



XXVIII. On the limits of vision: with special reference to the vision of insects

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57 and 59), or 27·3 times as much. If the proportion of increase of temperature to that of surface were known, the average magnitude of the particles of the finest insoluble powder might perhaps be calculated.

The evolution of heat by the mere contact of solids and liquids which do not in the ordinary meaning of the term "chemically unite," must to a minute extent affect the determination of the specific heats of insoluble powders by the method of mixing them with water. And if contraction of volume follows immediately upon its loss of heat, then the specific gravities of insoluble powders when arrived at by the process of weighing them, first in air and then in water, are probably also slightly influenced.

The heat produced by the mere contact of insoluble solids such as silica, alumina, &c. with water and aqueous solutions of salts, may account for that produced by spring-water, sea-water, mineral-water, &c., filtering through geological strata, and for that developed in other cases of underground temperature where ordinary chemical action is absent.

XXVIII. *On the Limits of Vision : with special Reference to the Vision of Insects.* By G. JOHNSTONE STONEY, M.A., D.Sc., F.R.S., Vice-President, Royal Dublin Society *.

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Introductory Remarks.

THE President of the British Association, at the recent meeting of that body in Nottingham, mentioned in his opening address that the image formed by the compound eye of an insect had been photographed. This suggests the inquiry how the image is formed, and what is the limit of the vision of which it is the physical basis. The investigation of this point shows that insects cannot see very minute objects, and the whole inquiry seemed of sufficient interest to be laid before the Royal Dublin Society, especially as it suggests much further study which the author could not attempt, but which there are other members of the Society most competent to undertake.

* From the 'Scientific Proceedings' of the Royal Dublin Society of the 20th December, 1893, Communicated by the Author.

SECTION I.—Of Vision in general.

As preliminary to the inquiry it is well to consider what are the causes that limit the amount of detail that can be seen by the instrumentality of eyes such as our own, the kind of eyes of which we know most. That there is such a limit to human vision may be easily seen by placing a well-illuminated ruling of parallel lines at different distances from the eye of a person whose vision is good. Let us suppose black lines ruled, as in fig. 1, on a white surface at intervals of one millimetre from the middle of one line to the middle of the next. If an observer with keen vision views these from a distance of eleven or twelve feet, he is able barely to make out that they are a ruling; beyond that distance, they seem one uniform grey surface, while from stations nearer to them he perceives the individual lines distinctly. Now, at a distance of eleven feet a millimetre subtends an angle of $1'$ (one minute). Hence we learn from observation that in order that two objects may be seen as two, they must, at least, subtend an angle of about $1'$ at the eye. If they subtend a less angle than this they are seen as one object.

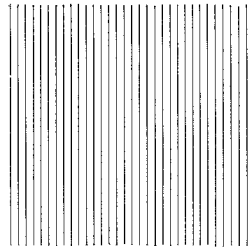


Fig. 1.

Millimetric Ruling.

Now there are three distinct causes, any one of which is by itself competent to put a limit of this kind to our power of distinguishing minute objects; and in persons with the best vision each of these three seems to put nearly the same limit as the other two. This adjustment between them is, no doubt, the result of development, since any further improvement on the lines of any one of these causes would be useless, unless it were accompanied by a simultaneous improvement in both the others.

One cause is the spacing of the cones that occupy the *fovea lutea*, into the small area of which about 7000 are packed. The *fovea lutea* is that spot in the retina which furnishes us with the exceptionally distinct vision which we have in the middle of the field of view. The cones are here without accompanying rods, and are at intervals of about $4\mu^*$, measuring from the middle of one to the middle of the next. This interval is about half the diameter of the red corpuscles

* The micron μ is the millionth part of a metre. This is the same as the thousandth of a millimetre, or the $1/254000$ th of an inch.

of human blood, an object familiar to every microscope-observer. Again, the "optical centre"* of the eye lies a centimetre and a half in front of this part of the retina; and at this distance the interval between adjoining cones subtends an angle of nearly $1'$. Hence, in order that the images of two points of light may fall on the corresponding parts of different cones, their distance asunder must subtend an angle of, or exceeding, $1'$ at the optical centre of the eyes; in other words, the interval between the objects in external nature that are being examined must subtend this angle at the eye. Thus we fail to see with the unassisted eye much detail which is revealed to us by the microscope. This happens if at a distance of ten inches, the distance of most distinct vision, the intervals at which these objects are spaced subtend an angle of less than $1'$. Such objects may, however, be seen with optical aid, provided it is such that the little interval subtends an angle exceeding $1'$ at the optical centre† of the object-lens used in the microscope, a point which, with the higher powers of the instrument, lies close to the object on the stage. But beyond this limit, and therefore beyond the reach of the microscope, there are still worlds of events in nature which we can never see, although we may infer the existence of some of them in other ways.

We have found that the spacing of the cones in the *fovea lutea* is competent to put a limit to the minuteness of the detail that can be seen with the naked eye. Now, the small size of the pupil of the eye also, and independently, determines such a limit. Astronomers are familiar with the fact that the image of a star (which is virtually the image of a point of light, since no telescope is competent to show the true disk

* From each point of a visible object a cone of rays, starting from that point as its apex, falls on the pupil. In passing through the eye this cone of rays is made to converge, and finally becomes a cone of rays advancing towards that point of the retina where the image is formed. The apex of the second cone is accordingly at this point. Most of the rays of the first cone are bent in passing through the cornea and optic lens, and advance in a new direction in the second cone. But there is one among them, which, in the second cone, continues in the same direction, or at least parallel to the direction which it had in the first cone. This ray is called the undeviated ray: It is easily seen that there is one such ray in the light coming from each point of the object. Now all the undeviated rays very nearly pass through a certain point which is situated close behind the optic lens, and $1\frac{1}{2}$ centimetre in front of the middle of the retina. This is the point which is called the "optical centre" of the eye.

† The optical centre of the object-lens of a microscope is the point where the "undeviated rays" cross (see last footnote). In compound microscopes this point lies in or in front of the object-lens, and with high powers is close to the object.

of a star) consists of a small round central patch called the spurious disk, surrounded by coloured rings which very rapidly fall off in brightness. This phenomenon is due to the interference of the light coming from the two halves of the object-lens, and is susceptible of mathematical treatment. It thus appears that the angular radius of the first dark ring, estimated from the middle of the object-lens, is

$$\theta = (1.22) \frac{\lambda}{A},$$

where λ is the wave-length of the light, and A the aperture, *i. e.* diameter, of the object-lens. This furnishes a boundary within which the central spurious disk lies, and up to which its faintest outlying portion barely extends. It also fixes the *minimum visibile* with that aperture, since two points would have begun to be blurred into one another if so close that the middle of the spurious disk of each lay on the first dark ring of the other. Let us then put into this formula, $\theta = 1' = .00029$ in circular measure (this is the limit already fixed by the rods and cones), and $\lambda = .6$ of a micron (which is the wave-length of yellow light). We thus find

$$.00029 = (1.22) \frac{.6}{A}$$

whence $A = 2524$ microns, which is very nearly $\frac{1}{16}$ of an inch. This, then, is the diameter of the pupil of the eye when of such size as to put the same limit on the visibility of small objects as the rods and cones do. Now, this is about the size to which the pupil of the eye shrinks when we scrutinize well-illuminated objects, and is the smallest to which it can be allowed to shrink without interfering with the vision of minute detail, by placing a further restriction beyond that imposed by the layer of rods and cones*.

Again, the eye viewed as an optical instrument is far from perfect. Its chromatic defect may be detected by placing the finger horizontally in front of the eye, and looking just over it at the bar of a window. In this way the window-bar is viewed through the upper half of the pupil, and is then seen

* It might be thought that with the more dilated pupil which we have in faint light, we could see more detail. But the reverse is the case; for instance, the two small double stars ϵ_1 and ϵ_2 Lyrae are more than 3' asunder, and yet, in consequence of their faintness, are nearly at the limit of what a very good eye can see distinctly as two objects. To eyes that are fairly good they appear as one object elongated, while persons may have tolerably good sight and not even see the elongation.

to be bordered with colour. Finally, the spherical aberration* of the eyes becomes conspicuous when we view a considerable star or planet with one eye. Instead of being seen as a point, it is seen as a small irregular patch with short tails from it, and of somewhat different shape according as it is viewed with the right or with the left eye. Now this is due to spherical aberration co-operating with another defect which it is difficult to disentangle from spherical aberration, and which is caused by the light having to pass through the other layers of the retina before reaching the rods and cones. These layers, however, do little harm in the *fovea lutea*, as here they are either absent or thin, so that the irregular image seen when we look *directly* at a planet is chiefly due to pure spherical aberration.

Now these defects, viz. the chromatic and spherical aberrations, including under the latter that further defect which arises while the light is crossing the retina, are dealt with in nature in the same way in which a photographer deals with them in his photographic camera, viz. by limiting the aperture, which diminishes the effect of these imperfections. We have already found that the aperture of the pupil is contracted as much as is compatible with the other conditions to be fulfilled. Now it is evident that a certain amount of the defects with which we are at present dealing, especially when rendered less operative by the limited aperture of the pupil, may be allowed to remain in the eye without rendering it incapable of distinguishing objects separated by 1' of angle, the limit already fixed by the rods and cones; and there can evidently be no tendency in evolution to effect any further improvement of the eye as an optical instrument. Accordingly, in persons with the best vision, the eye seems to have been just improved up to this point, leaving its outstanding defects still very conspicuous when searched for; and it is shortcoming in respect to these defects which is chiefly what makes one man's eyesight less perfect than another's.

We shall next deal with another preliminary remark, which it is well to make, as it will dispel the oft-repeated error that there ought to be some connexion between our vision and the position of the image formed on the retina. It is pertinent to point this out when engaged in inquiring into the vision of insects, for, as we shall see presently, the

* If a sphere be drawn round a point of the image formed by light of one wave-length, to represent the crest of one of the luminous waves advancing towards that point, the whole of the crest should reach that sphere at the same instant of time. There are, however, usually little deviations of some parts of the crest of the wave from this sphere, which defect is called spherical aberration.

image formed by compound eyes is erect, while that formed by single eyes, such as ours, is inverted. Neither position, however, nor a sideward position, nor any other, would be incompatible with our seeing the objects of the world around us exactly as we now do. For the direct physical adjunct of a visual perception in our mind of a point of the object, is not any event in the eye or along the optic nerve but in a more deep-seated part of the brain, probably in its occipital lobes which lie in the back of the head, over the cerebellum. Now (speaking from the physical standpoint) the way in which this event in the occipital lobe is usually evoked is by light from the point of the object being guided through the eye to one of the rods or cones, after which some event travels along one of those nervelets with attendant nerve-cells which penetrate the retinal layer from the expansion of the optic nerve, and each of which is associated with one individual rod or cone. This is succeeded by some event along one fibril of the optic nerve, after, which there seem to follow other events within the brain, which finally lead up to *that particular event* which, and which alone, is the true physical adjunct of the visual perception in our mind—our perception of that point of the object from which the light set out to enter the eye. I, for convenience, speak of this event as situated in the occipital lobe, although its location can hardly be said to be ascertained.

Now it is evident that the image on the retina is only one link in this long chain of physical causes and effects, and that the image might be erect as it is in the compound eyes of insects, or inverted as in our eyes, or might have any other orientation, and that nevertheless the positions of the rod or cone, nervelet, fibril of optic nerve, &c., could be so disposed as to produce precisely the same final event within the occipital lobe of the brain, as now occurs. Now it is this last alone which is essential, the others being only instrumental in bringing it about: it alone is the true physical adjunct of the visual perception which becomes part of the mind.

Again, although the train of causes and effects described above is the usual process by which this adjunct of perception is evoked, it is not by any means the only way in which it can be brought about, as is conspicuously manifested by dreams, and may be detected by a careful introspective study of the memory of visual perceptions. I am of opinion that in all cases, when remembering a past scene, there is some dim, usually a very dim, recurrence of the perception, or of parts of it: at all events, under some circumstances, this is distinctly the case. When, unfortunately, we lie awake for

several hours, especially under the influence of tea or coffee, until a feeling of weariness and an indisposition to any prolonged train of consecutive thought have come over us, I have observed that the revival of visual perceptions, when thinking about past scenes, becomes stronger and is easily perceived, and that in some cases it may become almost vivid. In extreme cases it even amounts to a kind of dreaming with the eyes open—the dream, however, differing from ordinary dreams by being one the progress of which we can ourselves direct. It is important to note that these visions are not based on any affection of the retina, and in this respect differ wholly from those spectral images which we see after gazing for some time at objects which somewhat dazzle the sight. These latter shift their position with every movement of our eyeballs; the others retain what we estimate to be their positions in space, notwithstanding that the eyes be moved about. Now this is very significant. It shows that the train of physical causes which lead up to that event in the posterior lobe, which is the adjunct of our perception of these visions, did not originate in the retina, but in a part of the brain where it could arise in conjunction with some of those events which are the physical adjuncts of our judgments about space. This is an important conclusion to have reached.

What is probably in reality only a further stage of these waking dreams is sometimes experienced in fever, when the patient has been for days without sleep. I myself saw apparitions in this way, after having been three days without sleep, those I saw having a marvellous appearance of reality, and being seen in the daylight when I could at the same time see in the ordinary way the objects about me in the room, except where one of these novel figures intruded. In these places the connexion with the retina seems to have been rendered more or less inoperative, and a visual perception, otherwise produced, was substituted for the ordinary one.

Another instructive and more agreeable way of making the observation is to experiment on ourselves when in that stage of drowsiness in which we seem to have fallen partially asleep, but not so much so but that we can still voluntarily direct our thoughts to some well-remembered scene, or, still better, first to one, and afterwards to another. If we repeatedly seize opportunities of making this experiment, we shall gradually accumulate instances of every degree of vividness, from the full distinctness of a dream in respect of colour, brightness, and form, down to the shadowy dimness of what we very imperfectly see in the exercise of ordinary memory. The same important observation may be made here as on a

former occasion. The objects so seen do not shift their positions when we voluntarily move our eyes about. They have their origin not in the retina, but in immediate connexion with the part of our brain which is directly related to our judgments about space.

Another interesting observation is of what happens when we get into what is sometimes called a "brown study"—thinking intently upon some past scene that engrosses our attention. On such occasions the visual image before "our mind's eye" becomes more vivid than usual, and in the same degree the image produced in the ordinary way of the external objects towards which our eyes may chance at the time to be directed becomes less distinct, and, in extreme cases, may almost fade out, so that even noteworthy events may happen in our presence which we do not see, or at least which do not impress us sufficiently for us to retain any memory of them.

Two experiences, one of a friend and one of myself, seem worth recording in this connexion:—

Some years ago this friend and I rode—he on a bicycle, I on a tricycle—on an unusually dark night in summer from Glendalough to Rathdrum. It was drizzling rain, we had no lamps, and the road was overshadowed by trees on both sides, between which we could just see the sky-line. I was riding slowly and carefully some ten or twenty yards in advance, guiding myself by the sky-line, when my machine chanced to pass over a piece of tin or something else in the road that made a great crash. Presently my companion came up, calling to me in great concern. He had seen through the gloom my machine upset and me flung from it. The crash had excited the thought of the most likely cause for it, and the event in his brain, which was the physical adjunct of the thoughts thus passing through his mind, were so associated with that other event in the brain, which is the adjunct of visual consciousness, that the one (speaking from the physical standpoint) evoked the other, perhaps faintly. This involved a visual perception in the mind faint, but sufficient on this occasion to be seen with sufficient distinctness when not overpowered by objects seen in the ordinary way through the eyes.

The experience I had myself was one which frequently occurred to me when a lad. Several of us boys were fond of witnessing sham fights in the Phoenix Park, at which some of the most conspicuous objects were the single horsemen who now and then galloped at full speed, with orders, from one part of the field to another. Almost always, after a day spent in viewing this spectacle, as I lay in bed at night I saw

vividly what seemed to be a tiny horseman galloping violently from right to left, or from left to right, as the case might be. All the movements of the horse were reproduced, the dashing about of the sabre-tasche, the coloured uniform, the movements of the horseman. It cannot have been in the retina that this revival took place. It must have been in a much more deep-seated part of the brain.

It would, I think, be of very great interest to ascertain from the inhabitants of a blind asylum, whether those who have recently had their retinas extirpated, or rendered functionless, continue to dream of scenery, so long as the memory of visual perceptions is recent. I should expect they would, as the structures which they have lost do not seem to be concerned in either memory or dreaming.

From a review of all the evidence it appears clear that the retinal image is only one of the stepping-stones in a rather long progress from the object in nature to the event in the brain which is the direct adjunct of visual perception. Why, then, it may be asked, is an image necessary? Why is it never absent? Why is not something quite different sometimes substituted for it? The following is, I think, a sufficient answer. There must be *some difference* in the events occurring in the occipital lobe in order that two points of an object may be seen distinct from one another. To bring this about either a different nervelet must have been acted upon in the organ of sight, or the same nervelet must have been differently acted on. In the case that actually occurs, it would appear that a different nervelet is acted upon when the points of the object are sufficiently separated to be seen as two, and that a difference of action on the same nervelet is reserved for exhibiting to us variations of brightness and colour, but not of position. Now this can manifestly be effected by distributing the points of an image of the object over an apparatus such as the layer of rods and cones, consisting of closely packed individuals, each of which is capable of acting on its own nervelet; or through an intermediate apparatus, which consists of channels for transmitting light as numerous as the rods and cones, each of which conducts the light from a specific point of the image to its own rod or cone, which latter may, in this case, be situated at a distance from the place where the image is formed. The first of these is the arrangement which we find in our own eyes; the other seems to be that which we find in the compound eyes of insects. Now it is doubtful whether any other machinery for bringing about the result than one or other of these two can be devised. These, at all events, are the ways in which nature attains the end; so that neither man nor nature seems to have found out

any other. But the position of the images, whether erect, inverted, or any other, is obviously immaterial. It is the ultimate effect within the occipital lobe of the brain that is alone essential.

SECTION II.—Of Vision with Compound Eyes.

After these preliminary remarks on vision in general, we seem to be in a position to deal intelligently with the inquiry—How is the retinal image formed in insects? and what kind of vision do they enjoy through the instrumentality of the compound eyes with which they are furnished? These questions may be most conveniently dealt with by describing a rough model of an insect's eye. Imagine a hemispherical shell of some transparent material, *e. g.*, half of a sixteen-inch globe of glass, that is, a globe of which the diameter is sixteen inches. Place your eye at its centre, and look through it at the objects of nature around you. Next, let an accurate picture of these objects be painted on the outside of the globe, so that when you place your eye at the centre you still see the same scene as before. Now let a network of scratches be made all over the painting, dividing it into patches, each of which is the size of a square quarter of an inch. This is about the size of the cross section of a lead-pencil. There will be about 6400 of these patches on the hemisphere. Next, let the paint of each patch be removed, and a single dab of paint substituted, of a tint and brightness which is the resultant of the part of the picture which fell within the patch. In this way, a somewhat coarse mosaic is substituted for the more perfect picture of the external world previously drawn. This coarse mosaic gives a rough imperfect representation of the external world, and represents correctly the vision which an insect has of it. The compound eyes of some insects, especially insects that attack other insects, have more numerous facets than what correspond to 6400 over a hemisphere; and in such cases the mosaic is less coarse, and the vision is proportionately better. Thus the eye of a dragonfly is better represented by substituting smaller patches, each the size of a square eighth of an inch. This increases the number over the hemisphere to 25,600. But there is a somewhat narrow limit to improvement in this direction, owing to its necessitating a diminution of the aperture of the lenses. The way that nature deals with this difficulty is by increasing inordinately the size of the compound eye of the insect out of proportion to its other features. In this way the number of the patches, one of which is formed by each facet, can be

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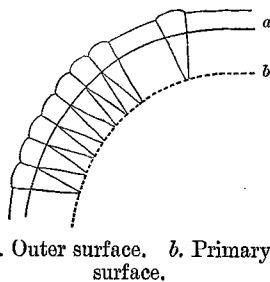
increased without diminishing too much the aperture of the little lenses.

With a mosaic such as is described above, the diameter of each patch subtends about a degree and eight-tenths ($1^{\circ}8$) at the centre of the hemisphere. Accordingly, the interval between two objects in nature would need to subtend an angle of about a degree and three-quarters at the insect's eye, to be distinguishable as two by the insect. Hence, if as far off as ten inches, the distance at which we see most distinctly, they would need to be separated by nearly the third of an inch to be seen by the insect as more than one object ; while, if close to the insect, only one-tenth of an inch off, the separation would need to be about the same as that which the human eye is capable of distinguishing at a distance of ten inches. Thus, the insect cannot see more detail upon its own antennæ, close as they are to it, than we can with our naked eye. We must, therefore, dismiss from our thoughts the mistaken impression that insects see very minute objects far beyond human vision. On the contrary, their vision is imperfect compared with ours. Still, it is evidently quite enough to enable a bee to be guided in its search after honey by the markings upon a flower, or effectually to assist a fly in its wanderings about the room, or in sopping up its food.

We have next to consider how this mosaic is formed. For this purpose let us again turn to our model. Suppose 6400 hollow conical funnels to be provided, each one inch long. Let them be slightly more than the thickness of a lead-pencil at their larger end, and tapering from this down to a diameter of a sixteenth of an inch at their smaller end. Let the insides of these funnels be blackened so as to stifle any light that falls on them. Fit a small lens of one-inch focus into the larger end of each, and then pack the funnels somewhat like the cells of a honeycomb, over the hemisphere spoken of above, the larger ends outwards, and the smaller planted on the middles of the little patches that were marked out on the hemisphere. The little lenses will then lie on an outer hemispherical sheet eighteen inches in diameter.

Let us fix our attention upon one of the little lenses, and consider how it operates. The light from distant objects in

Fig. 2.—The Funnels of an Insect's Eye (diagrammatic).



a. Outer surface. b. Primary surface.

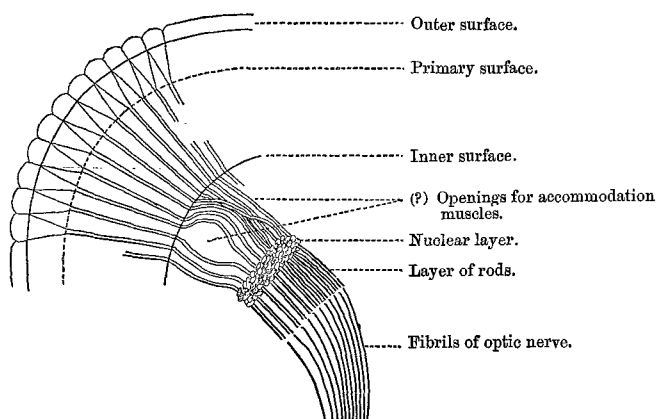
the external world would, if not interfered with, form an inverted image one inch behind this lens, that is, at the distance of the glass hemisphere, which we shall call the primary surface ; but it is prevented from forming more than one patch of that image by the blackened walls of the funnel. Accordingly, only one tiny patch of the image, one-sixteenth of an inch across, is actually formed. It is formed by the light which passes the whole way down the funnel and, emerging at its end, falls on the surface of the primary hemisphere. Here it produces one little fragment of the inverted image, the rest of the image which the lens is competent to form being extinguished by the blackened walls of the funnel. In the insect's eye the small portion of the image that emerges is, no doubt, a portion of a rather indistinct image, owing to the very small aperture of the lens ; but neither this nor its belonging to an inverted image is any detriment, since all the rays that go to form the little patch are transmitted to a single one of the pieces of apparatus in the insect, corresponding to the rods and cones in our eyes. They, therefore, can result in only one of the optic nervelets being affected, and in some one definite way ; in other words, the whole of the light forming one patch, or rather speck, of the image can produce only one elementary visual impression in the insect's mind.

It will be observed that the image that is formed resembles rather a mezzotinto engraving, which consists of separate specks, than a mosaic which consists of patches of colour large enough to touch one another ; and that it differs from the mezzotinto in that the specks are specks of light, instead of being, as in the engraving, specks of shade.

If we endeavour to make out what provision is made in compound eyes for enabling the insect to accommodate its vision to varying distances of the object, we find, upon a scrutiny of the section of such an eye, that the arrangement appears to be one which gives to an insect the very singular power of adjusting different parts of its field of view to different distances, and operates in a remarkably simple way which may be illustrated upon our model if we add somewhat to it. For this purpose let a third hemisphere be provided, concentric with the other two, but smaller—suppose with a diameter ten inches across. Let the funnels which have been spoken of, and which lie between the outer surface and the primary surface, be made of some extensible material like indiarubber, their outer ends being fastened to the lenses and their inner ends to threads of glass the thickness of thin knitting-needles, and extending, as in fig. 3, from the

primary surface to the inner surface. To make it possible to do this, the glass hemisphere which we have used to represent the primary surface may now be removed; it is no longer required, since its position is sufficiently indicated by the points of junction of the indiarubber funnels and the glass

Fig. 3.



Section of an Insect's Eye (diagrammatic).

threads. The outer surface of our model, which carries the lenses, should be a stiff immovable arch, but the inner surface is to be made of some material which is capable of slightly contracting. If, after constructing the model in this way, its inner surface is made to shrink a little*, this will pull the glass threads inwards and elongate all the indiarubber cones. In this way the narrow ends of the cones are brought farther from their lenses, into the position where the image of a near object would be formed. The model now represents the insect's eye when accommodated for the vision of near objects.

In this model the image of the outer world is formed either at the primary surface or at the inner surface, for a speck of light falling on the upper end of one of the glass threads will travel lengthwise along the thread and emerge from its lower end, being kept from escaping laterally by

* A diminution of the radius of the inner surface of the model to the extent of about one millimetre would effect a sufficient range of accommodation. The motion in the insect's eye may need to be more than in proportion to this, since the filaments, as well as the funnels of its eye, are probably extensible, which is not the case in the model.

total reflexions. Now, it seems probable that something of this kind actually occurs in the insect's eye. In fact the apparatus corresponding to the rods and cones of our eyes seems, so far as I can make out, to be situated, not at the primary surface where the image is first formed, nor even at the inner surface where the image may be reproduced in the way described above, but in a deeper situation with which the inner surface communicates only through curved transparent threadlets. Each of these threadlets seems to have a thin transparent core, and if this core be of sufficiently highly refractive material, it would, although curved, be competent to carry the light forward by total internal reflexions, from the lower end of one of the glass threads to one of the pieces of the apparatus which corresponds to the layer of rods and cones in our eyes*.

It is, perhaps, worth observing that an eminently useful adjustment which we cannot effect seems to be possible in an insect's eye. In fact, the inner surface of our model might be drawn inwards more at one place than another; and I am disposed to think that muscles, acting on the inner surface, are in the insect so disposed as to make this possible in its eye. Now this would effect an accommodation to the distances of objects which would differ in the different parts of the field of view†. Moreover, this result may be brought about in another way. The lenses and the funnels posterior to them vary in size from one part of the compound eye of a dragonfly to another, being largest in the position which I suppose to be about the middle of the eye, and gradually dwindling to about half this size near the margin‡. An equable contraction of the "inner surface" of such an eye would obviously effect a different accommodation in different

* The light is probably carried forward most effectually where, as in the dragonfly, the cores are less than a micron in section, *i. e.* not much more than the wave-lengths of the light that has to traverse them. Light would adapt itself to the sinuosities of such filaments, like sound in a speaking-tube.

† In the sections of the eyes of dragonflies, which I have examined, the filaments from the funnels down to the "inner surface" are enclosed within a sheath of fibres and are straight, but immediately after passing through the inner surface they are each apparently enclosed within a tube, and grouped in bundles, between which are open spaces which may, perhaps, in the living insect have been occupied by muscles. Muscles, in this situation, would be competent to effect the optical adjustment spoken of in the text. (See fig. 3.)

‡ The increased aperture of the lenses towards the middle of a dragonfly's eye, and the diminished curvature of the stratum in which they lie, both conduce to make its vision more perfect towards the middle of its field of view; and as this lies in the direction of the insect's flight, the arrangement must be of advantage to it in its pursuit of prey.

parts of the field of view. Accordingly, in one or other of these ways, or by a combination of them both, the insect may be able to adjust one part of its field of view for near objects, and other parts for more distant ones ; *e. g.*, a fly may be able to view distant objects around with the utmost distinctness of which its eye is capable, at the same time that it is closely scrutinizing the details of a lump of sugar and applying its proboscis rapidly to one minute crystal after another. As the adjustment which would enable it to do this would be of service to the insect, and as the construction of its eye admits of it, it seems likely that it is one for which provision has been actually made.

On a review of the whole subject we seem to have a satisfactory general insight into the process by which vision through compound eyes is carried on. Doubtless much detailed information of the minute anatomy of these interesting structures has been reached by microscopic anatomists ; but I am not acquainted with it, and have been obliged to rely on my own imperfect observations. It is, however, likely that, notwithstanding the diligence of microscopists, much still remains to be explored ; and this, I hope, may be followed up more intelligently if the general optical process is understood. It is on this account that I have endeavoured to trace it out, and especially because among my scientific friends there are to be found some of the most competent persons thoroughly to explore the whole of this interesting subject.

I have hitherto said nothing about vision through the isolated eyes with which insects are also furnished. They cannot, from the minuteness of their lenses, give them nearly so good vision of distant objects as man enjoys. And the limit is very possibly still more restricted by their being furnished with but a moderate number of rods and cones. It would be of interest to ascertain by observation whether this is so, and to collect such data as would enable us to estimate with tolerable exactness how far the imperfection goes.

[NOTE, added February 21.—It is not obvious why the apparatus of rods and cones in the human eye is nearly on as small a scale, and as closely packed over the rest of the retina as in the *fovea lutea*, since the amount of detail we can see in the corresponding parts of the field of view is immensely less. Possibly the line of the embryonic development of this layer may be such that it could not be evolved of the requisite minuteness in one part, without being made nearly as minute over the whole. The only other possible explanation seems to be that its being minute serves some other unknown purpose, as well as removing one of the three obstacles to our vision of small details.]