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ACCOMMODATION AND OTHER OPTICAL PROPERTIES OF THE EYE OF THE CAT

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SECTION I.

A direct method of determining the refracting power of the whole eye

WHEREAS previously the power of the eye as a whole has been determined by adding together the separately ascertained powers of the corneae system and the crystalline system, we have endeavoured to obtain a direct method for ascertaining the power of the eye as a whole that would be applicable to animals, and in certain special cases to man himself. It should be pointed out that the disadvantage of the previous methods has been that the power of the crystalline lens had to be ascertained by observations made on the position of the refracted images as seen through the refracting surface of the cornea.⁽¹⁾ So that, for example, the position and therefore the curvature of the posterior surface of the lens would be affected by any errors already made in the measurements previously obtained for the anterior and posterior

- A Illustrates basis of method of measuring focal length of whole eye. If K is ascertained by experiment H is readily calculated.
- B Illustrates method of calibrating scale of instrument, E —eye of observer, S —light source, M —mirror, G —scale, L^1 and L^2 —lenses, P —anterior principal point, I' and I'' are movable indices. The angles which the indices make at the point P are recorded against the scale reading.
- C Illustrates method of determining angle subtended by two retinal points, e.g., the bifurcation of a retinal vessel and the edge of the optic disc at the posterior nodal point of the observed eye by means of the instrument.
- D Illustrates appearance of the scale. The letters correspond to those in Table I. All the squares were subdivided into 100 parts as shown in top right-hand corner.

surface of the cornea, the anterior surface of the lens and the depth of the anterior chamber.⁽²⁾ Therefore the calculated power of the eye as a whole has been subject to error since the refracting powers of the separate parts from which it has been calculated have themselves been subject to ambiguity.

We have measured the power of the cat's eye directly by making use of the following physical relationship between the size of the object and the size of the image formed by a lens system.

In Diagram 1A is represented a complex lens system of which $N^1 N^2$ are the nodal points. Rays from two distant objects make with one another the angle a at the anterior nodal point N . Then the focussed images of those two distant objects on the screen also make the angle a with the posterior nodal point N^1 . If R is a screen placed at such a position that the lens system forms sharply focussed images of distant objects on to it, then if the value of the angle a is known and the distance between the images " k " is known, the distance between the posterior nodal point and the screen R is readily ascertained since it equals $2k \times \sin \frac{1}{2}a$. The instrument that we have made use of is the orthoscope supplied by Messrs. Watson and Sons, and we have made this into an instrument capable of measuring the angle by placing a ruled glass micrometer screen just in front of the field lens L^1 , as shown in Diagram 1B.

In this diagram is also shown the course of rays through the instrument to the eye. The calibration of the ruled glass screen in angular measure had to be performed by placing at a suitable distance from the instrument two indices I^1 and I^{11} . The angles subtended by the indices at the instrument were now ascertained by measuring the distances of the indices from one another and their mean distance from the anterior focal plane of the instrument. Preliminary observations showed that there was a gradual change in the angles representing ten fine scale divisions of the ruled glass screen, as one passed in a vertical or a horizontal direction. This was due to the considerable amount of coma introduced by the inclination of the lenses L^1 and L^2 to the optical axis. This inclination cannot be avoided, because it has to be introduced to eliminate the reflection that would normally take place at these lens surfaces as the beam of light from the source S passed by reflection at the mirror M along the optical axis of the instrument. The indices were therefore moved a step at a time, so as to correspond with the separate coarse divisions of the ruled screen marked A, B, C, D, E, and V, W, X, Y, Z, as shown in Diagram 1D, and in this way the angular values shown in Table I for the different divisions were obtained.

TABLE I.

Distance between indices at 100 cms.			Distance from instrument
Obs. H.	Obs. Y.	Mean	Angle
A B = 10.04	9.68	9.86	5.61
B C = 8.55	8.60	8.58	4.91
C D = 7.85	7.70	7.78	4.45
D E = 7.25	7.25	7.25	4.17
V W = —	—	8.85	5.08
W X = —	—	8.00	4.60
X Y = —	—	8.42	4.84
Y Z = —	—	8.42	4.84

The first factor of importance that came up for determination was the effect of the distance between the orthoscope and the lens system under measurement (e.g., an eye) on the power of that lens system as given by the instrument. The result of one such test is shown in Table II.

TABLE II.

Effect of distance between instrument and lens system under measurement:—

Distance in mm. between instrument and lens system under measurement.	Focal length of lens system in mm. as given by instrument.
36 mm.	16.5 mm.
96 mm.	16.12 mm.
Difference 60	0.38
„ 63 per cent.	2 per cent.

It will be seen that a considerable change in the distance (namely, 60 mm.) resulted in an error in the focal length measurements given by the instrument of less than 2 per cent. Therefore, if care were taken to preserve the distance between the instrument and the lens system at roughly 66 mm. (the place at which the anterior focal distance of the instrument was found to be situated), errors due to small variations in the distance between eye and instrument could be altogether neglected.

Method of using the instrument

The actual process of making measurements with the instrument described above will now be given in detail, because a number of points in the technique came up for consideration in the initial stages of the research, and accuracy was only obtained as the result of experience. The animal under investigation was invariably anaesthetized. In the case of the cat, either lighter anaesthesia with chloroform or rather deeper anaesthesia with urethane

was generally found necessary. The animal was placed comfortably inside a wooden box, cotton wool, straw and other packing being placed round it so as to prevent undue movement. Through the lid of this box the animal's head protruded, and it was held by the hand of an assistant, who turned the head gently so that the eyes faced in different directions as required by the observer at the eyepiece of the instrument. In a few cases only was it found necessary to apply any surgical instrument to the eye under observation. It was found, for example, in the case of one cat that when the anaesthesia was profound the nictating membrane tended to rise and obstruct the passage of light through the cornea. In these cases the ordinary spring speculum employed in ophthalmic practice was applied. The beam of light from the instrument was now directed into the eye under observation and the position of the images of the retinal vessels, blind spot, etc., as seen from the instrument noted. A considerable amount of time was usually required to get a suitable part of the retina under observation in the field of the instrument. As a rule the angular measurements were made from one edge of the blind spot to the bifurcation of one of the retinal vessels, a drawing being made of the appearance seen through the instrument as the view of the retina was projected on the ruled glass screen. The number of scale divisions, both vertical and horizontal, which corresponded to the distance between the blind spot and the bifurcation of the vessel was also noted on the drawing. The anaesthesia was now pushed to greater and greater depths until it resulted in the death of the animal. After that the eyeball was very carefully removed, its position in the head having been marked by passing a thin black ligature (e.g., sewing silk) through the sclera just beyond the corneo-scleral junction. The eyeball was now divided into two halves and the retinal half placed on a glass slide, the black thread remaining attached to one edge of it so that the proper position of the retina as it lay originally in the animal's head could be preserved. A micrometer microscope was now used for measuring the actual distance in millimetres between the edge of the blind spot and the bifurcation of the vessel which had been made the subject of measurement by means of the orthoscope. Reference had, as a rule, to be made to the drawing of the retinal vessels previously described, in order that there should be no possibility of mistake resulting in the measurement of a different blood vessel. From these two determinations, namely, the measurement of the angle ($=a$) subtended by this portion of the retina as seen from the orthoscope and the actual distance ($=d$) between the same structures as measured by the microscope micrometer, the focal length ($=L$) of the lens system of the eye can be ascertained, since L is equal to $d/2 \sin a/2$. The accuracy of this

method was ascertained by making some preliminary measurements on a glass lens system of known focal length. A glass lens of 55 mm. focal length was mounted in a hole in the side of a light-tight box, a cardboard screen being placed at a distance from the lens equal to its focal length. On this were mounted indices of black paper, the edges of which were placed 12 mm. apart. These were found to measure 21.8 scale divisions as observed through the orthoscope. The angle was found by reference to Table I to equal 12.3°. From these two values the power of the lens was found to be 56 mm., so that the difference between the true power and the measured power was 1 mm. Some values obtained by this method of measurement on the eyes of three cats are given in Table III.

TABLE III.

Measurements of focal lengths and power in dioptries of cat's eye:—

Number of cat	...	...	1	2	
Right or left eye	...	...	Rt.	Lt.	Rt.
Distance between images in mm. (= <i>d</i>)	...	...	3.44	4.00	1.7
Angle between images (= <i>a</i>)	...	...	11.86	16.2	6.7
Sine $\frac{1}{2}$ angle <i>a</i>	...	...	0.10337	0.1407	0.0584
Focal lengths	...	...	16.6 mm.	14.2	14.5
Power in dioptries	...	...	60.5	70.4	68.8
			Difference	1.6 D.	
Number of cat	...	...	...	3	
Right or left eye	...	...	...	Lt.	Rt.
Distance between indices	...	...	...	3.77	3.26
Angle between images (= <i>a</i>)	...	...	...	12.65	11.38
Sine $\frac{1}{2}$ angle <i>a</i>	...	...	...	0.1102	0.0976
Focal lengths	...	...	...	17.0	16.7
Power in dioptries	...	...	...	58.9	59.8
			Difference	.9 D	

It will be observed that the power in dioptries of the whole eye varies between 58.9 and 70.4, but in the case of the latter figure (which was one of the measurements obtained on Cat No. 2), the value may be rather above the normal, because this animal was not fully grown. Since growth would tend to increase the size of the eyeball it would therefore tend to make the apparent power in dioptries decrease. It will be seen further that the values obtained for the right and left eyes correspond well with one

another. In one case the difference was found to be 1.6 dioptre, and in the other case 0.9 dioptre. These values appear to us to show that a considerable degree of accuracy may be obtained by the use of this direct method of measuring the power of the eye, and this method can be applied in certain circumstances to the eye of man.

SECTION II.

Determination of the separate refracting powers of the cornea and crystalline lens

The radius of the cornea was measured, previous to the examination of the eye by the orthoscope as described above, by means of the instrument known as the "new" keratometer.⁽⁷⁾ In this instrument the two images of a suitable mire (one seen directly and one seen through a prism) are caused to come into coincidence by changing the position of the prism, and this instrument, when suitably calibrated, gives a direct measurement of the refracting power of the cornea. With this instrument the corneae of the cats under light anaesthesia were measured and the values are given in Table IV.

The power of the crystalline lens was obtained by removing the lens from the anterior half of the eyeball (which had been placed on one side after the removal of the retina for the purpose of the measurements described in Section I). The lens was placed in some mammalian Ringer's fluid in a small glass vessel with plane parallel glass sides. The trough containing the crystalline lens was placed on the stage of a micrometer microscope so that the centre of the crystalline corresponded with the optical axis of the instrument. A ruled glass micrometer was then attached to a ring placed in the plane of the mirror; the image of this ruled glass micrometer as formed by the crystalline lens was examined by the micrometer microscope.⁽⁶⁾ The values obtained are given in Table IV.

TABLE IV.

Powers given in dioptries:—

No. of cat... ..	1	2		3	
		Rt.	Lt.	Rt.	Lt.
Right or Left		42·2	41·75	39·1	38·75
Cornea	37·1	55·3	—	46·9	—
Lens actual	46·1	12·6	—	10·95	—
Correction	10·53	42·65	—	35·95	—
Lens effective	35·57	84·65	84·40	75·0	74·7
Lens plus cornea...	72·67				

It will be observed that the lenses in the case of Cats Nos. 1 and 3 were between 46 and 47 dioptries, that of Cat No. 2, i.e., the one which had a small eyeball, of rather higher power than the others, having a focal length of 55.3 dioptries.

From these two determinations (i.e., that of the power of the cornea and that of the power of the lens) the power of the eye as a whole can be ascertained by means of the use of Formula 16, *Gleichen's Modern Optical Instruments*, p. 42. One of the data required for the use of this formula is that of the depth of the anterior chamber of the eye. This was measured on one of the intact eyeballs of Cat No. 3 after death by means of a depth-measuring micrometer microscope. A small metal rod was passed through the cornea close to the corneo-scleral junction so that its point rested on the anterior surface of the lens. The apparent distance between the upper surface of the cornea and the anterior surface of the lens was now measured by first focussing one and then the other and ascertaining the movement in millimetres that had been necessary in order to do this. The following values were obtained, 4.35, 4.15, 4.45, 4.4 and 4.4, giving a mean of 4.35 mm. From this value the real distance between the surface of cornea and anterior surface of lens was ascertained by inserting suitable values into the formula:—

$$f^1 = \frac{F^1 f^2}{f^2 - F^2}$$

$F^1 = 25.7$, $F^2 = 34.3$, and therefore $f^1 = 3.74$ mm. The actual power of the crystalline lens in dioptries must therefore be reduced by $3.74 \times$ refraction of the cornea in dioptries $\times$ refraction of the crystalline lens in dioptries. The values obtained for this correction that must be applied to the lens, for the whole eye, for the cornea, for the actual lens, and for the cornea plus the corrected lens are given in Table IV.

SECTION III.

Consideration of the validity of Tscherning's criticism of Helmholtz's theory of accommodation

Tscherning has stated⁽⁹⁾ that measurements made on the crystalline lens of man, when removed from the eyeball, show that the lens is not in its fully accommodated condition as Helmholtz's theory leads one to suppose that it should be. And he states that Helmholtz's own figures demonstrate this lack of agreement. For this reason Tscherning himself advances an alternative theory of the method in which the accommodation of the eye takes place.⁽⁹⁾ The values that we had obtained are summarized in Table V. So far as we have been able to discover, no experiments have

ever been done on animals except perhaps the needle experiment of Henson and Voelckers⁽⁹⁾ which would tend to decide between these rival theories. We thought that it would be of interest therefore to apply the facts that we have obtained from the measurements described in the previous two sections to the elucidation of this problem:

TABLE V.

Values in dioptries :—

Lens plus cornea...	72·67	84·65	84·4	75·0	74·7
Whole eye ...	60·5	70·4	68·8	58·9	59·8
Difference ...	12·2	14·2	15·6	16·1	14·9
Mean difference ...	14·6				

It will be observed that the combined power of the lens and cornea exceeds that of the whole eye by a figure which varies between 12.2 and 16.1 dioptries. In other words, the lens plus cornea has a greater refracting power when the two measurements are made separately (the crystalline lens having no traction on it due to its suspensory ligaments) than that given by the whole eye when presumably the suspensory ligaments are in a state of traction, thus flattening the crystalline lens. We conclude, therefore, that the crystalline lens of the cat when the eye is not in an accommodated state is flattened by the pull of the ligaments to an extent that decreases its curves so as to diminish its power by approximately 14 dioptries, and this is entirely in favour of Helmholtz's hypothesis, and is equally at variance with that of Tscherning.

There seems to us to be little doubt, therefore, that in the cat, at all events, accommodation takes place in the manner that Helmholtz suggested, and when this conclusion is taken in conjunction with the findings of Grossmann⁽¹⁰⁾ and Hess⁽¹¹⁾ in the case of man, there would appear to be insuperable evidence against Tscherning's criticism. Grossmann found in the case of a man of 26 years with congenital absence of the iris that :—

1. The accommodated lens became 1.25 mm. smaller in diameter.
2. That it became 1.3 mm. thicker.
3. That the lens became tremulous owing to slackening of the suspensory ligaments, as Hess had described.
4. He also found that the lens surfaces near the centre of the pupil became relatively more curved than the more peripheral parts; an anterior and posterior lenticonus was formed.

The first three observations are quite incompatible with Tscherning's teachings; the last one agrees in showing that accommodation does to some extent affect central more than peripheral parts of the lens, which would account for the images obtained by Thomas Young⁽¹²⁾ with his optometer, confirmed by the experiments of Mannhardt⁽¹³⁾ and Schoen⁽¹⁴⁾. Evidence is, on the other hand, altogether wanting that more than a relative flattening takes place, whereas the unaccommodated lens has an anterior surface which is nearly spherical and 10 mm. radius. Tscherning's theory requires that while its central part becomes more curved, changing, say, from 10 mm. radius to 6 mm. radius, its peripheral part becomes flatter, its radius increasing beyond 10.

For this there is no evidence. What there is evidence for is a decrease in the radius both of the central and peripheral parts on accommodation, but of the two the peripheral suffers the less change. There is therefore relative but not actual flattening.

We thought it would be of interest to ascertain how much of this potential accommodation of 14 dioptries the cat actually makes use of during life; we therefore obtained some measurements of the amplitude of accommodation of one of the cats referred to above. The refracting power of the eye when under the influence of atropin was measured by the ordinary mirror test that is used in ophthalmic practice, and this was repeated with the eye under eserine. We found, however, that the contraction of the pupil under eserine was so strong that there was no pupillary aperture through which observations could be made, and therefore in one of the other cats we performed a preliminary iridectomy operation under deep anaesthesia. Subsequent observations did not give a greater difference than 3.5 dioptries between the values found for the eye when under atropin and for the same eye when under eserine, and it is possible either that the adult cat only makes use of 3.5 dioptries of the potential accommodation of 14 dioptries (because, possibly its ciliary muscles are insufficiently strong to exert the necessary traction) or it is possible that the eserine had not been allowed to act for a sufficiently long time, or there is a third alternative that it has not the same powerful effect on the accommodation in the case of the cat that it has in the case of man. (In this connection it is interesting to note that of the potential accommodation of about 10 dioptries possessed by a man of 26 years of age Grossmann was only able to find 5 using eserine and atropin.) We should mention at this point that we have found all three cats used for the purpose of these determinations to be almost emmetropic, which is at variance with the usual statement that the cat is short-sighted.

SECTION IV.

Light transmitting power and resolving power

The above measurements would hardly be complete without some attempt to ascertain in what way the cat's eye differs from man's eye as an instrument for receiving light from external objects and of forming sharply focussed images of these objects on the retina. We found that the maximum diameter of the pupil which the cat's eye gave when under the influence of atropin was very nearly 15 mm. Now our figures for the focal length of the intact adult cat's eye are approximately 14.3 mm.; the aperture ratio, that is the apparent pupil diameter, divided by the focal length has a value of approximately 0.97. In the case of man the maximum pupil diameter under atropin is approximately 10 mm., and the focal length as calculated by Helmholtz is approximately 15 mm., which gives the aperture ratio of 1.5. Now the efficiency of the eye as a light gathering organ varies as the square of the aperture ratio, and therefore the relative efficiencies of man's eye and the cat's eye are as 1.5^2 is to 0.97^2 , and this is found to give a value for the relative efficiency of 2.4, that is when the pupils in both cases are at their fullest dilation, or are at the same relative dilation. The luminosity of the images formed on the retina will therefore, in given circumstances, be 2.4 times as bright in the case of the cat as in the case of man.

We have now to consider the relative resolving powers. If both eyes were entirely free from aberration the focal lengths being so nearly alike, say, 14 mm. for the cat and 15 mm. for man, there would be no very obvious difference in the scale of retinal images that could be resolved in the two cases, assuming that the distance between the foveal cones are the same in cat and in man. But it is well known that spherical and chromatic aberrations form important factors in the case of the eye of man, and that considerable modification takes place in the images formed on the retina as the result of the phenomenon of diffraction. Now we have observed during these investigations considerable amounts of aberration in the cat's eye. Not only is the normal cornea of the cat apparently irregular in its surface, but also there is considerable change in curvature as one makes one's measurements away from the centre or at the centre. Further, when making measurements on the crystalline lens it was found almost essential to employ a colour-filter transmitting green rays because of the obvious chromatic difference of magnification and chromatic difference of focus that was manifest in the image. It would seem, therefore, that any gain from diminished diffraction which the cat might obtain owing to the large aperture ratio that it appears to employ is more than spoiled by the considerable aberrations

which are thus introduced at the same time. So that we would conclude that the ability to collect a large amount of light and therefore to form bright images on the retina is done at the expense of resolving power.

Summary

A method of determining the focal length of the eye as a whole in situ is described. It depends on the determination:—

- (a) of the angle subtended by the images of chosen retinal structures at the anterior nodal point of the eye, and
- (b) the actual distance between those same structures.

The values thus obtained for the right and left eyes of two cats were concordant to within 2.5 per cent., and the powers of the eyes were found to average between 60 and 70 dioptries. The powers of the corneas and crystalline lenses after removal from the eyeballs were also determined and were found to average 40 dioptries and 50 respectively.

From these values and those of the depths of the anterior chamber the average power of the fully accommodated eye was calculated to be about 80 dioptries, that is, roughly, 15 dioptries more than the direct values for the unaccommodated eye in situ. This kind of difference in value is in agreement with Helmholtz's theory of the accommodation of the eye, and is at variance with that of Tscherning. Other points with regard to the rival theories of accommodation and to the eye of the cat as an optical instrument are discussed.

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