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THE PROPORTION OF CILIARY MUSCULAR FORCE REQUIRED FOR ACCOMMODATION

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There is general agreement that gradual sclerosis of the substance of the crystalline lens causes the progressive reduction of the amplitude of accommodation of the eye with age. It is thought that the other components of the mechanism, the ciliary muscle, the lens capsule and the suspensory fibres of the zonule of Zinn, remain functionally unchanged, at least until there is evidence of general senility in the body. The manner in which this sclerosis will restrict the responsiveness of the lens to ciliary muscle contraction must depend upon the way in which the change in the curvature of the lens is brought about. Thus there have been two schools of thought regarding the relation of ciliary muscle contraction to change in the form of the lens at various ages.

Both schools agree that contraction of the muscle causes a reduction in the diameter of the ring-shaped ciliary body from which the lens is suspended. Thus as the muscle contracts during accommodation the tension of the suspensions is relaxed. They do not agree, however, as to the manner in which this reduction of tension causes an increase in the curvature of the lens. Helmholtz (1855) held the view that the lens is elastic, and when the muscle is not contracted, is held in a flattened condition by the tension of the suspensions. When the muscle contracts the elastic lens then assumes a more convex form. However, the substance of the young lens is quite soft and relatively inelastic. On the other hand, the enveloping tunic or capsule of the lens has marked elastic properties. Accordingly, the other view (Fincham, 1925) considers that contraction of the ciliary muscle with consequent relaxation of the tension of the suspensory ligaments gives freedom to the lens capsule to mould the lens substance into the accommodated form.

Thus the principal difference between the Helmholtz and Capsular theories is this: in the Helmholtz theory the relaxation of tension in the suspensory ligaments which occurs during accommodation was thought to permit the elastic lens substance, which had been deformed in the unaccommodated state,

to return to the more convex-free form. According to the capsular theory, on the other hand, such relaxation allows the highly elastic capsule to deform the lens substance from its unaccommodated state to the greater convexity required.

The adherents of Helmholtz's theory (Hess, 1903; Gullstrand, 1909; Fuchs, 1921) have considered that maximal accommodation depends upon the elasticity of the lens substance, which governs its ability to return to its free, i.e. accommodated, form when the tension under which it is suspended is reduced. The loss of accommodation with age must be owing, according to this theory, to loss of elasticity and a gradual flattening of the lens substance. This view implies that with increasing age the proportion of the total ciliary muscle power required to produce full accommodation will be reduced. Gullstrand has said that when, in presbyopia, the amplitude of accommodation is only, say 2 dioptres, the muscle contraction required to reach the near-point is not more than that necessary to produce 2 dioptres in youth, so that most of the ciliary muscle power must be latent.

The capsular theory, on the other hand, leads to the conclusion that as the lens substance becomes harder with age, greater force from the elastic capsule will be required to produce a given change of curvature. This force, in view of the elasticity of the supensions, can only be applied by greater contraction of the ciliary muscle. Consequently, a force approaching the full capacity of the muscle may be required to produce maximal accommodation whether it be some 15 or 16 dioptres in youth or only 1 or 2 dioptres in presbyopia. This view (Fincham, 1932) explains why we are unable to maintain our full accommodation for more than a short time and why the presbyope requires optical aid, although his near-point may not lie outside his near working distance.

The work of van der Hoeve & Flieringa (1924) appears to support the hypothesis that much of the muscle power becomes latent as age advances. They made experiments on the effect of partial cycloplegia upon the positive relative amplitude of accommodation, i.e. the amount by which accommodation can be increased beyond that which normally accompanies a given convergence. Their results, which were obtained subjectively, led them to conclude that the ciliary force required to raise the physical accommodation 1 dioptre is constant. To this unit they gave the name myodioptre. In a subject aged 31, they found the full force of the muscle to be 24 myodioptres, although only 9 were employed to produce maximal accommodation. On the other hand, Goldmann & Aschmann (1946), Aschmann (1947) and Goldmann (1948) found strong evidence for the capsular theory. They made experiments on the relative efficacy of the ciliary muscle in subjects with unilateral artificial paresis, from which they concluded that the excess of muscle power over the physical amplitude of accommodation was much less than that demanded by the Hess–Gullstrand version of the Helmholtz theory.

The methods which have been used in the investigation of this problem in the past have had to depend upon the measurement of the subjective near-point which is unreliable as a means of measuring total accommodation. Moreover, some uncertainty must arise from the need to rely upon the subject voluntarily making his maximum effort at the moment the test is made. In the study which is described in this paper recourse has been made to a method of inducing accommodation by stimulating convergence of the visual axes (Fincham, 1951). The need for voluntary effort by the subject to focus a fixation mark is thus eliminated. The actual change in the optical power of the eye as accommodation occurs has been measured objectively upon a constant portion of pupil, so that changes in pupil size do not affect the results.

The effects both of paresis and artificial stimulation of the ciliary muscle, produced by the action of drugs, have been studied by comparing the accommodative response to varying degrees of convergence under these conditions, with those which occur when the muscle is in its normal state. The results which are to be discussed throw light upon our knowledge of the mechanism by which accommodation is brought about.

METHOD

Apparatus

In these experiments it was required to measure those changes in accommodation which are stimulated by the act of convergence of the visual axes. Therefore the apparatus consisted of a combination of a special form of haploscope to stimulate convergence, with an objective optometer (Fincham, 1937*a*) with which the accommodation was measured. The general scheme of the apparatus is shown in Fig. 1. The haploscope differed in some respects from the form of instrument generally employed in experiments on accommodation—convergence relationships. It was necessary to eliminate the effects of changes in the vergence of the light reaching the retina (to which accommodation reacts). This was done by limiting the area of the pupils through which the light from the fixation marks passed to approximately 0·5 mm diameter. Thus the fixation marks were seen with pinhole vision and remained sharp, except for diffraction effects which do not stimulate accommodation. The principle of the fixation device is shown in Fig. 2. A', which is the image of the aperture A, forms the effective stop in the pupil which restricts the pencils of light from the fixation object O. Another variation that was made from the usual form of haploscope, was that stimulation of convergence was brought about by movement of the left fixation system only, while that for the right eye remained aligned with the axis of the optometer, which was fixed. (As innervations of accommodation and convergence are binocular, asymmetry of fixation should not affect the results of the experiment.)

The measurements of accommodation were made on the right eye. The fixation system which is normally incorporated in this optometer was modified to give the necessary narrow pencils of light and provided the fixation object for the right eye. For the left eye, a similar system was provided, which was attached to the optometer and was capable of lateral movement to allow for various interpupillary distances; it could also be rotated on a vertical axis about the centre of rotation of the eye, as shown in Fig. 1. Graphical calibrations were prepared relating the settings of the rotatable element with convergences for various interpupillary distances.

A means of centring the optometer upon the pupil of the eye is provided in this instrument. Centring of the fixation system for the left eye was determined by the interpupillary distance and the height of the left eye relative to the right. An adjustment had to be provided to move the left

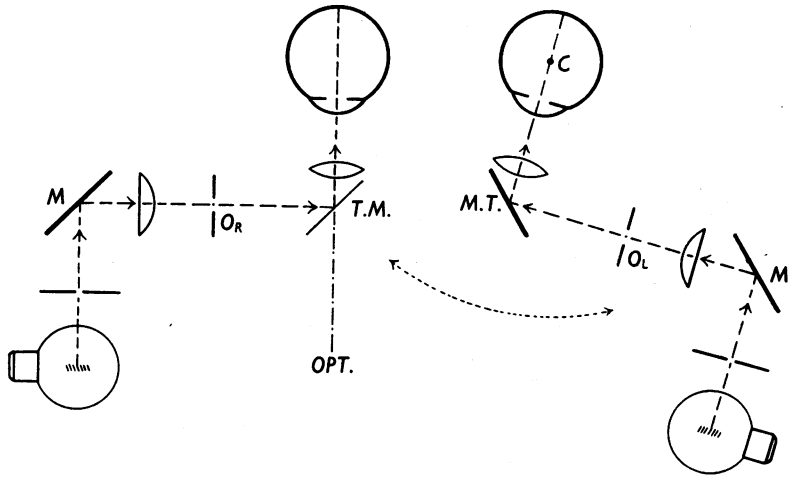

Fig. 1. General scheme of apparatus. O_R, fixation object for right eye; O_L, fixation object for left eye; C, centre of rotation of fixation system for left eye; *T.M.*, transparent pellicle mirror; *M.M.*, surface-silvered mirrors; *M.T.*, surface-silvered mirror, tiltable about a horizontal axis; *OPT.*, axis of optometer.

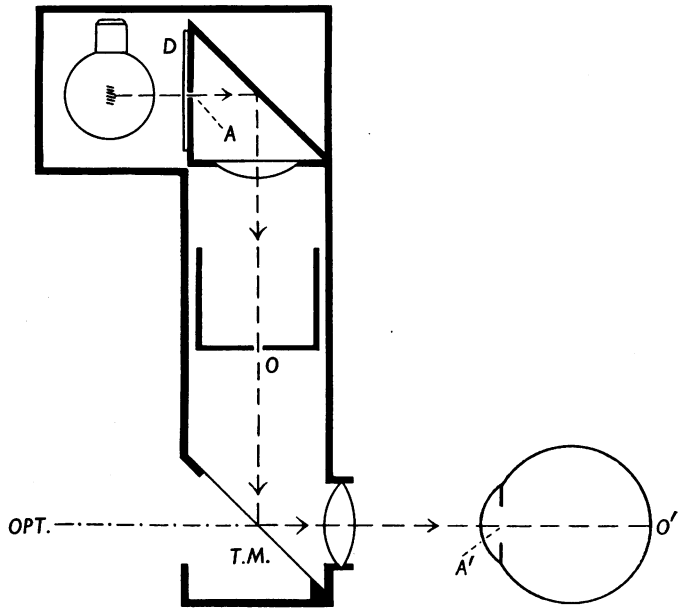

Fig. 2. Optical system of fixation device. *D*, diffusing screen; *T.M.*, transparent pellicle mirror; *OPT.*, axis of optometer. The aperture *A* is imaged at *A'*; the fixation object *O* is imaged at *O'*.

system vertically to correct for differences in height of the eyes, a common anatomical asymmetry. To ensure that the narrow beam of light from the left fixation system remained within the area of a small pupil, even though the eye rotated through large angles, it was necessary for the axis of rotation of the system to pass through the centre of rotation of the eye. This point is not fixed in any subject and may vary in position from one subject to another. The position used in these experiments was a mean of 15·5 mm behind the corneal vertex (George, Toren & Lowell, 1923).

The fixation object for each eye consisted of a white disk (subtending an angle of about 1°) with a small black spot in the centre. To verify that the single image seen by the subject resulted from the fusion of the images seen by each eye, the customary right and left identification marks were provided. To allow for small vertical muscle imbalances an adjustment for the height of the left image was provided by making the mirror *M.T.*, Fig. 1, tiltable about a horizontal axis. Many subjects were found to be unable to maintain fusion of the images during convergence, although apparently they had normal binocular vision. It is probable that the unnatural visual task of converging to fuse the images while the vergence of the light remains unchanged, calls for unusually highly developed fusion faculty.

Procedure

In carrying out the experiments the left fixation system was set at a separation from the optometer axis equal to the interpupillary distance, the subject's head was held in the head-rest of the instrument, and the distance adjusted to bring the axis of rotation of the left fixation system to the correct position, i.e. 15·5 mm behind the vertex of the cornea. This system was then rotated to the parallel position and the subject was instructed to view the fixation objects and if necessary adjust the apparent height of the left one; fusion then usually occurred and a reading of the refraction of the right eye was made while no convergence was in play. The left fixation system was then rotated to predetermined angles, thus stimulating convergence to 1, 0·5, 0·33 m, etc., the refraction of the right eye being measured for each condition. The convergence was continually increased in this way until no further accommodation changes occurred. The limiting measurement agreed closely with the maximum accommodation as determined by measurement of the subjective near-point.

As it was required to study the effect of age upon the rate at which accommodation was increased by increasing convergence, it was necessary to make this experiment upon a wide age-spread of subjects. It is known that individual factors other than age, e.g. heterophoria, may cause differences in the relation between the two functions, but the influence of these factors on the result tends to be eliminated when a sufficiently large number of cases is studied.

In order to test whether the whole force of the ciliary muscle was required to produce maximal accommodation, similar sets of measurements were made during slight paresis of the muscle by homatropine and also under the effects of eserine. The dose of homatropine was generally 1 drop of 0·05% solution instilled into the conjunctival sac of both eyes, but in one subject (P.S.) the effect of this dose was too great and 0·01% solution was used. On the other hand, in a coloured subject (H.A.St J.) a stronger (0·1%) solution was needed to cause slight reduction in accommodation. Measurements of the refraction during convergence were made at 5 min intervals after the instillation of the drug; the series which is recorded was taken as soon as any reduction in accommodation relative to convergence was detected. In most cases between 15 and 30 min was required for this effect. Eserine was used to enhance the response of the ciliary muscle to convergence, and thus to test the possibility of increasing accommodation beyond the normal maximum. The effect of eserine in contracting the pupil caused some difficulty in this experiment as the optometer cannot be used on eyes with pupils of less than 2·5 mm diameter. For these experiments, therefore, subjects with naturally large pupils were selected and doses of only 1 drop of 0·05% eserine solution (instead of the usual clinical strength of 0·5%) were given. This selection automatically precluded from the experiments presbyopes, who normally have small pupils.

RESULTS

Sixteen subjects found by preliminary tests to have a sufficiently good fusion faculty were selected for these experiments. In every case it was found that increases of convergence were accompanied by increases of accommodation. The relation of the two functions varied with the age of the subject; in older subjects not only was the maximum lower but the rate of increase of accommodation was less. This difference is well seen in Fig. 3 where results of the experiment on three subjects aged 23, 41 and 50 have been plotted. The slope of the curve appears to be characteristic of the age of the subject, and in Fig. 4 this is confirmed. In this graph, the tangent of the angle of the line relating accommodation to convergence is plotted against age in fifteen subjects. It will be noticed that one of these (E.F.F., the present writer) appears twice. The first result was made in 1940, the second in the present investigation, and these are the only measurements made on a single individual over a period of time.

The experiment on the effect of slight paresis of the ciliary muscle by homatropine was made on subjects of ages varying from 28 to 48 yr. The results are shown in Figs. 5 and 6. In no case was a reduction of accommodation relative to convergence detected without a corresponding reduction in the maximum of accommodation. The effect of eserine was tested on four subjects with the results shown in Table 1. In the case of only one of these subjects (P.S.) was it possible to continue increasing convergence until accommodation remained unchanged. This result is shown in Fig. 7. In other cases the effect of the drug on the pupil was rapid, and with the added stimulus of convergence the pupil became too small to allow readings to be taken. It cannot be presumed that any of these results shows the effect of the full force of the ciliary muscle, because in order to avoid great contraction of the pupil only very small doses of eserine were given.

It should be emphasized that the increase in accommodation measured in these four cases under eserine was a true gain in optical power and not an effect of increased depth of field due to pupil contraction.

DISCUSSION

Total power of the ciliary muscle

No attempt has been made in this work to assess the total power of the ciliary muscle to produce accommodation in the presence of an ideally responsive crystalline lens. Such assessments as have been made in the past were based upon certain assumptions arising from Helmholtz's theory of accommodation. As the power of the muscle can only be measured by its effect upon the lens, its consideration as a separate entity is justified only if the muscular contraction is always proportional to the change in dioptric power of the eye. This

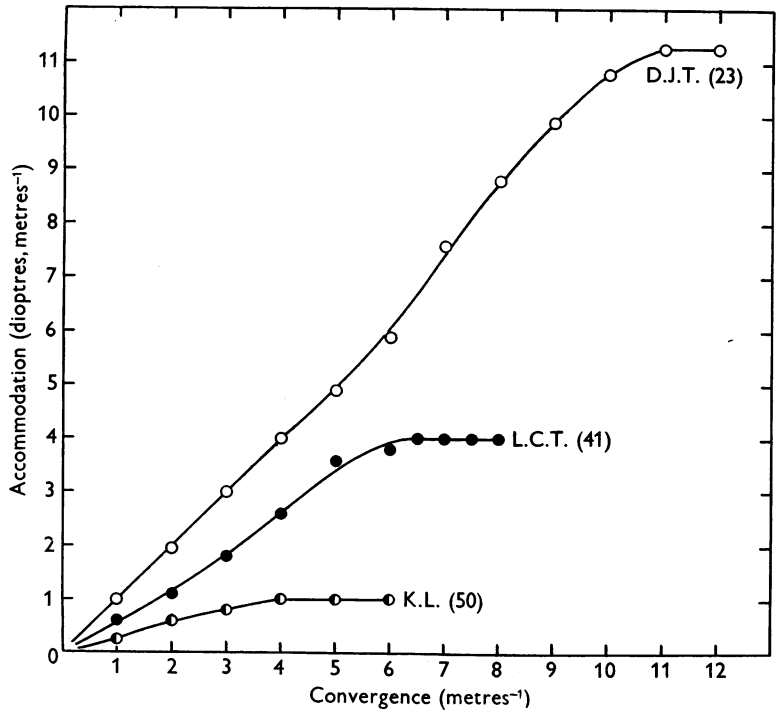

Fig. 3. Accommodation induced by convergence. Results on three subjects of different ages. Both the maximum and the rate of increase of accommodation relative to convergence become less with age. Convergence is shown in the units metres^{-1} as comparable with dioptres of accommodation.

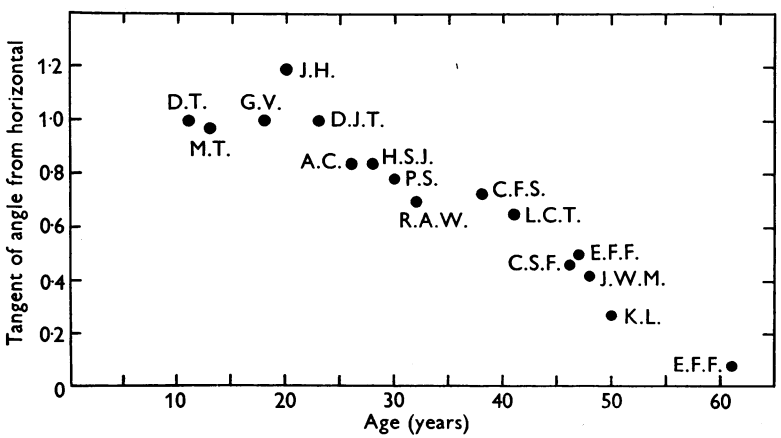

Fig. 4. Variation of slope of accommodation-convergence line with age. Tangent of the angle of the accommodation-convergence line (see Fig. 3) plotted against age in fifteen subjects.

would be the case if Helmholtz's theory were correct, for the ultimate force producing the increase in convexity of the lens would be contained within the lens itself, and the role of the muscle would be only to allow this force to

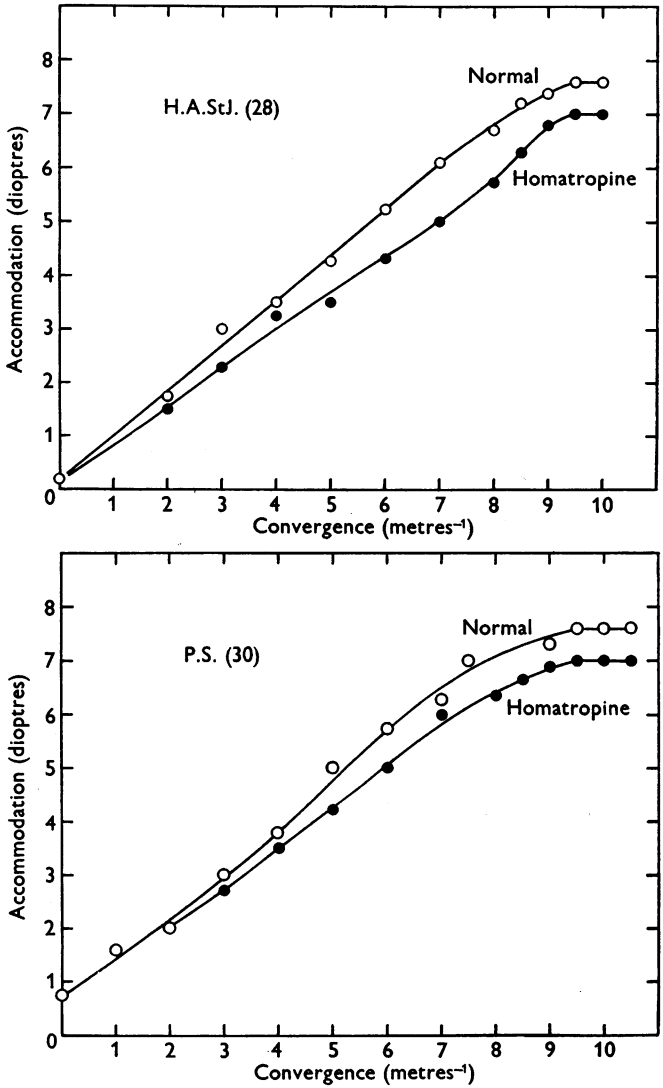

Fig. 5. Effect of slight paresis of the ciliary muscle upon accommodation induced by convergence

operate. If, on the other hand—as the age of the subject advances—the muscle is called upon to do more work for a given change of convexity of the lens, then the power of the muscle cannot be measured by instruments which record the number of dioptres of accommodation.

The increase of accommodation with increasing convergence

(*a*) *The influence of age.* These experiments have shown that when the controlling influence of the vergence of the light at the retina is removed, convergence of the visual axes causes the accommodation to be increased by an amount which, in young subjects, is sufficient to focus the eyes to the distance for which they are converging. At all ages convergence, when sufficient, causes the eyes to accommodate for the near-point. As age advances not only does

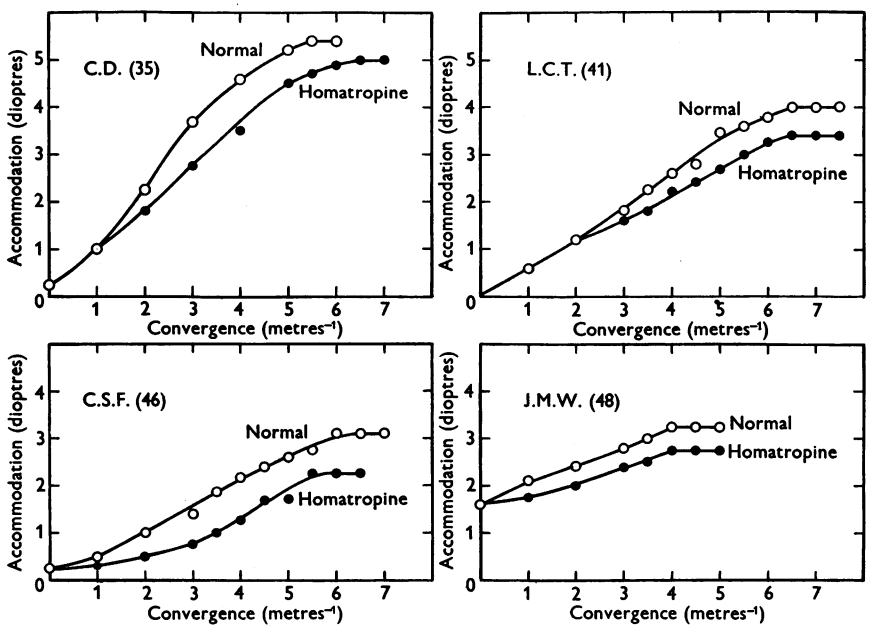

Fig. 6. Effect of slight paresis of the ciliary muscle upon accommodation induced by convergence.

the dioptric value of the near-point become less but the rate of increase of accommodation in relation to convergence is reduced. This second point is brought out by the graph (Fig. 4) where the slope of the line relating accommodation to convergence in fifteen subjects is plotted against their age.

(*b*) *Relationship to accommodation theory.* The reason for the change in the slope of the line with age, shown in these experiments, may be that more contraction of the muscle is required to produce a given change in the gradually hardening lens. If the Hess–Gullstrand interpretation of the Helmholtz theory were correct we should expect the curve relating induced accommodation to convergence to have the same slope throughout life and merely be shortened as the near-point of accommodation recedes. We must conclude therefore that

the hypothesis of a unit of ciliary muscle power, the myodioptre, which is obtained by measuring the effect upon the lens of the muscular contraction, and is constant throughout life, is invalid.

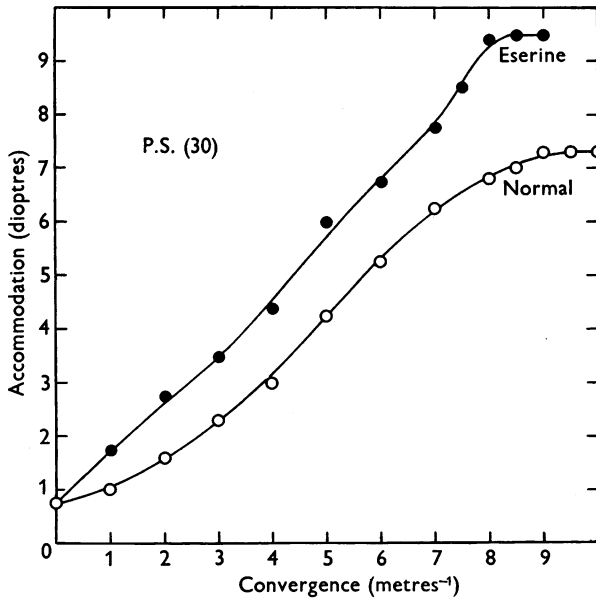

Fig. 7. Effect of eserine upon the accommodation induced by convergence.

TABLE 1

Subject	Age (years)	Maximum accommodation, normal (dioptres)	Maximum accommodation under eserine (dioptres)
A.F.D.	27	8·25	10·5
H.A.StJ.	28	6·8	9·25
P.S.	30	7·3	9·5
C.D.	35	5·25	6·7

Experiments with homatropine

The experiments on the effects of homatropine test whether maximal contraction of the ciliary muscle is required to produce full accommodation at all ages. Acceptance of the Helmholtz theory entails the belief that a gradually diminishing part of the total power of the muscle is used as the amplitude of accommodation decreases with age, so that in presbyopic eyes most of the muscle force remains latent. Fuchs (1921), who held this view, thought that the total power of the muscle was sufficient to produce 15 to 20 dioptres of accommodation in youth and that the muscle power was maintained throughout life. If this were the case a subject of 48 years of age with an amplitude of accommodation of 2 dioptres would use only one-tenth of the power of his

ciliary muscle. As Duane (1925) pointed out, if this were true the effect of a cycloplegic in this case would not be manifest until it had paralysed nine-tenths of the power of the muscle; not till then would that small part of the total muscle force required to produce accommodation be affected. We should therefore expect that to affect the near-point larger doses of the cycloplegic would be necessary in older subjects than in the young, in whom more of the total power of the muscle is effective, and that minimal doses of cycloplegic should leave the near-point of older subjects unaffected. Duane observed that this was not in accordance with clinical experience, and it does not agree with the present results.

Minimal amounts of paresis in a ciliary muscle receiving its normal nervous signals from the central nervous system must lower the force exerted by the muscle at all values of convergence, so that the slope of the graph relating accommodation to convergence must diminish. If, however, Helmholtz were right and the whole force of the muscle is not required to produce maximal accommodation, slight paresis should not affect the near-point. The graph relating accommodation to convergence would be reduced in slope, but should reach the same maximum when sufficient convergence is exerted. The results show that this is not the case, for whatever the age of the subject, as soon as any effect of paresis appeared, causing a reduction in the slope of the graph, the maximum of accommodation was reduced as well.

Owing to uncertainty regarding absorption and effect of the drug, it was not always possible to adjust the dose—or the time of its action—so that very slight effects could be studied. However, the results obtained on the subject L.C.T. (aged 41 yr, normal amplitude of accommodation 4 dioptres) show a good example of the effect (Fig. 6). In this case reaction to the drug was first recorded when it had caused the ratio of accommodation to convergence to be reduced by about 20%. At this point the total accommodation was then found to be reduced from 4 to 3·4 dioptres, thus approximately the whole of the normal power of the muscle must be required to produce full normal accommodation.

Experiments with eserine

Since the loss of accommodation with age is generally attributed to lens hardening it might seem impossible for eserine to increase the maximal power of the eye. However, there is no evidence that the lens substance could not at any age be moulded into a more convex form if the capsule were given the necessary freedom. We know that the lens removed from the eye, and thus freed from all tension, has curvatures which are at least as great as the average of those found in the fully accommodated eye of the same age. The radius of curvature of the anterior surface of a lens removed from a freshly excised eye of a man of 65 yr was found to be 9 mm (Fincham, 1932). This value may well represent a greater optical power than the eye was capable of producing

by voluntary accommodation. It is not uncommon to find the radius of this surface to be 12 mm *in situ* in the unaccommodated eye, and a change of radius from 12 to 9 mm is consistent with accommodation of more than 2 dioptres, whereas a person of 65 usually has an amplitude of accommodation of considerably less than 1 dioptre.

Eserine appeared to enhance the response of the ciliary muscle to the stimulus of convergence so that the ratio of accommodation to convergence and the maximum accommodative power of the lens were increased. The importance of the result was not merely that the maximum of accommodation was reached with less convergence effort as may have been expected, but that the maximum was also considerably increased. This ability of the eserinized ciliary muscle to exceed the normal physiological response is comparable to the phenomenon recorded with the gastrocnemius muscle by Brown, Dale & Feldberg (1936).

Before assuming, however, that this increase of power was caused by an increased convexity of the lens it is necessary to examine another possibility. The effect of additional contraction of the ciliary muscle will be to reduce still further the tension under which the lens is suspended, and Hess (1896) has shown that with high efforts of accommodation the lens suffers some displacement. This effect was taken by Hess and later by Gullstrand (1909) to be evidence that the muscle was capable of contracting beyond the amount to which the lens could respond. Hess showed that the displacement was always in the direction of gravity, i.e. downward when the visual axis was in the horizontal plane, and forward toward the cornea if the visual axis was directed vertically downwards. This forward movement of the lens increases the optical power of the eye, so that the near-point is slightly closer than normal when the head is held forward with the eyes directed downward. Hess found that the lens moved foward by 0·15 mm and Fincham (1937*b*), using the slit-lamp, found that the depth of the anterior chamber of a fully accommodated eye of a young subject was 0·2 mm less when the visual axes were directed downwards, than when horizontal. Calculation shows that if, in an eye accommodated by 8·5 dioptres, the lens were moved forward by 0·25 mm the increase in power of the eye would be only 0·277 dioptre, and a forward movement of as much as 1 mm, which is improbable, would cause an increase of 1·78 dioptres.

In the experiments described in this paper the eyes were always in the normal position with the visual axes horizontal, so that any displacement of the lens by gravity would probably have been perpendicular to the axis and not forward toward the cornea. Such a movement would result primarily in astigmatism. In order to detect this the fully accommodated eserinized eye was measured in both the horizontal and vertical meridians but no appreciable astigmatism was found. The actual changes in the curvature of the lens surface can of course only be proved by measurement of the third Purkinje image. Unfortunately such a demonstration was not possible in the present experiments

because of the effect of eserine in contracting the pupils. Nevertheless, the arguments above seem to point unequivocally to the conclusion that the accommodation additional to the normal physiological maximum, which is brought about by eserine, is the result of increased curvature of the lens, and should be regarded as an extension of the normal mechanism.

These experiments with drugs have shown that if the ciliary muscle is weakened at all, the amplitude of accommodation is reduced, and that if the contraction of the muscle is enhanced, accommodation is increased beyond the normal maximum. It appears, therefore, that maximal accommodation is determined by the degree of contraction of the ciliary muscle as well as the flexibility of the lens substance. At the physiological near-point as well as at intermediate states of accommodation, the resultant power of the eye is governed by a condition of balance between the freedom given to the capsule by the contracting muscle and the resistance of the lens substance to deformation by the capsule. As age increases this resistance steadily becomes greater until all accommodation is lost.

SUMMARY

1. Apparatus has been designed to stimulate accommodation of the eye by convergence alone and eliminate the clues normally received from changes in vergence of the light at the retina.

2. It was found that under these conditions the physiological maximum of accommodation can be induced by convergence.

3. The rate of increase of accommodation with increasing convergence is reduced with age. This appears to be caused by the need for greater ciliary force to produce a given amount of accommodation.

4. Artificial paresis of the ciliary muscle sufficient to produce the slightest reduction in accommodation relative to convergence also causes the maximum of accommodation to be reduced at all ages. Therefore, maximal accommodation requires the maximal force of the ciliary muscle.

5. The effect of eserine is to enhance the contraction of the ciliary muscle accompanying convergence. This results in an increase of accommodation relative to convergence.

6. Under eserine the maximal accommodation is increased above the physiological maximum. Three cases between the ages of 27 and 30 showed an increase of more than 2 dioptres.

7. These findings are in accord with the capsular theory of the mechanism.

8. The amplitude of accommodation is not limited solely by the hardness of the lens substance. At the physiological maximum there is a condition of balance between the freedom given to the capsule by the contracting muscle and the resistance of the lens substance to deformation.

I wish to thank Mr W. H. A. Fincham for calculating the effect of movement of the crystalline lens. Thanks are also due to those who acted as subjects; Misses J. Howells, P. Strange, D. J. Taylor, G. Villermet, Drs K. Tansley, L. C. Thomson, R. A. Weale, Messrs A. Cragg, A. F. Deverell, C. Downing, C. S. Flick, H. A. St John, J. W. Morris, C. F. Seath, D. Thomson and M. Thomson.

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