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THE RECIPROCAL ACTIONS OF ACCOMMODATION AND CONVERGENCE

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In normal binocular vision the faculties of accommodation and convergence operate in unison. When attention is directed from a relatively distant object to a nearer point, convergence of the eyes is stimulated so that correspondence of the retinal images is maintained. At the same time the need to refocus the retinal images provides a stimulus to accommodation. Thus the basic stimuli to the binocular adjustment for near vision are (*a*) the temporal displacement of the retinal images relative to one another, (*b*) the change in the vergence of the light reaching the retina. (The term 'vergence' is used throughout to refer to the degree of divergence or convergence of the light: it is measured in dioptres.)

Donders (1864) showed that some latitude of action is possible between accommodation and convergence; there is an amplitude of accommodation corresponding to each convergence value, while on the other hand convergence can vary relative to a fixed condition of accommodation. In determining such amplitudes each function in turn requires to be held in a fixed state of action, while the other is varied. The need to provide a stimulus, in order to fix either one of the two mechanisms while the other is changed, leads to the question how far either function, being unstimulated, responds in sympathy to stimulated changes in the other.

As it is necessary to avoid the direct stimulation of the mechanism when its induced reaction is being studied, the response of convergence to accommodation can be detected only during monocular fixation, since the need for binocular fusion is the stimulus to convergence. This relationship, accommodative convergence, is well known, and is commonly measured in clinical practice, but there has always been a question whether a similar relation holds in the opposite direction, i.e. the reaction of accommodation to convergence. Thus Christoferson & Ogle (1956) wrote: 'To what extent convergence-accommodation exists is uncertain because the difficulties of measurement have prevented definitive results'. These difficulties arise from the need to eliminate the direct stimulation of accommodation by light vergence, while at the same time presenting to each eye sufficiently well-defined images to stimulate binocular fusion and to control convergence.

We should expect these relationships to be interlinked. The response of each mechanism to its appropriate stimulus will be influenced by the reflex innervation it is receiving from the other mechanism, an effect which in turn will influence the freedom of action of accommodation and convergence relative to one another. The age of the subject might also be expected to influence the relation between the two functions. Since the accommodative mechanism becomes less efficient as age increases without a concomitant decline in convergence, some compensatory adjustment in the related innervations will be necessary to keep the relation between the two functions the same.

Although most of these problems have been studied by many workers in the past, the diversity of the opinions which have been expressed has led us to attempt a new experimental approach to the whole subject. The results of these experiments have provided further evidence of the manner in which accommodation is controlled, and lead to some new conclusions regarding the reciprocal actions of accommodation and convergence.

METHODS

Apparatus

Before describing the technique of the experiments it may be helpful to outline the general conditions that were required as regards both the control of the stimuli to accommodation and convergence, and the measurement of the responses. The Coincidence optometer was used in the objective measurement of ocular refraction. The various devices required to control fixation and to stimulate accommodation and convergence were incorporated in this instrument.

A fixation object with fine detail to stimulate accommodation was required for each eye. The light from these objects had to enter the eyes with variable and known amounts of divergence. In order to stimulate convergence it was necessary for the fixation device before one eye to be capable of rotation about the centre of rotation of the eye, which necessitated also an adjustment for interpupillary distance. As the optometer allows the measurement of the refraction of a predetermined diameter of pupil this was fixed at 3 mm in all the experiments. To ensure that the subject was using the same part of the eye's optical system, provision was made that the pencils of light from the fixation objects had a diameter of 3 mm at the pupil whenever it was required to give a direct stimulus to accommodation. For experiments on the induction of accommodation by convergence it was necessary to reduce the aperture of the light from the fixation objects to 0·5 mm without appreciably changing the luminance of the image. For the measurement of convergence during monocular fixation, a vertical line of light (Maddox streak) had to be presented to the non-fixing eye.

The general scheme of the fixation apparatus was a haploscope shown in Fig. 1. The fixation system of the right eye consisted mainly of the device which is incorporated in the standard model of this optometer. A special object was substituted and the illuminating system modified to give control of the diameter of the light pencils by the addition of apertures at A, and the lens B. This optical system produced an image of the apertures at A at the subject's pupil. The divergence of the light from the object was changed by moving the object along the axis relative to the lens L. Scales were provided on each system to show the dioptric value of the vergence at the eye.

The design of the fixation object is shown in Fig. 2. To the subject it subtended an angle of 1° when placed at the position of zero light vergence. Within the circle were two rings of pairs of white marks: in the outer ring the marks had an angular separation of 2′ at the eye, and in the inner ring the gaps subtended an angle of 1′. These stimulated accommodation and checked visual acuity. The white dot outside the ring was above in the object for the right eye and below for the left and so provided evidence of binocular fusion.

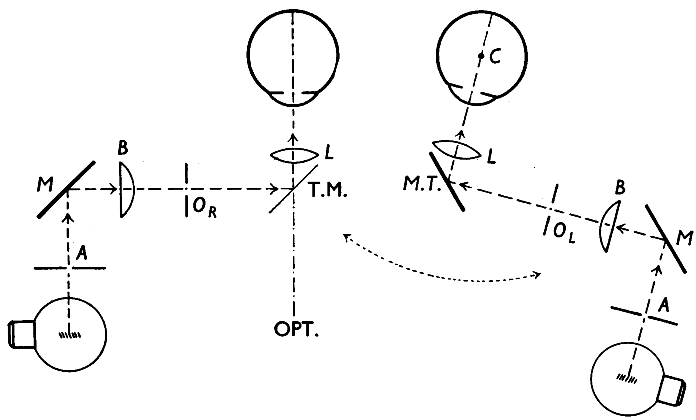

Fig. 1. General scheme of binocular fixation apparatus. *AA*, apertures limiting effective pupils; *BB*, lenses which with *LL* image *AA* in pupils; O_R and O_L, fixation objects; *M,M* and *M.T.* surface-silvered mirrors; *LL*, lenses imaging O_R and O_L; T.M., transparent pellicle mirror; OPT., axis of optometer; C, centre of rotation of fixation system for left eye.

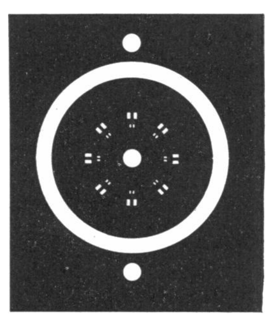

Fig. 2. Fixation object.

The subject's aspect of this modified form of the optometer is shown in the photograph (Fig. 3). For the sake of clarity the head-rest has been removed. The tube *T* contains the fixation system for the left eye. It can be rotated about the axis *CC* which passes through the centre of rotation of the eye when the instrument is correctly positioned. Adjustment for interpupillary distance can be made when the screw clamp *S* is released. The light vergence from the object for the right eye is altered by means of the knurled head *H*, which is part of the standard instrument. The vergence from the left object is adjusted by moving it along its tube with the rod *R*. The light from each object is reflected into the eye by a mirror at 45°, through the lenses *L*, *L* which are alike. The mirror for the left eye can be tilted on a horizontal axis by the screw *V*, altering the height of the image and thus compensating for small vertical errors of muscle balance. The apertures which control the diameters of the pencils of light at the pupils are contained in the plates P_R, P_L. By sliding these plates the pencil widths can be changed from 3 to 0·5 mm. A neutral filter fixed over the larger aperture equalizes luminance of the object in the two cases.

The rotating limb also carries the means of measuring convergence during monocular fixation. A small optical system for this purpose is strapped to the tube *T*. It consists of a miniature 2 V lamp with a condensing lens illuminating a fine slit aperture, which is followed by a lens having the slit at its principal focus. Below the lens is fixed a small mirror at 45°, seen in Fig. 3 at *N*. When this system was to be used for measuring convergence the whole limb was moved down by means of a rack and pinion, so that the small mirror came before the left eye. The subject then saw with this eye a fine vertical line of light instead of the fixation object. In the circuit to the 2 V lamp is placed a press button switch so that the streak of light appears only when the button is pressed. Presenting the streak as a flash eliminated the possibility of it being fused with the

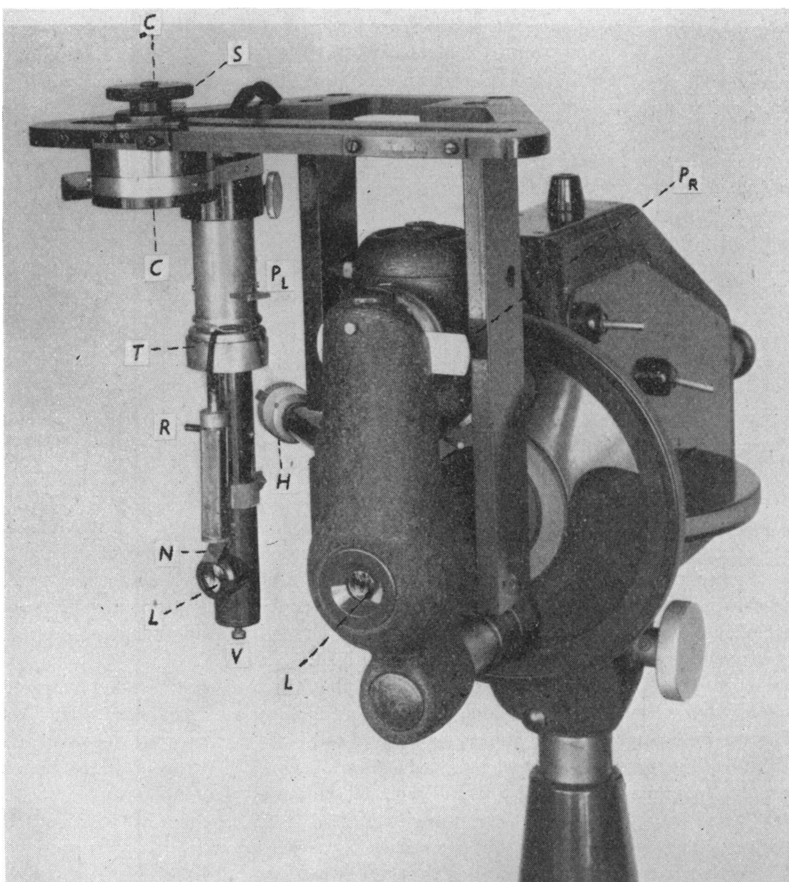

Fig. 3. Coincidence optometer (subject's aspect). *T*, tube containing fixation system for left eye; *LL* (see Fig. 1). *CC*, axis of rotation of left fixation system; *H*, control of object distance for right eye; *R*, control of object distance for left eye; *S*, screw clamp fixing interpupillary distance; P_R and P_L, sliding plates with apertures *A* (Fig. 1); *N*, mirror of system for measuring accommodative convergence; *V*, screw for tilting mirror *M.T.* (Fig. 1).

object seen by the right eye. The scales showing the convergence in degrees and also those giving the dioptric vergence of the light from the fixation objects were made to face the operator and so are not seen in this aspect of the apparatus.

Calibration of apparatus

The accuracy of the relevant scales was checked when the apparatus was set up. The zero position for the fixation objects was found by observation from the position of the subject with a telescope focused for parallel light. The divisions for each dioptre of divergence were found by placing the appropriate positive lens in the eye position before the apparatus and moving the object along its path until the image in the telescope again appeared sharp. The dioptric scale of the optometer measuring the refraction of the eye is calibrated in spectacle refraction, and the results given in the paper are also on this scale. The following method was used to check the instrument. A model eye was constructed consisting essentially of a high quality photographic lens and a 'retina' which could be moved toward or away from the lens by a micrometer screw. Across a small hole in the opaque retina was placed a fine cross-line. This was illuminated from behind and the light emerging from the lens observed with a telescope. The emmetropic position for the retina allowed the cross-line to be seen sharply. The model eye was then calibrated for each dioptre of myopia or accommodation by placing the appropriate negative lens at the spectacle position and adjusting the length of the eye until a sharp image reappeared in the telescope. The model eye so calibrated was then used to check the scale of the optometer. The accuracy of the convergence measurement depended upon the parallelism of the two fixation systems in the zero position. A pentagonal prism was placed before the lens L of each system. The prisms were so arranged that one reflected the upper half of one image and the other the lower half of the other image. The light so reflected was again observed in a telescope. When the two systems were parallel the two half images fitted together to make a complete circle as in Fig. 2.

Procedure

About twenty-five subjects have been employed. Most of these have been used for the study of convergence-induced accommodation in which a wide age spread was required. In the other experiments chiefly young subjects were used because they have a large amplitude of accommodation. These younger subjects were all nearly emmetropic and approximately orthophoric for distance, and had good binocular near vision.

The following three measurements were made on most subjects, (1) accommodation under normal conditions of equality between light vergence from the objects and stimulus to convergence; (2) accommodation and accommodative convergence with monocular fixation; and (3) convergence-induced accommodation. In addition, two other experiments were made on a number of subjects, the changes in accommodation when convergence was changed but the light vergence of the objects remained constant, and finally the relative amplitude of accommodation. These five experiments are shown schematically in Fig. 4.

The subjects were first shown an enlarged photograph of the fixation object and instructed how to recognize that fusion of the two images was being maintained. They were then shown the images in the optometer with the objects set to give zero light vergence for right and left eyes. The left limb of the instrument was then moved outward beyond the parallel position. The subject then saw two images and was told to bring them to the same height by means of the screw V (Fig. 3). The adjustable limb was then swung in to read 0°, i.e. the parallel position. In most cases the subjects fused the images, but sometimes it was necessary to swing the movable limb in a little further to obtain fusion and then to return it to the parallel position when comfortable fusion was maintained.

Accommodation when light vergence (D) *equals convergence* (M.A.) (*Fig.* 4*A*). The refraction of the right eye was measured while the subject in effect had binocular vision for a distant object. The two objects were then moved to give a light divergence of 1 dioptre and the convergence stimulated to 1 metre angle by adjustment of the movable limb of the apparatus. The refraction was again measured, and a similar procedure followed for each dioptre up to 6 or 7 for young subjects and to the near point for older ones. In each case the setting of the objects in dioptres was made to agree with convergence in metre angles. The subjects maintained binocular fusion throughout and were instructed to concentrate their attention on the finer detail of the fixation object.

Accommodation and accommodative convergence with monocular fixation (*Fig.* 4*B*). The fixation object was presented to the right eye only. The adjustable limb of the apparatus was racked down so that the mirror *N* (Fig. 3) came before the left eye and the subject saw a vertical line of light when the lamp was flashed on with the press button switch. The fixation object was adjusted to produce various degrees of light divergence from 0 up to 6 or 7 D. The subject was instructed to concentrate attention on the fine detail of the object and at the same time to swing the adjustable limb so that the line of light appeared to pass through the central dot of the object and to signal when the line was steady on the object. The line of light was shown to the subject in periodic flashes, to minimize any possibility of fusion with the fixation object. The observer who had been keeping the centring and refraction measuring systems of the optometer trained, made an immediate setting when the subject gave the signal. Convergence and accommodation were thus measured as nearly simultaneously as possible.

Convergence induced accommodation (*Fig.* 4*C*). In this measurement it is necessary to eliminate the effect of light vergence which has a controlling influence on accommodation, and therefore the pencils of light from the fixation objects were limited to 0·5 mm diameter by means of the stops *A*, *A* (Fig. 1). The subjects were instructed to maintain fusion. The convergence was stimulated and the accommodation was read for each metre angle of convergence. The position

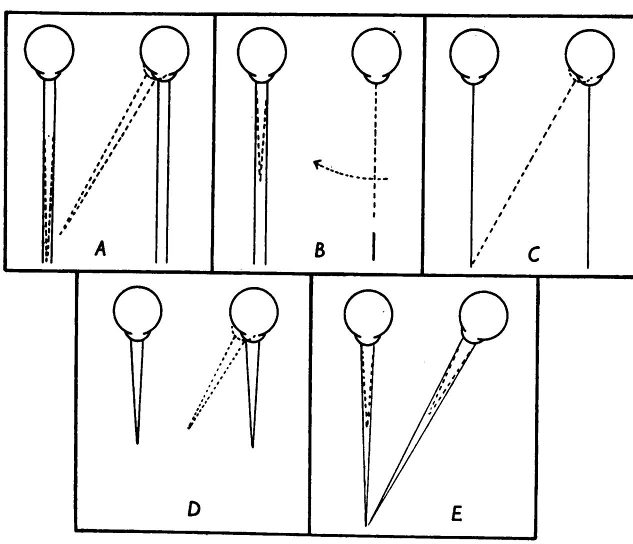

Fig. 4. Scheme of experiments: the accommodation of the right eye was measured in each case. *A*, normal condition of vision of a near object; vergence of light in dioptres equals convergence in metre angles. *B*, measurements of accommodative convergence; fixation object is seen by the right eye only. Accommodation is stimulated by increasing the divergence of the light. Before the left eye is a vertical streak of light which can be moved to measure the convergence which accompanies accommodation. *C*, measurement of convergence-induced accommodation; the vergence of the light from the fixation objects is rendered ineffective by the use of very small entrance pupils; accommodatiou is measured as convergence is stimulated. *D*, the effect of changing convergence while the divergence of the light from the object remains constant. *E*, the amplitude of accommodation relative to fixed convergence; at various states of convergence the light vergence is changed and the amplitude of change of accommodation is measured.

of the fixation objects with regard to the lenses *L*, *L* appeared to have no influence on the results, but it was found expedient to move the objects towards the lenses occasionally to reduce diffraction and thus give the subject more comfortable vision.

Changes in accommodation with fixed light vergence and changing convergence (*Fig.* 4*D*). The larger apertures at *AA* (Fig. 1) giving light pencil diameters of 3 mm at the pupil were used. The fixation objects were set to give a divergence of the light of 3D for right and left eye. The subjects were instructed to maintain fusion while the apparatus was set to stimulate various states of convergence from 0 to 8 M.A. The divergence of the light from the objects was not changed. The accommodation was measured for each state of convergence. The subjects experienced blurring of the image over a great part of the test but were able to maintain fusion.

The relative amplitudes of accommodation (*Fig.* 4*E*). Changes in accommodation were stimulated while the convergence was fixed at various states. At each metre angle of convergence the fixation objects were moved from their normal position where light vergence (D) was equal to convergence (M.A.), either toward or away from the lenses. The accommodation was measured for each dioptre change in the light vergence produced in this way. Again during part of the tests the subjects experienced blurred vision but readings on accommodation were taken so long as increases or decreases in the divergence of the light caused corresponding changes in accommodation.

RESULTS

For the values obtained in these experiments the reader is referred to the graphs, which show individual results which have been selected as characteristic of many. Although convergence had to be measured in degrees of angle it has been recorded in metre angles (M.A.), i.e. the reciprocal of the distance to which the eyes were converging. The geometrical value of this unit varies with the inter-pupillary distance, but it is used here in preference to the degree or the prism dioptre (Δ) used in clinical studies, because it bears a direct physiological relation to the dioptre, the unit of accommodation.

Accommodation with equal convergence and light vergence

The curves marked 'Normal' (Figs. 5, 8 and 9) record the accommodation in binocular vision when the convergence in metre angles is equal to the divergence of the light from the object in dioptres. Therefore differences between accommodation and convergence mean that accommodation was not equal to the light vergence. It will be seen that in some cases there was a distinct deficiency or lag of accommodation. These curves have been included in the records of certain other relationships for comparison. For instance, in the graph of relative amplitude of accommodation Fig. 9, the normal curve shows how accommodation can be changed in a positive and negative sense. Also by plotting the normal curve on the same graph as that showing convergence-induced accommodation (Figs. 5, 8), we see how much the normal binocular accommodation depends upon its other stimulus, light vergence.

Accommodative convergence

These values were obtained while the subject was viewing the fixation object at various near distances with one eye and resolving the fine detail. The position of convergence taken up by the other eye and the accommodation in the fixing eye were measured at the same time. In the graphs, Figs. 5 and 10, the figures against the points on the curve give the divergence of the light from the fixation object in dioptres, i.e. the stimulus to accommodation. It will be seen that the actual accommodation is sometimes appreciably less than this. This discrepancy was found to be greater with monocular fixation than with binocular, in cases with low accommodative convergence.

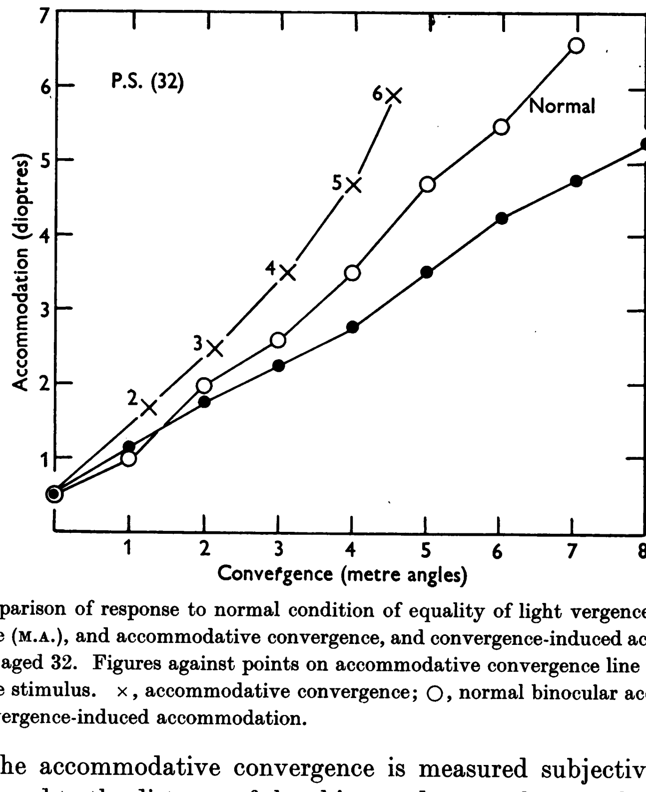

Fig. 5. Comparison of response to normal condition of equality of light vergence (*D*) and convergence (M.A.), and accommodative convergence, and convergence-induced accommodation. Subject aged 32. Figures against points on accommodative convergence line show the light vergence stimulus. ×, accommodative convergence; ○, normal binocular accommodation; ●, convergence-induced accommodation.

When the accommodative convergence is measured subjectively it is of course referred to the distance of the object and not to the actual accommodation. This point is mentioned again here because it gives rise to considerable differences between objective measurements and those recorded by the subjective method. Two examples from our results will illustrate this. So that they can be compared with the usual clinical results the amount by which the convergence differs from the accommodation which induces it, 'heterophoria at near' is given in prism dioptres (Δ). In the case of J. W., when the fixation object was at $\frac{1}{3}$ m the convergence was less than 3 M.A. by 8·7Δ, so that by the subjective method he would be considered 8·7Δ, exophoric. But he was not accommodating 3D but only 1·6D, and as his convergence was 1·6 M.A. he should be described as orthophoric. The subject D.E., when viewing an object at 25 cm with one eye was found to converge the other eye to the same distance and therefore by the subjective method would be recorded as orthophoric: but the accommodation was found to be only 3 D instead of 4 D which meant that she was esophoric 5·9Δ.

It is often stated that accommodative convergence shows great variations from time to time. While we would not claim that its relation to accommodation is fixed, it appears that the variations are mainly relative to the vergence of the light from the object and not the actual accommodation. We found that when a subject was viewing a near object slight relaxation of mental attention caused both accommodation and convergence to be reduced. When the attention was concentrated on the finest detail of the object both accommodation and accommodative convergence were increased. However, the relationship was the same in both cases, the points merely fell on different parts of the curve.

Convergence-induced accommodation

This experiment showed that when the light vergence effect was eliminated the accommodation varied in direct proportion to the convergence. Previous tests had shown that by making the eyes converge, accommodation could be induced up to its full amplitude. Some results obtained in the present investigation are given in Figs. 5, 7 and 8. They are included in these graphs for comparison with other results. The age of the subject is given in each case and it will be noticed that the slope of the line relating accommodation to the convergence by which it is induced is less in the older subject. This relation between age and convergence-induced accommodation has previously been shown (Fincham, 1955), but since then more evidence has been obtained. The reaction has now been tested in twenty-two subjects, and repeat tests have been made on seven subjects after a lapse of 2 years. The effect of age on this reflex is shown (Fig. 6) by plotting the tangent of the slope of the line against age. The results of repeated tests are shown by the subject's initials. This record shows that up to the age of about 24 years the induced accommodation is equal to the convergence, and that above that age there is a steady decrease in the response as age increases.

The effect of changing convergence with fixed light vergence

The results of this experiment are given in Figs. 7 and 8. Whereas in the previous experiment the use of very narrow pencils of light from the fixation objects rendered light vergence ineffective, in this experiment the light pencils had a diameter of 3 mm at the pupil, so that light vergence could act as a control of accommodation. The vergence was kept fixed at 3 D but the convergence which also controls accommodation was changed from zero to 6 or 7 M.A. The general result of the operation of these two controls was that accommodation increased with convergence but not at a uniform rate. As the value of the accommodation approached that of the light vergence, its increase relative to convergence was reduced. The curve is seen to be more horizontal but still tends to be upwards. At this period of the test the accommodation was not very different from the light vergence and the subject had clear vision of the fixation object. But with continued increase in

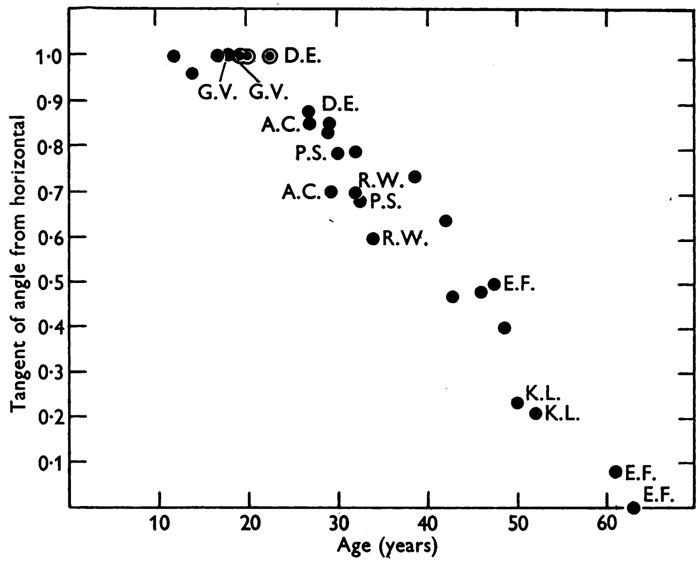

Fig. 6. Variation of slope of convergence-induced accommodation line with age. Initialled points show results of tests on the same subjects at different ages.

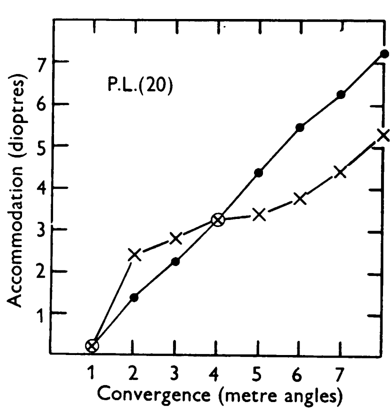

Fig. 7

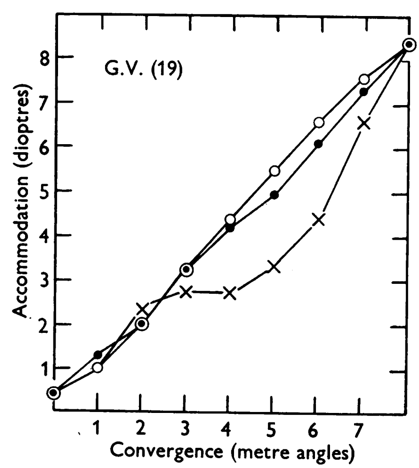

Fig. 8

Fig. 7. Effect of changing convergence while divergence of light from object remains at 3D; ●, convergence-induced accommodation; ×, constant light vergence of 3D.

Fig. 8. As Fig. 7: ●, convergence-induced accommodation; ×, constant light vergence of 3D; ○, normal binocular accommodation.

convergence the accommodation increased, although slowly at first, until it was above the light vergence of 3D, and then the light vergence control appeared to become less effective and accommodation followed convergence. The effect of the fixed light vergence can be estimated by comparing the graph of these results with the curve showing convergence-induced accommodation given in the same figure.

The results in the relatively horizontal part of the curves are the same as would be obtained in attempting to measure the relative amplitude of convergence to accommodation. If this measurement had been made by the subjective method, as in the past, it would be assumed that while the subject had clear vision the accommodation was 3D. This would mean that over the amplitude of convergence covered by the relatively horizontal part of the curves in our results, the accommodation remained unchanged. We see from the results given here that this is not true. The significance of this point is considered in the discussion.

The relative amplitude of accommodation

Fig. 9 shows the range within which accommodation can be changed from the amount which is the normal accompaniment of various states of convergence. The upper and lower curves show the positive and negative limits of accommodation for each metre angle of convergence. In the experiment not only were these limits recorded but also the response for each dioptre change in

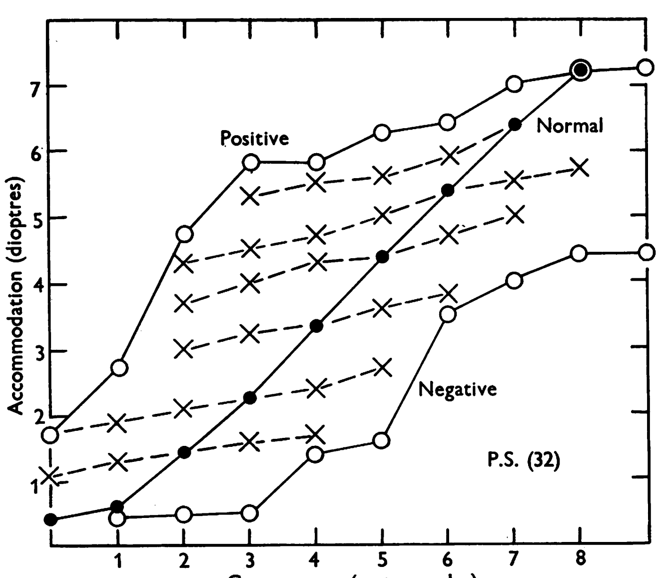

Fig. 9. Positive and negative amplitudes of accommodation relative to fixed convergence; broken lines join points obtained with equal light vergence.

the light vergence, and the broken lines in the graphs join the values which resulted from the same light vergence. The dioptric value of this vergence is given by the points on the normal line through which the broken lines pass, read against the convergence scale.

The change in accommodation was less than the change in light vergence: nevertheless, over a considerable range, the subject experienced clear vision, even to resolving gaps in the fixation object subtending an angle of 1 minute. When the difference between light vergence and accommodation got beyond the range of tolerance the subject reported that the object appeared blurred, but in spite of this further changes in vergence still caused changes in accommodation. The limits were recorded when no further change in the same direction as the vergence could be produced.

Discussion

Convergence-induced accommodation

The importance of these results lies in their relation to the age of the subject (Fig. 6). Up to the age of about 24 years the exercise of convergence gives rise to an equal amount of accommodation, so that a graph relating induced accommodation in dioptres to convergence in metre angles on equal scales gives a line of approximately 45° slope. In most cases this line is almost straight, but in some the accommodative response per metre angle of convergence is less at the lower levels. Above the age of 24 there is a gradual reduction in the reaction, so that each metre angle gives rise to less than one dioptre of accommodation.

The consistent agreement of this induced accommodation with convergence in young subjects leads to the conclusion that in all cases when the eyes converge an innervation to accommodation is produced sufficient to cause the young lens to focus to the distance for which the eyes are converging. It seems unlikely that the reduction with age in the ratio of convergence-induced accommodation to convergence is caused by a change in the relative innervations to the two functions. A more probable cause is the progressive sclerosis of the crystalline lens causing a reduced response to a given innervation and contraction of the ciliary muscle, the ratio of the two innervations remaining approximately the same.

Although the convergence-induced accommodation becomes less with age the normal binocular accommodation for any distance beyond the near point is not reduced. The graph (Fig. 5), comparing the induced accommodation with normal binocular accommodation, shows that in middle age amounts of between 1·5 and 2·0D more accommodation may be used than that induced by convergence. This reduction in the contribution which convergence-induced accommodation makes to the total accommodation employed in near vision is inconsistent with it being a conditioned reflex. The requirement of normal binocular vision which could condition a reflex is equality of accommodation and convergence, but this would require a steady increase in the reflex innervation to the ciliary muscle as age increases. As the response of accommodation to convergence becomes less with age we conclude that convergence-induced accommodation is an unconditioned reflex, with approximately constant relation between the innervations of the two mechanisms.

The control of accommodation by light vergence and convergence of the visual axes

In binocular vision of near objects accommodation is governed by the result of the integration of two distinct reflexes. We have seen that when the eyes converge to produce fusion of the retinal images of a near object, reflex innervations are sent to the accommodation 'centre'. Whether this accommodation so evoked is sufficient to give clear vision depends upon the age of the subject. The brain also receives information from the retina regarding the focus of the images. It has been shown (Fincham, 1951) that up to amounts of 1·5–2·0 D in error of focus the retinal signals inform the brain whether the light is convergent or divergent at the retina. This gives rise to the differential accommodation reflex which will correct inadequacies in the accommodation induced by convergence.

In this case the two controls simply augment one another, but under certain experimental conditions they may act in opposition. Figs. 7 and 8 show the results of experiments in which the light vergence was kept constant, 3 D, while the convergence was changed. Under these conditions the recorded accommodation was the result of the integration of the innervation caused by the constant light vergence stimulus, and that stimulated by varying states of convergence. When the visual axes were parallel there was no accommodation, the reflex control from the zero convergence appeared to be sufficiently strong to neutralize the effect of the light vergence. As the eyes were made to converge, accommodation came into play. At first the convergence, being less than 3 M.A., had a restraining influence upon the effect of the light vergence stimulus of 3 D. Then as convergence was increased the restraint became less until convergence and light vergence being equal, as in normal binocular vision, both ordered the same amount of accommodation.

When convergence was made to exceed the light vergence the parts played by the two controls changed over. Now it was the light vergence stimulus which restrained the effect of convergence upon accommodation. But as the accommodation was made to increase by increasing convergence, the effect of the fixed light vergence stimulus became less until it had no influence on the accommodation, which then increased with the convergence. This is probably accounted for by the earlier finding that the accommodation reflex to light vergence change depends upon the nature of the retinal image and is ineffective if the image is out of focus by more than about 2 dioptres.

Relative amplitudes of accommodation to convergence and convergence to accommodation

The opinion has been commonly held that just as accommodation could be increased or decreased within certain limits, while convergence remained fixed, as was shown by Donders (1864), so conversely convergence could be varied while accommodation remained unchanged. Landolt (1886) stated that the relative amplitude of convergence to fixed amounts of accommodation was implied by the existence of relative amplitudes of accommodation. He said it was unnecessary to measure amplitudes of convergence because the diagram showing how accommodation can be varied with different states of convergence must show at the same time the different amounts of convergence which can exist for each dioptre of accommodation. This appears to be a logical conclusion, but many investigators have claimed that it is not true in practice. Reference to Fig. 9 shows that various states of convergence can exist in the presence of certain fixed amounts of accommodation: however, some difficulty occurs in the experimental verification of the statemeut.

In the earlier experiments, upon which Donders (1864), Landolt (1886) and Maddox (1898) based their conclusions, accommodation was measured subjectively. If a subject had clear vision for an object at a fixed distance while prisms of various power were placed before the eyes, and binocular fusion was maintained, it was concluded that accommodation had remained fixed while convergence had altered. The powers of the prisms used base out and base in, while fusion was still held, were said to give the relative positive and negative amplitudes of convergence. When the change in the refraction of the eye is determined by an objective method, it is found that, while the vergence of the light from the fixation object is kept constant, changes in convergence are accompanied by changes of accommodation in the same direction although the subject may still have clear vision. This was recorded by Adamson & Fincham (1939) and was thought to mean that relative amplitudes of convergence did not exist. The difference between the subjective and objective measurements of accommodation is unexplained except on the assumption that there is some visual tolerance to errors in the focus of the retinal image. This tolerance, which is most noticeable when the balance of stimulation of convergence and accommodation is upset, is important. It permits ametropic and presbyopic patients to have comfortable vision as soon as they start to wear correcting lenses, and also allows some latitude in the adjustment of binocular instruments, so that it is unnecessary to match exactly the angle between their visual axes with the vergence of the light from the eye-pieces.

However, as the purpose of our experiments has been to study the interaction of accommodation and convergence upon one another from the physiological rather than the clinical aspect, we have been concerned with the visual tolerances only in respect of the bearing they have upon the actual latitude between the two functions. We have seen from the measurements of accommodative convergence and convergence-induced accommodation that when either mechanism receives no stimulus which would either cause it to change, or hold it in a fixed condition, it will react to alterations in the other mechanism. In the measurement of relative amplitudes each mechanism is subjected to two influences. In the case of the fixed mechanism it has its own stimulus tending to hold it in the fixed condition and the induced innervation from the other mechanism which is changing. In the case of the changing mechanism it receives its own changing stimulus and at the same time an induced innervation from the other mechanism which is receiving a fixed stimulus. Experimental results show that these forces are always in operation, but it will be seen that a 'relative amplitude' of one function can exist only if it is possible for the other mechanism to be held by its own stimulus in a fixed condition against the induced innervation it receives from the mechanism which is altering. Now the greater the visual tolerance the weaker will be this holding effect of the fixed stimulus, and if one mechanism has more tolerance than the other it will also have a higher relative amplitude.

It is well known that there is little tolerance to errors in convergence. We are very sensitive to diplopia and once fusion has been obtained by suitable adjustment of convergence it is held on to firmly, as though the act of fusion locked the convergence mechanism with respect to the position of the retinal images. Accommodation behaves quite differently. Here there is great tolerance to discrepancies between light vergence and definition of the retinal image, and even when vision is blurred because the accommodation is below the amount required for the light vergence, a further response in accommodation may result from a still further increase in divergence of the light. However, when this discrepancy between the light vergence and accommodation passes a certain limit the vergence ceases to stimulate accommodation.

Although accommodation is tied to its stimulus, light vergence, the connexion is loose. In fact accommodation is under the control of two factors, light vergence and convergence of the visual axes. To each of these it is attached as by an elastic coupling. In normal binocular vision both these forces pull in the same direction and accommodation is readily changed. If, as in the measurement of relative amplitude of accommodation, light vergence is changed while convergence remains fixed, accommodation will change with the vergence but to a less degree. The two controls could be applied in opposite directions by such amounts that accommodation remains unchanged. Therefore, in order to measure the relative amplitude of convergence, i.e. the amount by which convergence can be changed while accommodation is fixed, the light vergence must also be changed so that its stimulation acts in the opposite direction to the effect of the convergence. For positive relative convergence it will be necessary to reduce the light vergence from the fixation objects, and to increase it for negative amplitudes of convergence. This has not been done experimentally but the effect can be deduced from the curves of relative accommodation (Fig. 9). In these the points marked X show the accommodative response to certain light vergences and convergence of the visual axes. The broken lines join the points obtained with the same light vergence. Hence we see that if the light vergence remains constant accommodation is changed in the same direction as convergence but to a less degree. These broken lines correspond to the more horizontal parts of the curves in Figs. 7 and 8 which were obtained by changing convergence while the light vergence was kept fixed. This is what is done in attempts to measure relative amplitudes of convergence. Similar results were obtained by Fry (1937) using a refined subjective method.

The records of relative amplitude of accommodation obtained in these experiments have a quite different meaning from those resulting from the subjective methods of measurement. In the earlier work the end-points were determined by the subject's detection of the commencement of blurring. The light vergence was then recorded as the amount of accommodation in play. In the objective method described here, positive and negative changes in accommodation were stimulated by changing the light vergence from the object, and actual changes in accommodation were recorded without respect to subjective sharpness of the image. The end-point was found when no further change in the refraction of the eye could be produced by changing light vergence. The subject experienced blurred vision some time before this point was reached. If the change in light vergence was carried 0·5 or 1·0D beyond the end-point the accommodation was seen in some cases to suffer a change of about 0·5D in the reverse direction, i.e. when the vergence was increased beyond the positive relative amplitude the accommodation was reduced, and when at the limit of negative relative accommodation the vergence was still further reduced, the accommodation was seen to increase slightly. It appears that owing to the holding effect of convergence the accommodation changes more slowly than the light vergence which stimulates it, and hence the images get more and more out of focus. When the degree of error in focus reaches a certain amount, the light vergence loses its effect as a stimulus and accommodation begins to return to the amount dictated by convergence.

Accommodative convergence

During monocular fixation, e.g. when one eye is occluded, accommodation is found to be accompanied by varying amounts of convergence of the non-fixating eye. This is known as accommodative convergence (Maddox, 1889). Some workers concerned with the clinical aspect of the subject have thought that differences between the accommodation and the convergence which it evokes are evidence of the maladjustment of the two functions and have called the condition 'heterophoria for near'. When the non-fixating eye is found to be directed to the point for which the eyes are accommodated the subject is said to be 'orthophoric for near'. This condition is not the average of the large variation which is found, and so cannot be considered as normal. It is usual to find that the accommodative convergence is lower than the accommodation (Maddox, 1889), a condition which has been called *physiological exophoria* for near; on the other hand, some of our subjects showed convergence slightly in excess of the accommodation in use. Except in respect of the lag of accommodation, the relation of accommodative convergence to accommodation shows no correlation with other data. It is said to be unaffected by age, and low accommodative convergence is not necessarily evidence of weakness of the convergence function; it was found in some subjects with amplitudes of convergence above the average. The wide variations in these relations which occur in subjects with the same refractive conditions and normal comfortable near vision have not so far been accounted for.

The stimulation of accommodation in monocular vision

Since accommodative convergence can be detected only in monocular vision, i.e. in the absence of fusion and when no direct stimulus is given to convergence, it is always assumed to be a secondary reaction to accommodation. But, as we have seen that the act of convergence always produces an innervation to accommodation, it may be the case that in monocular vision, convergence, being free from fusion, can be called into play to produce part of the innervation to accommodation. In *binocular* near vision accommodation is under the dual control of the light vergence stimulus and convergence. We suggest that in *monocular* near vision the method of stimulation is similar except that convergence receives no direct stimulation and is not governed by fusion. The proportion in which these two controls are applied appears to be of no importance and may vary from one subject to another. If the reaction to light vergence change is efficient, less stimulus from convergence will be required and the accommodative convergence will be low. A high accommodative convergence would be found in those cases where the reflex to light vergence is small and more convergence effort has to be called upon to make up the deficiency in accommodation. We do not suggest that the accommodative reflex to small changes in light vergence causes no convergence reflex—if that were so the accommodative convergence graphs would be vertical lines in the lower parts of their course—but it is probable that this convergence is small in amount. Some subjects manifested only a small accommodative convergence in monocular vision, but when convergence was used to induce accommodation the two functions increased equally.

Most trained subjects would claim to be able to produce accommodation in monocular vision by voluntary effort, or they can by effort see clearly through a negative lens whose power does not exceed their amplitude of accommodation. We have seen that accommodation is partly dependent upon convergence for its initiation, and it therefore seems probable that the willed effort to accommodate is applied to the convergence mechanism which is motivated by skeletal muscle rather than to the ciliary muscle with its parasympathetic nerve supply. This would mean that accommodation in both binocular and monocular vision is an involuntary act controlled partly as a reflex resulting from the effect of the light vergence at the retina and partly as a reflex from the voluntary effort of convergence.

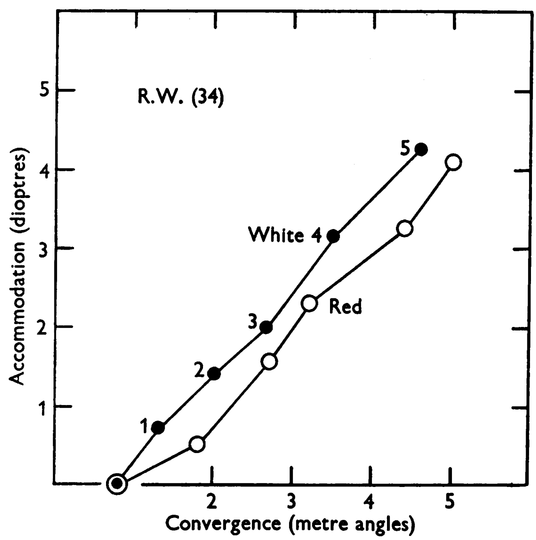

Fig. 10. Accommodative convergence with white fixation object ● and red fixation object (○).

It may not be possible to verify this hypothesis, but some evidence that accommodation in monocular vision depends upon both the light vergence stimulus and convergence is given by the results of measuring accommodative convergence using a red fixation object. In the study of the accommodation reflex (Fincham, 1951) it was found that in some subjects this reflex depended upon the chromatic aberration of the eye. Although the accommodation reacted well to changes in light vergence from a white object, the response to changes of vergence from an object illuminated with monochromatic light was either absent or greatly retarded. Some subjects showing this characteristic were selected for the experiments on accommodative convergence. We see from the results with red light (Fig. 10) that the accommodative convergence is increased in relation to accommodation. When the accommodative reflex to light vergence is eliminated by the use of monochromatic light the subject is conscious of blurring of vision when a small change is made in the vergence of the light, and must make a willed effort to see clearly. This effort is applied to convergence and the accommodation is secondary to it. Thus the accommodative convergence is increased. There was also more instability of both accommodation and convergence than with a white fixation object. The reflex to light vergence not only initiates the adjustment of accommodation when the error of focus is relatively small, but also controls the focus of the eye once the image is sharp; it is the fine adjustment to accommodation. The removal of this control would account for the instability of accommodation that was seen in this experiment. Not only were the subjects conscious of the need for a willed effort to bring the object into focus but also they had difficulty in maintaining clear vision. We should not expect convergence alone without the stabilizing effect of fusion to produce steady accommodation.

Lag of accommodation

We have referred to the discrepancy which often occurs between the amount the eyes accommodate and the vergence of the light from the fixation object. In many cases the accommodation is appreciably less than is required theoretically to produce a focused retinal image, a condition known as 'lag of accommodation'. It is of course only shown when the measurement is made objectively and although this condition is more common with monocular fixation it frequently occurs in binocular vision. Our results show that there is a trend towards a greater deficiency in accommodation in subjects with high accommodative convergence, whereas in cases with low accommodative convergence the accommodation in binocular vision is equal to or may slightly exceed the divergence of the light from the object. It appears that accommodation is more accurate in subjects with low accommodative convergence.

We have said that low accommodative convergence occurs in subjects who, because their reflex to light vergence is efficient, do not need to exert much convergence to produce the required accommodation in monocular vision. When these subjects view a near object binocularly they must converge to produce fusion, and this causes more accommodation to be added to that which was in use for monocular vision. On the other hand, those subjects who exhibit a high accommodative convergence are having to make use of convergence in order to produce sufficient accommodation for monocular vision of near objects. Thus with binocular fusion no more convergence is exerted and therefore the accommodation remains the same as with monocular vision.

Finally, let us consider what happens in binocular vision of near objects under normal conditions. Since the tolerance to errors in convergence is small, while on the other hand accommodation need not be precise, we should expect the stimulus to convergence to be dominant. The act of converging the visual axes to produce fusion of the images of the fixation object also stimulates accommodation. In young subjects the accommodation so induced is sufficient to focus the eyes for the fixation object but at the same time the reflex to light vergence comes into operation. This acts as a fine adjustment of accommodation stimulating its increase where necessary to produce retinal images of adequate definition so long as the object is not within the subject's near point. Thus the nerve centre which controls accommodation must be informed on the effort of convergence and the state of light vergence at the retina, and from the integration of this knowledge determines the necessary innervation to the ciliary muscle. The questions of the site of this controlling centre and the processes by which the final innervation to the ciliary muscle is evolved must be left as problems for the neuro-physiologists.

SUMMARY

1. The response of accommodation to light vergence and convergence has been measured objectively.
2. The controlling effect of convergence upon accommodation in the absence of the effects of light vergence has been studied.
3. Convergence-induced accommodation has been measured in twenty-two subjects; seven of these were repeated after a lapse of 2 years. The results show that up to the age of 24 years, the convergence-induced accommodation is equal to the convergence, and above that age it gradually diminishes.
4. Accommodative convergence with monocular fixation was measured and related to both accommodation and the light vergence stimulus.
5. Measurements of accommodation were made both while the light vergence was constant and convergence was changed, and while convergence was constant and the light vergence was changed. The results of these measurements are given in the form of graphs of relative amplitudes of accommodation and convergence.
6. It is concluded that accommodation is induced by convergence as an unconditioned reflex.
7. Accommodation is controlled only by light vergence and convergence of the visual axes, to which it reacts in a reflex manner. These controls act in combination; they can be in unison as in normal binocular vision or in opposition as when relative amplitudes are measured.
8. The theory is advanced that accommodative convergence occurring during monocular fixation is not secondary to accommodation. It is thought to be a manifestation of the convergence effort called upon to induce the necessary accommodation to augment that which derives from the light vergence stimulus.

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