Formation of Images in the Eye.

It is necessary only to call to mind the general arrangement of the different structures in the eye and to apply the simple laws of refraction, in order to comprehend precisely how images are formed upon the retina.

The eye corresponds to a camera obscura. Its interior is lined with a dark, pigmentary membrane (the choroid), the immediate action of which is to prevent the confusion of images by internal reflection. The rays of light are admitted through a circular opening (the pupil), the size of which is regulated by the movements of the iris. The pupil is contracted when the light striking the eye is intense, and is dilated as the quantity of light is diminished. In the accommodation of the eye, the pupil is dilated for distant objects and contracted for near objects; for in looking at near objects, the aberrations of sphericity and achromatism in the lens are more marked, and the peripheral portion is cut off by the action of this movable diaphragm, thus aiding the correction. The rays of light from an object pass through the cornea, the aqueous humor, the crystalline lens and the vitreous humor, and they are refracted with so little spherical and chromatic aberration, that the image formed upon the retina is practically perfect. The layer of rods and cones of the retina is the only portion of the eye endowed directly with special sensibility, the impressions of light being conveyed to the brain by the optic nerves. This layer is situated next the pigmentary layer of the choroid, but the other layers of the retina, through which the light passes to reach the rods and cones, are perfectly transparent.

It has been shown that the rods and cones are the only structures capable of directly receiving visual impressions, by the following experiment, first made by Purkinje: With a convex lens of short focus, an intense light is concentrated on the sclerotic, at a point as far as possible removed from the cornea. This passes through the translucent coverings of the eye at this point, and the image of the light reaches the retina. In then looking at a dark surface, the field of vision presents a reddish-yellow illumination, with a dark, arborescent appearance produced by the shadows of the large retinal vessels; and as the lens is moved slightly, the shadows of the vessels move with it. Without going elaborately into the mechanism of this phenomenon, it is sufficient to state that Heinrich Müller has arrived at a mathematical demonstration that the shadows of the vessels are formed upon the layer of rods and cones, and that this layer alone is capable of receiving impressions of light. His explanation is generally accepted and is regarded as positive proof of the peculiar sensibility of this portion of the retina.

Theoretically, an illuminated object placed in the angle of vision would form upon the retina an image, diminished in size and inverted. This fact is capable of demonstration by means of the ophthalmoscope; as with this instrument the retina and the images formed upon it may be seen during life.

All parts of the retina, except the point of entrance of the optic nerve, are sensitive to light; and the arrangement of the cornea and pupil is such, that the field of vision is, at the least estimate, equal to the half of a sphere.

If a ray of light fall upon the border of the cornea, at a right angle to the axis of the eye, it is refracted by its surface and will pass through the pupil to the opposite border of the retina. Above and below, the circle of vision is cut off by the overhanging arch of the orbit and the malar prominence; but externally the field is free. With the two eyes, therefore, the lateral field of vision must be equal to at least one hundred and eighty degrees. It is easy to demonstrate, however, by the ophthalmoscope, as well as by taking cognizance of the impressions made by objects far removed from the axis of distinct vision, that images formed upon the lateral and peripheral portions of the retina are confused and imperfect. One has a knowledge of the presence and an indefinite idea of the general form of large objects situated outside of the area of distinct vision; but when it is desired to note such objects exactly, the eyeball is turned by muscular effort, so as to bring them at or very near the axis of the globe. This fact, with what is known of the mechanism of refraction by the cornea and lens, makes it evident that the area of the retina, upon which images are formed with perfect distinctness, is quite restricted. A moment's reflection is sufficient to convince any one that in order to see any object distinctly, it is necessary to bring the axis of the eye to bear upon it directly.

In examining the bottom of the eye with the ophthalmoscope, the yellow spot, with the fovea centralis, can be seen, free from large blood-vessels, and composed chiefly of those elements of the retina which are sensitive to light. If at the same time, an image for which the eye is perfectly adjusted be observed, it will be seen that this image is perfect only at the fovea centralis; and if the object be removed from the axis of vision, there is a confused image upon the retina, removed from the fovea, at the same time that the subject is conscious of indistinct vision. In the words of Helmholtz, "It is only in the immediate vicinity of the ocular axis that the retinal image possesses entire distinctness; beyond this, the contours are less defined. It is in part for this reason that in general we see distinctly in the field of vision, only the point that we fix. All the others are seen vaguely. This lack of distinctness in indirect vision, in addition, depends also upon diminished sensibility of the retina: at a slight distance from the fixed point, the distinctness of vision has diminished much more than the objective distinctness of retinal images."

At the point of penetration of the optic nerve, the retina is insensible to luminous impressions; or at least, its sensibility is here so obtuse as to be entirely inadequate for the purposes of vision. This point is called the punctum cæcum; and its want of sensibility was demonstrated many years ago (1668) by Mariotte. The classical experiment by which this important fact was ascertained is generally known as Mariotte's experiment. The following account is quoted *verbatim:*

"I fasten'd on an obscure Wall about the hight of my Eye, a small round paper, to serve me for a fixed point of Vision; and I fastened such an other on the side thereof towards my right hand, at the distance of about 2. foot; but somewhat lower than the first, to the end that it might strike the *Optick*

Nerve of my Right Eye, whilst I kept my Left shut. Then I plac'd myself over against the First paper, and drew back by little and little, keeping my Right Eye fixt and very steddy upon the same; and being about 10. foot distant, the second paper totally disappear'd."

In this experiment the rays of light from the paper which has disappeared from view are received upon the punctum cæcum, at the point of entrance of the optic nerve. If the observer withdraw himself still farther, the second circle will reappear, as the rays are removed from the punctum cæcum. With the ophthalmoscope, the point of penetration of the optic nerve may readily be seen in the living eye. If the image of a flame be directed upon this point, the sensation of light is either not perceived or it is very faint and indefinite, and it is then probably due to diffusion to other portions of the retina.

The relative sensibility of different portions of the retina has been measured by Volkmann and has been found to be, in an inverse ratio, equal to about the square of the distance from the axis of most perfect vision. This observer calculated the distance between the sensitive elements of the retina at which he supposed that two parallel lines would appear as one. In the axis of vision, the distance was 0·00029 inch (7·366 μ), and at a deviation inward of 8°, it was 0·03186 inch (809·244 μ), a diminution of acuteness of more than a hundred times.

Visual Purple and Visual Yellow, and Accommodation of the Eye for Different Degrees of Illumination.—The outer segments of the rods of the retina sometimes present a peculiar red or purple color, which disappears after ten or twelve seconds of exposure to light. This was first observed by Boll (1876) in the retinæ of frogs that had been kept for a certain time in the dark. From his preliminary researches, Boll concluded that this coloration of the retina exists only during life and persists but a few moments after death; that it is constantly destroyed during life by the action of light and reappears in the dark; and finally that it plays an important part in the act of vision. Kühne and others have since confirmed and extended the original observations of Boll; and the visual purple (rhodopsine) has been noted in the mammalia and in man. It has been extracted from the retinæ of frogs and dissolved in a five-per-cent. solution of crystallized ox-gall, still presenting in solution its remarkable sensitiveness to light (Ayres). Finally it has been found possible to fix images of simple objects, such as strips of black paper pasted upon a plate of ground glass, upon the retina, by a process very like that of photography.

The visual purple is produced by the cells of the pigmentary layer of the retina and from them is absorbed by the outer segments of the rods. It is not present in any part of the cones and does not exist, therefore, in the area of distinct vision, at the fovea centralis. The rapid disappearance of the color under the influence of actinic rays of light renders it necessary to examine the retina under a non-actinic (monochromatic) sodium-flame (Ayres). When thus examined and gradually exposed to actinic rays, the color quickly fades into a yellow and finally disappears, being restored, however, in the dark.

If the choroid and the pigmentary layer of the retina be removed, the rods are bleached, and the color is restored in the dark when the choroid is replaced. In the eye of the frog, kept in the dark, the hair-like processes which extend from the pigmentary layer of the retina downward between the rods and cones are retracted, and the pigment is then contained chiefly in the cells themselves. After prolonged exposure of the retina to light, these processes, loaded with pigment, extend between the cones as far as the limitary membrane (Kühne).

The fact that visual purple has never been found in the fovea centralis is opposed to the theory that its existence is directly essential to distinct vision; nevertheless, certain phenomena observed in passing from a bright light to comparative obscurity, and the reverse, show that the purple has, at least, an important indirect action. In passing from the dark to bright light, the eye is dazzled and distinct vision is difficult. It may be assumed that this is due to unusual general sensitiveness of the retina to light, on account of the excessive quantity of visual purple which has accumulated in the dark, and that distinct vision is restored when the retina is bleached to a yellow, which seems to be the most favorable condition for the exact appreciation of visual impressions, under full illumination. On the other hand, it requires time for the eye to become accustomed to a dim light; and during this time the yellow is changing to purple. These changes in the color of the retina have been actually observed (Ayres). Investigations of the absorption-spectra of the purple and yellow have shown that the purple allows the actinic rays to pass perfectly, while the yellow completely absorbs these rays (Kühne). The existence of visual purple seems to be most favorable to the imperfect and shadowy vision which occurs under dim illumination, when the exact appreciation of minute details is impossible. In the condition known as night-blindness, it is probable that the visual purple has become exhausted beyond the possibility of prompt restoration such as is normal; and persons so affected can not see at night, although minute vision under a bright light may not be affected. In certain cases of this kind, the normal conditions may be restored by a few days' seclusion in the dark. What is called functional night-blindness frequently occurs in sailors during long, tropical voyages, and is due to the excessive action of diffused light upon the retina. "That the affection is local, is shown by the fact that darkening one eye, with a bandage, during the day, has been found to restore its sight enough for the ensuing night's watch on board ship, the unprotected eye remaining as bad as ever" (Nettleship).

The change of the visual purple to yellow is readily effected, but the farther change to white is slower and more difficult. Conversely, the change from white to yellow is slow and the change from yellow to purple is comparatively prompt. One use of the colors purple and yellow seems to be to accommodate the retina for vision under different degrees of illumination. The purple adapts the eye to a feeble illumination, and the yellow, to a full illumination. This being the case, it is manifestly proper to speak of a visual yellow (Kühne) as well as of visual purple.

That the accommodation of the eye to different degrees of illumination is due to the changes in the colors produced by the pigmentary layer of the retina and not to different degrees of dilatation of the pupil, is shown by the fact that a person does not see better in the dark when the pupil has been dilated by atropine (Loring). In a very dim light there is no possibility of exact accommodation for near objects, which, when small, can not be seen distinctly; and the contraction of the pupil which attends accommodation for near vision does not occur. It is possible that under dim illumination, parts outside of the fovea, which are insensible to vision under a bright light, receive visual impressions. Under these conditions the pupil is dilated and rays impinge on portions of the retina not used in direct vision. A natural extension of this idea would confine distinct vision and the appreciation of minute details to the action of the fovea centralis, in which there is no visual purple, other parts of the retina, under full illumination, not being used. To express this in a few words, the fovea centralis is used by day, and the adjacent parts of the retina, by night.

Mechanism of Refraction in the Eye.

An object that is seen reflects rays from every point of its surface, to the cornea. If the object be near, the rays from each and every point are divergent as they strike the eye. Rays from distant objects are practically parallel. It is evident that the refraction for diverging rays must be greater than for parallel rays, as a necessity of distinct vision; in other words, the eye must be accommodated for vision at different distances. Leaving, however, the mechanism of accommodation for future consideration, it may be stated simply that the important agents in refraction in the eye are the surfaces of the cornea and the crystalline lens. Calculations have shown that the index of refraction of the aqueous humor is sensibly the same as that of the substance of the cornea, so that practically the refraction is the same as if the cornea and the aqueous humor were one and the same substance. The index of refraction of the vitreous humor is practically the same as that of the aqueous humor, both being about equal to the index of refraction of pure water. Refraction by the crystalline lens, however, is more complex in its mechanism; depending first, upon the curvatures of its two surfaces, and again, upon the differences in the consistence of different portions of its substance. In view of these facts, the conditions of refraction in the eye in distinct vision may be simplified by assuming the following arrangement:

The cornea presents a convex surface upon which the rays of light are received. At a certain distance behind its anterior border, is the crystalline, a double convex lens, corrected sufficiently for all practical purposes, both for spherical and chromatic aberration. This lens is practically suspended in a liquid with an index of refraction equal to that of pure water, as both the aqueous humor in front and the vitreous humor behind have the same refractive power. Behind the lens, in its axis and exactly in the plane upon which the rays of light are brought to a focus by the action of the cornea and the

lens, is the fovea centralis, which is the centre of distinct vision. The anatomical elements of the fovea are capable of receiving visual impressions, which are conveyed to the brain by the optic nerves. All impressions made upon other portions of the retina are comparatively indistinct; and the point of entrance of the optic nerve is insensible to light. Inasmuch as the punctum cæcum is situated in either eye upon the nasal side of the retina, in normal vision, rays from the same object can not fall upon both blind points at the same time. Thus, in binocular vision, the insensibility of the punctum cæcum does not interfere with sight; and the movements of the globe prevent any notable interference in vision, even with one eye. The sclerotic coat is for the protection of its contents and for the insertion of muscles. The iris has an action similar to that of the diaphragm in optical instruments. The suspensory ligament of the lens, the ciliary body, and the ciliary muscle, are for the fixation of the lens and its accommodation for distinct vision at different distances. The choroid is a dark membrane, for the absorption of light, preventing confusion of vision from reflection within the eye.

Refraction by the cornea is effected simply by its external surface. The rays of light from a distant point are deviated by its convexity so that, if they were not again refracted by the crystalline lens, they would be brought to a focus at a point situated about $\frac{4}{10}$ of an inch (10 mm.) behind the retina. Without the crystalline lens, therefore, distinct, unaided vision generally is impossible, although the sensation of light is appreciated. In cases of extraction of the lens for cataract (aphakia), the crystalline is supplied by a convex lens placed before the eye.

The rays of light, refracted by the anterior surface of the cornea, are received upon the anterior surface of the crystalline lens, by which they are still farther refracted. Passing through the substance of the lens, they undergo certain modifications in refraction, dependent upon the differences in the various strata of the lens. These modifications have not been accurately calculated; but it is sufficient to state that they contribute to the accuracy of the formation of the retinal image and to the production of an image practically free from chromatic dispersion. As the rays pass out of the crystalline lens, they are again refracted by its posterior curvature and are brought to a focus at the point of distinct vision.

The rays from all points of an object distinctly seen are brought to a focus, if the accommodation of the lens be correct, upon a restricted surface in the macula lutea; but the rays from different points cross each other before they reach the retina, and the image is inverted.

Calculating the curvatures of the refracting surfaces in the eye and the indices of refraction of its transparent media, it has been pretty clearly shown, by mathematical formulæ, that the eye—viewed simply as an optical instrument, and not practically, as the organ of vision—presents a certain degree of spherical and chromatic aberration; but these calculations are not very important in a purely physiological consideration of the sense of sight.

In most calculations of the size of images, the positions of conjugate foci, etc., in normal and abnormal eyes, a schematic eye reduced by Donders, after the example of Listing, is regarded as sufficiently exact for all practical purposes. This simple scheme represents the eye as reduced to a single refracting surface, the cornea, and a single liquid assumed to have an index of refraction equal to that of pure water. The distance between what are called the two nodal points and between the two principal points of the dioptric system of the eye is so small, amounting to hardly $\frac{1}{100}$ of an inch (0·254 mm.), that it can be neglected. In this simple eye, there is assumed to be a radius of curvature of the cornea of about $\frac{1}{5}$ of an inch (5 mm.) and a single optical centre situated $\frac{1}{5}$ of an inch (5 mm.) back of the cornea, the "principal point" being in the cornea, in the axis of vision. The posterior focal distance, that is, the focus, at the bottom of the eye, for rays that are parallel in the air, is about $\frac{4}{5}$ of an inch (20 mm.). The anterior focal distance, that is, for rays parallel in the vitreous humor, is about $\frac{3}{5}$ of an inch (15 mm.). The measurements in this simple schematic eye can easily be remembered and used in calculations.

Astigmatism.

In the normal human eye the visual line does not coincide exactly with the mathematical axis; but there is still another normal deviation from mathematical exactness in the refraction of rays by the cornea and the crystalline lens, which is of considerable importance. If two threads, crossing each other at right angles in the same plane, be placed before the eyes, one of these threads being vertical, and the other, horizontal, when the optical apparatus is adjusted so that one line is seen with perfect distinctness, the other is not well defined. In other words, when the eye is accommodated for the vertical thread, the horizontal thread is indistinct, and *vice versâ*. If the horizontal line be seen distinctly, in order to see the vertical line without modifying the accommodation, it must be removed to a greater distance. This depends chiefly upon a difference in the vertical and the horizontal curvatures of the cornea, so that the horizontal meridian has a focus slightly different from the focus of the vertical meridian. A condition opposite to that observed in the cornea usually exists in the crystalline lens; that is, the difference which exists between the curvatures of the lens in the vertical and the horizontal meridians is such that the deepest curvature in the lens is situated in the meridian of the shallowest curvature of the cornea. In this way, in normal eyes, the aberration of the lens has a tendency to correct the aberration in the cornea; but this correction is incomplete, and there still remains, in all degrees of accommodation, a certain difference in vision, as regards vertical and horizontal lines.

The condition just described is known under the name of normal, regular astigmatism; but the aberration is not sufficiently great to interfere with distinct vision. The degree of regular astigmatism presents normal variations in different eyes. In some eyes there is no astigmatism; but this is rare. According to Donders, if the astigmatism amount to $\frac{1}{40}$ or more, it is to be considered abnormal; which simply means that beyond this point the aberration interferes with distinct vision.

From the simple definition of regular astigmatism, it is evident that this

condition and the degree to which it exists may easily be determined by noting the differences in the foci for vertical and horizontal lines, and it may be exactly corrected by the application of cylindrical glasses of proper curvature. Indeed, the curvature of a cylindrical glass which will enable a person to distinguish vertical and horizontal lines with perfect distinctness at the same time, is an exact indication of the degree of aberration. Regular astigmatism, such as just described, may be so exaggerated as to interfere very seriously with vision, when it becomes abnormal. This kind of aberration, however, which is dependent upon an abnormal condition of the cornea, is remediable by the use of properly adjusted, cylindrical glasses.

Irregular astigmatism, excluding cases of pathological deformation, opaque spots etc., in the cornea, depends upon irregularity in the different sectors of the crystalline lens. Instead of a simple and regular aberration, consisting in a difference between the depth of the vertical and the horizontal curvatures of the cornea and lens, there are irregular variations in the curvatures of different sectors of the lens. As a consequence of this, when the irregularities are very great, there is impairment of the sharpness of vision. The circles of diffusion, which are regular in normal vision, become irregularly radiated, and single points appear multiple, an irregularity described under the name of polyopia monocularis. Accurate observations have shown that this condition exists to a very moderate degree in normal eyes; but it is so slight as not to interfere with ordinary vision. In what is called normal, irregular astigmatism, the irregularity depends entirely upon the crystalline lens. If a card with a very small opening be placed before the eye and be moved in front of the lens, so that the pencil of light falls successively upon different sectors, it can be shown that the focal distance is different for different portions. The radiating lines of light observed in looking at remote, luminous points, as the fixed stars, are produced by this irregularity in the curvatures of the different sectors of the lens.

While regular astigmatism, both normal and abnormal, may be perfectly corrected by placing cylindrical glasses before the eyes, it is impossible, in the great majority of cases, to construct glasses which will remedy what has been called irregular astigmatism.

Movements of the Iris.

There are two physiological conditions under which the size of the pupil is modified: The first of these depends upon the degree of illumination to which the eye is exposed. When the illumination is dim, the pupil is widely dilated. When the eye is exposed to a bright light, the retina is protected by contraction of the iris. The muscular action by which the iris is contracted is characteristic of the smooth muscular fibres, as can be readily seen by exposing an eye, in which the pupil is dilated, to a bright light. Contraction does not take place instantly, but an appreciable interval elapses after the exposure, and a more or less gradual diminution in the size of the pupil is observed. This is seen both in solar and in artificial light. The second of these conditions depends indirectly upon the voluntary action of muscles.