma may be taken as the same as the angle Alpha, their distinction being a refinement having little practical value.

**Relationship of the Two Visual Axes.**—When the motor muscles are so adjusted that the two visual axes are directed to the same point at infinity, they are presumed to be *parallel*, although actually they are slightly *convergent*. When the six motor muscles of each eye are completely at rest, the two visual axes usually *diverge*. This means that most people exert slight convergence of their eyes in order to fix a distant object.

**Muscles of the Lids.**—In addition to the muscles mentioned, there is the *levator palpebræ*, which raises the upper lid, and the *orbicularis*, which forms a thin layer of fibres lying underneath the skin, and surrounding the orbit for a considerable distance, which, by its contraction, squeezes the lids together and draws together the folds of skin round the eye.

### Muscles connected with the Eye.

| Muscle. | Action. | Nerve-Supply. |
|---|---|---|
| External rectus ... | Rotates the front of the eye out | Sixth |
| Internal rectus ... | Rotates the front of the eye in | Third |
| Superior rectus ... | Rotates the front of the eye up and slightly in | Third |
| Inferior rectus ... | Rotates the front of the eye down and slightly in | Third |
| Superior oblique ... | Rotates the front of the eye down and out | Fourth |
| Inferior oblique ... | Rotates the front of the eye up and out | Third |
| Levator palpebræ ... | Raises the upper lid | Third |
| Orbicularis... ... | Closes the lids | Facial |
| Sphincter of ciliary | Accommodation | Third |
| Radiator of ciliary | | Third (or sympathetic?) |
| Sphincter of iris ... | Pupillary action | Third |
| Dilator of iris (?) ... | | Sympathetic (?) |

**Faulty Action of a Muscle.**—If one of a pair of motor muscles is much weaker than the other, or is paralysed, the other has uncontrolled action and the eye squints. From the foregoing table it will be seen that paralysis of the sixth nerve causes the eye to squint inwards. Paralysis of the third causes drooping of the eyelid, external squint, and a dilated pupil. Paralysis of the fourth nerve is somewhat masked by the action of the inferior rectus, but when both eyes are directed downwards, the unequal movements of the two eyes cause the squint to be evident.

**The Orbit.**—The *orbit* is the hollow cone of bone in which the globe is located, its axis diverging outwards about 10°. It is lined with fatty tissue, forming a bed for the globe, and lying in it are the muscles, nerves, and bloodvessels which supply the eye. Behind the conjunctiva, and enclosing the muscles and the concealed part of the globe of the eye, is a folded membrane called *Tenon's capsule*, which is continued back to the optic foramen, so that the fluids in the sac can pass out between the membranes of the brain. The capsule must be divided before a muscle can be exposed, as is done in the operation for squint. The connexion of the capsule with the brain explains how wounds and injuries around the eye may prove fatal if they become infected.

**The Conjunctiva.**—The *conjunctiva* is a transparent mucous membrane, containing minute bloodvessels, which covers the whole of the front of the eyeball and, folding over, lines the lids. It protects the eye itself, and prevents dust and insects from getting to the side of, or behind, the globe or into Tenon's capsule. The small red glandular projection at the nasal angle of the conjunctiva is termed the *caruncula*. It is covered with a small free fold of conjunctival tissue, the *plica* *semilunaris*, which is the vestigial relic of the *membrana nictitans*, or third eyelid, common to a large number of mammals, being highly developed in the horse, in all ruminants, and in birds, and which is also found in many reptiles, frogs, etc. Occasionally it is quite conspicuous in man, but never sufficiently so as to be functionally active. That part of the conjunctiva which covers the cornea is normally free from bloodvessels. If bloodvessels are seen there, it is an indication of disease.

**The Eyelids.**—The *eyelids* are formed of skin, beneath which there is a thick layer of dense connective tissue, termed the *cartilage*, and a thin muscular layer. At the free edge of the lid the skin passes abruptly into the mucous membrane, which lines the back of each lid, and is directly continuous with the conjunctiva. The upper lid serves as a protector to the eye and a means of keeping its front surface moist. Some glands situated near the lashes provide an oily secretion which lubricates the surface. The opening between the lids is termed the *commissure*, and the outer and inner angles, formed by them at their juncture, are respectively the *outer* and *inner canthus*.

**The Lachrymal Apparatus.**—The *lachrymal apparatus* consists of a *gland*, two small *canals*, a *sac*, and a *duct*. The gland for secreting moisture is situated just above the outer angle of the lids. The lachrymal secretion is carried by the movement of the upper lid over towards the inner canthus, and fills there the small cavity near the caruncle. It is then drawn up through a minute opening in each lid, called the *punctum*, into the lachrymal canal, which leads to the lachrymal sac, and thence, through the nasal duct, into the lower cavity of the nose, where it is evaporated or passes into the throat. An excessive secretion of moisture, greater than can be conducted away by the two puncta and canals, results in a flow of tears.

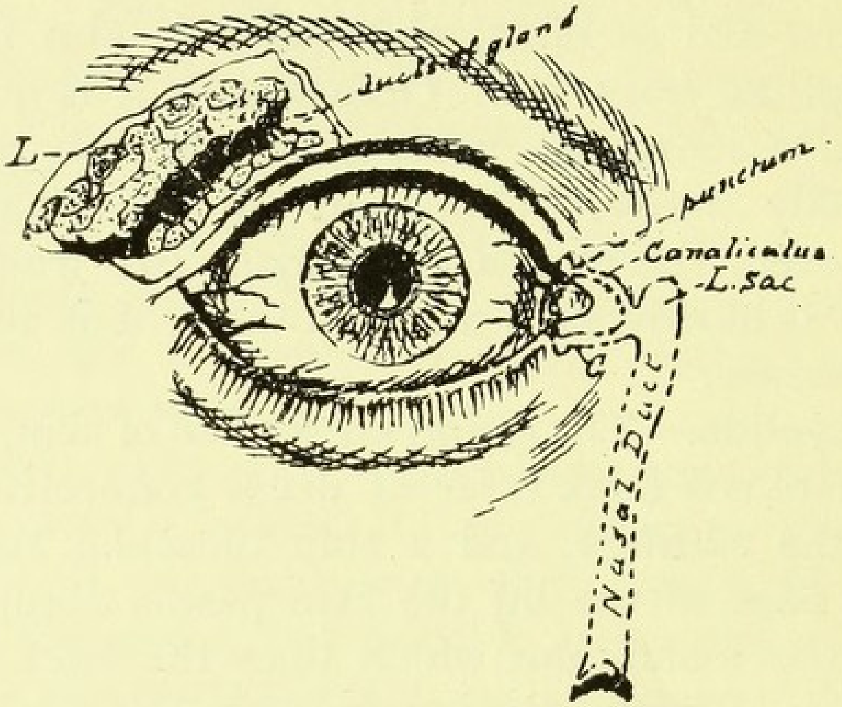

Fig. 7.—**The Lachrymal Apparatus.**

**The Eyebrows and Eyelashes.**—The *eyebrows* consist of stiff hairs lying horizontally. They help to shade the eyes and prevent moisture from the forehead falling on to the eyes. The *eyelashes* are stiff curved hairs placed at the margins of the lids. They help to shade the eyes and prevent dust and insects from entering.

# CHAPTER II

## VISION

**Visual Requisites.**—The requisites for clear vision are transparency of the media, the *receptive* faculty of the retina, *transmissive* faculty of the optic nerve, and the *perceptive* faculty of the brain. In addition to these, there are three others with which the optician is more concerned, namely:

*Refraction*, or the power of bringing light, diverging from distant objects, to a focus at the retina.

*Accommodation*, or the auxiliary refracting power of the eye required for bringing light, diverging from near objects, to a focus at the retina.

*Convergence*, or the action of the internal recti by which the two visual axes are directed to the same object, so that single vision may obtain at all distances.

The refraction of the eye, when accommodation is at rest, is termed the *static* refraction, while that derived from accommodation is the *dynamic*; the two combined constitute the *total* refractive power of the eye.

**The Catoptric Test.**—That the front surface of the crystalline changes during accommodation is proved by this test, which is sometimes referred to as Purkinje's test, and must not be confused with the Purkinje's images described later on. If a flame be held a little on the one side of the optic axis and the observer's eye be at an equal angle on the other side, there can be seen in an observed eye—(1) a bright virtual image of the flame reflected from the cornea, acting as a convex mirror; (2) a virtual image reflected from the front surface of the crystalline, also acting as a convex mirror—this image is rather larger and more diffused than No. 1; (3) a bright, very small real image reflected from the back of the crystalline, acting as a concave mirror. When the eye accommodates, No. 2 image becomes smaller, clearer, advances and moves towards the centre of the pupil. This shows that the front of the crystalline has become more convex. Images 1 and 3 do not change, showing that the other surfaces are not affected by accommodation.

**The Optical Capacity of the Eye.**—The eye, although only 1 inch in length, is capable of perceiving objects of every magnitude down to $\frac{1}{500}$ inch, and with a range varying from a few inches to an infinitude of miles. The optical apparatus of the eye is specially constructed for collecting and arranging light rays, so that they may impress the retina with a distinct image of the object seen. The eye, besides possessing a nervous function, is at once a camera, a microscope, and a self-adjusting telescope.

Owing to the refractive media, a sharp picture of an object can be formed upon the retina. By means of the accommodative power, objects at various distances can be distinctly seen without the necessity of approaching or moving away from them. By means of the motor muscles, objects situated in various positions, in relation to the observer, can be viewed without movement of either the head or the object. The iris and lids enable the quantity of light admitted to the interior of the eye to be regulated. By means of the choroid, superfluous light is absorbed and internal reflection prevented, and when darkness is necessary the light is shut out by the lids.

**The Sense of Sight.**—The sense of sight may be defined as a mental appreciation of external objects by means of the visual organs. It is the most important of the senses, being the chief factor in the education and intellectual development of man. By its aid the form, colour, size, distance, position, and characteristic details of objects become known.

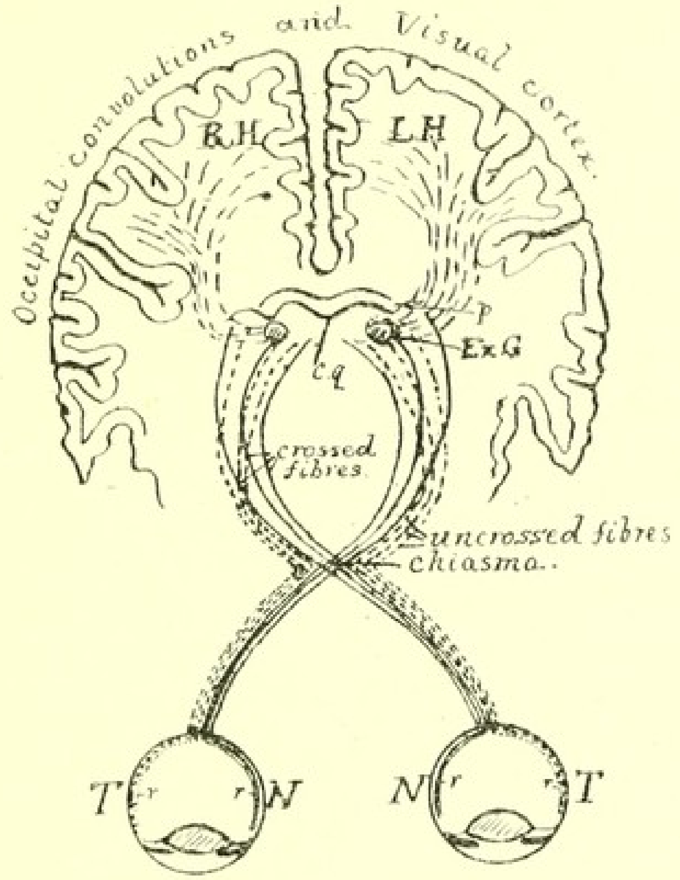

Fig. 8.—**Diagram illustrating the Course of the Fibres of the Optic Nerve from the Eyes to the Brain.**

The fibres belonging to the nasal half of the fundus cross over, at the chiasma, to the opposite hemisphere of the brain. The fibres which are distributed over the temporal half of each eye are confined to its corresponding side of the brain. Thus the right halves of the two visual fields go to the right hemisphere, while the two left halves pass to the left.

*RH*, *LH*, Right and left hemispheres of the brain.
*ExG*, External geniculate body.
*Cq*, Corpora quadrigemina, or optic lobes.
*P*, Pulvinar. *r r*, Retina.
*N*, Nasal. *T*, Temporal.

**The Optic Nerve.**—The optic nerves are incapable of conveying other sensation than that of light. Before the era of chloroform, when the nerve was divided, patients were wont to declare that they felt no pain, but merely saw a flash of light.

The two optic nerves, after passing through apertures at the back of their corresponding orbits, meet each other underneath the brain, and many of the fibres cross (decussate) over to the opposite nerve, so that, after meeting, each nerve is then composed partly of its own fibres and partly of the fibres of the opposite nerve. The nerves may then be followed to several centres, but especially to two masses of nerve cells, the *optic lobes* or *corpora quadrigemina*, from whence fibres may be traced to the convolutions at the back of the brain, or visual cortex, as it is called. The final terminations of the optic nerve are not arranged in regular order, as are their other ends in the rods and cones of the retina, but appear to be distributed irregularly.

Apparently this does not matter, as the mind assigns the proper relative position of each cell terminal of a fibre, *no matter where it is placed*. All that appears to be necessary is that the peripheral or retinal ends should be placed in their respective relations to one another, so that each terminal receives a stimulus corresponding in relative position, intensity, and colour, to the corresponding point in the object itself. This stimulus, possessed of these properties, is then implanted in the brain cell at the other end of the fibre, which, being done, it matters little where these cells are situated, since the sensations are picked up and assigned their right position by the mind. But how this is done is unknown, for the moment the light wave reaches the retina all our knowledge with regard to what happens in vision ceases. We do not even know what the nature of the force is which conveys the sensation of vision to the brain—whether it is an electric current or not; nor can we assign to the five known centres of vision in each half of the brain their respective functions, much less do we know how they act.

**The Retinal Image.**—The retinal image is inverted, but upright vision is brought about by a mental process, and it is only necessary for ourselves, or any animal which possesses eyes, to learn by experience the position of three points in the picture space of the field of vision, occupying together a vertical and a horizontal direction, and the correct position of everything else in the picture follows as a matter of necessity. For in whatever position the picture falls on the retina, all parts of the view preserve the same relative position to one another.

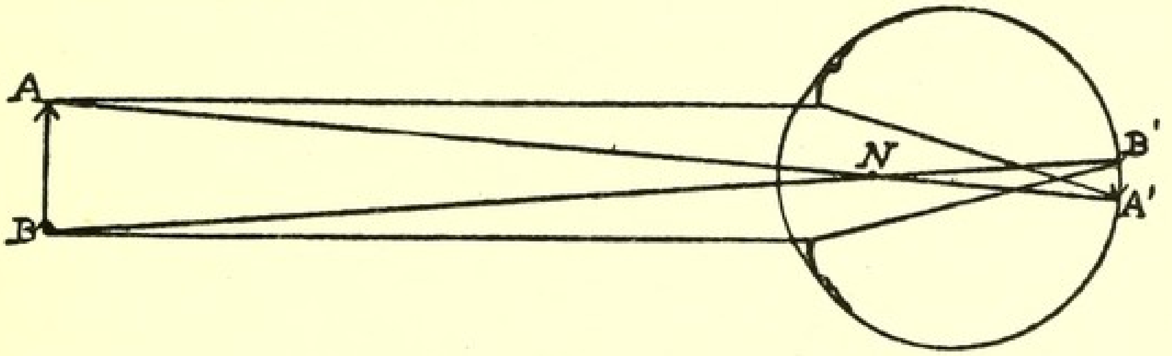

Fig. 9.—**Diagram showing the Course of Rays from an Axially-placed Object to the Retina.**

*A B* is the object, and *B' A'* the inverted retinal image. *N* is the nodal point.

**Visual Projection.**—The sense of sight lies in the brain, and the latter sees not the inverted retinal image, but the projected virtual mental image of the object, the sensation excited by the impingement of the light rays on the retina having been communicated to the brain by means of the fibres of the optic nerve. From experience and education the rays are referred back to a distance closely coinciding with that which they travelled before entering the eye, and so to their points of origin. Thus the projected mental image usually corresponds in every respect with the object viewed. It is the mental picture that is *seen*, not the object, although it is commonly said that one does see the object itself.

The direction of each mental projection is, generally speaking, outwards through the nodal point, or backwards in the direction of the axial ray of the incident beam of light. But the mental projection is not always thus made, and habit, or some unknown cause, must have an effect in this connexion. Particularly is this illustrated by the mental projection of a shadow cast on the retina when light is parallel in the vitreous.

Also, under certain conditions the projected mental image does not coincide with the object. Since the image is mental, it may be formed anywhere; and if the stimulating light has suffered refraction or reflection before entering the eye, the size or position of the image may differ considerably from the object, the brain image being formed according to the refracted or reflected rays, and not according to the original direction of light. Thus, if the retinal image be formed by rays reflected from a mirror, the brain picture is conceived as behind the mirror, at the same distance from its surface as the object itself is in front of it. The virtual image is thus seen according to the direction of the rays after reflection by the mirror, the eye being in that position in which such rays can enter it. One can see in a mirror (and therefore in front of him) the images of objects actually situated behind his back, for the rays having entered the eye from the face of the mirror, are referred back in that same direction.

If the retinal image be due to rays refracted by a prism, the object appears shifted towards the edge of the prism, because the rays, after refraction, being turned towards the base, enter the eye as if they came from an object situated in a position nearer the edge, and are mentally referred back accordingly. So, also, an object viewed through a convex or concave lens is seen respectively larger or smaller, the rays after refraction being in the first case less divergent and therefore projected to a greater distance, and in the latter case more divergent and therefore projected to a shorter distance, than they would have been had they not been refracted by the lens. The image of an object seen through a prism or lens is as distinct and vivid as if nothing were placed between the eye and the object, yet the mental image does not in these cases correspond to the object itself.

**Position of the Image.**—The faculty of seeing an object in its proper position as regards distance is one that is acquired by habit. It is, in fact, the faculty of mental projection backwards of the incident rays of light over the same distance which they travelled before entering the eyes. One who sees things under new conditions, as through lenses, or in an unaccustomed climate, may make mistakes as to the distance of an object, but he will never conceive the object as upside down or displaced laterally, and one who is in the habit of seeing things under certain conditions judges much better their distance than one to whom such conditions are new.

Since the mental projection of the stimulus caused by light incident on the retina determines the appearance of the image seen, an inverted image of an object results when a strong convex lens is held a certain distance in front of the eye. The light, passing through it, is converged, and forms in the air an inverted image, and the rays, diverging from this image, enter the eye to form an upright retinal image of the original object, so that the mental impression is that of an inverted image of the object ; the same thing happens if a landscape be observed through an astronomical telescope.

If a pin-hole disc be held about an inch from the eye, the rays of light passing through the aperture are so divergent that, after refraction, by the media of the eye, they are parallel in the vitreous. If, then, a pin be held head upwards between the disc and the eye, so that the head and part of the shank intercept some of the light, an upright shadow of the pin is cast on the retina. This causes an enlarged inverted mental image of the pin to be formed.

**Binocular Vision.**—Binocular vision, or the simultaneous projection by the two eyes of a single image of an object seen, is always better than monocular vision. Size, form, distance, and perspective are better conceived; the mental impression resulting from two retinal images seems to be intensified, so that the object is seen more clearly. This may be demonstrated by looking at some print, first with the one eye only and then with both, and it rarely happens that binocular vision fails to cause the print to be seen with greater sharpness and blackness.

**Corresponding Retinal Images.**—A single image is seen by the two eyes because the light from the object falls on corresponding parts of the two retinæ. That proceeding from the right of the object reaches the retina to the left of the macula of each eye ; that from the left of the object is incident to the right of the macula of each eye, while the light from the centre of the object has its focus at the fovea centralis of each. The mental projection is then such that the two images coincide in space.

**Non-Corresponding Retinal Images.**—When the two retinal images do not fall on corresponding parts of the two retinæ double vision results, because there are two distinct mental impressions, which are referred to different positions in space. If one eye be slightly pressed, so that light is focussed on a part of the retina which does not correspond to that of the other, two images of a single object result, because different nerve fibres in the two eyes are stimulated. When the two retinal images exactly correspond, corresponding nerve fibres in each eye are excited, and the impression is the more intense on account of the double stimulus.

**Light Sensation.**—It is supposed by some that the sensation of light is due to the stimulus given to the terminals of the rods, and discriminating differences of details to that given to the cones. The macular region, where the retinal elements are most closely grouped, is more sensitive than the peripheral regions, where they are less so, the number of rods and cones in a given area decreasing as its distance from the macula increases. At the ora serrata, where the retina terminates, both are very imperfectly developed, and there is in consequence only perception of light. At the macula the cones are much more abundant than the rods, and at the fovea the rods are entirely absent, so that it may be deduced that acute vision depends on the cones rather than on the rods. On the other hand, objects of feeble luminosity appear to be better seen by the rods than by the cones. For instance, a very faint star, invisible at the fovea, can be seen if its image falls a little to one side of it. Many nocturnal animals have few or no cones at all.

**Purkinje's Images.**—The experiment of Purkinje seems to prove that the perceptive faculty for light lies in the outer terminals of the cones. This experiment consists of moving a flame by the side of one's own eye, when looking towards a black wall in a darkened room. A picture of the observer's retinal bloodvessels on a dark brown background will be observed; and, as a rule, both the macula and the fovea can be seen, surrounded by capillary loops, none of these being visible inside the macular area. This perception of one's own retinal vessels is possible because they lie in a plane anterior to the percipient layer of the retina. With care, and under favourable circumstances, the retinal field may be traced almost up to the disc, but the latter can never be seen by this method, because there is there no percipient layer.

Fig. 10.—**The Blind Spot Test.**

**Mariotte's Experiment.**—The end of the optic nerve, as it is seen when looking directly into the eye through an ophthalmoscope, is totally insensitive to light. This can be proved by closing one eye (say the left) and looking with the right eye at the above cross held in the axis of vision. If now the page be slowly withdrawn or approached towards the eye, a position will be found at which the round patch becomes invisible; and either on withdrawing or approaching the page from this position, the patch again comes into view. By moving the page sideways, the same result can be obtained. In this way the area of the blind spot can be mapped out on paper, and its exact size calculated. Such measurements show it to be about 2·2 millimetres in the vertical direction, and a little less in the horizontal—*i.e.*, slightly larger than the optic disc itself.

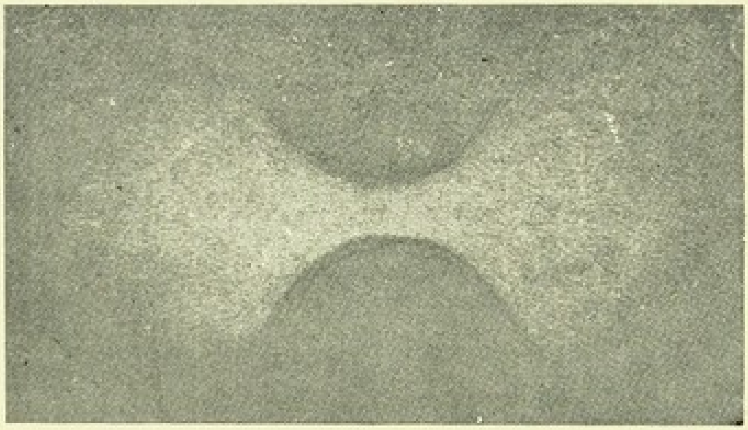

Fig. D.—**Haidinger's Tufts**.

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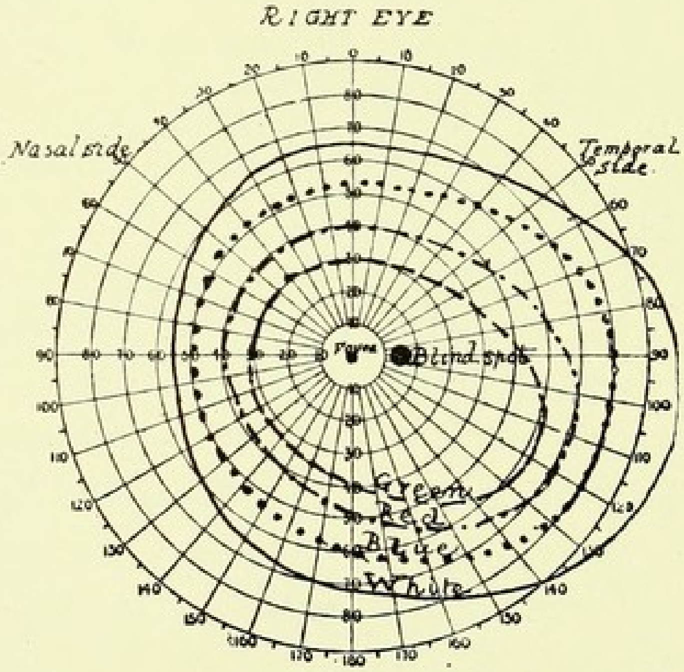

Fig. 11.—**Field of Vision of the Right Eye.**

The outer black continuous line shows the field for white; the dotted lines show the fields for blue, red, and green respectively.

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**Haidinger's Tufts.**—On looking at a bright sky, through a Nicol prism, one will sometimes see a pair of small yellow cones joined end to end, like an hourglass (see Fig. D). These are known as Haidinger's tufts or brushes. At right angles to the tufts a pale blue or violet colour usually fills the concavities on each side of the tufts. The major axis of the tufts coincides with the plane of polarization of the Nicol, and turns with it when rotated. After a few seconds the tufts vanish, but immediately reappear on slightly rotating the Nicol. If a deep cobalt blue glass be held before the prism, the tufts appear smaller and of a dark reddish tint, due to the absorption of the yellow rays by the blue glass.

The cause of this phenomenon is not due to the crystalline, since it may be seen by an aphakic eye. Professor W. F. Barrett has shown that if a screen which cuts off all orange and yellow rays be held before the eye while looking at a bright white surface, a dark reddish patch is seen in the blue field because the macula lutea is opaque to blue-green light. If now the Nicol prism is placed in front of the glass, the tufts are seen in the position of the dark patch, showing that they are, in some way, caused by the macula. Their yellow colour is probably due to the colour of the macula, the blue filling the concavities being the result of complementary contrast. Haidinger's brushes are held to prove that the light of direct vision is polarized, and that the eye is capable of analyzing polarized light. The tufts are longest when the plane of polarization is horizontal, thus showing that the yellow spot has a longer horizontal than vertical diameter.

**The Field of Vision.**—The angular extent over which an eye can see without moving is called the *field of* *vision.* It is usually measured by the perimeter. Approximately it extends:

| | |
|---|---|
| Outwards, 90°. | Upwards, 50°. |
| Inwards, 60°. | Downwards, 70°. |

But these measurements vary considerably with each individual. The field is largest for white, then for blue, yellow, red, and green in the order given, being about 10° less for each colour.

The two fields overlap towards the middle, so that the central portion only of the binocular field of vision is truly binocular, the outer portions being monocular.

Colours are barely distinguishable at the periphery of the field; indeed, the outer parts of the retina may be said to be colour blind, although less so for some colours than for others, except to a bright transmitted light, such as is afforded by a coloured glass disc placed in front of a lamp.

The *field of fixation* is the angular extent over which the eye can see when it is allowed to rotate, without moving the head. It does not differ much from the field of vision except downwards.

**Defects of the Eye: Transparency.**—The eye is not free from defects, although these are small compared with the wonderful properties which it possesses; in ordinary vision, moreover, they are not noticeable. It is doubtful whether the cornea and vitreous are absolutely transparent; the crystalline lens certainly is not, especially in old age. In the crystalline, also, the differences in the indices of refraction of the various parts may be such that the rays diverging from a single luminous point cannot unite in a common focus.

**Sphericity of the Surfaces.**—The cornea is never perfectly spherical, so that a difference obtains in the refractive power of the various parts of any single meridian. Also, it has usually a greater curvature in its vertical than in its horizontal meridian; moreover, the curvature of the crystalline may vary. These variations of curvature, however, are not sufficiently great to constitute an appreciable astigmatism.

**Chromatic Aberration.**—The eye suffers from chromatic aberration, so that the red and violet rays can only be brought to a focus at the retina, at the same time, if the violet rays diverge from some near point, while the red diverge from infinity. Since, however, red and violet light possess little luminosity compared with yellow and green, the fact that the former are out of focus at the retina is not of importance, and chromatism is not noticed in ordinary vision, for then yellow light, on which vision chiefly depends, is in focus at the retina, and the circles of confusion caused by red and violet light are of equal size. The effects of chromatism are more frequently experienced by ametropes; for instance, an astigmat sometimes sees coloured fringes on the bars of the astigmatic chart. The existence of chromatism can be proved by looking at a light through a cobalt blue glass, which blocks out the centre of the spectrum, and admits only red and blue light. If the eye be ametropic, or made so by lenses, the colours are separated. Also by occluding half the pupil, so that the eye acts with prismatic effect, coloured fringes are seen.

**Spherical Aberration.**—Spherical aberration always exists, although it is to a large degree rectified by the peculiar formation of the crystalline, which is denser at the nucleus, and has therefore a higher refractive index than the periphery. Here also the iris, acting as a diaphragm, cuts off the marginal rays, and the pupil becomes smaller in near vision, which compensates for any increased spherical aberration due to the increased obliquity of the incident rays. Spherical aberration can be proved by finding the far-point of an eye, rendered myopic, if necessary, respectively for the centre and the periphery of the refracting system. This is done by occluding for the first the periphery, and for the second the centre of the pupil.

**Direct and Indirect Vision.**—In order that an object may be seen clearly, its image must be formed on the macula ; this is *direct vision.* When images are formed on other parts of the retina, they cause *indirect vision,* and the force of the impression conveyed to the brain, and therefore the clearness of the mental image decreases in proportion to the distance from the macula. If the retina were equally acute all over, as to its receptive faculty, vision would be extremely confused, since it would be impossible for the brain to appreciate, at the same moment, so many details as would be simultaneously communicated to it.

**The Law of the Macula.**—Man and monkeys are the only mammals which possess a true macula, so that probably they alone see sharp details of objects. In all other mammals the macula is wanting, being replaced by a large sensitive area. This enables them to see clearly over a larger field than we do, but not so distinctly over a small area. Lindsay Johnson discovered that all animals which possess a macula have also parallel vision and the power of convergence, and, conversely, all animals which have the power of convergence, and have parallel vision, possess a macula. This is known as *the law of the macula.* From this it follows that, without exception, all mammals, except man and monkeys, possess more or less of an external squint.

**Indistinctness of Indirect Vision.**—When an object is viewed, the centre of it, being pictured on the fovea, is clearly seen; the rays of light from the other parts of the object, falling on less sensitive portions of the retina, are seen with a degree of distinctness only sufficient to assist in comprehending that which is in the line of direct vision. It is so natural for a person to turn his eyes and the lines of direct vision towards an object he wishes to see, that it is extremely difficult to fix the attention on an object situated in the periphery of the field of vision.

**Movements of the Eyes.**—Except for side-glancing and when reading, a person usually turns his head towards the object. Keeping the eyes elevated or turned towards one side for any length of time is irksome, although depression of the eyes, as in reading or walking, is not so. Dr. Lindsay Johnson has found that it is exceedingly rare for animals (except fishes and certain reptiles) to move their eyes. They find it easier or more convenient to turn their heads towards an object which has to be viewed.

**Doubleness of Indirect Vision.**—If an object is not at the point of regard, it is seen, not only indistinctly, but also double, the images being formed on non-corresponding parts of the two retinæ. But this doubleness of vision is not noticed, since the mental images are indistinct, and the mind is principally engaged by that which is pictured on the macula. That objects which are not at the point of fixation appear double may be proved by taking mental note of them while looking at some other object. Thus, if two pencils be held in the median line before the face, the one a few inches behind the other, and the eyes be directed to the more distant one, then the nearer one will be seen double; or, if the near one be regarded, the further one is seen double. In this experiment the double images are seen fairly distinctly, because they are formed near to the macular region. A similar experiment can be made by putting a pair of red glasses in front of the eyes and looking at some object; a lighted candle being held between the object and the eyes, or beyond the object, a double flame is very distinctly noticed.

This fact is patent to every one who has used a gun or rifle, the doubling of the near sight necessitating the left eye being closed while taking aim, unless the right-hand image of the near sight can be ignored, in which case both eyes may be kept open with advantage.

Let a needle be viewed through two pin-hole perforations in a card, about $\frac{1}{16}$ inch apart. The needle then appears single; but if a more distant or nearer object be fixed, the needle appears double. If the right aperture is covered the left image disappears, and *vice versa.* This is known as *Scheiner's experiment*, and illustrates the doubling of objects whose images are not formed at the macula.

**Illumination and Vision.**—If, owing to the intensity of illumination, the retina be excited too much, vision is not clear, nor is it when the retina is insufficiently excited by an inadequate illumination. Thus, objects invisible during twilight are distinctly visible at noon. Best vision results from a sufficiency of light, and the influence of the size of the pupil is felt in this connexion. When the illumination is dull, the pupil is enlarged by the relaxation of the sphincter of the iris; when it is bright, this muscle contracts the pupil, so that less light is admitted to the eye. But habit enables a person to see under conditions of illumination which would be impossible for those unaccustomed to them. Even under ordinary circumstances, a sudden change from brightness to partial obscurity, or *vice versa*, makes clear vision impossible, as when one passes from bright light into a photographic developing-room, or from the latter to the former, although in a few minutes the eyes, becoming accustomed to the altered illumination, see with sufficient distinctness.

**Divisions of Visual Perception.**—The sense of sight may be divided into three classes of perception—namely, light, colour, and form.

*The light sense* is that faculty of distinguishing illumination and its graduations of intensity. The distinction between light and darkness is the lowest degree of this faculty, and if it be absent there is complete blindness. On the light sense depends the power of the retina to adapt itself to various degrees of illumination. One who has a high degree of this faculty distinguishes objects under a lesser illumination than another who possesses it in a lower degree; the former also more easily distinguishes slight differences in luminosities of very low intensity.

*The colour sense* is the faculty of distinguishing between, and appreciating, light waves of varying frequency or length.

*The form sense* is the faculty of recognizing outline or shape; it is the power of differentiating between those parts of the retinal surface which are stimulated by incident light and those parts which are not so stimulated.

The sense of form may be absent while the senses of light and colour exist—that is to say, a person may be able to distinguish between day and night and between different coloured lights, yet he may not be able to distinguish outline. The sense of light—that is, the ability to distinguish between light and darkness—may be present without either of the other two faculties, and the light and form sense may exist without there being the faculty of distinguishing colours. In the few cases which have been recorded, it has been proved that persons suffering from total colour blindness may have fairly good sight without any perception of colour whatever.

**Continued Retinal Impression.** — The retinal stimulus, caused by the impingement of light, lasts for a certain time before the effect passes away; it is estimated at about one-fifth of a second. Thus, if a small luminous body move with great rapidity, as it causes a fresh stimulus at every point of the retina on which its image is formed, each follows the other with such celerity that the impressions previously excited have not had time to cease before the succeeding ones are caused, and the consequence is the mental impression of a streak of light. This is illustrated by a falling star, by lightning, or by the sensation of continuous motion, as seen projected by the bioscope.

**Faculty of the Retina.** — The term 'perceptive faculty' in reference to the retina is hardly correct; more justly the term 'receptive faculty' should be applied. The retina does not see, it merely receives the impression from which the mental appreciation results; but the term is convenient, and, as previously mentioned, the faculty of clear mental appreciation of external objects is directly proportionate to the number of cones existent in that part of the retina on which the image is formed.

**Multiple Perception.**—As only the macular image is distinctly appreciated, one cannot clearly see simultaneously two objects which, although in front of one's eyes, are situated at different distances. Thus, if looking through a window at a house on the opposite side of the street, the former can be clearly distinguished, and the latter is then indistinct, or the house can be seen distinctly when the impression formed by the window is vague and ill-defined. Of course, if the window be comparatively near, accommodation and convergence play a part in this fact; but even when neither of these functions is brought into play the same holds good.

**The Macular Image.**—Only a moderately sized image—*i.e.*, one which does not subtend an angle exceeding about 5°—can occupy the macular area at a given time. The object, of which this is the image, is appreciated distinctly, while everything else which is within the angle of view is seen with a varying degree of indistinctness. The more distant the field looked at, the greater is that part of it which can have its image on the macula, and which therefore can be included in direct vision. The nearer the object viewed, the smaller is that portion of it which can be seen clearly at a given moment. Thus, in reading, a couple of short words comprises all that can be distinctly seen without moving the eyes or the book; or, to use a familiar example, a halfpenny will cover the area of distinct vision at 10 inches.

**Estimation of Direction.**—Estimation of the direction of an object depends on the part of the retina receiving the impressions of the rays diverging from it, and on the position, relative to the macula, of the part of the retina so impressed. If the rays fall to the right of the macula, the object is conceived to the left of the observer; if to the left of the macula, it is conceived to be on the right. If the rays impinge on the retina above the macula, the object is conceived towards the ground; if they fall below, it is conceived upwards.

**Estimation of Position.**—Estimation of the position of an object as so much to the right or left, above or below, depends, therefore, on indirect vision. The direction may be roughly considered perpendicular to the part of the retina occupied by the image, although actually it is not quite so. Estimation of direction or position seems to be the one faculty which is possessed by the peripheral portion of the retina to as great an extent as by the central region.

**Estimation of Motion.** — Estimation of motion depends on the images of the object passing over the retinæ, so that they occupy successively positions which gradually vary in distance from the maculæ. The motion thus conceived represents, however, only a change in the relative positions of the objects seen and the observer; and it might be either object or observer that has changed position, so that estimation of motion is sometimes deceptive. Thus, when viewing a landscape from a moving train, it seems as if the trees, fields, and houses were going past the train rather than that the observer is passing these objects; so also if one be seated in a stationary train, and another moving train passes by, the observer is uncertain whether the former is moving and the moving train is stationary. He can only be certain whether he or his eyes are moving, or whether the object viewed is moving, when other senses confirm the one or the other fact.

The muscular action which is exercised when walking, or the jolting experienced when driving, serves to diminish an error of judgment in this connexion. The optical illusion of telegraph-poles passing a moving train occurs because the observer is seated, and there is little to help him in conceiving that he is the moving body, and that the telegraph-poles are stationary.

Conception of the amount of, or the celerity of, movement depends on the change of position of the retinal picture, or on the extent of the muscular action exerted by the motor muscles necessary in order that the object may be kept in view. The more distant the object in motion, the smaller is the apparent movement, because the object appears to move through a much smaller angle in a given time. When the moving object is near, it moves through a much greater angle in a given time, or else a much greater muscular action is needed to keep it in view, and therefore the rate of progression seems more rapid.

When a very distant object is seen, it is difficult to judge whether it is stationary, moving away from, or coming towards, the observer. The image occupies the same position on the retina; no muscular action is needed to keep it in view, and for a certain length of time there is no appreciable change in the size of the retinal image. Only when the retinal image becomes appreciably smaller does the mind conceive that the body is moving away, or when the diminished distance causes an increase in the size of the retinal image can the observer be sure that the object is approaching.

The peripheral portions of the retina seem to be fairly sensitive to motion, and the motion of an object seen by indirect vision can be justly estimated, for actually the conception of motion is only the conception of successive changes of direction.

**Estimation of Distance.**—Estimation of the distance of an object viewed results from habit and education. If the object be very distant, but yet recognizable as a certain thing, as a cart or man, its distance is estimated from the extent of the retinal area occupied by the image—that is to say, its distance is judged from its apparent size; for knowing that at, say, 20 feet it would look of certain size, and as in its present position it looks so much smaller, habit teaches the observer to calculate that it is distant so many hundreds of yards.

When the conditions under which the object is viewed are unusual, estimation of distance is more difficult, which fact proves that something beyond comparison of the size of the present retinal image with the remembered size of a similar object, placed at a known distance, is needed in order to estimate distance

In Africa and other parts, owing to the dryness and the rarity of the atmosphere, distant objects are seen more distinctly, and then seem to be remarkably near to those who are unaccustomed to the climate. Distances are similarly deceptive to most people in foggy weather, nor can distances be accurately judged by the landsman at sea, nor by the townsman in the country. Estimation of range is absent in such unaccustomed conditions.

Children frequently mistake the distance at which an object is placed, and people newly supplied with glasses make mistakes as to the distance of an object seen even when quite close at hand. One frequently hears a person state that with his glasses the ground, etc., seem nearer to, or further from, him than they used to appear.

With objects within 20 feet, it is comparatively easy to estimate their distance, because people are more accustomed to seeing such objects, and the muscular action involved in converging and accommodating assists unconsciously in the estimation of short distances. The nearer the object is situated, the more convergence and accommodation are exerted; consequently, the greater the exertion of these functions, the shorter is the distance that the object is conceived to be. Thus, anything which causes either accommodation or convergence to be exerted also causes the object viewed to seem nearer; therefore prisms, bases out, which cause greater convergence effort, make an object viewed through them seem nearer, or an object viewed through concave sphericals also seems nearer owing to the extra accommodative effort made. Prisms, bases in, by preventing convergence, and convex sphericals by preventing accommodation, have the effect of causing objects viewed through them to seem further away. As red rays need more accommodation in order that they may be focussed at the retina, so an object coloured red seems nearer than other coloured objects at a similar distance; at least, this is so in emmetropia and hypermetropia, but myopes generally state the reverse. If there be diplopia, and a red glass be placed in front of the one eye, a candle-flame seen by the eye, before which this glass is placed, usually appears nearer than the other.

**Estimation of Form.**—Estimation of form is dependent on the mental recognition of the outline of the retinal image, and for flat surfaces this suffices. It almost entirely depends on central vision, as the peripheral portion of the retina is peculiarly insensitive to form.

The form of a solid body is similarly conceived, but there is, in addition, the mental appreciation of the shadows caused by it, and of the position of other bodies in relation to it, which aid considerably in the recognition of the form of solids; but the principal assistance is derived from the slightly different sense of perspective projected to the two eyes. If a square box be viewed by the two eyes simultaneously, the image of the outline of the front surface is received by each eye; and the images occupying corresponding positions on the two retinæ, the projected mental images are perfectly fused. But the right eye also receives an image of the right side of the body, while the left eye has an image of the left side. Each eye sees its corresponding side of the solid body which is not seen by the other eye.

**Estimation of Solidity.**—Thus binocular vision aids in estimating dimensions, and especially depth. If a small square box be held in front of the two eyes, and the one eye be occluded, the top and one side only can be seen. When the other eye is opened, the other side comes into view. It is almost impossible to accurately estimate depth without binocular vision. When one eye is closed, all things seem more or less without depth, and it is only our knowledge of the real form of objects, aided somewhat by shadows and the position of neighbouring objects, that prevents objects from being conceived quite flat in monocular vision. Objects which are situated beyond, say, 50 feet appear more or less flat, as then the oblique binocular view does not obtain.

Height and width can be estimated almost as well by a single eye as by two, but both are required for the estimation of depth. How binocular vision helps in the estimation of dimensions may be noted by viewing a near object first with one eye alone and then with both eyes.

The stereoscope illustrates binocular vision and conception of solidity. The picture to the right is of a view as seen by the right eye ; that to the left is of the same view as seen by the left eye. The images of similar points in the two pictures fall on corresponding points of each retina, the right-hand picture being seen by the right eye only, and the left by the left eye only. Thus a single mental impression is produced : it is that of a complete view, as seen by both eyes simultaneously.

**Estimation of Size.**—Estimation of the size of an object depends on the extent of the retinal area occupied by its image, and therefore on the number of rods and cones stimulated. The size of the retinal image is governed by the visual angle, formed at the nodal point by the secondary axial rays proceeding from the extremities of the object. The nearer the object is to the eye, the larger is this angle, and *vice versa*. Since secondary axial rays are presumed to pass straight through the nodal point, the angle formed behind the nodal point is the same as that formed in front; therefore, the larger the angle subtended by the object, the larger is the image formed on the retina. The apparent size of an object decreases directly as its distance from the eye. An object distant 1 yard subtends a certain-sized visual angle, which becomes half that size if the distance between the object and the eye be increased to 2 yards, while the angle is one-fourth the size if the distance becomes 4 yards. But habit enables the observer to estimate the true dimensions of an object independent of the visual angle, so that one does not imagine a thing to be half the size of some other object because the one is at double the distance of the other. The size of most things is known, and that of unknown objects is estimated by making an unconscious comparison between them and surrounding known objects.

**Aids to Estimation of Size.**—As convergence and accommodation aid in the estimation of distance, so they also unconsciously help in judgment as to size. If an unknown object project a certain-sized retinal image, and requires a certain effort of convergence and accommodation in order to be clearly seen, it is conceived to be of a certain dimension. The same retinal image, combined with a smaller muscular effort, would cause a conception of greater size, while a greater muscular effort would cause it to be conceived smaller. The more convergence and accommodation exerted in order to see an object, the smaller it seems to be, quite independent of its actual distance; the less of these functions exerted, the larger it seems. And since the effort of convergence mentally decreases size, an object seen through prisms, bases out, seems small, while through prisms, bases in, it seems large. In the first case more convergence is exerted, in the latter less. So, also, since accommodation decreases apparent size, convex lenses, placed close to the eyes, make an object appear larger, while concave lenses so placed make it smaller. In the former case less accommodation is exerted, in the latter more. Also a convex lens carries the nodal point forward, so that the retinal image is larger, and a concave lens carries it backward, so that the retinal image is smaller. Although the visual angle becomes smaller as the distance of an object is increased, yet the greater the distance of the object, the larger does the mind conceive it to be. For this reason, although the virtual image produced by the lens is further or nearer than the object itself, yet the mind conceives it at the real distance when a lens is used in ametropia. It may be noted that the estimations of distance and size are closely connected, and, indeed, it is difficult to separate them.

A white object against a black background appears larger, and a black object against a white background appears smaller, than it really is; this occurs because the various coloured rays comprised in white light are refracted to different extents, and, being dispersed, the outer rays form a kind of halo or fringe, which encroaches on the neighbouring black space, with the result that the black appears diminished and the white increased in size. This effect is exaggerated in myopia.

When seen by the two eyes, an object looks larger than if seen by one only; this is due, perhaps, to stereoscopic effect, and perhaps to the increased mental stimulus.

The estimation of the comparative size of various objects (comparison of size) depends on their images being formed successively on the macula by means of rapidly achieved movements of the eyeball, so that the different retinal areas stimulated by the images are mentally compared. The smallest difference in size that can be appreciated is about one-twentieth the size of the whole. Thus, if two objects be respectively 40 and 42 millimetres in length, they may be recognized as being of different size, but not so if 40 and 41 millimetres.

**The Size of the Retinal Image.**—The size of the retinal image of a given object varies in different eyes independent of the angle under which it is formed. It is governed by the distance between the nodal point and the retina—that is, on the distance which the axial rays have diverged from each other, on departure from the nodal point, when they reach the fundus. The farther these rays travel, the more they are separated, and therefore the greater is the retinal area occupied by the picture. This explains why to an eye, from which the lens has been removed, objects seem larger than to the fellow eye, for with the sight corrected by the lens the nodal point is shifted forward and the retinal image is thereby enlarged.

The retina is further from the nodal point in myopia, so that objects are seen large by a myope, while in hypermetropia the distance between the retina and the nodal point being shorter, a hypermetrope sees things small. To a myope, also, without correcting lenses objects seem large although blurred, owing to the extent of the retina occupied by the diffused images, and, in addition, to the distance between the nodal point and the retina. But the comparative size of objects—and it is by comparison one judges—is the same for all eyes. Every one must see an object that is 1 foot long as just one-third the length of one that is 1 yard long, whether he be a myope or a hypermetrope.

**The Effect of Lenses on the Retinal Image.**—As the retinal image is large in myopia, but diminished by concave lenses, that of the myope with his corrective glasses should be the same as that of an emmetrope. The further the glass is from the eye, the smaller and less defined does the image become, and in consequence the myope prefers to wear his glasses as near to the eyes as possible, because he thus increases the size of the retinal images. Also, as both the concave glasses themselves and the accommodative effort they engender cause objects to appear smaller, the myope usually prefers weaker glasses, or none at all, for close work. As the retinal image is small in hypermetropia, but is enlarged by convex lenses, that of the hypermetrope with his corrective glasses should also be the same as in emmetropia, and the further they are from the eye, the larger does the image become. Since the convex lenses themselves and the decreased accommodative effort needed with them may cause objects to appear large, the hypermetrope often prefers rather strong lenses for close work. It is supposed that in hypermetropia and myopia the retinal image of a distant object is of exactly the same size as in emmetropia when the corrective lenses are located in front of the eyes at the anterior focal distance of the emmetropic eye—that is, some 20 millimetres from the nodal point. The correcting lens merely shifts the image to a position nearer to, or further from, the nodal point without altering its size as formed by the eye, unaided by the lens, if no accommodation is exerted. The image thus formed by the unaided eye is the same as in emmetropia, but it is not at the retina; the lens then brings it to the retina without altering its size.

This would not be true, owing to the slightly different positions of the nodal points in myopes and hypermetropes, if the lens were not exactly at the anterior focal plane of the eye.

**Visual Separation of Adjacent Points.**—The number of rods and cones stimulated, governs the clearness with which an object is seen; so that when it is necessary to view an object with precision, the light from it must fall on the macula, where the retinal elements are most closely packed. When the image is formed at the macula, every point on the object can be distinguished if each point image occupies a cone and is separated from the adjacent points by a distance also equal to the diameter of a macular cone—namely, 0·002 millimetre.

**Calculation of the Retinal Image.**—The size of the retinal image of any object, bears the same relation to the size of the object itself, as the distance between the nodal point and the retina bears to the distance between the nodal point and the object.

In an emmetropic eye it is usually estimated that the nodal point is 15 millimetres from the retina, so that the proportion becomes as follows: As the distance of the object is to the size of the object, so is 15 millimetres to the size of the retinal image. Thus, to make the calculation, the size of the object must be multiplied by 15, and the quantity obtained divided by the distance of the object, care being taken that both the size and distance of the object be expressed in the same terms, the result being then in millimetres. The distance of the object from the eye is taken as being from the nodal point of the eye.

Suppose an object is situated 30 metres from the eye, and that it is 2 metres in diameter, then $\frac{2 \times 15}{30} = 1$ millimetre, which is the size of the retinal image. In making the calculation for a myopic or hypermetropic eye, a greater or smaller distance respectively must be taken for the distance between the nodal point and retina, with the result that the retinal image is larger in the first case and smaller in the second.

Thus, if the distance between the nodal point and the retina were only 13 millimetres, the retinal image would be $\frac{2 \times 13}{30} = 0{\cdot}886$ millimetre, instead of 1 millimetre.

**Visual Acuity.**—Visual acuity is the measure of the faculty of receiving images, transmitting them to the brain, and having them there interpreted. The visual acuity of an eye depends on the nervous functions of the optic nerve and retina, the transparency of the media, and the refractive power of the eye; also, apart from these conditions, it depends on the size of the retinal image, and, therefore, is governed by the distance between the nodal point and the retina.

**The Visual Angle.**—The visual acuity is determined by the size of the smallest retinal image which causes the mental perception of a definite object, or, as is more usual, it is determined by the smallest interval between two points or lines which will permit of these being seen as double and not fused into one, at a given distance. The image itself cannot be measured, but it can be calculated, since it is always proportional to the visual angle, and the smallest object whose details can be recognized by the average normal eye is one which subtends at the nodal point an angle of 5′; but a bright object, such as an illuminated wire, a minute speck of glistening metal, or a spider-web in a bright field, can be clearly seen when it subtends a very much smaller angle—one, perhaps, of only a fraction of a second. The brighter the light from the object, or the greater the contrast of the surrounding field, the smaller is the object that can be seen; thus, if white, a smaller object can be distinguished than if coloured. Also a long body can be better distinguished than a round one; a thin line can be seen when a point of similar diameter cannot.

An extremely minute point of light, such as a star, subtends an angle at the eye so small as to be without magnitude, and therefore, as such, invisible. What is seen is the light emitted from the star, and not the source of light itself. Its stellate appearance is due to imperfections of the eye, and especially of the crystalline. For a round body the smallest visual angle under the most favourable circumstances may be taken as $20''$ to $25''$, and for a line as $3''$ to $5''$, while that for a wire or spider-web in a bright field may be $\frac{1}{4}''$.

**The Determination of the Visual Acuity.**—In sight-testing, the visual acuity of the naked eye—that is, the eye unaided by lenses—must be learnt, as well as that of the eye when the error of refraction is corrected. Since the visual acuity of the eye is really its power of sight under the most favourable conditions, the latter is the real visual acuity, while the former is not; but both must be noted and recorded, so as to judge of the improvement that is made in the sight by the lenses applied.

The correction of any error of refraction is usually made by adapting such lenses as give the best sight possible; but no fixed rule can be given, since so many factors have to be considered.

**Snellen's Types.**—For the practical measurement of visual acuity in sight-testing, square block letters are employed; these are known as Snellen's types, after their inventor. They are made so that the diameter of the smallest part of each is just one-fifth of the diameter of the whole letter. An object is recognized by its smallest dimensions, so, also, one letter is distinguished from another by its smallest parts—viz., its limbs; and it is, therefore, the angle subtended at the nodal point by the limbs of the letter that determines whether that letter be distinguished as such or not.

Each letter, at the distance for which it is made, subtends an angle of 5′ at the nodal point, and each part of the letter subtends an angle of 1′, these being taken as the smallest angles under which the average normal eye can recognize them. The size of a cone at the macula is said to be about 0·002 millimetre. An angle of 1′ is subtended by an arc of 0·00435 millimetre, therefore an image formed under an angle of 1′ covers about two cones. The retinal image formed under an angle of 5′ is 0·022 millimetre in diameter when the distance between the nodal point and retina is 15 millimetres.

On a test chart, the letters range from very large (9 centimetres) to very small ones (4½ millimetres) respectively, for distances varying between 60 metres (200 feet) and 3 metres (10 feet), and each letter, and its various parts, at their respective distances subtend precisely the same angles. They are numbered according to the distance in metres or feet at which they subtend the angles mentioned.

**Expression of the Visual Acuity.**—The visual acuity, or the degree of vision, is represented by the equation $V. = \frac{d}{D}$, which means that the visual acuity V. is equal to $d$, the distance at which the test is made, divided by

D, the distance at which the smallest recognized letter ought to be seen. Or *d*, the distance at which the smallest legible letter is seen, divided by D, the distance at which that same letter would subtend an angle of 5′ at the nodal point, is the fraction which represents the existing acuteness of vision.

Suppose at 6 metres No. 12 is the smallest line of letters that is legible, then V. = 6/12; 6 being the distance at which the test is made, and 12 the number of the smallest legible letters; or, stated in other words, 6 metres is the distance at which No. 12 is legible, and 12 metres is the distance at which a No. 12 letter would subtend an angle at 5′ at the nodal point.

**Angular Size of Test Types.**—The exact length of each letter on the test card is equal to the arc of an angle of 5′ on a circle, the radius of which is the distance at which it should be seen if the eye were at the centre of the circle; the diameter of each arm of the letter being equal to an arc of 1′ on the same circle.

**Jaeger's Types.**—For near work a graduated series of ordinary small types, first arranged by Jaeger, is employed. Arbitrary numbers are given to them, No. 1 being the smallest. A person normally can read No. 1 at 10 inches. If sight is impaired, he can read, say, J. 3 or J. 4 at 10 inches.

**Normal Vision.**—If V. = 6/6, the vision is said to be normal, because at 6 metres one can distinguish that letter which represents the average degree of acute vision. Many people have a visual acuity that is better than 6/6—namely, $6/4\frac{1}{2}$, or even 6/3; they can distinguish objects under smaller angles than those of 5′ and 1′. This especially applies to young people, and it should be said that normal vision, up to a certain age, is that represented by $6/4\frac{1}{2}$. Lindsay Johnson has recorded cases among the natives of the

Upper Congo in which they could be proved to see three of Jupiter's moons with the naked eye, confirmed by the natives marking their relative positions on paper, which were found to agree with the positions as seen through a field-glass. These natives showed an acuity of 6/1·5, and even 6/1·2.

**Variation in Normal Vision.**—Visual acuity decreases with age, and 6/6, 6/9, and 6/12, might be regarded as normal vision for people at the ages of, say, respectively, sixty, seventy, and eighty. It further varies with the mode of life—whether country or city—and with the health of the individual, and to a great extent also with the nature of their occupations.

V. = 6/6 or 6/9 is regarded as normal vision where there is any considerable degree of ametropia which has been previously uncorrected; where the eye has not been in the habit of receiving clear images, the nervous function is dormant, and the mind fails to appreciate the sharp impressions received on the retina. In such cases it is generally found that the use of the proper corrective lenses improves the visual acuity in course of time.

**Acuity and Range of Vision.**—The acuteness of vision is almost the same as the sense of form, but is quite distinct from range of vision and the refractive power of the eye, in which the acuity may be good, but the range of vision restricted, as in myopia, high degrees of hypermetropia, or presbyopia. In these conditions a person may have very good sight, with or without glasses, but not be able to see so far or so near as he should.

**Acuity of Vision and Refractive Condition of Eye.**—The refractive power may be perfect, while the visual acuteness remains very low owing to amblyopia, opacities, etc It may be worth mentioning here that a small nebulous opacity of a portion of the cornea near the centre of the pupil, which is invisible unless illuminated by oblique light, reduces the acuity of vision enormously. Again, while there may be a high degree of refractive error, the visual acuity may be very good with glasses. And even without glasses, the fact that the sight is normal does not preclude the possibility of a considerable degree of hypermetropia or a low degree of astigmatism existing. In this case the deficiency in the refraction which would cause the degree of vision, without glasses, to be less than normal is overcome and corrected by accommodative effort. It must be remembered also that the visual acuity of an uncorrected myope of, say, 6/24, which can, by suitable glasses, be brought up to normal, is far more useful to the person than the same degree of acuity in a defective eye, whether it be due to an old ulcer of the cornea, opacities in the lens, or disease of the retina or optic nerve.

**Variation in Visual Acuity.**—The reason why the visual acuity is better in young than in old people is that the media of the eye in youth is exceedingly transparent, while in old age some of this transparency is lost. Moreover, the physiological activity of the retina and optic nerve is more acute in youth.

The visual acuity is reduced in the higher degrees of hypermetropia, because accompanying the undeveloped globe there is a certain absence of development in the retina and optic nerve. This is apart from the fact that in highly hypermetropic and astigmatic eyes, when glasses have not been worn, want of use has reduced the visual acuity.

In myopia, unless the defect be of so high a degree as to have caused fundus changes, the visual acuity is usually good. Very high visual acuity is also met with in the low degrees of hypermetropia—that is, in those cases where the defect is sufficiently low to be actively overcome by accommodation; then the eye is accustomed to sharp retinal images, and the sense of sight is kept correspondingly acute.

For other reasons, also, the visual acuity of some eyes is greater than that of others, just as some people have a more acute sense of hearing or feeling. A minute object, invisible to one person, might be recognized by another. It is generally greater for distant objects among savage races than among civilized people, and, as a rule, it is higher among the inhabitants of country districts than among those of cities. Training and habit account for these facts, because those who are in the habit of constantly using their eyes for distance naturally see remote objects better than those who are not so trained. On the other hand, the more highly civilized and educated races, or persons, generally have a better perceptive faculty for near objects than those who are not so much accustomed to using their eyes for close work.

Investigations on the acuteness of vision among people of different ages, classes, and races, go to show that a slight degree of hypermetropia, between 0·50 and 1 D., is the normal condition, and those persons who have the keenest sight are generally slightly hypermetropic. This degree of hypermetropia may be compared to the fine adjustment of a microscope. Every microscopist knows that he can resolve details better by moving the fine adjustment to and fro while the object is under observation than he could do if the focus were fixed and no alteration possible, although the focus might be correct. Now, in low hypermetropia the ciliary muscle allows of this slight play to and fro exactly as occurs with the microscope adjustment. Animals possessing keen sight, such as foxes, lynxes, lions, tigers, wolves, and jackals, are found by Lindsay Johnson to be slightly hypermetropic.

It has been proved that alcohol and certain drugs temporarily lower the visual acuity, as does fatigue both of the body generally and of the retina in particular. Thus, a microscopist, or astronomer, if he is anxious to resolve fine details, such as diatoms or double stars, will be much more likely to succeed if he closes his eyes for a few minutes before looking into the instrument. He will notice, further, that after intently gazing through the eye-piece for several minutes the very fine details will become blurred, but the sharpness can always be recovered by an interval of rest.

**The Visual Threshold.**—The lowest degree of visual acuity consists of the bare appreciation of the difference between light and darkness; one possessing less than this is quite blind. The lowest limit of light that can be observed by an eye is termed its *light threshold;* and this varies in different people. It can be represented for a normal eye by a piece of white paper feebly illuminated and placed about 200 metres away on a black background. It is said that the fovea is not the most sensitive part of the retina to very feeble luminants.

**Fechner's Law.**—According to Fechner, a difference of about 1 per cent. in two sources of illumination can just be appreciated. This holds good when the light is fairly bright. If, however, the light is very feeble or very strong, so small a difference cannot be noted. Thus, suppose some grey figures on a white background: no matter what amount of light may be received, the proportions absorbed and reflected by the two must be the same, and in a large extent of varying illumination the difference between them could be seen, but not so if the light be excessively low or excessively dazzling.

**Visual Fatigue.**—Visual fatigue results if a retinal impression is long continued. Under ordinary circumstances visual fatigue is not noticed, the retina being refreshed by the gaze being constantly turned from one object to another, so that a fresh impression is made on that part of the retina previously occupied by some other image; also some degree of rest is obtained for the retina by frequent blinking; the pupil being covered for the moment by the lid, the light is excluded, and no retinal impression is then received.

During sleep the retinal function is for some hours entirely inactive, the eye being in darkness. Sleep is thus the preserver and restorer of the retinal function; and this is shown by the weakened condition of the sight of those who, for some reason, have been deprived of the usual quantity of repose. The lids not being quite opaque, sleep is more refreshing when the room is in total darkness; the brighter the light, the less true rest do the eyes obtain.

It has been long known that green fatigues the eye least of all the colours; next blue and grey or neutral tint; then purple, yellow, orange, and red, the last two being the most fatiguing. Card and billiard tables are therefore covered with green cloth and Venetian blinds painted green. In nature green, grey or neutral tint, and blue are the prevailing colours, while red and orange only occur in patches or at sunset; hence the eye is able to bear those colours best which are the most widely distributed in nature.

When a person passes from bright sunlight into a dull light, nothing is clearly distinguished for a short time; the inability to see under such circumstances may be so great as to cause a temporary blindness. This is partly caused by retinal fatigue rendering clear vision for the time impossible in a feeble light, and partly by other causes already referred to on page 20.

**Demonstration of Retinal Fatigue.**—Retinal fatigue can be demonstrated by the following simple experiment: Cover half a sheet of white paper with black velvet, and look steadily at both. Then one part of the retina will be strongly stimulated, while the other part is at rest; as soon as the eye begins to get tired, remove the velvet, and the part of the paper last uncovered will appear very vivid and bright, while the rest is dull or grey by contrast.

Another experiment, which shows how the functional activity of the retina is temporarily diminished by continued use, is to put in front of one eye a dark smoked glass for some minutes, when, on its removal, the difference in the intensity of the impressions received by that and by the other eye is quite marked.

**After-Images.**—The altered action of the retina under fatigue, due to over-stimulation, produces '*after-images*.' In the experiment previously mentioned the dark grey is the after-image of the original bright white, and the bright white is the after-image of the original black. If a person looks at a white spot on a black background until the eyes are fatigued, and then turns his eyes to a sheet of grey paper, he will very shortly see a dark spot on a white background, this being the after-image of the original white spot on a black background.

Saturation of the retina by a certain colour produces an after-image of its complementary colour; if a red spot is looked at, the after-image is blue-green; if the spot is blue-green, the after-image is red.

After-images consisting of colours complementary to the original are *negative*, and due to retinal exhaustion. Such an after-image is, however, not always of the complementary colour, as it varies somewhat with the background. If one looks fixedly at a bright light, such as the filaments of a glow-lamp, and then shuts his eyes, an after-image which is the same colour as the original will be seen. This is a *positive* image, caused by the continuation of the original retinal stimulation, and it changes through various colours before it disappears. If during its continuance the eyes be turned to a white surface, a black negative after-image is seen. Looking at the sun with the naked eye, or through an unprotected telescope, is very dangerous, since it may produce an after-image, due to a change in the macula, which may last for months, or even cause a permanent partial blindness.

## CHAPTER III

## COLOUR VISION AND BLINDNESS

**Composition of Solar Light.**—Solar light is white, and can be decomposed into a spectrum consisting of the colours red, orange, yellow, green, blue, indigo, and violet; but some authorities omit the indigo and consider the spectrum to consist of six colours; and some even omit the yellow, which colour, indeed, occupies but a small space in the spectrum. Of these, red, green, and violet are termed *primaries*, because they cannot be produced by mixing other colours; the others are termed *secondaries*, because they can be so produced. Thus red and green in varying proportions produce orange or yellow, while green and violet produce blue or indigo. A mixture of all the spectral colours produces white light, which is regarded as the standard, because it is that to which we are most used; and a body or light which appears white is often said to be colourless, as distinct from that which exhibits a characteristic colour. So also black is colourless, and it may be briefly defined as absence of light.

But all the spectral colours are not required to produce white light, and the term *complementary colour* is applied to that which produces white light when mixed with another colour.

**Complementary Colours.**—The following are complementary colours :

Red is complementary to bluish-green.
Orange ,, ,, ,, greenish-blue.
Yellow ,, ,, ,, blue.
Green-yellow ,, ,, ,, violet.
Green ,, ,, ,, purple.

Purple is not in the spectrum, and is produced by mixing red and violet.

**Brightness of Colours.**—In the spectrum the central colours—yellow and green—are the brightest. In a prismatic spectrum the red end appears brighter than the blue, because it is more crowded together, and for the same reason the blue end seems to occupy a relatively larger area than the red ; but this is not the case with the spectrum produced by diffraction.

**The Sensitiveness of the Eye to Colours.**—The human eye seems to be more sensitive to yellow, whether as spectrum or reflected light ; it is the colour which appears brightest in feeble luminosity, and green is the next. Yellow also is said to be the soonest appreciated as a colour. But generally, as a characteristic and recognized colour, red is the most persistent when viewed in reduced light, or at increased distances, or under reduced area of exposure. It penetrates haze, fog, or smoked glass more than any other colour, while the other colours follow, more or less, in the order of the spectrum.

It is not easy to compare the intensities of coloured lights, nor to decide when a colour appears or disappears, and a distinction must be made between the recognition, under extreme circumstances, of variously coloured lights or bodies, and of their actual colours. Moreover, in any experiments, much depends on the conditions under which they are made, on the intensity of the colours compared, and on the person making the comparisons; for some eyes, without being colour blind, are more sensitive to some colours than to others.

**Colours in Pigments.**—The primary colours of pigments, or colouring matter, are not the same as those of light: being red, yellow, and blue. The complementary colours of pigments, and the effects of mixing various colours, differ also from those of light. Thus blue and yellow pigments produce green, while the same colours in the spectrum produce white light when mixed. The *tone*, or *hue*, is that quality of a colour which distinguishes it from other colours, as red, green, etc. Its *brightness* or *intensity* is that quality which depends on the amount of light: a colour is dark or light according to the quantity of light proceeding from the body. Its *saturation* or *purity* is that quality which depends on its freedom from admixture of white (or black): yellow diluted with white becomes straw, diluted with black it becomes brown.

**The Colours of Objects.**—An object appears of a certain colour because it absorbs rays of certain wave-lengths and reflects others, the latter corresponding to the colour of the object. Thus, a red object absorbs all the colours of the spectrum except red, which it reflects; a black object reflects practically no light; a white one reflects all the light it receives. But a red object must receive red light, or it cannot reflect it; consequently, if the red be excluded from the light, a red object appears black. A white object, seen by coloured light, is really coloured, although it would be mentally accepted as white. If the light is very feeble all bodies appear equally black. A black body is equally black in all lights.

Consequently, *artificial colour blindness* can be produced by excluding from the eye a certain part of the spectrum, for what the eye does not receive it cannot appreciate.

The true colour of a body is that which it exhibits in white light; its colour is modified in artificial light. Therefore, any coloured body can appear changed in colour by illuminating it with coloured light, or viewing it through coloured glasses. Using the complementary colour produces blackness, while the same colour in the glass or light causes such a viewed coloured object to appear white. On looking at a red object on a green ground through a piece of red glass, one sees a white object on a black ground. A red object on a white ground, seen through a red glass, appears nearly white, while the white background appears pink, so that the two can be barely distinguished.

**Perception of Black.**—Black may be considered a colour in a certain sense, for if an object reflected no light at all, it would be invisible, whereas we find this is not the case. According to Hering, black causes a distinct sensation, the complement of, or opposing sensation to, white.

Also, the visual sensation one experiences in a totally dark room is quite different from that of an image which is projected on to the blind spot of Mariotte (optic nerve end). In the former case, one undoubtedly perceives the darkness; in the latter case, one does not perceive anything, and, therefore, one is unconscious of the gap in the visual field.

**Purity of Colours.**—An absolutely black body does not exist in nature; even lamp-black and soot reflect some light, which perhaps renders them visible, and allows of their form and solidity being recognized. Similarly, there is no object which reflects all the light it receives; pure, fresh snow, which is the whitest of all bodies, absorbs some 30 per cent. of the light it receives. Grey is a mixture of white and black. The colours of pigments are never quite pure, and it is extremely difficult, if not impossible, to match a spectrum colour exactly with a pigment.

**Shadows.**—Shadows cast by coloured light appear to be of the complementary colour to that of the light. The shadow of white light appears grey or black, because less light, or none at all, is reflected from it. When the illumination of the ground is coloured, the light received from it may be considered as the zero of the scale of colour sensation, and the darkened space then appears complementary to that light. If two shadows are cast—the one by a red light and the other by white sunlight—the shadow resulting from the red light appears greenish as the result of contrast with the other shadow, which on receiving red light appears tinged with that colour.

**The Mental Standard of White.**—Saturation of the retina by any colour causes the standard of colour to be displaced; the mind accepts that colour as the zero, just as white is considered to be the zero under ordinary circumstances. Thus, if on a coloured sheet a very small piece of white be placed, the white appears of the complementary colour to that of the sheet. If the sheet be red, this appears more nearly white, and the white then appears bluish-green. It would appear that one considers as white that which reflects most light, and generally that a white body is white whether seen by sunlight or coloured artificial light, although actually the appearance would be quite different if a comparison were possible. We do not, in reddish gaslight, take white to be other than white, for our standard is then altered for the coloured light. Sunlight seen through coloured glasses appears to differ so little from white that it is difficult to state what colour it does actually appear, and the same occurs if sunlight is focussed by a coloured glass.

**Theory of Colour Vision.**—The usually accepted interpretation of colour vision is that known as the Young-Helmholtz theory. According to these scientists, the retina possesses three sets of elements, each one responding to one of the three primary colours—namely, red, green, and violet. It is supposed that red light stimulates the *red* retinal element mainly, but also to a lesser extent the green, and to a still lesser extent the violet. Similarly, the *violet* retinal elements are mainly stimulated by violet light, but this also slightly stimulates the *green* and *red* retinal elements. So also the *green* elements are mainly, and the *red* and *violet* elements slightly, excited by green light.

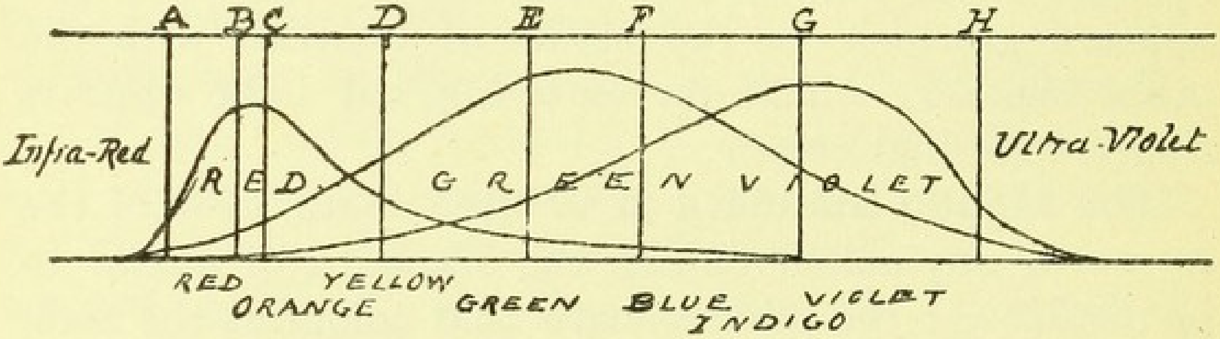

Fig. 12.—**Diagram showing the Chromatic Curves of the Three Primary Colours as seen by the Eye.**

The letters above refer to Fraunhofer's lines. The height of the curve corresponds to the intensity ; the length shows the part of the spectrum covered.

Stimulation of all three elements produces the sensation of white; stimulation of one produces vision of a primary colour; and stimulation of two (or the three) to varying extents causes sensation of different secondary or tertiary colours.

Colour blindness—that is, inability to appreciate one of the primary colours—results if one of the retinal colour elements be absent or inactive. Thus it is thought that if one has no *red* elements, red light, on entering the eye, would stimulate the *green* elements slightly, and violet still less, causing a sensation similar to that of feeble green light. Probably feeble red light would not be appreciated at all by one deficient of the *red* retinal elements.

Hering's theory is based on the supposition that there are three pairs of sensations—viz., black and white, red and green, blue and yellow. The sensation of white results from decomposition of the black-white substance, while darkness results from the regeneration of this substance. Red or green results from decomposition and regeneration of the red-green substance, and similarly blue and yellow with the blue-yellow substance. Absence of the colour-producing substance causes colour blindness.

There are other theories of colour vision, and it is possible that while some of the retinal elements (namely, the cones) are stimulated equally by all colours, others (the rods) are stimulated by light of certain frequencies only, and not by others; or we may suppose that the retina contains properties in the rods or cones whose length, or other conditions, adapt them especially each for stimulation by a certain part of the spectrum. Moreover, there are reasons for believing that the brain contains a centre for colour separate from that which exists for form, and possibly a third centre exists for the perception of light alone.

**Colour Blindness.**—Colour blindness may be of so slight a degree as to amount to nothing more than a weak sense of colour. The history of man, as embodied in the literature of the ancients, would seem to point to the fact that the sense of colour is a progressive one. Thus, the colours mentioned in the Books of the Old Testament and by ancient writers are few in number, so that the perception of different colours and shades of colour may have grown along with the developments of painting and the fine arts. To-day, among ribbon and wool dyers, and especially milliners, the sense of colour is highly developed, as evinced by the power of sorting out the thousand shades and hues seen in ribbons and dress materials. It may, then, be reasonable to suppose that colour blindness is a reversion to an ancestral state, when the colour sense was in its infancy; and from inability to distinguish between two closely allied colours, or a slight shortening of one or the other end of the normal spectrum, down to total colour blindness, every degree of deficiency may be found.

The red end of the spectrum may be entirely deficient, so that a person may fail entirely to distinguish between red and green. This condition is termed "*Daltonism*," from John Dalton, who suffered from it and was the first to describe it. Again, there may be dark bands in the spectrum along which the sense of colour is entirely wanting. Total colour blindness is a rare condition in which no colours at all are appreciated, and all objects appear black, or white, or grey, or at least of one uniform tint.

**Classification of Colour Blindness.**—A classification of persons according to their colour vision, or according to the colours they seem to appreciate and the errors they make, may be made thus:

(*a*) Those who only see one colour, or who confuse all colours.

(*b*) Those who see two colours, or who confuse all colours between red and yellow-green, or those between blue-green and violet.

(*c*) Those who see three colours, or who confuse red, orange, and yellow, also green with purple and grey, and confuse blue-green, blue, and violet.

(*d*) Those who see four colours, or who confuse adjacent colours, such as red and orange or blue and violet.

(*e*) Those who see five colours, or who confuse closely allied colours such as orange-yellow and yellow-orange, or blue-green and green-blue.

To complete the series we may add—

(*f*) Those who recognize six colours, and therefore have what is commonly regarded as normal colour vision.

**Causes and Classes of Colour Blindness.**—Colour blindness is, as a rule, congenital, and it is probably hereditary. Also an acquired form of colour blindness results from jaundice, and from drugs such as santonin. Tobacco causes colour blindness for red and green, over and around the macular area, which is accompanied by more or less amblyopia; this central colour blindness is characteristic of tobacco amblyopia. Surgeons, however, differ as to whether tobacco alone can cause it—*i.e.*, without indulgence in alcoholic stimulants. In some people, in addition to causing central colour blindness, tobacco causes a partial paralysis of accommodation, often confined to one eye.

Colour blindness is usually binocular, but cases have been recorded of a monocular affection, especially in the acquired form. Temporary colour blindness can be caused by excessive stimulation of the retina by any one colour, as is found when after-images of colours are seen. An after-image is of the colour complementary to the original colour, because only those retinal elements which can appreciate the complementary colour are capable of stimulation; the others being exhausted temporarily by the previous saturation, are therefore incapable of action.

Artificial colour blindness can be caused by the employment of coloured glasses or monochromatic light, as previously stated; and it is instructive, if one wishes to understand something of the errors made by the colour blind, to view mixed coloured wools in monochromatic light, or through a pair of coloured glasses, especially spectrum blue glasses, and attempt, under these conditions, to match the test-skeins.

## Tests for Colour Blindness.

It must be remembered that in testing colour blindness one has to deal with those who are often ignorant of their defect, or who, if not, are unwilling to acknowledge it.

**The Wool Test.**—The usual method of testing is by means of the Holmgren wools, which consists of matching certain test-skeins from a group of other skeins comprising all colours and shades. The test skeins are: (1) pale pure green; (2) purple (or rose) containing approximately equal proportions of red and blue; (3) bright red.

Nos. 1 and 2 are complements of each other. No. 1 is of all the spectrum colours the nearest approach to white, or, rather, grey, while purple is not contained in the spectrum at all.

In the test the light-green test-skein is given to the subject, and the confusion wools are mixed and placed in a heap. The subject is asked to select from the heap such skeins as resemble the test-skein. A person having normal vision will select only greens; one having feeble colour vision will select other colours, such as greys and fawns; one having true colour blindness will select markedly different colours as well as greys, etc., such as light pinks, yellows, or blues.

The confusion made with No. 1 test-skein determines colour blindness, but not its nature.

In the second stage of the test, the purple skein is presented, and the confusion wools being again mixed, the subject is asked to match No. 2 test-skein. One who has normal or feeble colour vision will make no mistakes. One having partial colour blindness will select deep purples. One having red blindness will select blues and violets, since he appreciates the blue of the test-skein, but not the red. One having blue blindness will select reds and oranges, since he appreciates the red of the test-skein, while the blue does not influence his retinæ. The green-blind individual selects greys and greens, because for him the combination of red and blue contains all the colours of the visible spectrum. Purple, therefore, appears to him the same as grey, as does also green, for which colour he is blind. It may be added that blue blindness is extremely rare.

The final test is made with the bright red test-skein, and serves rather to illustrate the errors of those who are colour blind. The red-blind person may select darker shades, and the green-blind lighter shades, both in any other colours, as green, blue, etc., besides reds. This occurs because to a red-blind person a red object does not appear black, nor does a green object so appear to one who is green-blind. Such objects to them appear grey, because colours are never pure, but give off other rays besides the red or green respectively; also all the retinal elements are, to a certain extent, stimulated by all light.

**Other Tests.**—Some of those who are well qualified to judge claim that wool-matching is a very unsatisfactory test, since colour-blind persons can readily be coached up to match correctly almost any shades of wools. In consequence of this, many other tests have been designed, such as coloured glasses, intensity test plates or letters, coloured powders or papers, shadows cast by means of coloured lights, contrasting colours contained in revolving discs, lanterns, flags, etc.; but of all methods, the spectroscope and the polariscope are, undoubtedly, the most delicate from a scientific point of view.

It may be mentioned that the Board of Trade examination for sailors mainly consists of coloured glass discs in front of a lantern, which are obscured by the intervention of ground-glass and neutral tint discs.

**Distinguishing Colours by the Colour Blind.**—A person who is red or green blind may often be able to distinguish between these two colours by the difference in their intensities. Thus a red-blind person viewing a red and a green light of equal intensities would see the green light very much brighter than the other, owing to his failing to appreciate much of that proceeding from the red light; only if the green light happens to be viewed in a fog, or under circumstances which reduce its intensity, it might appear then the same as the red.

Thus, while it is quite impossible to cure colour blindness, it is possible to enable a colour-blind person to distinguish one colour from another by means of the use of coloured glasses.

# CHAPTER IV

## DIOPTRICS AND CONSTANTS OF THE EYE

**The Emmetropic Eye.**—The average emmetropic eye is supposed to be of certain length and size, to have surfaces of certain curvature and media of certain refractive indices, as given in the following paragraphs. This average emmetropic eye is termed the *Schematic Eye ;* while if it is, for the sake of simplicity, reduced to a single refracting body, as any compound refracting system may be, it is termed the *Reduced Eye.*

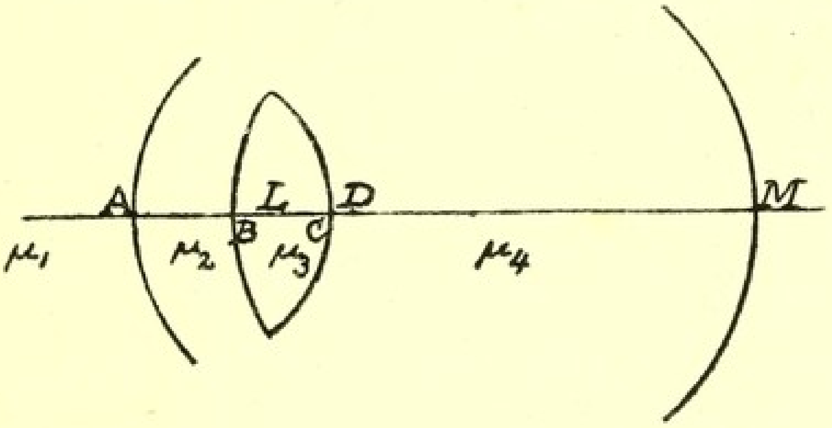

Fig. 13.—**The Refracting Surfaces and Media of the Eye.**

**The Optical System of the Eye.**—The eye as an optical system consists of three refracting surfaces—A, B, and C—combined with a concave mirror M. The cardinal points of the eye may be found by calculation or by construction, and in the calculation the two back refracting surfaces are considered as forming a double convex lens L, while the concave mirror does not enter into the calculation, since the principal focus of the three refracting media lies at its surface.

To calculate the cardinal points of the *schematic* eye, it is necessary—

1st. To find these points for the first system—the cornea A.

2nd. To find these points for the second system—the lens L.

3rd. To combine the two systems A and L, as illustrated in Fig. 13.

Suppose the cornea A (Fig. 13) to have a radius $r_1$ of 8 mm., the front surface of the crystalline B a radius $r_2$ of 10 mm., and the back surface C a radius $r_3$ of 6 mm. The distance AB from the cornea to the crystalline is 3·6 mm.; BC $= t$, the thickness of the crystalline, is also 3·6 mm. Consider $\mu_1$. $\mu_2$, $\mu_3$, $\mu_4$, the four media through which the light passes, to have the following refractive indices: $\mu_1 = 1$, $\mu_2 = 1{\cdot}333$, $\mu_3 = 1{\cdot}450$, and $\mu_4 = 1{\cdot}333$.

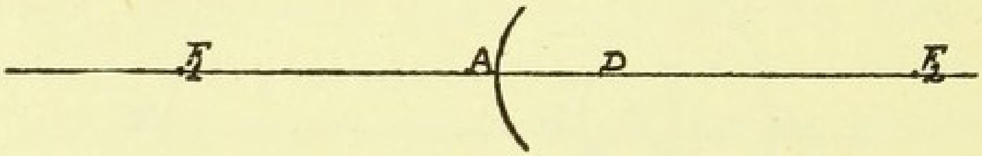

Fig. 14.—**The Optical System of the Cornea.**

**The Optics of the Cornea.**—The anterior focal length, $F_A$, of the cornea A (Fig. 14) is represented by the formula

$$\frac{r_1\,\mu_1}{\mu_2 - \mu_1},\ \text{or,}\ F_A = \frac{8 \times 1}{1{\cdot}333 - 1} = 24\ \text{mm.};$$

and the posterior focal length, $F_B$, is expressed by

$$\frac{r \times \mu_2}{\mu_2 - \mu_1},\ \text{or,}\ F_B = \frac{8 \times 1{\cdot}333}{1{\cdot}333 - 1} = 32\ \text{mm.}$$

$$\text{The ratio } \frac{24}{32} = \frac{1}{1{\cdot}333} = \frac{3}{4} = \frac{\mu_1}{\mu_2}$$

and $32 - 24 = 8 =$ the radius of curvature.

The principal point is at A; the nodal point is at D, the centre of curvature, which is 8 mm. behind A.

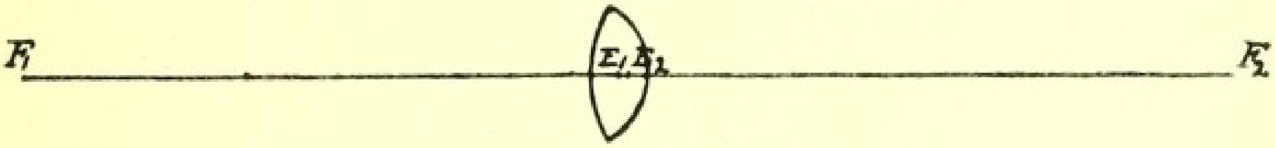

Fig. 15.—**The Optical System of the Crystalline.**

**The Optics of the Crystalline.**—Being given a refractive index of 1,450, and having similar media on both sides of $\mu = 1{\cdot}333$, the relative index $\mu_r$ of the crystalline lens is expressed by

$$\frac{\mu_3}{\mu_2}, \text{ or, } \mu_r = \frac{1{\cdot}450}{1{\cdot}333} = 1{\cdot}087.$$

The anterior and posterior focal lengths are equal, and may be represented by $F_C$, and the thickness of the lens by $t$.

$$\text{Then } F_C = \frac{r_2\, r_3}{(\mu_r - 1)\left(r_2 + r_3 - t\,\dfrac{\mu_r - 1}{\mu_r}\right)} = \frac{r_2\, r_3}{(\mu_r - 1)\,\text{N}};$$

$$\text{or, } F_C = \frac{10 \times 6}{(1{\cdot}087 - 1) \times \left(10 + 6 - 3{\cdot}6 \times \dfrac{1{\cdot}087 - 1}{1{\cdot}087}\right)}$$

$$= \frac{60}{0{\cdot}087 \times 15{\cdot}72} = \frac{60}{1{\cdot}368} = 43{\cdot}86.$$

In this case the anterior is equal to the posterior focal length because the first and last media are of similar refractive indices—that is, $\mu_2 = \mu_4$; also, the principal points coincide with the nodal points, and so may be termed the equivalent points.

The distance of the first equivalent point, $E_1$, from the front surface, B, is found by

$$\frac{r_2\, t}{\mu_r\, N}, \text{ or, } E_1 = \frac{10 \times 3{\cdot}6}{1{\cdot}087 \times 15{\cdot}72} = \frac{36}{17{\cdot}06} = 2{\cdot}1 \text{ mm.}$$

The distance of the second equivalent point, $E_2$, from the back surface, C, is found by

$$\frac{r_3\, t}{\mu_r\, N}; \text{ or, } E_2 = \frac{6 \times 3{\cdot}6}{1{\cdot}087 \times 15{\cdot}72} = \frac{21{\cdot}6}{17{\cdot}06} = 1{\cdot}26 \text{ mm.}$$

The distance $E_1\, E_2 = T_C$, and

$$T_C = 3{\cdot}6 - (2{\cdot}1 + 1{\cdot}26) = 0{\cdot}24 \text{ mm.}$$

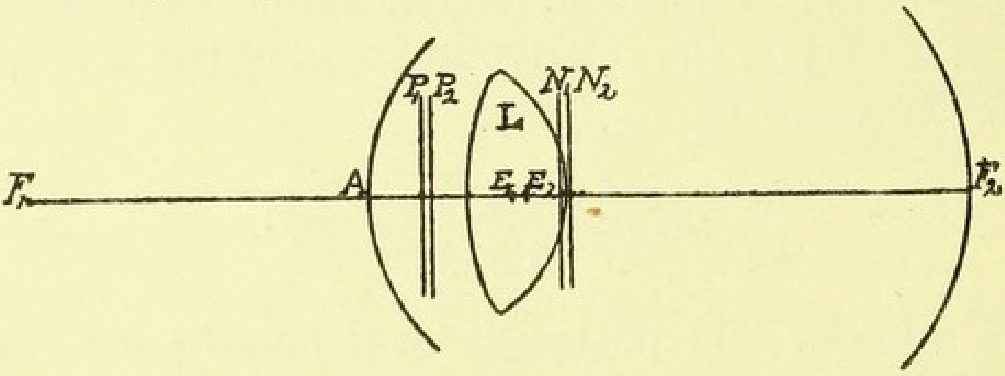

Fig. 16.—**The Optical System of the Eye.**

**The Optics of the Eye.**—Combining the two systems A and L (as in Fig. 16), the distance between the adjacent principal points of A and L = $d$, and $d = A\, E_1 = 3{\cdot}6 + 2{\cdot}1 = 5{\cdot}7$ mm.

The anterior focal length, $F_1$, of the eye is then obtained from

$$\frac{F_A\, F_C}{F_B + F_C - d};$$

$$\text{or, } F_1 = \frac{24 \times 43{\cdot}86}{32 + 43{\cdot}86 - 5{\cdot}7} = \frac{1052{\cdot}64}{70{\cdot}16} = 15 \text{ mm.};$$

and the posterior focal distance is $\dfrac{F_B\, F_C}{F_B + F_C - d}$;

$$\text{or, } F_2 = \frac{32 \times 43{\cdot}86}{32 + 43{\cdot}86 - 5{\cdot}7} = \frac{1403{\cdot}52}{70{\cdot}16} = 20 \text{ mm.}$$

The ratio $\frac{15}{20} = \frac{1}{1\cdot333} = \frac{3}{4} = \frac{\mu_1}{\mu_4}$,
and $20 - 15 = 5 =$ the radius of curvature of the ideal refracting surface.

The distance of the first principal point, $P_1$, behind the cornea is

$$\frac{F_A\,d}{F_B + F_C - d}\text{; or, } P_1 = \frac{24 \times 5\cdot7}{32 + 43\cdot86 - 5\cdot7} = \frac{136\cdot8}{70\cdot16} = 1\cdot95 \text{ mm.}$$

The distance of the second principal point, $P_2$, in front of $E_2$, the second equivalent point of the crystalline, is

$$\frac{F_C\,d}{F_B + F_C - d};$$

$$\text{or, } P_2 = \frac{43\cdot86 \times 5\cdot7}{32 + 43\cdot86 - 5\cdot7} = \frac{250}{70\cdot16} = 3\cdot56 \text{ mm.}$$

Then $P_2$ lies behind the cornea at a distance of $A\,P_2$, which is $3\cdot6 + 3\cdot6 - (1\cdot26 + 3\cdot56) = 2\cdot38$ mm.

The distance T between the principal points is

$$T = P_2 - P_1 = 2\cdot38 - 1\cdot95 = 0\cdot43 \text{ mm.}$$

The nodal points, $N_1$ and $N_2$, are located thus:

Since $P_1\,F_1 = N_2\,F_2 = 15$ mm.,
and $P_2\,F_2 = N_1\,F_1 = 20$ mm.,
then $P_1\,N_1$ or $P_2\,N_2 = 20 - 15$ mm. $= 5$ mm.;
so $A\,N_1 = 1\cdot95 + 5 = 6\cdot95$ mm.,
and $A\,N_2 = 2\cdot38 + 5 = 7\cdot38$ mm.
then also $N_2 - N_1 = 7\cdot38 - 6\cdot95 = 0\cdot43$ mm.

### Tabulated Positions of the Cardinal Points.

Distance from Cornea in mm.

$F_1 = 13\cdot05$ $P_1 = 1\cdot95$ $N_1 = 6\cdot95$
$F_2 = 22\cdot38$ $P_2 = 2\cdot38$ $N_2 = 7\cdot38$

$F_1$ is 15 mm. from $P_1$ and 20 mm. from $N_1$
$F_2$ is 20 mm. from $P_2$ and 15 mm. from $N_2$

The interval between two principal points is so small that they can be regarded as one, P; so also can the two nodal points be taken as one, N.

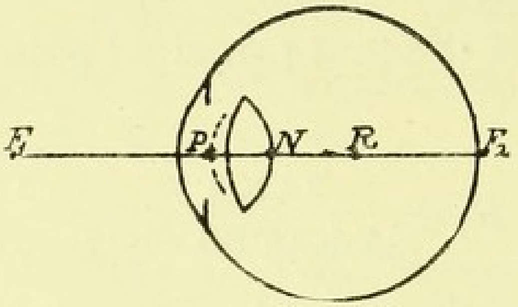

Fig. 17.—**The Schematic Eye.** (Natural size.)

## Simplified Cardinal Points.

The distance of $F_1$ from P = 15 mm.
,, ,, $F_2$ from P = 20 mm.
,, ,, P from the cornea = 2·2 mm.
,, ,, N from the cornea = 7·2 mm.
,, ,, N from P = 5 mm.
The length of the optic axis = 22·2 mm.

**The Significance of the Principal and Nodal Points.**—The principal point marks on the optic axis, the ideal refracting surface, or the imaginary plane on which the refraction of the three surfaces of the eye is presumed to be united, and from which the focal distances are measured. The nodal point is that at which the secondary axes cut the principal axis—that is to say, those rays which pass through the nodal point are not deviated, and the angle which an object subtends at the nodal point governs the size of the retinal image.

**The Cardinal Points.**—The two focal points, the two principal points, and the two nodal points constitute the six cardinal points of the eye.

## Table of the Constants of the Eye.

**The Cornea**:

| | | |
|---|---|---|
| 1. | Thickness of the cornea ... ... | 1 mm. |
| 2. | Index of refraction of the cornea ... | 1·333 mm. |
| 3. | Radius of curvature of the cornea ... | 8 mm. |
| 4. | Anterior focal length of the cornea | 24 mm. |
| 5. | Posterior focal length of the cornea | 32 mm. |
| 6. | Principal point of the cornea is at the cornea. | |
| 7. | Nodal point of the cornea is behind it ... ... ... ... | 8 mm. |
| 8. | Refractive power of the cornea for emergent light ... ... | 42 D. |
| 9. | Refractive power of the cornea for entering light ... ... | 31 D. |

**The Humours**:

| | | |
|---|---|---|
| 10. | Index of refraction of the aqueous and vitreous ... ... ... | 1·333 mm. |
| 11. | Thickness of the crystalline ... | 3·6 mm. |
| 12. | Index of refraction of the crystalline (taken as) ... ... ... | 1·45 mm. |
| 13. | Relative index of refraction of the crystalline *in situ* $\frac{1\cdot450}{1\cdot333}$ = | 1·089 mm. |
| 14. | Anterior radius of the crystalline ... | 10 mm. |
| 15. | Posterior radius of the crystalline ... | 6 mm. |
| 16. | Anterior and posterior focal lengths of the crystalline ... ... | 43·86 mm. |
| 17. | First equivalent point of the crystalline ... ... ... | 2·1 mm. |
| 18. | Second equivalent point of the crystalline ... ... ... | 1·26 mm. |
| 19. | Refractive power of crystalline *in situ* ... ... ... ... | 23 D. |

**The Eye:**

| | | |
|---|---|---|
| 20. | Anterior focal length of the eye ... | 15 mm. |
| 21. | Posterior focal length of the eye ... | 20 mm. |
| 22. | Position of the principal point behind the cornea ... ... | 2·2 mm. |
| 23. | Position of the nodal point behind the cornea ... ... ... | 7·2 mm. |
| 24. | Refractive power of the eye for entering light ... ... | 50 D. |
| 25. | Refractive power of the eye for emergent light ... ... | 66 D. |
| 26. | Length of the optic axis ... ... | 22·2 mm. |
| 27. | Distance between cornea and front of crystalline ... ... | 3·6 mm. |
| 28. | Distance between cornea and back of crystalline ... ... | 7·2 mm. |
| 29. | Distance between cornea and centre of rotation, R. ... ... | 13·2 mm. |
| 30. | Distance between nodal point and centre of rotation, R. ... ... | 6·0 mm. |
| 31. | Distance between retina and centre of rotation ... ... ... | 9·0 mm. |

**Effect of Altered Refractive Indices and Conditions.**—If the crystalline lens were in air its focal length would be about 8 mm. If the aqueous were absent, and the two surfaces of the cornea were presumed to neutralize each other, the posterior focal length of the crystalline would be about 20 mm., and the anterior about 16 mm. Thus, removal of the cornea and aqueous would not materially affect the refractive power of the eye, only the principal and nodal points would lie much nearer to the retina, and the eye would be hypermetropic to about the same extent as when the crystalline is removed—namely, some 10 D. If the eye is in water the effect of the cornea and aqueous is lost, and the eye is highly hypermetropic to the extent of about 26 D. If, however, a diver uses a helmet, having flat glasses in front of the eyes, he sees the same as if he were in air and looking into a tank of water.

Increase of the refractive index of the cornea, cortex of the lens, or of the vitreous, would cause the eye to have less refractive power, or would lengthen the focal length, while an increase of $\mu$ of the aqueous or of the nucleus of the lens would increase the refractive power or shorten the focal length. The first would cause hypermetropia and the second myopia. A decrease in the $\mu$'s would cause respectively the opposite conditions.

Advancement of the crystalline would cause increase of refractivity; its retirement towards the retina would have a contrary effect.

## The Reduced Eye.

**Reason for the Reduced Eye.**—For convenience in calculations, the eye may be reduced to a single refracting body, from which the crystalline is presumed to be absent, so that there is only one refracting surface and medium, the cornea, which is at the ideal refracting plane (*i.e.*, the principal plane) of the schematic eye, and it is given a radius of curvature suitably corresponding to this position.

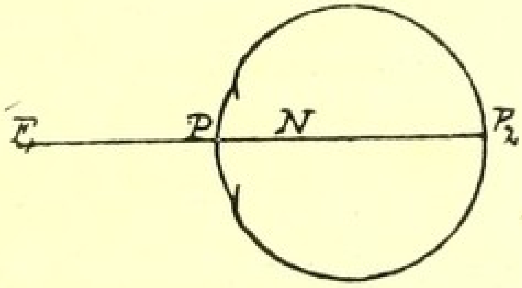

Fig. 18.—**The Reduced Eye.** (Natural size.)

**Constants and Calculations.**

The refractive index is 1·333.

The radius of curvature is 5 mm.

The principal point, P, is at the cornea.

The nodal point, N, is at the centre of curvature, 5 mm. behind the cornea.

$$\text{Then, } F_1 = \frac{5}{1\cdot333-1} = 15 \text{ mm. in front of P,}$$

$$\text{or 20 mm. in front of N.}$$

$$F_2 = \frac{5 \times 1\cdot333}{1\cdot333-1} = 20 \text{ mm. behind P,}$$

$$\text{or 15 mm. behind N.}$$

Thus the focal lengths and the distance P N are the same as in the schematic eye.

The two focal points with the single principal and nodal points constitute the four cardinal points of the reduced eye.

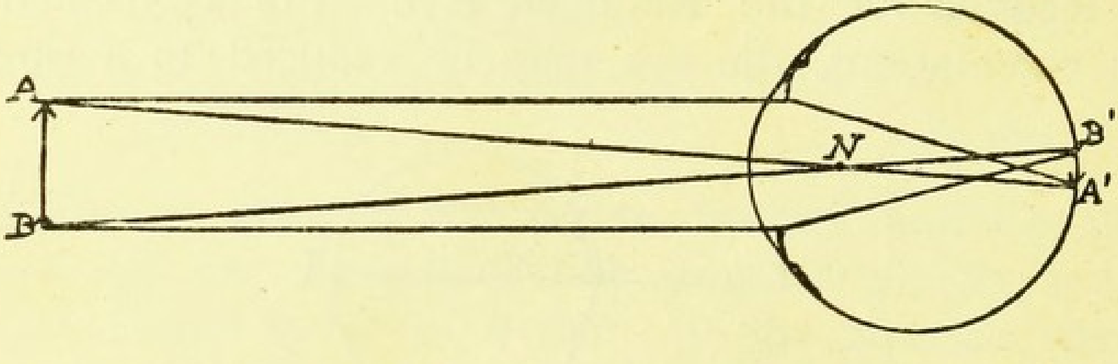

Fig. 19.—**Diagram showing the Relative Sizes of A B, the Object, and B′ A′, its Image, at the Retina.**

**The Retinal Image.**—The dioptral power of the reduced eye is (as in the schematic eye) 66 D. for emergent and 50 D. for entering light. Since the secondary axial rays cross at the nodal point, the size of the image formed at $F_2$ is, however, equal to that formed by a lens whose power is

$$1/F_1 = 1/15 = 66 \text{ D.}$$

If an object (AB) 10 cm. long is 6 m. from the apex of the cornea, it is $600+0{\cdot}5=600{\cdot}5$ cm. from N, while its image B′ A′ is 15 mm. from N; and since both subtend the same angle at N, its size is found from

$$\frac{10\times 15}{600{\cdot}5}.$$

This varies quite inappreciably from the ordinary calculation for the size of the retinal image, which is

$$\frac{\text{Size of object}\times 15}{\text{Distance of object}}=\frac{10\times 15}{600}=0{\cdot}25\text{ mm.}$$

The size and distance of the object must be expressed in the same terms—viz., yards, metres, etc.—and the result is always in mm.

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