THE HUMAN EYE;

ITS

OPTICAL CONSTRUCTION

POPULARLY EXPLAINED.

R. E. DUDGEON. MD.

24/ii/18

93, ALBERT STREET,
N.W.1.

Dear Sir Herbert Parsons

Herewith the book by Dudgeon & the sub-aqueous spectacles made by Culver about 1885 from data given at par 45. I fear that the book is only of historical interest now to you, but if more than this please keep it. In any case I shd not use the specs until the Summer, as I have given up winter bathing in fresh water. I am very grateful to you for

yr Kindness & attention to us
both this morning.

Yours faithfully
S. M. Porter.

7/- net

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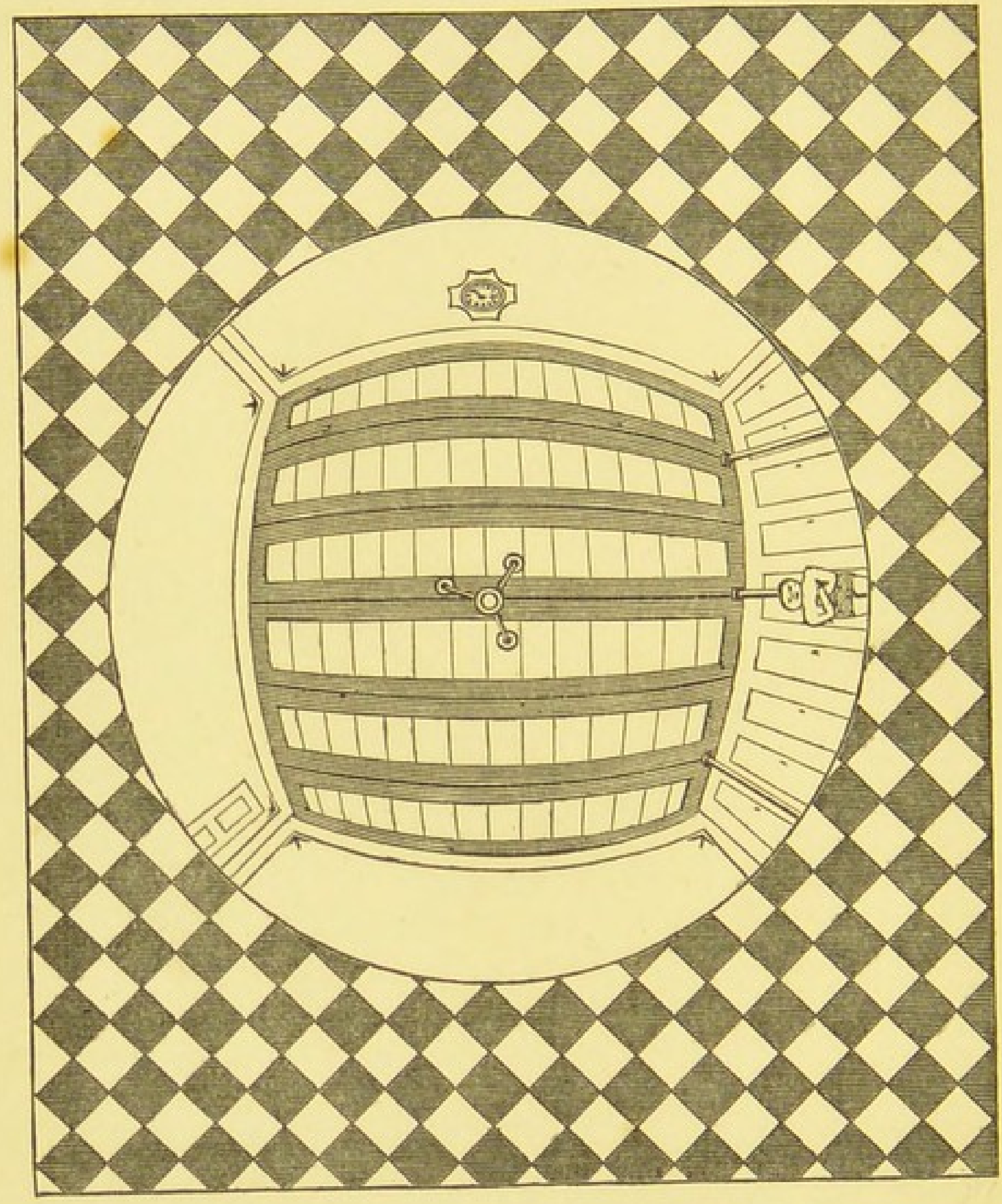
FIG. 18.



VISION UNDER WATER. (*See page* 42.)

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BY

R. E. DUDGEON, M.D.

LONDON:

HARDWICKE AND BOGUE, 192, PICCADILLY, W.

1878.

PREFACE.

THE novel views in this little work respecting subaqueous vision, air lenses, and visual accommodation were first promulgated in two pamphlets, entitled, 'Notes on the Dioptrics of Vision,' and 'The Mechanism of Accommodation,' published in 1871 and 1872. They were also explained in lectures delivered in 1871 before the Sunday Lecture Society and in 1872 at the Sunday Evenings for the People. Again, in August 1872, the Author read a paper at the meeting of the International Ophthalmological Congress respecting his views on the mechanism of accommodation, which is published in the Transactions of the Congress. Since the date of these publications and lectures, further experiments and observations by the Author himself and by some continental physiologists have confirmed the correctness of the views he originally put forward respecting the mechanism of visual accommodation, and as these views have excited some interest both in this country and in Germany, the Author has been induced to write a more complete treatise on the optics of vision in plain and untechnical language, so as to enable those not conversant with optical science to understand this important and interesting subject. The Author believes that a popular method of treatment of his subject is perfectly compatible with scientific accuracy. In the special optical part of this treatise he has confined himself to those optical facts and principles which have a direct bearing on the optics of the eye.

The Author has limited himself strictly to his subject, which is the optical construction of the normal human eye. The reader will therefore not expect to find a full account in this small volume of those large subjects the physiology, anatomy, histology, pathology, and comparative anatomy of the eye, each of which would require a large book for its proper treatment, and could hardly form the theme of a popular treatise.

CONTENTS.

THE HUMAN EYE;

ITS

OPTICAL CONSTRUCTION.

1. THE human eye is an optical instrument of a peculiar and complex character, differing in some important respects from any of the optical instruments with which we are familiar, but yet resembling some of these instruments in the general principles of its construction. 1. REFRACTION

2. Optical instruments are of various kinds, from the simple lens familiar to all in the spectacles we wear in our old age and the burning glass we played with in our childhood, to the complicated arrangement of lenses, diaphragms, chambers and screens in our compound microscopes, our refracting telescopes and our photographic cameras. All these optical instruments have one feature in common, namely, the *lens*.

3. A lens is a transparent body of peculiar shape, which possesses the property of refracting rays of light passing through it, that is to say, of deflecting them in certain directions, according to its shape and refractive power.

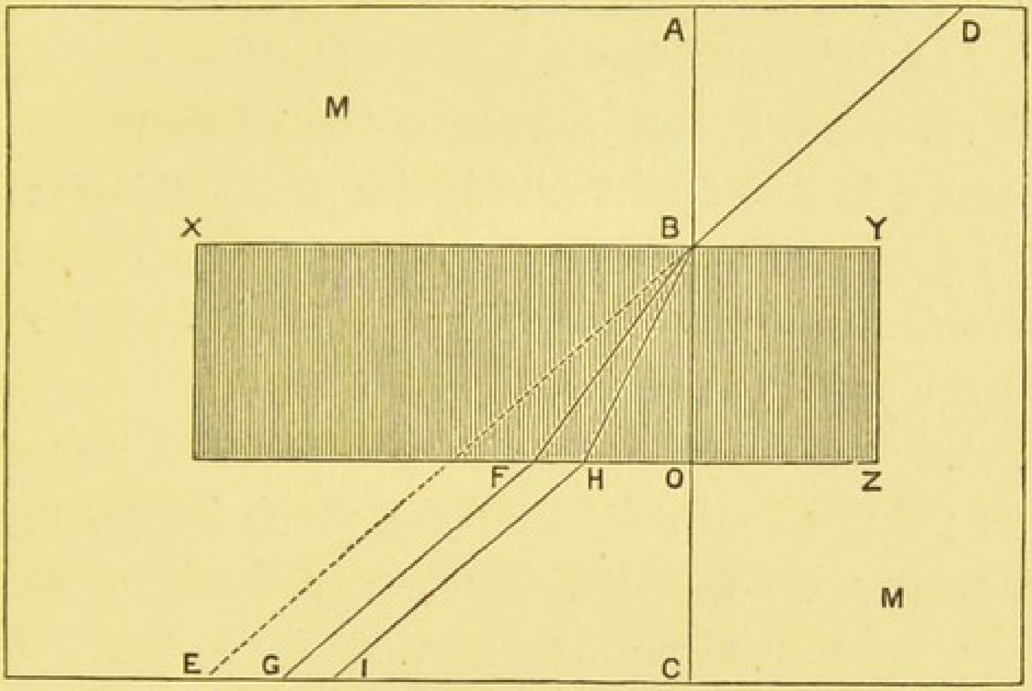
4. In order to understand the nature and properties of a lens, it will be necessary to explain what is meant by the refraction of light.

When a ray of light from a transparent medium of a certain refractive power impinges perpendicularly on a transparent medium of a different refractive power, it passes through without deflexion, but if it impinges on this second medium obliquely, it is deflected from its original course and proceeds onward through the second medium in a new direction. The amount of divergence from its original course will depend on two things. First, the degree of obliquity with which the ray strikes the second medium; second, the difference betwixt the refractive power of the first and the second medium.*

* Refraction is now usually explained to be caused by a retardation of the velocity of the vibrations of the ray of light, by the obstacles presented to its free passage through a so-called refractive medium. The phenomena of the spectrum are held to be due to this retarding effect acting with more or less power on the different coloured rays of which white light is composed. I have not thought it desirable or necessary to enter into fuller details on the subject of the cause of refraction. We have only to do here with the effects.

5. Fig. 1 represents the refraction of a ray of light through a transparent substance with parallel sides. When the light A, from a less refractive medium M, falls perpendicularly to the surface X Y of the more refractive medium X Z, it passes through the new

FIG. 1.



There is no incident ray to BHI and it is not referred to in the text.

medium to the opposite side O without being deflected. When it now passes, still perpendicularly, into the less refractive medium M, it continues the same course without deflexion, so that the ray of light from A to C is perfectly straight.

6. But if the ray of light D strike the surface of the more refractive medium obliquely, it will not traverse it in the straight course D E, but will be deflected or

drawn towards the perpendicular B O, and strike the opposite surface at F. On emerging into the less refractive medium M, which it enters obliquely, it will be deflected away from the perpendicular O C, in the direction F G, parallel to the direction of its incidence D B.

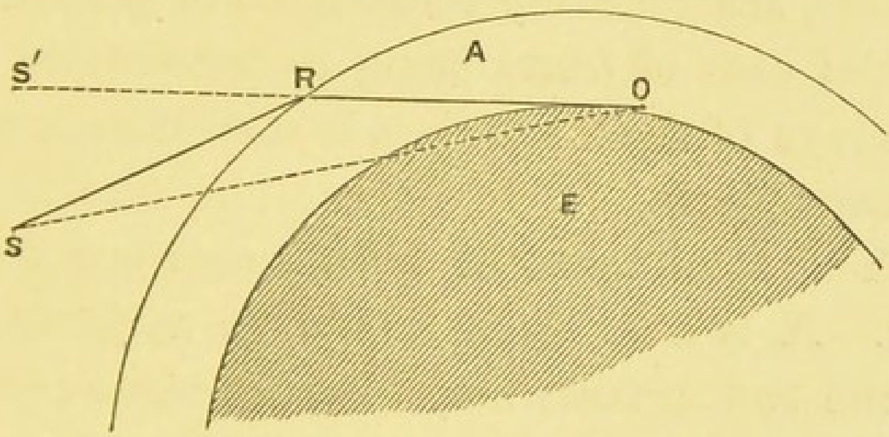
7. Hence the rule of refraction may be stated thus: A ray of light entering a more refractive transparent medium from a less refractive transparent medium obliquely, is deflected towards the perpendicular; but if it passes obliquely from a more refractive medium into a less refractive medium, it is deflected away from the perpendicular.

8. All transparent media possess the refractive power; fluids and solids have a much higher refractive power than gases, but many fluids possess a higher refractive power than some solids. Thus, carbon sulphide and oil of cassia possess a greater refractive power than plate and crown glass. The diamond has nearly the highest refractive power of any transparent substance, and it is this property that imparts to it its peculiar brilliancy. The refractive power of a transparent substance is not always in proportion to its density. A high degree of refractive power has been supposed to indicate a great degree of combustibility, and Sir Isaac Newton

inferred the combustibility of the diamond from its remarkable refractive power.

9. Our atmosphere possesses a considerable degree of refractive power, a circumstance well known to astronomers. It is only when they are in the zenith, that is to say, perpendicularly above us, that the stars are seen in their true positions; as they approach the horizon the rays of light from them are deflected by the atmosphere. It is this refractive power of our atmosphere that enables us to see the sun several minutes before it rises and after it sets. To an observer at O (Fig. 2), on the surface of the earth

FIG. 2.



E, the sun, which is really below the horizon at S, appears to be above the horizon at S′, in consequence of its rays, which impinge obliquely on the earth's atmosphere A, being refracted from their original direction S R, in the new direction R O; the real position of the sun being in the line O S. But in spite of the considerable refractive power of the earth's atmosphere compared with that of interstellar space, the air being the least refractive of the transparent media in which our optical instruments are used, is regarded as unity in calculating the refractive powers of other transparent media employed for optical purposes.

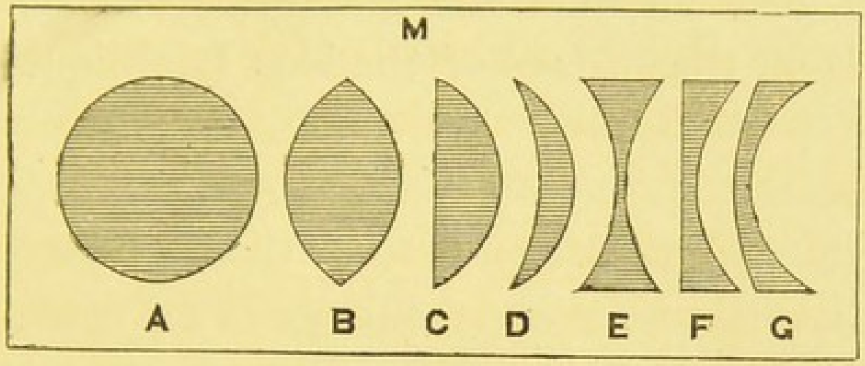
10. The refractive properties of transparent substances have been taken advantage of for constructing instruments, called lenses, by means of which the rays of light are deflected in certain required directions.

Lenses, which form the basis of most optical instruments, are generally constructed of glass, and the two chief uses of *lenses* being to concentrate and to scatter rays of light, the glass is shaped so as to effect these two objects.

11. The chief forms of glass lenses are shown in Fig. 3. A is a *spherical* lens, B is a *double convex* lens; the two surfaces may have the same convexity, as in the illustration, or may have different convexities. C is a *plano-convex* lens, one side being plane, the other convex. D is a *meniscus*, where one side is convex, the other concave, the convexity being greater than the concavity. E is a *double concave* lens. In such lenses the concavities may be the same

or dissimilar. F is a *plano-concave* lens, one surface plane, the other concave. G is a *concavo-convex* lens, the concavity being greater than the convexity.

FIG. 3.



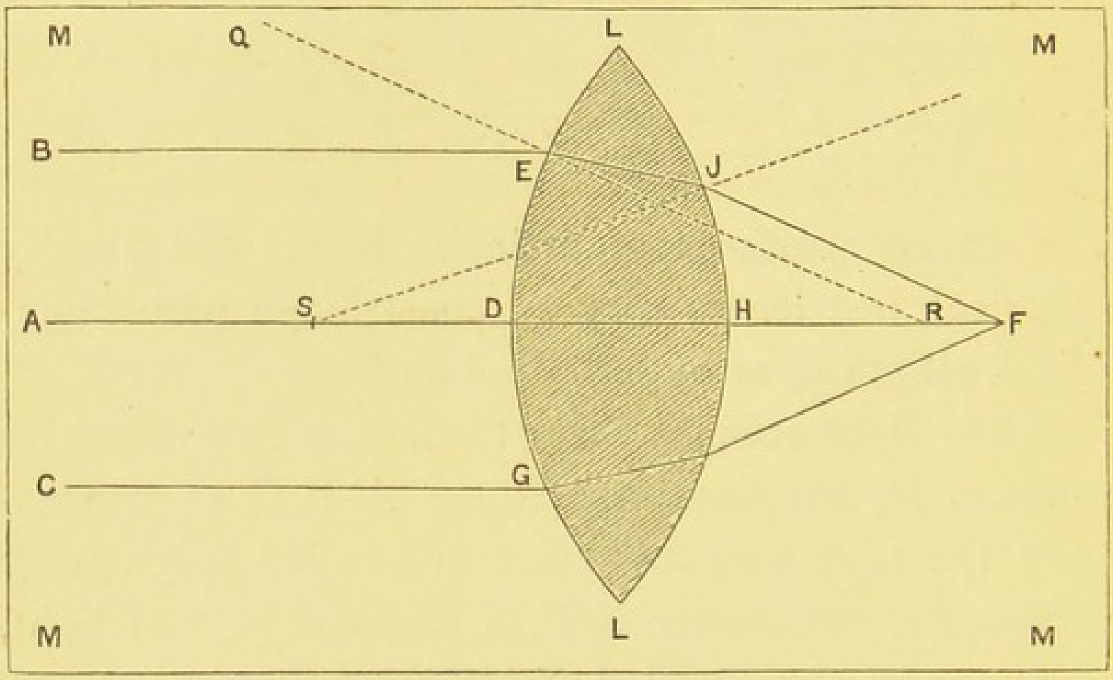
The curved surfaces of artificial lenses are usually spherical, but lenses may be constructed with cylindrical, elliptical, or hyperbolical surfaces.

When light reaches them through a less refractive medium M, the four first forms A, B, C, D concentrate the rays, and are what are called *magnifying* glasses, the remainder E, F, G disperse rays of light, and are sometimes called *diminishing* glasses.

12. The subjoined diagram (Fig. 4) explains how parallel rays of light proceeding from a less refractive medium are concentrated to a focus by a double convex lens made of a more refractive substance. The parallel rays A, B, C, impinge on the surface of the lens L L, at the points D, E, G. As the centre ray A strikes the lens at D perpendicularly to its surface, it passes

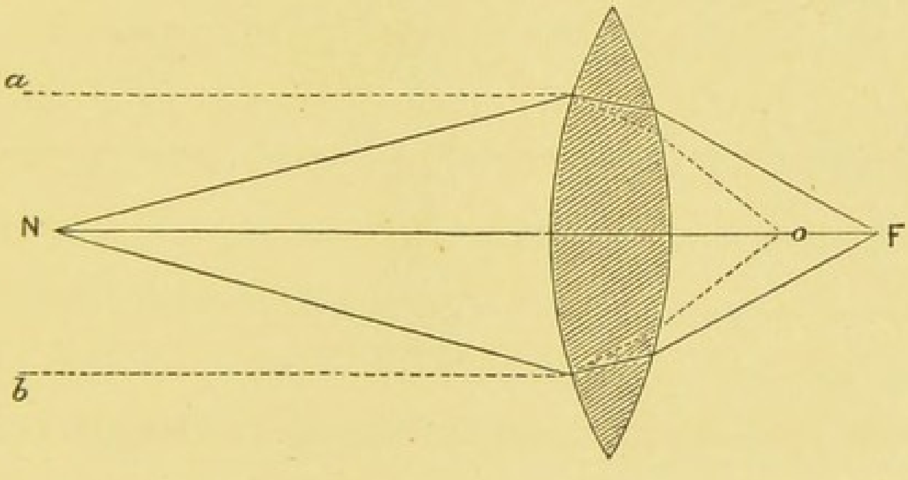
through the lens in a straight line, and as it emerges from the opposite side of the lens at H, perpendicularly to the surface of the less refractive medium M, whose shape is determined by that of the lens, the ray still goes on in a straight line. But the ray B impinges on the surface of the lens L obliquely at E

FIG. 4.



(R Q is the prolonged radius of the surface L E L, and B E Q is the angle of incidence of the ray B), and as L has a greater refractive power than the medium whence the ray comes, the ray is now in its passage through L deflected towards the perpendicular of the surface E of the lens. The radius R E of the convex surface L E L of the lens, is the perpendicular to the front of its surface at E. So in passing through the lens the ray B is deflected at E, so that it strikes the opposite side and emerges at J; but here it enters the less refractive medium M obliquely to its surface at J, and is accordingly deflected away from its perpendicular (the radius S J of the surface L J L prolonged). This new deflexion directs it to F, where it meets the undeflected central ray A and the corresponding parallel ray C at the opposite periphery of the lens. All intermediate parallel rays between B and C likewise meet at F, and this is called the focus of the lens. ?

FIG. 5.

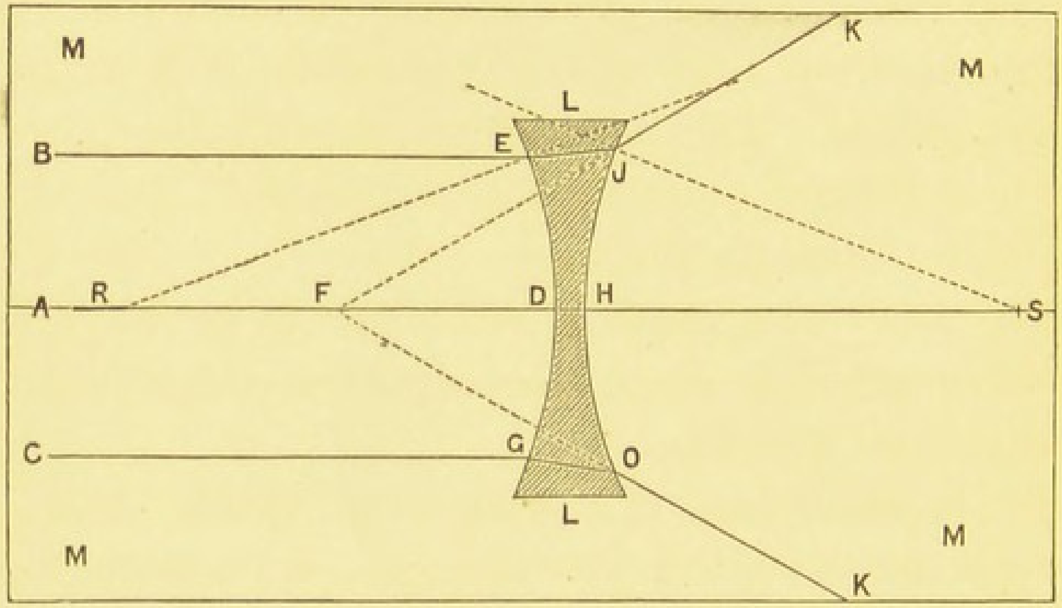


13. Rays of light proceeding from a luminous object at a considerable distance, impinge on the lens in nearly parallel lines. But when the luminous object is near the lens, the rays of light from it strike the lens in divergent lines. In the latter case the focus

is found at a greater distance behind the lens, as shown in Fig. 5, where the rays proceeding from a near object are focused at F, whilst parallel rays *a*, *b*, are focused at *o*.

14. When parallel rays of light proceeding from a less refractive medium pass through a double concave lens made of a more refractive medium they are dispersed. This will be understood by the following diagram, Fig. 6. The parallel rays of light

Fig. 6.



A, B, C, impinge on the surface of the lens at D, E, G. As the centre ray strikes the lens at D perpendicularly to its surface, it passes through the lens in a straight line, and as it emerges from the opposite side of the lens at H, perpendicularly to the surface of the less refractive medium M, whose shape is determined by that of the lens, the ray still goes on in a straight line. But the ray B impinges on the surface of the lens L obliquely at E (B E R in its angle of incidence), and as L has a greater refractive power than the medium through which the ray comes, the ray is now in its passage through L deflected towards the perpendicular. The perpendicular is ascertained by prolonging the radius R E of the surface E D G. On emerging at J, it enters the less refractive medium M obliquely to its surface, and is consequently deflected away from the perpendicular S J, in the direction J K. The same thing takes place with the ray C at the opposite periphery of the lens L and with all intermediate parallel rays. ?

The focus of a concave lens is said to be the point F, where the rays would meet if prolonged backwards in their final direction.

15. In every case of refraction of light by lenses, the amount of the deflexion depends on the difference between the refractive power of the lens and the medium through which the rays of light are transmitted to it. This refractive power of a transparent medium is called its index of refraction. As the atmospheric air is the medium of least refractive power employed in optical operations, its index of refraction

is called 1. Glass, which has an index of refraction of 1·5, is the usual substance of which optical lenses are made. But some substances of which lenses may be made have a much higher or a much lower index of refraction than glass. Thus the index of refraction of diamond is as high as 2·4, and water has an index of refraction of 1·3. The rule for calculating the amount of deflexion a ray will undergo in its transmission from air through a lens, I need not detain the reader by explaining. It is expressed in these terms: The sine of the angle of incidence is to the sine of the angle of refraction as the index of refraction of the lens is to 1. Thus if the lens be of water, the sine of the angle of incidence to the sine of the angle of refraction will be as 1·3 to 1; if of glass, as 1·5 to 1; if of diamond, as 2·4 to 1, and so on.

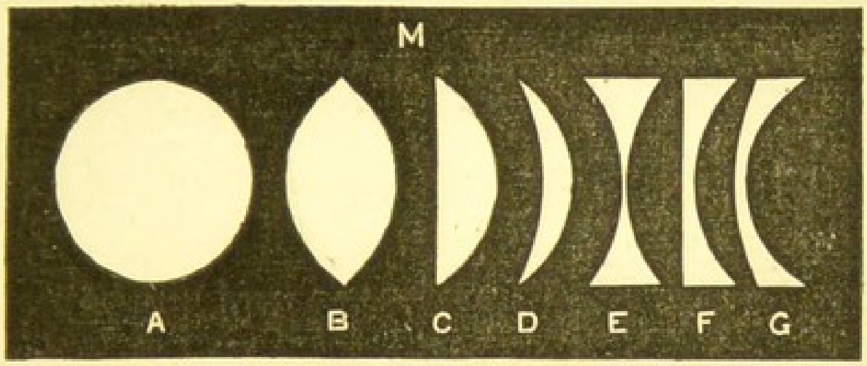
16. But when a glass lens is used in a medium whose index of refraction is greater than that of air, as for instance in water, then the sine of the angle of incidence to that of refraction will be as 1·5 to 1·3. In other words, the rays of light impinging on a glass lens immersed in water, will be much less deflected than when the same lens is used in air; it will consequently concentrate the rays of light at a much greater distance behind it in water than in air.

17. Lenses may be made when the relations betwixt

the lens and the surrounding medium through which it receives the rays of light may be just the opposite of those just described. The surrounding medium may be the most refractive, the lens itself the least refractive.

18. Lenses of this description (Fig. 7) may be similar in shape to those formerly described, but their

Fig. 7.

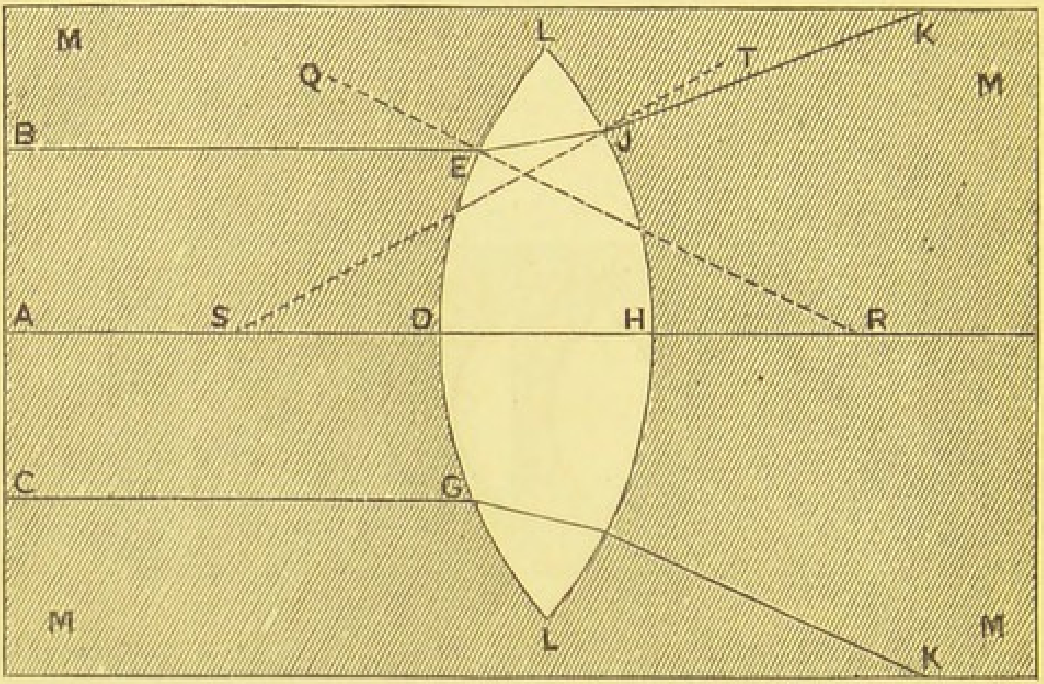


qualities will be precisely the opposite of theirs. Thus the sphere A, double convex B, plano-convex C, and meniscus D, will cause the rays of light to diverge; whereas the double concave E, plano-concave F, and concavo-convex G, will cause the rays of light transmitted through them to converge.

19. This will be understood from the following diagrams. The parallel rays A B C (Fig. 8), passing through the more refractive medium M, impinge on the surface of the lens L L (which is composed of a less refractive medium than M), at the points D, E, G.

The centre ray A, striking the lens at D perpendicularly to its surface, passes through the lens without any deflexion of its course, and as it also strikes the

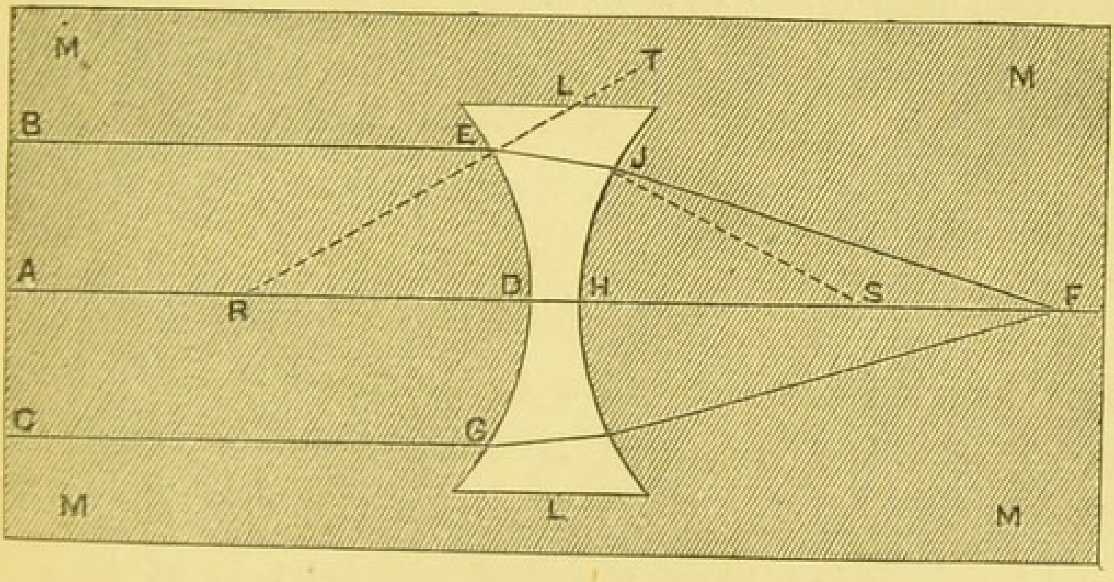
FIG. 8.



surface of the more refractive medium at H, perpendicularly to its surface, it continues on a straight course. The ray B impinges on the surface of the lens at E obliquely (its angle of incidence being B E Q), so on passing through the less refractive lens it is deflected away from the perpendicular R E and emerges at J. Here it enters the more refractive medium M obliquely (its angle of incidence being E J S), so in passing through this medium it is again deflected towards the perpendicular S T, and proceeds in the course J K. The same thing happens to the ray C on the opposite periphery of the lens. Thus it will be seen that this double convex lens, because it receives the rays of light from a medium of greater refractive power, acts precisely like a double concave lens receiving rays from a less refractive medium than itself. On both sides the more refractive medium has a concave shape.

20. When parallel rays, passing through a more refractive medium, strike a double concave lens made of a less refractive medium, they converge to a point

FIG. 9.

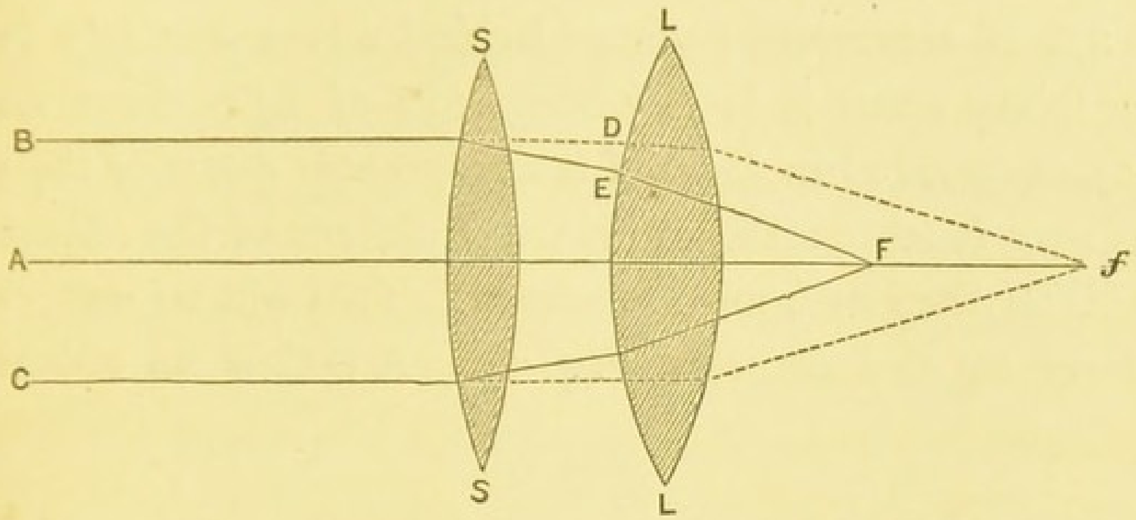


behind the lens, as seen in Fig. 9. The ray A, falling perpendicularly to the surface of the lens L at D, passes through the lens, emerges also perpendicularly to the surface of the medium M, and is not deflected. The ray B impinges on the surface of the lens at E obliquely (its angle of incidence is B E R), and as the lens L is a less refractive medium than that it leaves, the ray is deflected away from the perpendicular R T, and strikes the opposite surface of the lens at J. Here it enters the more refractive medium M at J, and is consequently deflected towards the perpendicular S J, and joins the ray A D H at F. As the ray C on the opposite periphery of the lens and all intermediate parallel rays likewise meet at F, this is the focus of the lens L. Thus it will be seen that a double concave lens constructed of a less refractive medium, immersed in a more refractive medium, acts like a double convex lens made of a more refractive substance in a medium of less refractive power. On both sides the more refractive medium has a convex shape.

21. A combination of lenses is frequently used. In some cases it is desirable to increase the refractive power of the lens, and thereby shorten its focus. This is shown in Fig. 10, where the ray B, which would otherwise have entered the lens L at D and been refracted to *f*, suffers a previous refraction by the supplementary convex lens S, and entering the lens L at E already deflected, is focused at F. The

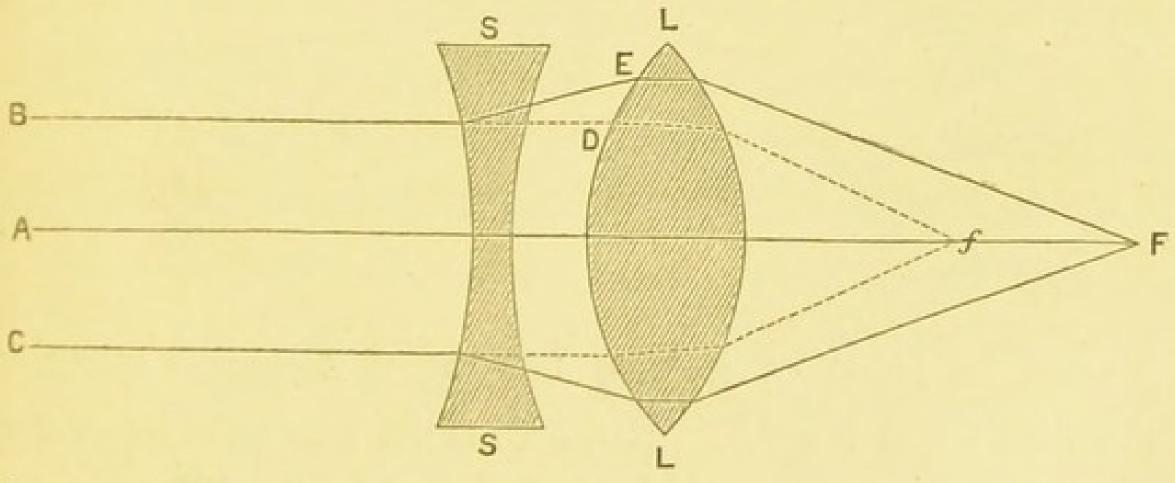
same thing happens to the ray C, while the central ray A, which strikes both lenses perpendicularly, proceeds in an undeflected course and joins the other rays at F.

FIG. 10.



22. In other cases it may be wished to decrease the refractive power of the lens, and thereby lengthen its

FIG. 11.

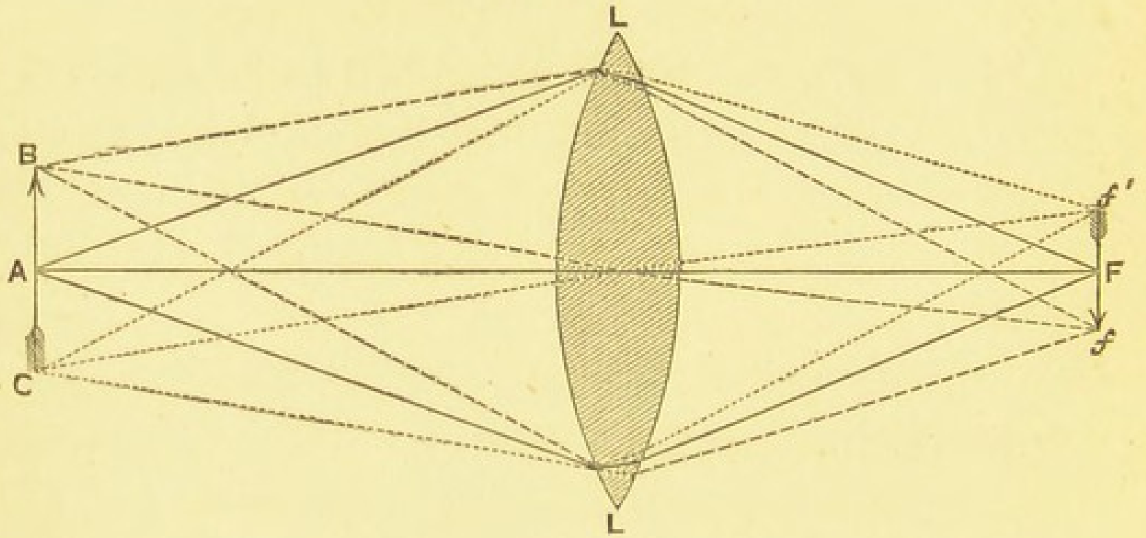


focus. This is done (Fig. 11) by adding a concave lens S to the too refractive lens L. The ray of light

B, which would otherwise have entered the lens L at D, and been refracted to *f*, undergoes a previous refraction by the supplementary concave lens S, and enters the lens L at a different angle E, and is consequently focused at F.

23. If a screen be placed behind a lens precisely in its focus when it is receiving rays of light from an object situated in front of it at a greater distance than its own focal length, an inverted picture of the object will be thrown upon the screen. This will be understood by the diagram Fig. 12. A B C is an object

Fig. 12.



placed in front of a lens L L at a distance greater than its focal length. Rays of light emanate in every direction from every point of the object. Those proceeding from the central point A are focused, as already explained, behind the lens, at F. The rays proceeding from the point B are focused at *f*, as shown by the interrupted line; whilst the rays from the point C are focused at *f′*, as shown by the dotted line. A screen placed at F*f f′* will exhibit an inverted and smaller picture of the object A B C.

24. It is this property of the lens, of depicting the image of an object in front of it beyond its focal length on a screen placed behind it in its focus, that is utilized in the construction of the camera obscura and photographic apparatus. From what has been previously said, it will be obvious that for the picturing on the screen of distant objects whence the rays of light impinge on the lens in nearly parallel lines, the screen must be placed nearer the back of the lens than when it is wished to picture the image of near objects, whence the rays impinge divergently on the lens. In the former case, as already explained, the focus is shorter than in the latter.

25. If the position of the screen is fixed, then the alteration required in order to focus objects perfectly upon it, must take place in the position of the lens, which may be moved nearer the screen for distant objects, and farther from the screen for near objects. Or if it be impossible to move either screen or lens, which must consequently preserve the same relative positions, then it will be necessary to increase the refractive power of the lens, whereby its focus will be

shortened for near objects. This may be done by—1, using a lens of greater convexity; 2, by employing a lens of the same convexity, but made of a more refractive material; or 3, by employing a supplementary convex lens, as shown at Fig. 10, where the original lens is adapted for distant objects; or 4, by making use of a supplementary concave lens, as shown at Fig. 11, where the original lens is already suited for the focusing of near objects; or 5, by presenting the lens obliquely to the object, whereby the focal distance is diminished.

The rudimentary optical facts above detailed will render intelligible the principles of the optical construction of the eye.

IV. THE EYE-LENSES.

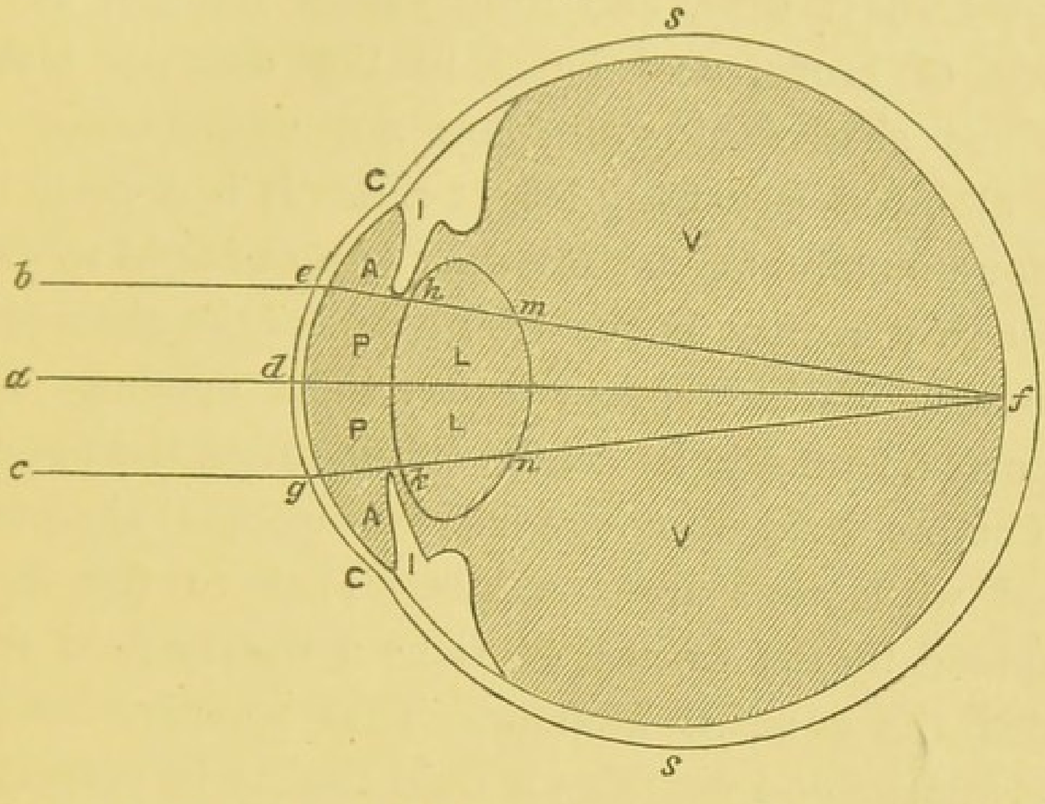
26. The optical instrument the eye most nearly resembles, is the photographic camera. In both we have an inverted image of external objects thrown upon a sensitive screen at the back of a dark chamber.* In the case of the eye, however, the dark chamber is filled with a highly refractive aqueous medium, and the lens is a compound one, composed of two media of different refractive powers.

27. Fig. 13 is a diagram of the normal human eye.

* It belongs to physiology to explain how it is that objects pictured upside-down on the retina are seen in their proper position. We need only say here that it is not the retina which perceives, but the brain, to which impressions on the retina are conveyed by the optic nerve.

S S is the hard, thick, opaque case called the *sclerotic*, which encloses the dioptric media of the eye. It is nearly spherical in shape, and lies in a hollow of the skull called the orbit, where it is surrounded by a

FIG. 13.



series of muscles which turn it in every required direction. This opaque case does not constitute a complete sphere. In the front part of it is a circular opening, which is occupied by a firm transparent structure C C, more convex in shape than the case itself, and resembling a watch glass; this is called from its horny consistence the *cornea*. At a short distance behind the cornea there is suspended a contractile membrane I I, called the *iris*, with a circular hole in its centre capable of being made larger or smaller by the contractions of the membrane. The membrane is of various colours in various eyes; it gives what is called the colour to the eye. In the human eye it varies from light grey to the most intense violet blue, and from yellow through every shade of brown and hazel to the deepest black. Various shades of green are not uncommon. In the albino it is usually bright red. It is a perfectly opaque membrane, not allowing a ray of light to pass through it, except in the albino, where the absence of colouring matter renders it not quite opaque. The circular opening in its centre P P is called the pupil.

The iris divides the eye into two unequal chambers filled with transparent media. That to the front, bounded by the cornea, contains a watery fluid A A called the aqueous humour. That bounded by the sclerotic behind contains a fluid similar in properties to the aqueous humour, but enclosed in a finely reticulated membrane, which holds its fluid contents together even after removal from the eye, causing it to look like a lump of glass—hence its name, *vitreous humour*, V V. The refractive power of cornea and aqueous and vitreous humours is nearly identical, and is very nearly the same as that of water.

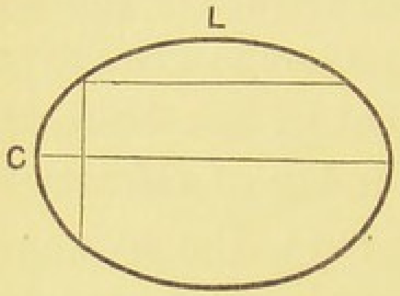
Immediately behind the iris, bathed in front by the aqueous humour, and behind imbedded in the front of the vitreous humour, is a transparent double-convex lens-shaped body L L, enclosed in an elastic membrane. This lens is called the *crystalline lens.* It is composed of concentric layers of various refractive power, increasing towards the centre. Its average refractive power is not much greater than that of the aqueous and vitreous humours. While the index of refraction of the latter may be stated as 1·33, the average index of refraction of the crystalline lens is certainly not more than 1·39, probably less. The crystalline lens is commonly spoken of as "the lens of the eye," but this is misleading, for it is not the only nor yet the chief lens of the eye, but may rather be looked on as a supplementary lens, as far as the human eye is concerned, though, as we shall see hereafter, in certain other classes of animals it is the chief or even the sole ocular lens.

28. The curvatures of the two surfaces of the crystalline lens are not alike; thus its front is less convex, while its back is more convex than the cornea.*

* The curvatures of cornea, and front and back of crystalline lens are usually stated to be as follows: the cornea has a radius of curvature of 8 millimètres, the front of the crystalline lens has a radius of curvature of 10 millimètres, and its back a radius of curvature of 6 millimetrès; but as those surfaces are not spherical, these measurements can only be considered as averages.

29. The surfaces of cornea and crystalline are not spherical, but ellipsoidal. They are segments of a figure like what is represented here (Fig. 14). The cornea is a segment of an egg-shaped body cut from its long diameter C; the surfaces of the crystalline lens are segments of a similar section cut from its short diameter L.* This will make the apex of the cornea its most convex part, while the apices of the surfaces of the crystalline lens will be the least convex. This shape of the surfaces of the refractive media of the eye endows them with peculiar optical properties.

FIG. 14.



30. When parallel rays of light, i. e. rays of light from a distant object, impinge upon the eye, they first come in contact with the convex surface of the cornea. The cornea, having a refractive power nearly identical with that of the aqueous humour it encloses, the two together form a homogeneous lens, bounded in front by the outline of the cornea, behind by the anterior surface of the crystalline. The form of this lens, it will be observed, is that of the meniscus (D, Fig. 3), for the *convexity* of the cornea is, as before observed, greater than that of the anterior surface of the crystalline,

* Oblate spheroidal is the name sometimes applied to this figure. It signifies a sphere flattened at the poles, like the figure of the earth.

which determines the shape of the *concavity* of this aqueous lens. However, it differs from the ordinary meniscus in this, that the concave surface does not come in contact with the air, but is in close apposition with a more refractive medium than itself; so that, in tracing the rays of light through the aqueous humour, we have only to take into consideration the convergent refraction caused by its convex surface, and not, as in the case of a glass meniscus, the divergent refraction caused by the concave surface.

The ray *a* (Fig. 13), falling perpendicularly to the surface of the cornea at *d*, passes through the dioptric media of the eye without refraction to the back of the eye. The rays *b* and *c*, which strike the cornea at *e* and *g*, passing from a less refractive medium, the air, into the more refractive medium obliquely to its surface, are deflected towards the perpendicular, as before explained (*see* Fig. 4). This will bring these rays in the direction *e h*, *g k*, when they will impinge on the surface of the crystalline lens at *h* and *k*. The crystalline lens, being a more refractive medium than the aqueous humour, the rays from the latter, striking its surface obliquely, are deflected again towards the perpendicular of the anterior convexity of the crystalline, and proceed in the direction *h m*, *k n*, and passing into the less refractive medium of the vitreous humour, they are again deflected, this time away from the perpendicular of the posterior curve of the crystalline lens, which brings them in the direction *mf*, *nf*, where they join the central ray at *f*, on the line of the visual axis of the eye.* The interior of the eye-case is lined with a sensitive screen, called the *retina*, a nervous expanse of wonderful construction, that forms the termination of the optic nerve.

31. This nervous screen, on which the picture of external objects is thrown, is only perfectly sensitive to the images formed on it in a small point exactly in the axis of vision at *f*, where is the focus of rays proceeding from objects directly in front of the eye. The field of view of the eye is very extensive, but the portion of this field, where the image of external objects is perfectly seen, is a very minute point, called the yellow spot. In this spot the arrangement of rods and cones, of which the retina is made up, is different from what it is on other parts of the retina.†

32. In consequence of this arrangement it is only

* These alterations in the direction of the ray of light are so slight, that they are not exhibited in the cut.

† Although the yellow spot in the axis of vision is the only part of the retina capable of distinctly perceiving the picture of objects thrown upon it, it is actually not so sensitive to *light* as the surrounding parts of the retina. Of this we may convince ourselves if we darken the room sufficiently without excluding all light. Then, if we look straight forward, we shall be able to see the forms of white objects, such as pieces of white paper, lying on either side, but on directing the eye to these objects, that is to say, on allowing them to be focused on the yellow spot, we cannot see them at all.

necessary that the rays of light in the line of the visual axis, i. e. the rays directly in front of the eye, should be accurately focused on this small point of the retina; the remainder of the retina would not be able to perceive distinctly the objects pictured upon it, though they may be perfectly focused. The lightning-like rapidity of the eye's movements neutralizes the defective sensibility of the remainder of the retina, and enables us, if not to take in a whole landscape at a glance, at all events to see every portion of it in succession with the utmost distinctness by a rapid sweep of our eye. In this way each individual portion of the landscape is accurately focused on the small perfectly sensitive spot of the retina, and the impression on the mind is as if the whole view were distinctly seen at once.

It is probable, indeed certain, that the image of external objects is distinctly focused on a much larger space than the small yellow spot that is alone capable of perceiving it perfectly, but it is impossible that the whole field of vision, so extensive as it is, can be accurately focused. Practically, however, this is of no consequence, for the perfectly sensitive point of the retina being exactly in the axis of vision, it is no detriment to our perception of external objects if the whole of the remainder of the retina received an imperfectly focused picture.

33. From what has been stated it will be seen that the eye has a considerable resemblance to the photographic camera. Both have a dark chamber, and one or more lenses, so arranged as to throw a picture of external objects on a sensitive screen* at the back of this dark chamber. But the eye differs in some important respects from the photographic camera. While the dark chamber of the latter is filled with the same medium as that through which the rays pass to the lens of the camera, viz. air, the dark chamber of the eye is filled with a highly refractive medium, which forms, in fact, the principal lens of the eye, for the chief refraction is performed by the aqueous humour, the crystalline lens only being as it were a supplementary lens, effecting a slight additional refraction of the incident rays.

Rays of light, entering the camera of the eye from the air by its anterior lens, do not again pass into air before being focused on the sensitive screen behind, as they do in the photographic camera.

34. In the eye we find an arrangement for cutting off superfluous rays of light that might interfere with

* Recent observations seem to show that the resemblance between the screen of the eye and that of the artificial camera is greater than was supposed. Thus Kühne found that the image of an object thrown upon the retina during life is actually visible as a rose-coloured picture on that membrane after death. (See 'Nature,' vol. xv. p. 296.)

the perfection of the image cast on the retina. This is called a *diaphragm* in optical instruments. The iris I I, which is the diaphragm of the eye, is placed just in front of the crystalline lens, and has the power of contracting and dilating its opening, called the *pupil*, P P, to regulate the admission of rays of light. In fact, in ordinary conditions of the eye, the iris, which is an opaque membrane, covers up a large portion of the crystalline lens, and allows only its central portion to receive the rays of light. The size of the pupil regulates the amount of light admitted into the eye. When the image would be blurred by the admission of rays of light in excess, the pupil contracts and shuts off these rays. Accordingly the pupil contracts, as a rule, in strong light and dilates in obscure light. When the refractive media of the eye become less accurate, as they do in old age, the pupil has a tendency to contract, and thus correct, to some extent, the faulty refraction of the ocular lenses. But the contraction of the pupil is not carried far enough to obviate all the inaccuracies of the defective eye-lenses of old age. Accordingly, we are forced to supply, by artificial means, the additional refractive power the defects of our refractive media require.

35. I have stated that the chief lens of the eye is

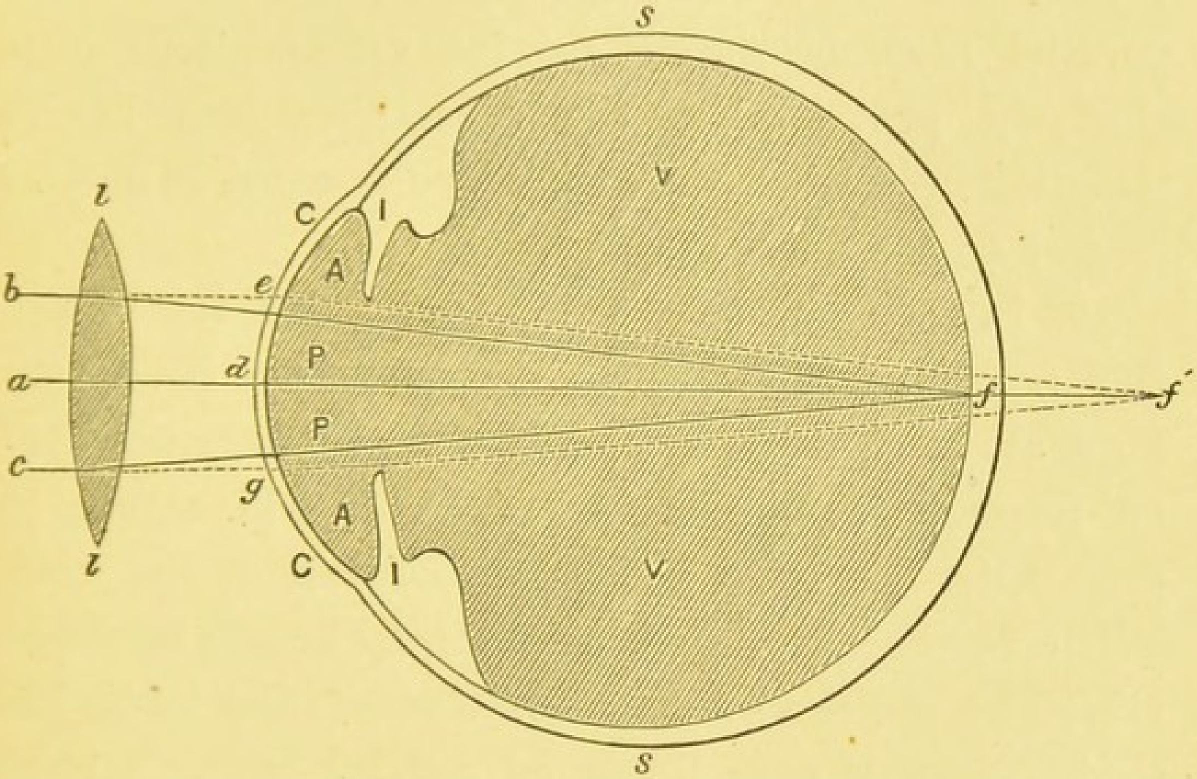
that formed by the cornea and aqueous humour. By this I mean that the first refraction of rays of light at the cornea and aqueous humour is greater than the second caused by the crystalline lens. And yet the crystalline lens is constructed of a medium of greater refractive power than the cornea and aqueous humour; it is moreover a double convex lens, one surface of which is greatly more convex than the single convex surface of the aqueous lens, which, as before remarked, is a meniscus. Did it receive the rays of light as the aqueous lens does from the slightly refractive medium, the air, the refractive power of the double convex crystalline lens would greatly exceed that of the aqueous meniscus. It would, in fact, bring the rays to a focus 4 or 5 millimètres behind it. But as the crystalline lens is suspended in a medium (the aqueous and vitreous humours) whose refractive power is but slightly inferior to its own, rays of light passing into it from this medium are only very slightly deflected from their course.

It would be difficult by calculation to ascertain the precise amount of refraction of the rays of light effected by each of the ocular lenses, but we can experimentally do this.

36. In the operations for the cure of cataract, the crystalline lens is removed from the eye, or at all

events from the line of vision, so that rays of light penetrate to the sensitive screen of the ocular camera only refracted by the cornea and aqueous humour. This refraction is not sufficient to form a clear image of external objects on the retina. The focus of the lens formed by the refractive media of the eye without the crystalline lens is considerably behind the retina.

FIG. 15.



37. This will be apparent from the diagram (Fig. 15). The rays *a*, *b*, *c*, entering the cornea at *d*, *e*, *g*, would suffer no further refraction, and this refraction would unite them in a focus beyond the retina, say at *f′*, but being intercepted by the retina they form on it

a blurred and confused image. In order to correct this, a lens *l l* is used to give the refraction to the rays necessary, in combination with the further refraction effected by the cornea, to bring them to a focus on the retina at *f*. The lens *l l* required for this purpose will precisely represent the refractive power of the lost crystalline lens. It is found that a glass lens of 4 inches focus will generally restore perfect vision for distant objects, i. e. will focus parallel rays accurately on the retina. This conclusively proves that the crystalline lens in its situation in the interior of the eye is equal to a glass lens of 4 inches focus in air.

38. In the same way we may infer that the refractive power of the cornea and aqueous and vitreous humours is equal to a glass lens, which superimposed on a glass lens of 4 inches focus, will suffice to reduce the focus to 1 inch (the diameter of the eye). What the focus of such a lens may be can be ascertained by the modes of calculation familiar to optical students, or it may be found out by trying several lenses over a 4-inch lens. In this way we shall find that a glass lens of 1½-inch focus, if superimposed on a glass lens of 4 inches focus, will reduce the focus to 1 inch. We thus prove that the refraction of the eye deprived of its crystalline lens is equal to a

glass lens in air of $1\frac{1}{2}$-inch focus; hence it would throw the image of distant objects half an inch behind the retina.

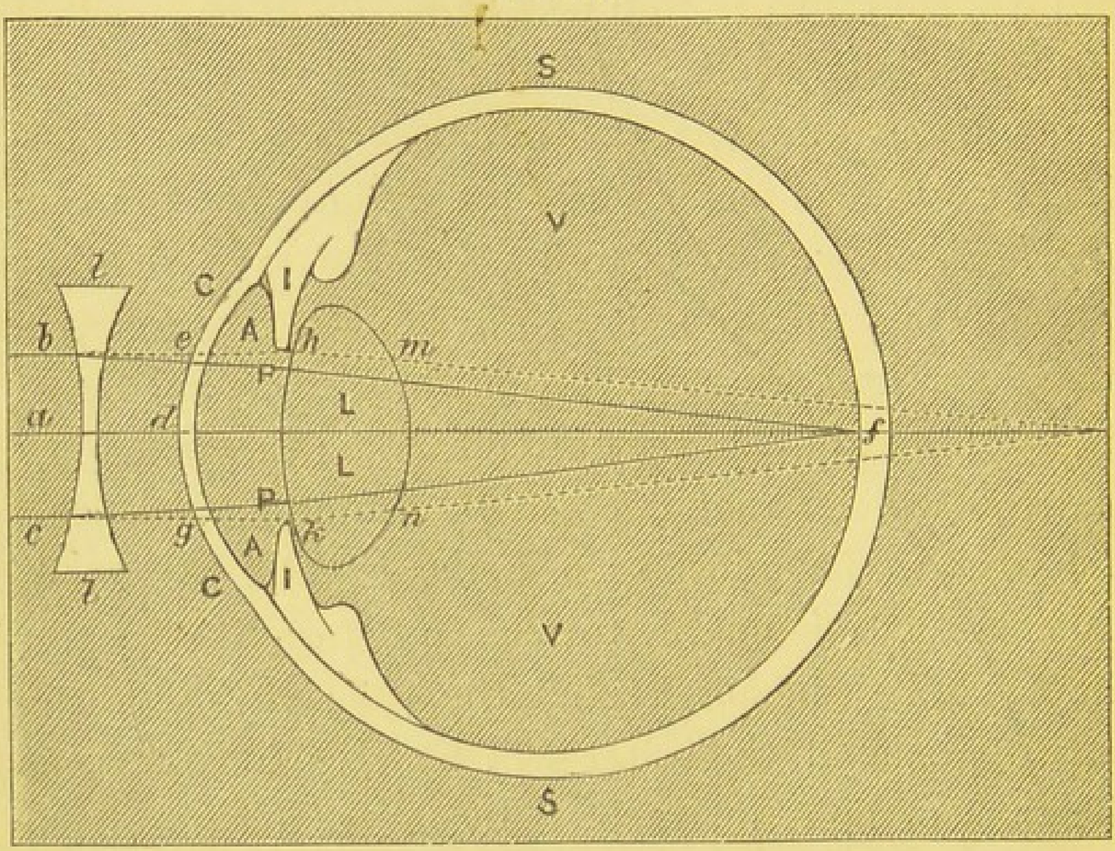
39. But we may ascertain the precise value of the aqueous lens by extinguishing its refractive power in the living human eye, and ascertaining what power of lens will suffice to restore perfect vision.

40. As before observed, the refractive power of the aqueous and vitreous humours is almost identical with that of water. If then we immerse the eye in water, and allow it to receive the rays of light through this medium, it is obvious that these rays will suffer no further refraction from those media of the eye; that in fact, the only refraction they will now undergo will be that effected by the crystalline lens, which, as we have just seen, being equal to a lens of 4 inches focus, is unable to focus rays of light nearer than about 3 inches behind the eye; vision, consequently, beneath the water will be very indistinct, as the rays of light intercepted by the retina are so far from their true focus. It is obvious that this must be so, for, as shown by Fig. 16, the rays of light suffer no deflexion at *e* and *g*, but only at *h*, *k*, *m*, and *n*, and at these points only the trifling deflexion that can be caused by a lens of a certain convexity constructed of a medium little superior in refractive

power to that through which the rays of light are transmitted to it.

41. And yet I have been again and again assured by persons fond of diving that they can see quite well when under the water, so little observant are some

FIG. 16.



persons of what actually occurs under novel and perhaps agitating conditions. The sight which in reality remains to us when immersed in the clearest water is the perception of light and of colour, but only the vaguest perception of form. And even this poor amount of vision only remains for objects at a small distance from us; a few yards off, even objects of considerable size are unseen.

42. In order to restore perfect vision under water we must use a lens capable of concentrating the rays of light transmitted to it through water into a focus at $1\frac{1}{2}$ inch behind it; this being the focus of the aqueous lens lost by immersion in the water.

43. If we use a glass lens for this purpose it is obvious that it must be a much more powerful lens than what would have a focus of that length in air. For while the refractive index of air compared with that of glass is as 1 to 1·5, the refractive index of water compared with that of glass is only as 1·33 to 1·5. Hence glass will refract the rays of light to a very much smaller extent in water than in air, in fact about one-fourth. I have found experimentally that a glass lens which has a focus of three-eighths of an inch in air will have a focus of $1\frac{1}{2}$ inch in water. Therefore a glass lens of this power will be required in order to enable an eye immersed in water to see distinctly, and I have practically proved that this is so.

44. But it is obvious that water being itself a medium of high refractive power, it would be better to avail ourselves of a medium either of much greater refractive power than itself, or of much less. Now it

is difficult to procure a transparent medium of much greater refractive power than glass for use in the water. Diamond, which would do, its refractive power being as high as 2·4, is for obvious reasons not to be thought of. But there is nothing to prevent us using a medium of very inferior refractive power to water in the construction of subaqueous lenses. The medium of least refractive power is air. The relations of lens medium to surrounding medium being reversed, the shape of the air lens must be also reversed, as before shown. We must use here a double concave air lens in place of the double convex glass lens.

45. By taking two of the old-fashioned highly-curved watch glasses, and fixing them in a ring with their concavities outwards, we enclose a portion of air of the shape of a double concave lens. Immersed in water, this air lens will refract the rays of light from objects reaching it through the water, convergently. It will resemble in its optical properties a double convex glass lens in air, as I have explained above (§ 20).

46. I found that a double concave air lens, made with two sections of a glass globe of 2 inches diameter, constitute a lens of 1½-inch focus when immersed in water. This lens accordingly supplies the refractive power lost by the eye when immersed in water. In the diagram (Fig. 16) the dotted line shows the course of the rays of light transmitted to

the eye when immersed in water. They are not focused at the retina, so that the image formed on the retina is very indistinct, as it must be when so imperfectly focused. The continuous line shows how the rays of light are first deflected by the concave air lens *l*; this deflexion, in the case of a lens whose curves are such as stated above, being sufficient to make up for the loss of refraction by the extinction of the aqueous humour lens when it receives the rays of light through the identically refracting watery medium.

47. I thought it might be advantageous, or at all events agreeable, to be able to see distinctly when diving; so I constructed a pair of spectacles fitted with air lenses of the kind just described. It is obvious that spectacles fitted with air lenses would be much more convenient for diving than glass lenses. For whereas the glass lenses required for subaqueous purposes are of such very short focus in air (only three-eighths of an inch), that they would prevent all vision when the diver came to the surface, these air lenses would offer no impediment to perfect vision in the air, and so might continue to be worn with equal advantage both in air and water. I found, however, that the two sections of a glass globe which form the concave air lens, have in the air the effect of a very weak concave glass lens, such

a lens as is used to correct the slightest degree of short sight. The cause of this is that the inner concave surface of the glass globe is a curve of smaller radius than the outer convex surface. Thus it is a concavo-convex lens, though of very small power. But when two such glasses are placed together the refraction they produce is appreciable, and somewhat impairs perfect vision to a non-myopic eye.

48. In order to counteract this slight refraction in the lens when used in the air, in place of having the glasses made of sections of a glass globe, I had them ground with surfaces of precisely the same curvature. By this means I obtained glasses for my air lenses which, having their surfaces of precisely the same curve, cause no deflexion of the rays of light. These lenses therefore restore perfect vision beneath the water, and offer no impediment to perfect sight in the air.

V. VISION UNDER WATER.

49. Vision below the water, if the latter is quite clear, is with lenses of this description quite perfect for both near and distant objects. Thus with them we can see to read the smallest type at the distance of a foot, while we can also see objects at many yards distance. Everything below the water is seen in its proper proportions, and without any distortion whatever. Thus the pattern of the porcelain tiles on the bottom and sides of a bath, as in many of the swim-

ming baths in London, anything lying upon the floor of the bath, such as coins, stones, pins, or other small articles, the bodies and limbs of other bathers, and any objects floating in the water, are all seen distinctly and accurately.*

* In 1871 I published a pamphlet entitled 'Notes on the Dioptrics of Vision,' in which I gave a description of the air lenses for use under water. This pamphlet I sent to several scientific gentlemen, and among them to the late Sir John Herschel, through his publishers, Messrs. Longmans. A few days afterwards I received the following letter :—

"Sir, "Collingwood, *Jan.* 22, 1871.

"I beg to acknowledge, with thanks, your paper, 'Notes on the Dioptrics of Vision.'

"The idea of employing a double concave *air lens* in water, instead of the more obvious double convex *glass* one, is ingenious, as it ceases to *be* a lens as soon as it is out of the water, and (barring distortion from wet external surfaces) would not impede vision if used as spectacles out of water. Excuse me, however, if I remark that the way in which the principle of construction is stated in page 8, line 10, &c., had to myself, on a first rapid perusal, the effect of creating some degree of obscurity as to the actual disposition intended, which was only dissipated, as I read on, by the use of the term 'air lens' in page 15, line 8, when all became clear.

"I have the honour to be, Sir,
"Your obedient servant,
"J. F. W. Herschel.

"P.S.—On reperusal I see the principle is all very clearly stated in page 5, line 10, *et seq.* But this, by turning over two leaves at once, I unluckily missed.

"P.S.—M. Chossat long ago pointed out the non-sphericity of the crystalline lens, and showed that the curvature was that of an *oblate* spheroid, the central portion being less curved than the exterior.

"Dr. Dudgeon."

50. The effect of perfect vision, such as these lenses afford, beneath the surface of the sea is curious and unexpected. If the sea is perfectly clear, as it is on many parts of the coast, when we dive, say from 6 to 10 feet in water of about 20 feet in depth, we see the bottom most distinctly; every stone, every shell, every leaf of seaweed that may be growing on the sand is distinctly visible over a considerable space. But on looking around us horizontally we are surprised at the gloom of the prospect. However bright the day may be above, we seem to be looking into the depths of an obscure cavern, wherein is

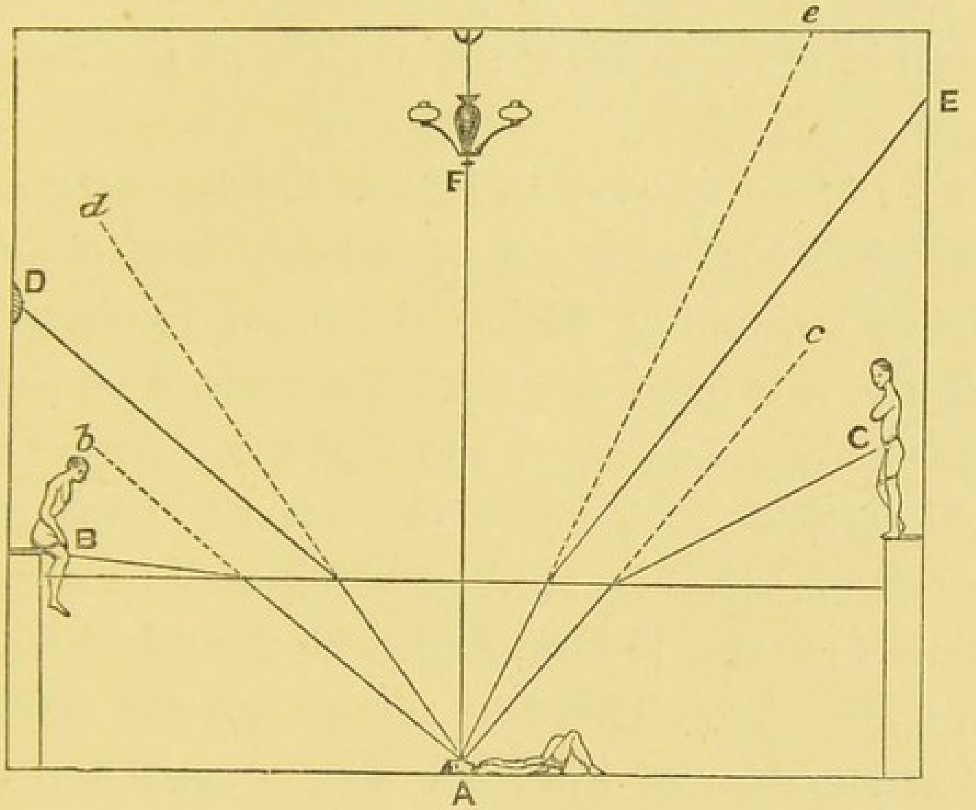
"No light, but rather darkness visible."

The weird void that seems to extend all around us, unless where it is broken by a fragment of floating seaweed, some air-bubbles hastening up to the daylight, or perhaps the white limbs of some distant fellow-bather, seems unaccountable under a bright sunshine.

If we turn on our back and look upwards, we shall find that the light seems not to penetrate all the surface, but only a limited portion of it. The surface of the sea is seldom so smooth as to enable us to note exactly what takes place, but if we will gently glide to the bottom of an ordinary swimming bath when the surface is undisturbed by other bathers, we shall see what remarkable effects are produced by the refractive power of the water on the rays of light coming to it from the air.

51. In the diagram (Fig. 17) I have endeavoured to represent what will be seen by an observer looking up-

FIG. 17.



wards from the centre of the bottom of a small swimming bath. The knees of the bather B will appear to be at *b*; the middle of C's body will be elevated to *c*: the clock D will be raised to *d*; the wall of the room at E will be at *e*. The lamp F being directly above the observer's eye, the rays of light proceeding from it perpendicularly will suffer no refraction, consequently the lamp will be seen in its true place. All parts of the room and all the objects in it, except what are immediately above the observer's head, will be more or less distorted. Objects must be at a certain elevation in order to be seen at all by the immersed observer. The reason of this is, that rays of light must impinge on the water at a certain angle (about 10° from the horizontal) in order to enter the surface of the water and be refracted.

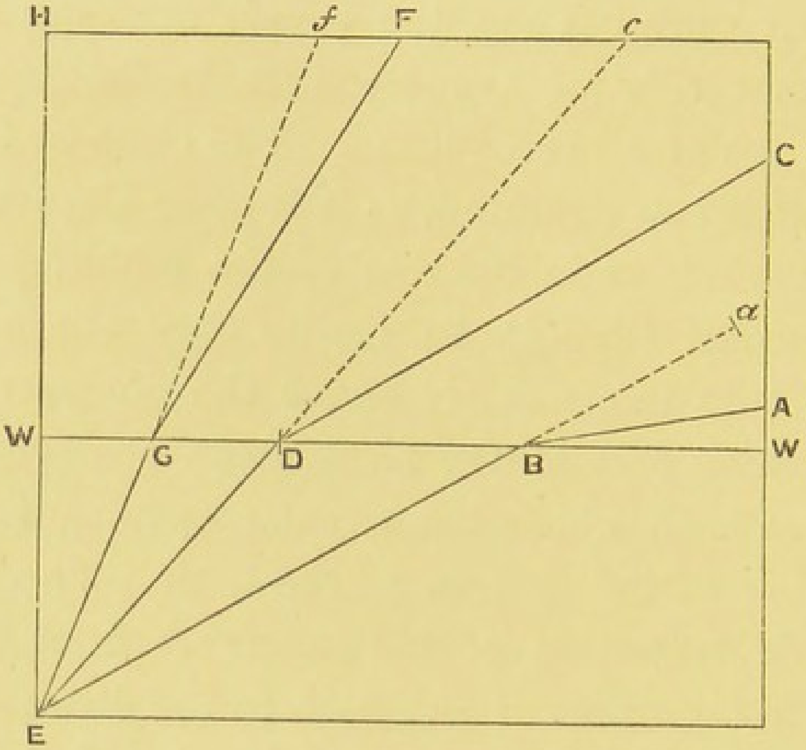
Fig. 18 * will convey an idea of the appearances seen by an observer immersed in the centre of one of the London swimming baths. In order to observe this perfectly, it is necessary that the surface of the bath be perfectly undisturbed, and that the observer should let himself down beneath the water without causing any movement of its surface, which may be done after repeated trials. He must also be furnished with air-lens spectacles. The first thing that will strike him is that the floor of the bath is accurately and vividly pictured on the under surface of the water, as though that were a mirror of silvered glass. This picture of the floor is pierced by a circular opening, cut out as sharply as if done with a knife, and the edge of the opening is fringed by a delicate iridescent border. Through this opening the whole of the room and its contents are visible, with the exception of the parts and objects very low down. Thus in the bath we

* See frontispiece.

have here depicted, a border about 2 feet high, ornamented with scroll work, is not visible to the immersed observer. All objects, except those immediately above the observer's head, are more or less distorted; the nearer they are to the horizon the more distorted they are. Thus, the person standing on the right-hand side of the woodcut is flattened and dwarfed out of all recognition. The clock at the top of the cut is less distorted, as it is more elevated; but even the windows in the roof of the building appear to be curved (though in reality they are not so), except those immediately above the observer. The most striking part of the phenomena observed is the sharpness with which the circular opening is cut in the picture of the bottom of the bath. There is no noticeable transition of indistinctness from the pictured porcelain tiles of the bath to the distorted view of the objects above the water in its circular frame. A very careful observation may indeed detect a ghostly prolongation of the pattern of the bottom of the bath a little way beyond the edge of the circular opening, but it is so very indistinct that it is not noticed unless steadily looked for.

The explanation of these phenomena will be found in the subjoined diagram (Fig. 19). A ray of light from an object A impinging on the surface of the water W W at an angle of 80° from the perpendicular is refracted at B at an angle of about 60°, whence it is prolonged to the eye below the water at E. The eye sees the object whence the ray A proceeds in the

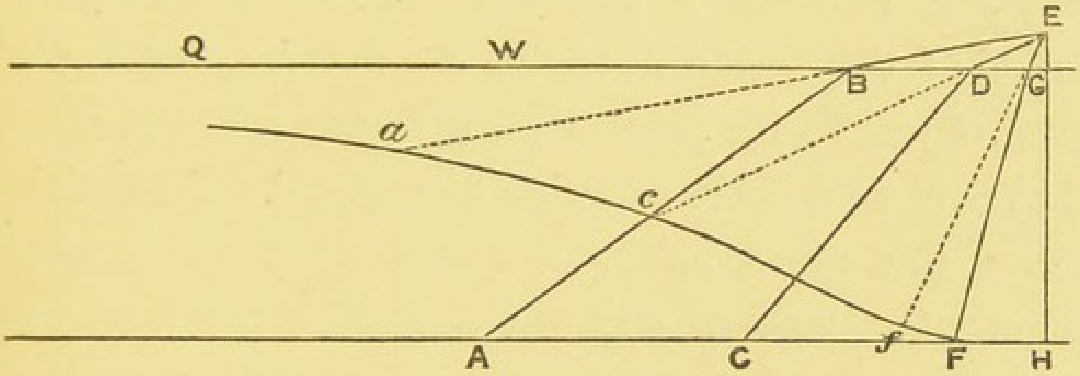
FIG. 19.



refracted direction, consequently at *a* in place of at A. The point C sends a ray which, striking the surface of the water at an angle of 60° at D, is refracted thence to the eye at an angle of 40° from the perpendicular, and seems to be at *c*. So also a ray from the point F impinging on the water at an angle of 30° from the perpendicular is deflected at C at an angle of 20° to the eye at F, by which it will be seen at *f*. The rays from H, striking the surface of the water perpendicularly, suffer no refraction in their course to the eye at E, and therefore H is seen in its true position. Beyond the point B, where the rays of light from the lowest point outside the water capable of being refracted are bent towards the eye, the under surface of the water acts as a mirror, reflecting with perfect accuracy and distinctness the floor of the bath.

The converse of these phenomena may be observed from above the water by the eye placed at E (Fig. 20) at a very small height above the surface of the water.

FIG. 20.



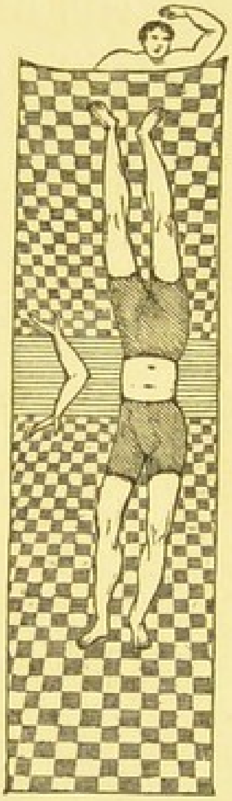
The rays proceeding from the bottom of the bath at H, directly beneath the eye, being perpendicular, suffer no refraction, and the point H is accordingly seen in its true position. On the other hand, the rays from the point F at an angle of 10° from the perpendicular on emerging from the water at G are refracted to the eye at an angle of 13°, and the point F appears to the eye at *f*. So also the rays from the point C, produced at an angle of 40° from the perpendicular, are refracted when they reach the surface of the water W at D, at an angle of 53° to the eye at E, and the point C will consequently appear to the eye as if at *c*. The rays from point A, at an angle of 53° from the perpendicular, are refracted to the eye at B at an angle of 70°, and the point A will seem to the eye to be at *a*. Hence to the eye at F the floor of the bath appears to rise upwards towards the surface of the water with a strong curve, and the bottom of the bath disappears beneath the surface of the water at Q. Beyond this point the bottom of the bath is not seen, and the surface of the water becomes a mirror, reflecting external objects with perfect accuracy.

It requires a little practice to make the observations I have described under the water. To slip gently beneath the surface without agitating the water, and to place oneself face upwards at the bottom of the bath and make observations with distinctness in such a novel situation, is not without its difficulties. I would advise those who attempt the feat to wear a nose-clip, otherwise the water will fill the cavity of the nose and cause a disagreeable sensation.

The phenomena described may be partially observed in the large glass tanks of our aquaria. If we place the eye near the bottom of the glass plate that forms the side of such a tank and look upwards, we see the bottom of the tank and the fishes in the water reflected from the under surface of the top of the water, and at the side next the eye a semicircular opening fringed by an iridescent ring,* through which objects in the air above are seen distorted as I have described.

To the immersed observer the appearance of a bather standing at a short distance from him is very droll. I have endeavoured in the cut (Fig. 21) to represent what we see. We shall suppose that the water reaches to his waist. We see the body in an upright position as far as the waist standing on the tesselated floor of the bath. Above and joined to this figure is an inverted reflexion of the bather, standing on the mirrored tesselated floor. Above this again, we have the circular opening in the reflected floor, through which we see the head and shoulders of the bather unæsthetically flattened.

FIG. 21.



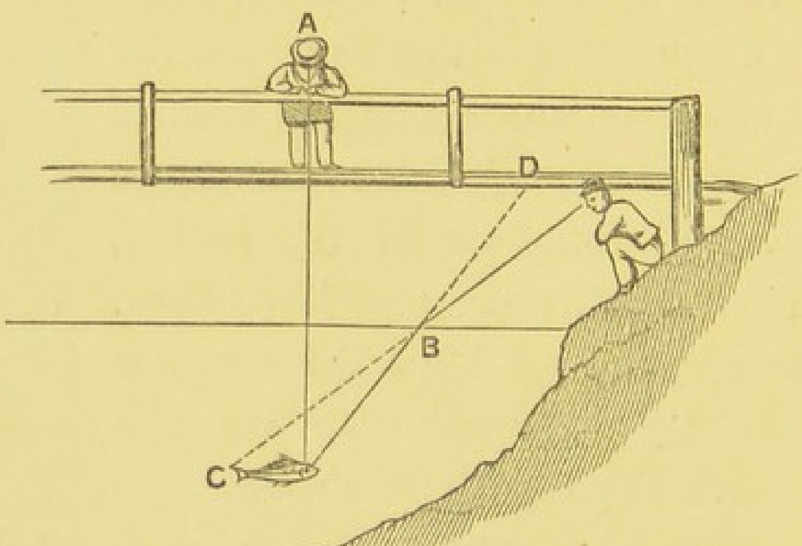
52. Though, to the immersed observer, the picture

* Owing, I suppose, to the great refractive power of the thick plate-glass forming the side of the aquarium tank, the iridescent fringe is broader and brighter than it appears to the immersed eye.

of objects above the water and the reflexion of the bottom of the bath are broken into fragments by every agitation of the surface, the distinctness of objects immersed in the water is no more affected by any movement of the water, provided only the water be clear and of equal density throughout, than is that of objects in the air, to an observer in the air, by a breeze of wind.

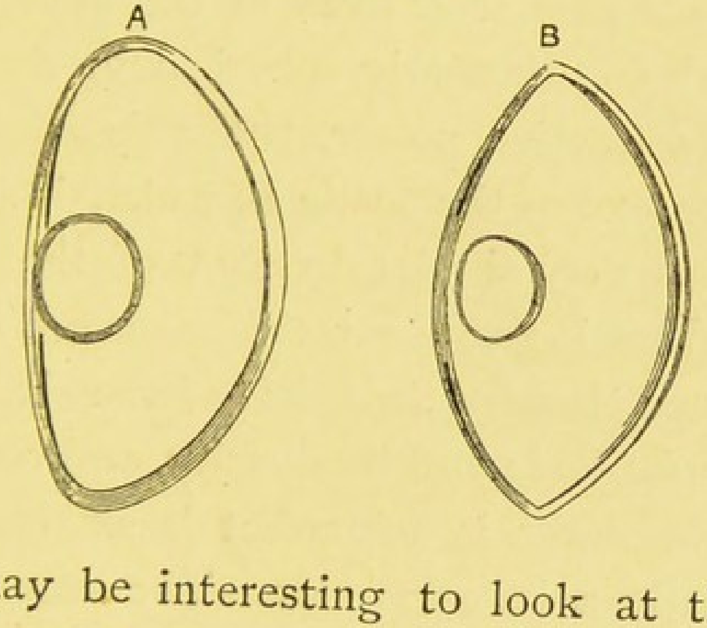
53. To a fish in clear smooth water a man on the bank will be as distinctly visible as the fish is to the man; only, unless the observer is placed directly above

FIG. 22.



the fish, each will appear to the other to occupy positions more or less far from their true places. Thus the observer on the bridge at A (Fig. 22) receives and transmits rays of light in a perpendicular direction from and to the fish, consequently both he and the fish will see one another in their true places. But the rays from the man on the bank striking the water obliquely are refracted at B. The consequence of this is that the man on the bank sees the fish at C, and the fish sees the man at D. This disagreement of the true with the apparent position of objects in the water seen from the side, is a fact familiar to those who have attempted to shoot fish in the water. One has to aim considerably below the fish in order to hit it.

FIG. 23.



54. It may be interesting to look at the optical construction of the eyes of fishes and other aquatic animals and see how it is that they can see distinctly in the watery medium where they are obliged to live.

Fig. 23 shows diagrammatic sections of the eye of a skate A, and the eye of a turtle B. In the skate's eye, and generally in the eyes of fishes, the cornea is nearly quite flat, the aqueous humour is insignificant, and there is virtually no anterior chamber, for the crystalline lens comes up close to the cornea. A convex cornea filled by an aqueous humour would be of no use in the water, the refractive index of the water being identical with that of the aqueous humour. Accordingly the refraction of the rays of light has to be effected entirely by the crystalline lens, which is nearly spherical, and of much greater refractive power than the corresponding organ in animals which pass their lives in the air. The crystalline lens being so nearly spherical in shape, and of such high refractive power, the axis of the eye is short. The eye of the turtle B, which is so much in the water, is very similar to that of the fish. The crystalline lens is very near the cornea. The lens is smaller proportionally than that of the skate, nor is it nearly so spherical; and its density, and consequently its refractive power, is somewhat less. Hence it has proportionally a longer focus. The cornea is more convex than that of the skate. There is nothing in the configuration or the optical construction of the eyes of fishes or amphibia which should prevent them seeing, with tolerable, if not with perfect, distinctness in the air as well as in the water, for the refractive power of the crystalline lens will be the same whether the animal is in water or in air, as this lens is still enveloped in a watery medium (the aqueous and vitreous humours) when the animal is in the air. The fish having no eyelids nor any lachrymal apparatus, its cornea will be apt to become dim by exposure to the air,* but the turtle is well supplied with the requisite apparatus for maintaining the transparency of the eye in air. Ophidian reptiles have no eyelids or lachrymal apparatus, but they do not require them, as their cornea is transparent though dry.

VI. ACCOMMODATION.

55. But to return to the human eye. We have hitherto been considering the optical properties of the eye in relation to the incidence of parallel rays, that is, to the vision of distant objects, the rays of light proceeding from which approach the eye in nearly parallel lines. But, as is well known, the normal eye is capable of focusing distinctly on the retina the image of objects moderately near the eye, as near indeed as from 6 to 10 inches. Now it was shown above (Fig. 5) that the divergent rays of light proceeding from a near object are focused at a greater distance behind a lens

* Some fishes are capable of living a long time out of water, such as the climbing perch of Ceylon. The transparency of the cornea in such fishes is probably preserved by some peculiarity in its construction.

than the nearly parallel rays from a distant object. In other words, the same refractive power is unable to focus the images of near and distant objects on a screen at the same distance behind it. In order that the divergent rays from the near object should be accurately focused on the screen, one of two things must happen: 1, either the distance between the back of the lens and the screen must be increased; or, 2, the refractive power of the lens must be increased.

56. As the optical apparatus of the eye is subject to the same laws that govern the refraction of light in our optical instruments, the same rules that apply to the latter must equally obtain in the former. Hence in the vision of near objects, either the distance of the screen, i. e. the retina, from the eye lenses must be increased, or the refractive power of these lenses must be increased.

57. The most diverse views as to the means by which one or other of these operations is effected have been held, and are still held, by distinguished physiologists and physicists. Thus Kepler supposed that the eye was lengthened and shortened by the action of the ciliary processes. Others have held that an elongation of the eyeball, in order to adapt the eye for near vision, was effected by the pressure of the external muscles of the eye. Huygens thought

that the crystalline lens, in near vision, approached the cornea by the pressure of the external muscles, or that the convexity of the crystalline lens might be increased by the same means. Porterfield imagined 3. Porterfield. that the crystalline lens was drawn backwards and forwards by the ciliary processes. We now know that the ciliary processes are not muscular, and are incapable of motion, and that the pressure of the external muscles can have no influence on the position or shape of the crystalline lens, and cannot elongate the eyeball, which, moreover, is not elongated in adapting the sight to near objects. Sir David Brewster* maintained, with Huygens, that, in 4. Brewster. near vision, the distance of the crystalline lens from the retina is increased, and he conceived this to be effected by some unexplained mechanism at the base of the iris. But this idea makes no account of the aqueous humour, which would have to advance along with the crystalline lens and its appendages, as it is an incompressible fluid, and cannot escape to the back of the lens during its supposed forward movement.

58. As, then, the idea of an increase of the distance between lens and retina had to be abandoned, it was necessary to assume an increase of the refractive

* 'Treatise on Optics,' p. 302.

power of the eye lenses or of one of them during near vision. The more convex the surface of a lens, *cæteris paribus*, the shorter its focus. So, then, it is obvious that if by any means the convexity of one or both of the eye lenses could be increased, the requisite shortening of their focus for the vision of near objects would be effected.

59. Some contended that the convexity of the cornea was increased in near vision, by the simultaneous contraction of the external muscles of the eyeball causing the globe to be squeezed into a flatter shape posteriorly, and thus made to bulge and become more convex in front. The principal advocate of this notion was Sir Everard Home,* who constituted himself the opponent of Dr. Young's view (to be mentioned presently). He invented an instrument by which he alleged he could measure the exact extent of the increase of convexity that occurred in the cornea. That no alteration occurs in the convexity of the cornea during accommodation is known by the unaltered size of the reflected image of the candle flame, and is proved by my own observations under water, where accommodation remains perfect, though the refractive power of the cornea and aqueous humour is extinguished.

* 'Phil. Trans.,' vol. lxxxv.

60. So the cornea being abandoned, the increased refractive power had to be sought for in the crystalline lens. Dr. Young, in 1801,* contended that the convexity of this lens was increased in near vision, which is the opinion held by most writers on optics at the present day. He said that this increase of convexity was caused by the automatic action of the crystalline lens, which was a muscle, as its fibrous structure showed. In this he followed Descartes, who held that the crystalline was a muscle, the ciliary processes being its tendons, and that it increased or diminished its convexity, and thus adjusted itself to vision at different distances, by means of its muscular power.† It is now known that the fibres of this lens are not muscular.

6. Young.
7. Descartes.

61. In 1849 a distinguished German surgeon, Maximilian Langenbeck,‡ thought he could prove the increased convexity of the crystalline lens in near vision by the changes in position of the image of a candle's flame reflected from the different surfaces of the eye lenses. He set himself to discover how this increase of convexity was brought about, and satisfied himself that it was effected by a circular muscle that

8. Langenbeck.

* 'Phil. Trans.,' vol. xci.

† 'Edin. Encyclop.,' Art. "Optics," p. 564.

‡ 'Klin. Beiträge aus dem Gebiete der Chirurgie und Ophthalmologie.' Göttingen.

surrounded the edge of the crystalline lens. This muscle he called the *musculus compressor lentis accommodatorius*, and he gives an admirable picture of it in his book. Other observers have not been able to see this muscle, so they have come to the conclusion that it was manufactured by the discoverer's scalpel, a fact not altogether without precedent in minute anatomy.

62. A young Dutch doctor, A. Cramer by name,* constructed an instrument by which he was enabled to observe with a microscope the changes in position of the reflected image of the candle with greater accuracy than could be attained by Langenbeck's method of holding the candle in his hand and inspecting the eye without any magnifying power. He asserted that what he saw proved the increased convexity of the crystalline lens in near vision; and he imagined that the increased convexity was caused in some unexplained manner by the muscular action of the iris.

63. Helmholtz,† the eminent physiologist and phy-

* 'Physiologische Abhandlung über das Accommodationsvermögen der Augen Leer,' 1855. (German translation of the Dutch original.)

† 'Physiologische Optik,' § 12. In this work will be found a most complete account of all the views that have been held by all writers on this subject. I have not thought it necessary to give more than the views of a few of the more conspicuous authorities.

sicist, likewise examined the eye as Cramer had done, but without a microscope, and is satisfied that it is by an increase in the convexity of the crystalline lens that accommodation for near vision takes place.

Donders * followed Cramer's mode of examining the eye, and adopts nearly the same view. 11. Donders.

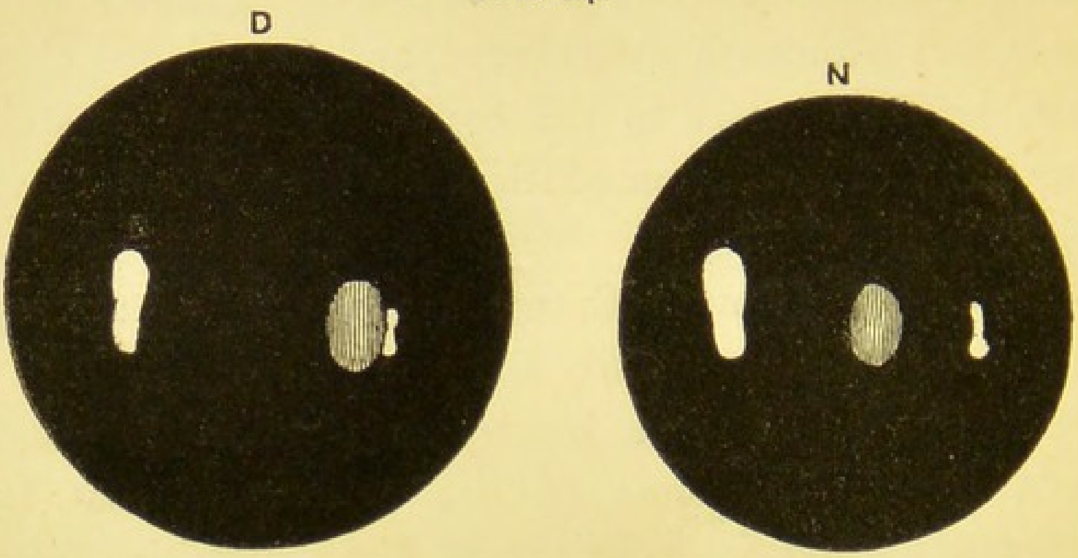
64. But while these illustrious physiologists and ophthalmologists come to the conclusion that, in accommodation for near vision, the crystalline lens increases in convexity, and therefore in refractive power; their observations of what really occurs in the catoptrical phenomena of the eye differ considerably. (3). Account of changes observed

Langenbeck only observed that the image of the candle flame reflected from the anterior surface of the crystalline lens *moved* when the eye was adjusted from distant to near vision and *vice versâ*.

65. Cramer describes this image as moving towards the corneal image in accommodation for near vision, and slightly diminishing in size. He gives a diagram representing the image of the candle flame as moving towards the corneal image and the centre of the pupil, and as of diminished size. (Fig. 24, D, the eye accommodated for distant vision, N, for near vision.)

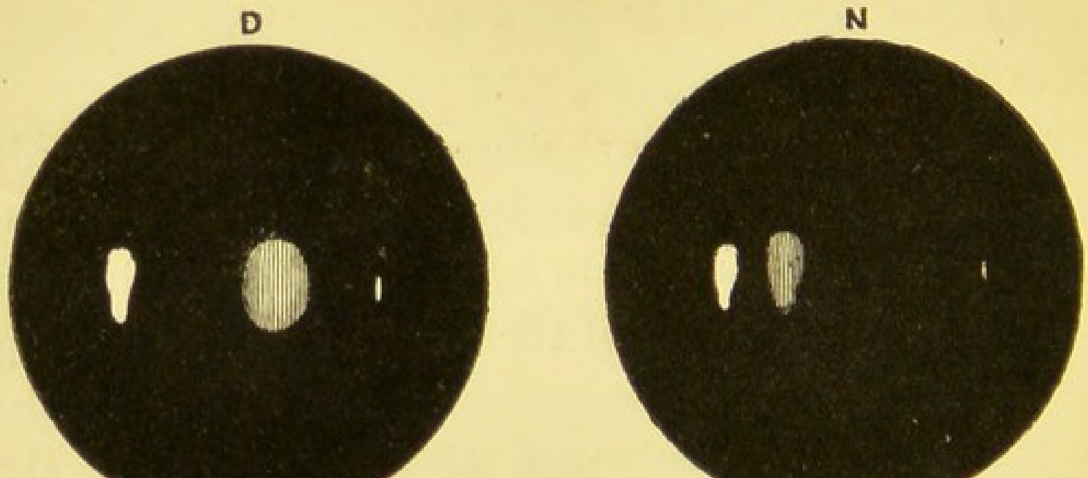
* 'Accommodation and Refraction of the Eye.'

FIG. 24.



66. Donders represents the same image as moving towards the corneal image but away from the centre of the pupil, i.e. towards the pupillary border of the iris. (Fig. 25, D, distant, N, near vision.)

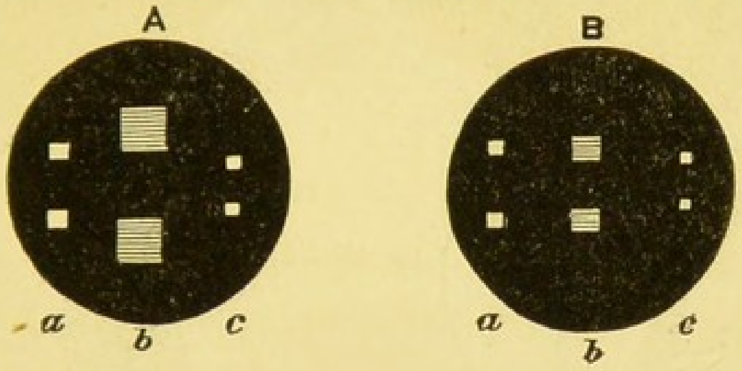
FIG. 25.



67. Helmholtz dwells most on the diminution of size of the candle-flame image reflected from the anterior

surface of the crystalline lens when the eye is adjusted for near vision. He says that it *generally* (*in der Regel*) also moves towards the centre of the pupil. The diagram he gives, however, shows no movement of the image to one side or the other, but only a diminution of its size. (Fig. 26.)

FIG. 26.



68. The following are the changes which he asserts * take place in the eye on being adjusted to near from distant vision:

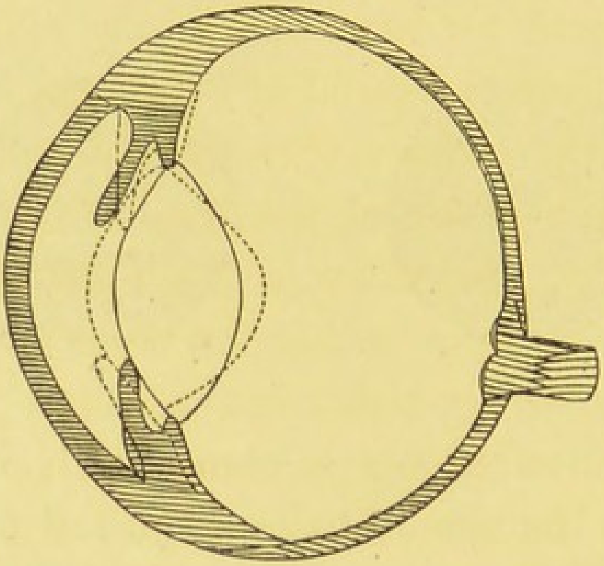
1. The pupil contracts. 2. The pupillary portion of the iris moves forward. 3. The peripheric part of the lens recedes. 4. The anterior surface of the crystalline lens becomes more convex and its vertex moves forwards. 5. The posterior surface of the lens becomes somewhat more convex, and does not sensibly change its place. The lens therefore becomes thicker in its centre, and its circumference must be diminished, or,

* 'Archiv. f. Ophthalmologie,' Bd. i., pt. 2.

to speak more correctly, its equator must be contracted.*

69. A somewhat similar idea is entertained by Hensen and Völcker in their joint work.† They give a diagram, Fig. 27, to illustrate the changes they suppose to occur.

FIG. 27.



It will be observed that the lens here depicted not only increases in convexity before and behind, but grows perceptibly larger in passing from distant to

* In his 'Physiologische Optik' he gives a figure to illustrate these changes very much the same as Fig. 28 farther on. The left half of the diagram represents the supposed form of the crystalline lens when at rest or accommodated for distance, the right half the same when accommodated for near vision.

† 'Experimental Untersuchung über den Mechanismus der Accommodation,' Kiel, 1868.

near accommodation. (The dotted lines indicate the change supposed to occur.) The authors do not blink this fact, but are quite equal to the task of explaining how this is so. The crystalline lens, they say, consists of a series of tubes arranged side by side. When the eye is in a state of rest, i. e. when it is accommodated for distant vision, these tubes are empty, but when it is accommodated for near vision, the ciliary muscle pumps water from the canal of Petit, which surrounds the lens, into these tubes, thereby increasing the size and altering the shape of the lens. This is a very pretty idea, that the canal of Petit should be, as it were, a main water-pipe with continuous supply, ready at any moment to let water into the service pipes of the lens whenever the tap is turned on by the action of the ciliary muscle. What a pity the ingenious authors do not inform us what effect this filling with water of the tubes of the crystalline lens would have on its refractive properties as a lens, why these capillary tubes do not keep themselves constantly filled without the assistance of the ciliary muscle, or how, being filled, they empty themselves again.

70. Explanations more or less satisfactory, or rather unsatisfactory, have been offered of the mode in which the ciliary muscle effects the supposed increase of

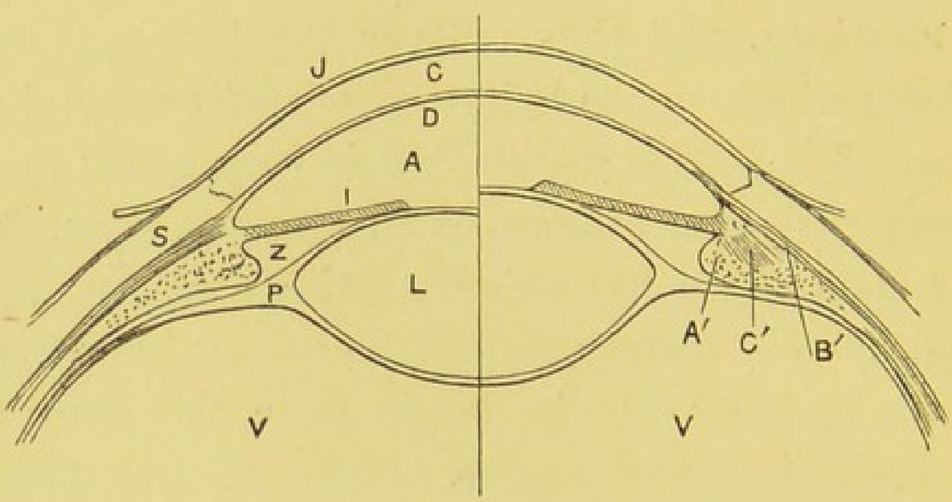
convexity of the crystalline lens in accommodation for near vision. The following is now the most generally received account of what occurs.

(c). Generally received Explanation

The crystalline lens is enclosed in a strong cartilaginous bag called the capsule, the special attribute of which is its elasticity. This capsule and its contents assume, when detached from the influence of its connexions, the thicker and more convex form which it takes in near accommodation, and the entire lens if subjected to a gentle antero-posterior squeeze will yield and become thinner and flatter, and when released will resume at once its thicker and more convex form.

It is thus evident that if the lens were, when at rest within the eye, free to adopt its own shape, the eye would be always accommodated for near objects, and would be useless for distant vision. It is therefore necessarily presumed that the periphery of the lens is continually under tension, which flattens its form and maintains it in that condition, i. e. the condition of accommodation for distant vision. This tension cannot be muscular in its origin, because were it so the muscular spasm must be constant and unremitting—a condition which cannot exist—and because it has been conclusively demonstrated that muscular relaxation (which may be artificially produced by atropia) is accompanied not by a shortening of the sight (i. e. by a thickening of the lens), but by the contrary condition. The cause of this tension is therefore to be ascribed to the passive elasticity of the structure attached to the circumference of the lens, and the muscular effort in near accommodation counteracts this elasticity, and thus relieves the lens-capsule of the force which prevents its assuming its natural curvature. The lens is maintained in its position by the suspensory ligament known as the zonule of Zinn. This attachment seems to be simply a thickened expansion of the hyaloid membrane which encloses the vitreous humour, and it takes its origin from the margin of that body, just where the retina terminates close to the posterior limit of the ciliary muscle. It is highly elastic, and its strength and elasticity are increased by the interweaving of radiating fibres of elastic tissue. It lies between the ciliary processes and the lens, and is attached to the anterior capsule, having between itself and the vitreous humour a space about the twelfth of an inch wide, immediately abutting on the edge of the lens. This space is called the canal of Petit, within which the edge of the lens is supposed to advance and recede during the changes of its form which take place in accommodation. To account for the continuous flattening of the lens this suspensory ligament is presumed to keep up an elastic pull upon the capsule. Outside or rather in front of it are placed two structures, the ciliary processes A′, and the ciliary muscle B′ C′, Fig. 28. The ciliary processes

FIG. 28.



J, conjunctiva; C, cornea; S, sclerotic; D, membrane of Descemet; A, aqueous humour; I, iris; L, crystalline lens; V, vitreous humour; Z, zonule of Zinn; P, canal of Petit; A′, ciliary process; B′, longitudinal fibres of ciliary muscle; C′, radiating fibres.

contain numerous blood-vessels, and the ciliary muscle is composed of longitudinal and circular fibres. The longitudinal fibres B′ arise from the membrane of the aqueous humour (Descemet's membrane) at its angle where it is reflected on the iris, and are attached posteriorly to the connective tissue of the choroid just where the retina ends, and where the ligament of the lens-capsule, the zonule of Zinn, arises. The circular fibres are wider in the meshes and are spread out upon the ciliary processes. The actual mechanism of accommodation is supposed to be as follows:

a. The retina becomes conscious of the confusion of the image produced by a near object as depicted on it by the lens flattened by the strain of the elastic capsule and its tense ligament. This consciousness of imperfect vision being conveyed to the brain, the brain sends its orders through the appropriate nerves to the ciliary muscle which

b. Contracts. Its circular fibres constrict the venous trunks, and this prevents the return of the blood through them to the choroid. This produces erection of the ciliary body, the effect of which on the lens's ligament is not very apparent.* The longitudinal fibres by their contraction draw together the anterior limit of the choroid (to which the lens's ligament, the zonule of Zinn, is attached). The elastic tension of this ligament is thereby counteracted, and the lens assumes its thicker and more

* Priestly Smith ('Brit. Med. Journal,' 6th Dec. 1873,) has shown by galvanic experiments on the enucleated eye of a rabbit that vascular turgescence has nothing to do with the changes in the crystalline lens during accommodation. On the other hand Mr. Norton ('Brit. Med. Journal,' 27th Dec. 1873) says that though part of the increased convexity in accommodation may be caused by the action of the ciliary muscle and iris, it is kept up by strangling the small vessels and retaining the blood in them like erectile tissue.

convex shape; its focus is thereby shortened, and the image of the near object is accurately pictured on the retina.

When the lens is thus relieved of the controlling pressure by its elastic covering and ligament, it is supposed to become thicker and more convex anteriorly. It accordingly is assumed that its anterior surface advances towards the cornea, and that its periphery recedes within the canal of Petit.*

71. Now this is a very pretty explanation indeed; the only question is, is it true? The advance of the anterior surface of the lens and its increased convexity must be accompanied by a diminution of its peripherical circumference. Has this diminution been observed? Otto Becker and Coccius say that they have observed this recession of the periphery of the lens in the eyes of albinos, and in cases where iridectomy had been performed. On the other hand, Von Graefe was unable to see any such recession in a case where the whole iris was accidentally removed, and in which the accommodation faculty remained intact, though the catoptric phenomena, above described, were plainly visible; and Donders failed to

* This, which is the explanation offered by Helmholtz, is given nearly in the words of Dr. A. H. Jacob in a lecture reported in the 'Med. Press and Circular' for July 26, 1876.

discover any such recession in eyes in which iridectomy had been performed. Thus the weight of authority is rather against the occurrence of a diminution of the peripheral circumference of the lens in accommodation for near vision, and the above explanation remains a doubtful hypothesis.

Then with regard to the hypothesis of the supposed increased convexity of the crystalline lens being occasioned by the contraction of the ciliary muscle causing diminution of the tension of the elastic structures enveloping the lens, and thus allowing the lens to assume its normal form, which is alleged to be more convex than it is when these elastic envelopes are not relaxed by the action of the ciliary muscle: if this view is to be accepted we encounter this little difficulty, viz. that in advanced life distant accommodation remains perfect, while the faculty of near accommodation is diminished or lost. Hence we must believe that the tension of the capsule with its connexions remains unimpaired or even increases in old age, while the muscular power of the ciliary muscle declines or is altogether lost. Does it not seem highly improbable that the supposed tension of these delicate structures should continue unimpaired or even increase with advancing years—for many presbyoptics require a convex lens even for distant vision?

Again, what reason is there for supposing that the muscular power of the ciliary muscle is so much impaired in old age when we find that the power of a neighbouring and analogous muscle, the circular fibres of the iris, is rather increased in old age, seeing that the pupil as a rule becomes more contracted as we grow older ?

In normal or emmetropic eyes the limits of distinct vision vary much with age. Fellenberg says that at ten years of age the "near point," that is, the minimum distance at which an object can be seen distinctly, is $2\frac{2}{3}$ inches distant from the front of the cornea ; at twenty years, $3\frac{5}{9}$ inches ; at thirty, $4\frac{4}{5}$ inches ; at forty, $6\frac{6}{7}$ inches ; at fifty, 12 inches ; at sixty, 24 inches ; and at seventy, 144 inches.* The "far point" of distinct vision for normal eyes is infinite distance at all ages ; but as before stated, many old persons require a convex lens for the distinct vision of even distant objects. The gradual increase of this "near point," as years increase, may, I think, be satisfactorily accounted for by the flattening of the eye lenses. That the cornea which gives its shape to the anterior aqueous lens becomes flatter in old age has been generally remarked, and I am convinced by

* 'Carpenter's Physiology,' 12th Edit., p. 801. These figures are probably averages, they are certainly not invariably correct.

repeated observations in old and young subjects of the catoptric appearances connected with the anterior surface of the crystalline, that the crystalline lens is also flatter in advanced age. Now we need not suppose that removal of the "near point" in advanced life is owing to a loss of power in the ciliary muscle, all we need say is that the action of the muscle cannot remedy the altered shape of the eye lenses.

72. Let us now consider the catoptric phenomena that have been observed in the change of accommodation from distant to near vision. When a candle is placed on one side of the eye and the observer looks at the eye on the level of the candle flame from the other side, three images of the candle flame are observed in the pupil: 1, a large, distinct, upright image of the flame on the side nearest the candle, the reflexion from the surface of the cornea; 2, a large indistinct, upright image of the candle flame near the centre of the pupil, the reflexion of the anterior surface of the crystalline lens; and 3, a small inverted image of the flame on the side most remote from the candle, the reflexion from the posterior surface of the crystalline lens. In the figures given by Cramer (Fig. 24) the large indistinct upright image of the flame is observed in accommodation from distant to near vision to move towards the bright upright corneal

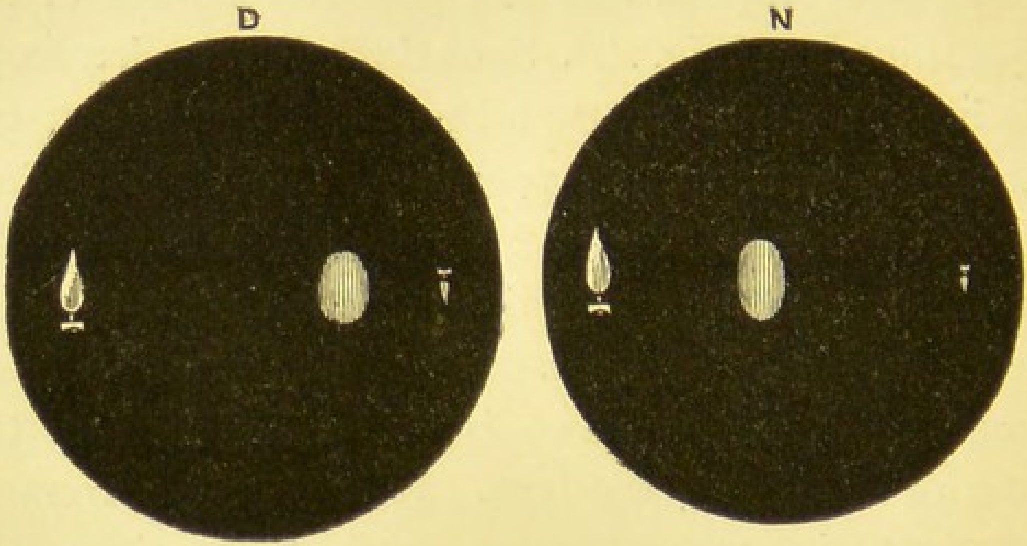
image, its size being slightly diminished. In the figure given by Donders (Fig. 25) of the same phenomenon, the image reflected by the anterior surface of the lens moves more markedly towards the corneal image, while it undergoes an even greater diminution in size. In the figure given by Helmholtz (Fig. 26) no lateral movement is indicated, the image is only represented as diminished in size in accommodation for near vision, but he says it *generally* moves towards the centre of the pupil. Had he *always* observed this movement towards the centre of the pupil, he would doubtless have said so, but his language leads us to suppose that it sometimes did not appear to move in the indicated direction, and possibly that it was occasionally observed to move in the opposite direction.

73. In order to observe the changes that occur in the image of the candle flame reflected from the anterior surface of the crystalline lens I constructed an apparatus similar in principle to that used and devised by Cramer, but modified in such a way that I could at will observe the eye from either side, while the candle was placed at the opposite side. While the eye under observation was steadily fixed on an object right in front of it, the light of the candle impinged on the eye at a small angle on one side of the line of vision, and I looked at the eye through

a microscope of 1-inch focus placed at a similar angle to the line of vision on its other side. In this way I could see the three images of the candle as they were reflected respectively from the cornea, the anterior surface and the posterior surface of the crystalline lens (Fig. 29). Seen through the microscope the images are of course all reversed, but I represent them here in their true position. The large distinct upright image is the reflexion from the cornea; the small inverted image is the reflexion from the posterior surface of the crystalline lens; the dim large image between these two is the reflexion from the anterior surface of the lens. It is always extremely indistinct in normal eyes, and looks like the ghost of an image when contrasted with the clear, well-defined images reflected from the cornea and posterior surface of the lens. The cause of this indistinctness and want of definition is the very slight convexity of the central part of the anterior curvature of the lens. In some myopic eyes I have examined, where the myopia was evidently, in part at least, owing to the abnormal convexity of the anterior surface of the lens, the image of the candle flame is much more distinct and considerably smaller.

Fig. 29 represents the appearance of the reflected candle flame in the pupil of the right eye when the candle is placed on the external side and the microscope is directed to the nasal side of the eye. D represents the positions of these images when the eye

FIG. 29.

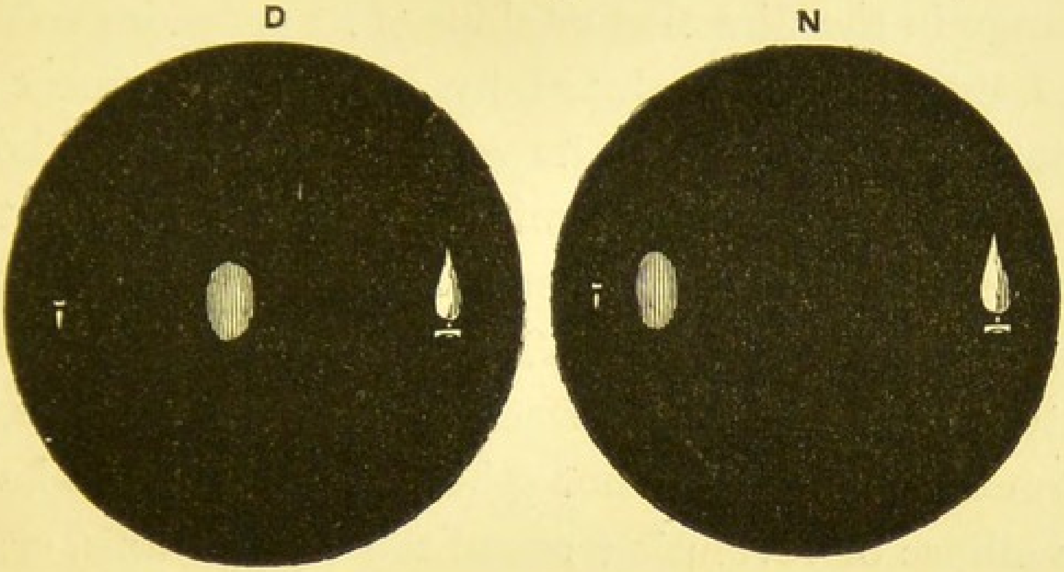


3. Candle placed on the external side.

is directed to a distant object, N the same images when the eye is directed to a near object, i.e. accommodated or adjusted to near vision. It will be observed that in the transition from distant to near vision the pupil contracts, and the dim image reflected from the anterior surface of the crystalline lens moves *towards* the corneal image; it also becomes somewhat smaller, showing that it is reflected from a more convex surface than before.

Fig. 30 represents the appearance of the reflected candle flame in the pupil of the right eye when the candle is placed on the nasal side and the microscope is directed to the external side of the eye. D shows the positions of these images when the eye is directed to a distant object, N the same images when the eye is directed to a near object. In the transition from

FIG. 30.



4 Candle placed on the nasal side

distant to near vision the pupil contracts, and the image reflected from the anterior surface of the crystalline lens moves away from the corneal image, becoming somewhat smaller at the same time.*

74. What is the inference to be drawn from the movement of the image reflected from the anterior surface of the lens in both these observations? Had there merely been an increase of the convexity of this surface accompanied by a forward movement of the lens, it is obvious that the movement observed would in both cases have been towards the apex of the con- 5. Explanation

* These appearances may, with practice, be quite well observed in appropriate eyes, viz. the normal eyes of young persons, by the naked eye without the aid of any apparatus.

vexity, to wit, the centre of the pupil. But, on the contrary, in both instances the reflected image moves towards the external edge of the pupil, showing that the actual change in the crystalline is merely a change in the direction or slope of its anterior surface, and that this is produced by a slight movement of rotation of the lens on its vertical axis from without inwards. The slight diminution in the size of the image shows that it is now reflected from a more convex part of the lens. This is accounted for by the actual shape of this surface of the lens, which is, as formerly pointed out, not spherical but ellipsoidal, viz. an ellipse of revolution round the shorter axis, or, as Sir J. Herschel calls it, an oblate spheroid (Fig. 14, L). Hence the centre is the flattest or least curved portion of the ellipsoidal surface, and consequently the reflected image will be larger when reflected from the centre than from any other point of the surface, as it rapidly increases in convexity from the centre outwards. The movement of rotation causes the candle flame to be reflected from a more convex portion of the lens, hence its diminution in size.

Spherical aberration

75. But, it may be asked, how will the supposed obliquity of the lens in accommodation from distant to near vision, have the effect of diminishing the length of the focus of the lens, and thus focusing the picture accurately on the retina, which was before

focused behind the retina? To this I reply that any one may convince himself that in an ordinary lens with spherical surfaces, a marked diminution of the length of the focus is produced by presenting the lens obliquely to the object. If this takes place in the case of a lens with spherical contours, in which the whole surface is uniformly convex, it will be much more marked in a lens of the ellipsoidal shape of the crystalline lens, where the movement of rotation brings a more convex portion of the lens into the axis of vision.

76. To this view it may be objected that in the case of ordinary glass lenses an oblique position causes the image depicted on the screen to be distorted by what is called spherical aberration of rays. True, but the contours of such lenses are spherical, whereas the shape of the surface of the crystalline lens is ellipsoidal, whereby little or no distortion is produced, as that is precisely the shape which was found by Descartes to obviate the spherical aberration of rays. But even with lenses of spherical contour, this aberration with consequent distortion of the image thrown on the screen may be corrected by interposing a diaphragm with a small opening between the object and the lens. And in the eye, as if to guard against the possibility of distortion by aberration of rays, the diaphragm interposed between the object and the lens, I mean the iris, diminishes the size of its orifice in

accommodation for near vision; that is to say, when the lens is, according to my supposition, presented obliquely to the object.* Hence, there is no possibility of a distorted image of the object being thrown on the yellow spot of the retina, which is the only part of the retina capable of accurately perceiving the image of objects. There is still another provision in the eye for obviating spherical aberration, and that is that the lenses of the eye are a combination of the meniscus (aqueous humour) and double convex lens (crystal-

* The power of a small orifice to correct the greatest amount of distortion from interfering rays is shown by a simple experiment. The normal eye of an adult cannot see to read small print nearer than 6 inches. Within that distance the type becomes more indistinct the closer it approaches the eye. But if we make a pinhole through a card and place it close to the eye, we can see to read printed matter of any size even as near as half an inch from the eye. At that distance we can even see the texture of fine cambric with microscopic definition. The cause of this is easily explicable from what we have before said regarding the course of rays of light impinging on the centre of a lens. The rays striking the lens in this part perpendicularly suffer no refraction. The effect of the pinhole is to exclude all rays but those that impinge perpendicularly on the centre of the eye lenses. Hence the image of the object close in front of the eye is pictured on the retina without the interference of the surrounding rays, which would fall obliquely on the lens, and being refracted out of focus would blur the picture. Observation of the effect of a small orifice in correcting aberrant rays, and of the fact that the pupil contracts in near vision, led Haller and some other physiologists to believe that contraction of the pupil was the sole factor in near accommodation. But this view has been sufficiently refuted by other observers.

line), which is exactly the combination found by Herschel to prevent spherical aberration in ordinary glass lenses.

77. There is, moreover, a provision in the optical construction of the eye to guard against chromatic aberration, by which term is understood that tendency of a lens to throw an indistinct image on the screen by reason of the different refrangibility of the different coloured rays of light. Thus the violet ray is most refracted in passing obliquely through a refracting medium, the red ray least. Supposing the screen is adjusted for focusing accurately the intermediate yellow or green ray, then the rays beyond that towards the violet side of the spectrum would be focused short of the screen, while the rays on the other side towards the red side of the spectrum would be focused behind the screen. In optical instruments this chromatic aberration is got rid of by using a compound lens, formed of a convex and a concave lens of two differently refracting media; usually a combination of flint and crown glass, which have different indices of refraction. A similar provision is made in the eye,* where not only is there a combination of

* At least in accommodation for near vision, where the anterior surface of the crystalline lens, supposing the ordinary view of its increased convexity in this act be accepted, becomes more convex than

two lenses of different refractive powers—to wit, the aqueous lens and the crystalline lens, but the latter lens is not of a uniform refractive power throughout its substance. Its refractive power increases from its superficies to its centre.

Thus the eye, considered as an optical instrument, is constructed on the most approved optical principles for obviating both spherical and chromatic aberration of rays of light.

78. It has been objected to my explanation of the change that occurs in the position of the crystalline lens in accommodation from distant to near vision, that I have not shown how this change is brought about by the action of the ciliary muscle. Considering the utter failure by those who contend for an increased convexity of the crystalline lens in near accommodation to show how this could be brought about by the action of the ciliary muscle, it might be

the convex surface of the anterior aqueous lens, and thus changes the meniscus form of the aqueous lens into a concavo-convex lens. The movement of rotation of the crystalline lens, which, according to my view, occurs in near accommodation, will virtually have the same effect on the anterior aqueous lens as its increased convexity, for owing to the peculiar oblate spheroidal or ellipsoidal form of the anterior surface of the crystalline lens, the rotation brings a more convex portion of the lens into the pupil; moreover, as before shown, the more oblique position as regards incident rays of a lens of even spherical contours is equivalent to an increase of its convexity.

pardoned me that I contented myself with showing what actually occurred, without attempting to conjecture *how* it occurred. But a careful study of the arrangement of the ciliary muscle in the works of distinguished physiologists and histologists, and an independent examination of many eyes of animals, enable me to offer, as I think, a very probable account of the part played by the ciliary muscle in effecting the torsion movement of the crystalline lens in near accommodation.

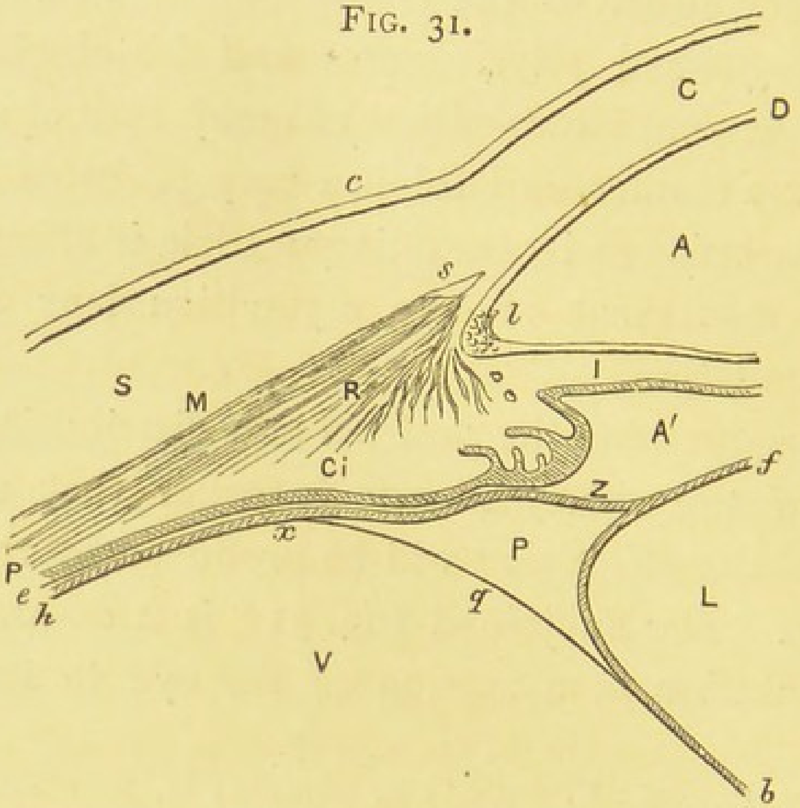
(ε). Action of the ciliary muscle.

Let us examine the position and distribution of the fibres of the ciliary muscle in order that we may judge of the effect that will be produced by their contraction. The subjoined Fig. 31 * is a diagrammatic representation of a section of the eye in its ciliary

* *C*, conjunctiva ; C, cornea ; S, sclerotic ; D, membrane of Descemet, lining the aqueous humour, and at *l*, forming the ligamentum pectinatum iridis ; A, anterior chamber of aqueous humour ; A′, posterior chamber of aqueous humour ; L, crystalline lens ; *f*, anterior wall of its capsule ; *b*, posterior wall of its capsule ; I, iris ; Ci, ciliary process ; *p*, its pigment layer ; *e*, its colourless epithelium ; V, vitreous humour ; *h*, its hyaloid membrane, dividing at *x*, into a thicker lamina Z, the zonula Zinnii, which runs on to the anterior wall, *f*, of the capsule of the lens with which it becomes blended, and a thinner posterior lamina, *q*, which becomes blended with the posterior wall of the lenticular capsule, *b* ; between these two laminæ enclosing the edge of the lens is, P, the canal of Petit ; M, the meridional fibres of the ciliary muscle ; R, the radiating fibres of the ciliary muscle ; *s*, the canal of Schlemm.

region, taken chiefly from Kölliker and Stricker, omitting the details of structure which do not concern the point we are at present inquiring into. The

FIG. 31.



ciliary muscle consists of two parts not distinctly separated, but running into one another. It arises from the internal wall of Schlemm's canal, *s*, and from the pectinated ligament of the iris, *l*, which is the reflected portion of the membrane of Descemet. The outer or meridional longitudinal fibres, M, run parallel with the sclerotic, and are inserted into the choroid membrane; the inner radiating fibres, R, are distributed to the ciliary processes. (H. Müller says the innermost of these fibres constitute an annular muscle, which he terms the *compressor lentis*, though how it compresses the lens in the position it occupies is not very clear.)

Now it is beyond a doubt that the origin of the muscle at the canal of Schlemm is its fixed point. The fibres there terminate in a dense fibrous structure, called by some the tendon of the ciliary muscle, which is merged in the substance of the cornea. The other end of the longitudinal fibres extends to the choroid, in which these fibres are spread out and lost; the radiating fibres spread out in the substance of the ciliary process. Now what must be the effect of the contraction of this muscle, which I prefer to consider as a whole, and not, as some authors assert, as two distinct muscles? Evidently it will pull forward the choroid membrane (the muscle is sometimes called *tensor chorioideæ*) and the ciliary processes, and if we accept the existence of an annular muscle, this will only assist the radiating fibres in pulling the ciliary processes still farther forwards and inwards.*

* I am aware that Dr. Henry Lawson ('Monthly Microscopical Journal,' Oct. 1869), from an examination of the eye of pheasants, comes to the conclusion that the action of the ciliary muscle is just the reverse of this, viz. that it pulls upon and retracts the periphery of the cornea, thus causing its centre to bulge and become more convex; but seeing that in other animals no increase of convexity in the cornea

Supposing one side of the muscle only to be thrown into action, what effect will be produced? The choroid membrane encloses and is firmly attached to the vitreous humour, therefore the traction exercised by the muscle on the choroid will move the vitreous humour forwards and inwards, and this motion will be carried on to the corresponding edge of the crystalline lens. But the radiating fibres, R, draw the ciliary processes, Ci, forwards and inwards, and the ciliary processes are intimately connected with the anterior thickened process of the hyaloid membrane, called here the zonule of Zinn; so intimately, indeed, are the ciliary processes dovetailed and united with the portion of the zonule on which they lie that we cannot separate them without leaving fragments of the pigment lamina, *p*, and epithelium, *e*, of the

has been detected, and that the anterior termination of the muscle is in a stiff and unyielding membrane, while its posterior is in the comparatively loose choroid, it is as impossible to conceive this action of the muscle on the cornea, as it is to imagine, *à la* Dundreary, his tail wagging the dog, in place of the dog wagging his tail. I have dissected numerous eyes of pheasants and can testify to the size and distinctness of the ciliary muscle. In other respects the optical construction differs from that of the human eye chiefly in these respects: the globe is much flatter, the crystalline lens is very thick, its anterior surface very slightly convex, while the posterior surface is very convex, but the shape of the curvature very distinctly that of an oblate spheroid, so that an oblique position must very sensibly shorten its focus.

ciliary processes adhering to the zonule. The zonule, *z*, after quitting the ciliary processes, passes on to the anterior wall of the lenticular capsule, with which it becomes blended a little beyond the edge of the lens, and this portion is sometimes called the *suspensory ligament of the crystalline lens.* Hence the forward movement of the ciliary processes will assist in pulling the lens forward, and thus give it the rotary movement on its axis I before described, whereby its focus is shortened so as to form a distinct picture of a near object on the retina.

79. This rotary motion is only possible on the supposition that the contraction of the ciliary muscle takes place on one side only in accommodation for near vision, whilst the muscle on the opposite side of the eye is in a state of relaxation.

80. There seems to me no reason to doubt that contraction of the ciliary muscle may take place in one portion of the muscle at a time. The motor nerve that supplies the ciliary muscle is derived from the third pair, which also regulates the movement of the circular muscle of the iris (which is contracted during near accommodation), and of several of the external muscles of the eye which are capable of independent movements.

81. It may be objected to my view that the ex-

ternal portion of both ciliary muscles is brought into action at the same time in accommodation for near vision; whereas in the movements of the eyeball, while the external muscle of one eye is in action, the internal muscle of the other eye is contracted. But in accommodation for near vision this is not so, for the two internal recti act simultaneously, causing convergence of the ball, or a slight internal squint; so that there is no improbability, but on the contrary by analogy a strong probability, that the external portions of the ciliary muscle of both eyes may act simultaneously, as the catoptric phenomena indicate. In voluntary inward-squinting we find that we naturally accommodate the eyes for near vision in the act of squinting.

82. It frequently happens that obscure points of the anatomy and physiology of human organs may be illuminated by an examination of the corresponding organs in other animals. Comparative anatomy and physiology have thrown a flood of light on our knowledge of the structure and functions of the human frame, and they may assist us in arriving at correct conclusions with respect to the action of the ciliary muscle. In the 'Journal of Anatomy and Physiology' for November, 1868, there is an interesting paper by Mr. R. J. Lee on the ciliary muscle in fishes, birds, and quadrupeds, which corroborates most strikingly the views

I have put forward. In this paper Mr. Lee shows that the ciliary muscle is absent in fishes, in which, as I have said above, the crystalline lens is of a spherical form, and hence no rotary movement could affect its refractive power; therefore no provision is made for altering its position. The iris of fishes, as Haller long ago remarked, does not move. This absence of a ciliary muscle, and this immobility of the iris, preclude the idea of an accommodative change in the eyes of fishes. On the other hand, the cat, which has a great range of accommodating power, has an extremely mobile iris, and its ciliary muscle is highly developed. It arises from the anterior border of the sclerotic close to the margin of the cornea, and passes backward to the choroid, forming so intimate a connexion with it as to appear really a part of that membrane. But it is especially in birds of the predacious sort, such as owls and falcons, that the accommodative faculty exists in the greatest perfection. In them the ciliary muscle is comparatively large, and its longitudinal fibres can be traced to their insertion in the choroid at a considerable distance from its anterior termination. By their contraction the choroid is drawn forwards, carrying with it the crystalline lens. There are likewise two rows of elastic fibres between the sclerotic and choroid, which yield to the muscular contraction of the ciliary muscle, but which serve to replace the choroid in its former position when the muscular contraction of the ciliary muscle is relaxed. "The whole arrangement described," says Mr. Lee, "is intended for the alteration of the position of the crystalline lens." He then goes on to say: "The result of the numerous dissections which I have made leads me to consider that the various theories which have been advanced at different times to explain the means by which the eye is enabled to adjust itself for distance, are inconsistent with the anatomy of the organ of vision, and I trust that it will not be thought presumptuous to express my belief that this phenomenon will be found to be explicable by the simple law of optical science, which requires nothing more than a change in the relative position of the lens and the retina to accommodate the sight to near and distant objects." What this change of relative position of lens and retina is I have endeavoured to show.

83. It has been observed that the time occupied in accommodating the eye for near vision is greater than that required for adapting it to distant vision; and this is strikingly obvious in viewing the movements of the candle-flame image reflected from the anterior surface of the crystalline lens. While the image moves slowly into its place when the eye is directed

to a near object, it springs rapidly back to its original seat when the eye is directed to a distant object. The cause of this is obvious, for in near accommodation the force of the ciliary muscle is exerted in overcoming the resistance of elastic structures in order to rotate the lens on its axis, whereas when the change takes place to distant accommodation the elastic forces and the internal portion of the muscle acting together cause the lens to resume its normal position with great velocity.

Czermak's phosphene

84. If the transition from near to distant accommodation takes place in the dark, there occurs, as Czermak* has remarked, a sudden flash of light in the eye, which he calls a *phosphène.* This phenomenon is, I believe, caused by the sudden springing back of the lens to its normal unaccommodated position, communicating a shock to the retina whereby the sensation of light is evoked, just as a slight blow on the eye will produce the sensation of a flash of light. At the same time the sudden relaxation of the ciliary muscle or tensor chorioideæ, permitting the strained choroid membrane to resume its position, will intensify the shock that produces the flash.

85. Another proof of the correctness of my view respecting the rotation movement of the lens in ac-

* 'Arch. f. Ophthalmologie,' Bd. vii.

commodation for near vision is afforded by the observations of Knapp, Adamük, and Woinow,* to the effect that the centre of the pupil moves at the same time towards the nasal side, consequently in the same direction as the lens. This movement does not take place in contraction of the pupil occurring without accommodative alteration in the eye. These authors hence infer that the crystalline lens produces this sideward movement of the pupil in accommodation. This is an important observation, as it proves beyond a doubt that one side only of the ciliary muscle is contracted in near accommodation, that this is the external side, and that the effect of the action of the muscle is to cause the lens to communicate a movement to the iris which pushes the pupil somewhat towards the inner or nasal side. The only possible movement of the lens whereby this could be produced is the rotary one I have described, and which the distribution of the muscular fibres of the ciliary muscle is exactly fitted to accomplish.

86. Whether the external portion of the ciliary muscle is the agent in the production of near accommodation in all positions of the eye I am unable to determine. My observations only apply to near

* 'Bericht über die Fortschritte der Anatomie und Physiologie im Jahre 1871,' 2tes Heft.

accommodation in respect to objects situated directly in front and on the level of the eye itself. It may be that when the eye is directed upwards or downwards, and at the same time accommodated for near vision, some other portions of the ciliary muscle are brought into play and the axis of rotation of the lens is varied accordingly. The intimate connexion of the action of the external portions of the ciliary muscles with that of the two internal recti muscles, might lead us to suppose that when other external ocular muscles are brought into play, other parts of the ciliary muscle may likewise act in accommodation. But this is a speculation that need not detain us.

87. I do not think much importance can attach to the increased thickness of the crystalline lens observed after death. Helmholtz and others have founded on this fact their explanation of the act of near accommodation, viz. that the crystalline lens is forcibly retained in the condition of accommodation for distance by the elastic tension of the zonule of Zinn, and that the effect of the contraction of the ciliary muscle is to relax this tension, and so enable the lens to assume the more convex form its own inherent elasticity impresses on it; the increased thickness of the lens observed when it is removed from its attachments being considered a proof that the more convex shape

Objections to Helmholtz' view.

it is alleged to assume in near accommodation is the form it will naturally assume when freed from restraint. But besides the objections to this view above stated there is this further objection, that the increased size of the lens which has long been known to occur after death is apparently caused by absorption of the aqueous humour by the tubules of the lens and around the lens beneath its capsule. The so-called liquor Morgagni, which is found between the capsule and lens, is now generally believed to be merely aqueous humour received into the capsule by endosmose *post mortem*. Very soon after death the transparency of the crystalline lens in the human subject becomes materially impaired, showing that something has occurred to diminish its dioptric properties, and this something is no doubt absorption of the aqueous humour, which will account at once for its increased thickness and its loss of transparency.

Working model of the eye.

88. In order to put my views to a still more stringent test, I constructed a working model of the eye of large size, in fact with dimensions ten times greater than the human eye. The curvatures of the various refracting media in the eye being ellipsoidal, of course I could not imitate them exactly, but I employed spherical curvatures as near the mark as possible. The globe of the eye is represented by a glass

globe 24 centimètres in diameter, with a hole cut out in front for the reception of a section of a globe of 8 centimètres radius, to represent the cornea. This of course is left clear, but the larger globe representing the sclerotic is painted black inside and white outside, a circular clear space being left in the axis of vision to show the picture formed on the retina. A diaphragm of vulcanized indiarubber is suspended 3 centimètres behind the cornea to represent the iris, perforated with a hole to imitate the pupil moderately dilated. The crystalline lens is made with two segments of globes respectively 10 and 6 centimètres radius of curvature, to represent the anterior and posterior surfaces of the lens, and 5 centimètres thick in the centre. These segments are united edge to edge by a brass ring, and the space thus formed is filled with a mixture of glycerine and water in equal proportions, which has a refractive power corresponding to that of the crystalline lens. The aqueous and vitreous humours are represented by water, with which the globe is filled. An object placed at a distance of about 15 feet is accurately pictured in the clear space left at the back of the globe, representing the retina in the axis of vision. On bringing the object nearer to the model eye the focus is thrown behind the globe. At a distance of 8½ feet the object is as much out of focus as it would be at 10 inches in the un-accommodated emmetropic human eye. A slight rotary motion of the artificial lens shortens the focus so as to bring it again accurately to the back of the globe corresponding to the retina in the axis of vision.

If a candle is placed at one side of the eye and we look into the pupil from the opposite side, the images of the candle reflected respectively from the cornea, anterior surface of the lens, and posterior surface of the lens, are plainly visible, the two former erect and large, the third inverted and small. When the rotary motion is given to the lens in order to accommodate the focus to a near object (at 8½ feet), the image reflected by the anterior surface of the lens is seen to move in precisely the same way as I have described as occurring in the human eye in near accommodation.

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