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FLUCTUATIONS OF ACCOMMODATION UNDER STEADY VIEWING CONDITIONS

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It is well known that under steady environmental conditions motor systems exhibit residual fluctuations or unrest. The tremor in skeletal muscles has been extensively studied and shows a dominant frequency component of 10 c/s (Schaefer, 1886). The pupil of the eye shows a physiological unrest with a high frequency component of 1·2 c/s (Stark, Campbell & Atwood, 1958). The tremor of the eyeball during steady fixation has been described as having dominant 30–80 c/s components (Ditchburn & Ginsborg, 1953). While investigating the characteristics of the accommodation response of the eye we noticed that the refractive power undergoes small fluctuations and it is the purpose of this paper to describe these.

Attempts to account for motor tremor have often led to feedback theory being invoked (Hammond, Merton & Sutton, 1956; Lippold, Redfearn & Vučo, 1957). The implication of the feedback concept in this connexion is that sensory information from, for example, muscle spindles is fed back to the motor control centre in order that a desired tension or length response of the muscle shall be achieved or maintained (Granit, 1955). In the accommodation system the sensory information comes from the retina and here we have the advantage of easy optical access by natural means, enabling us to manipulate independently the sensory information sent back to the controlling nerve centre, a facility not readily available in other motor systems.

Quantitative as well as qualitative data about its components and their interaction are necessary before a feedback system can be fully described and quantitative predictions made. In this paper we are reporting measurements that must be integrated into a quantitative description of the accommodation system if it is given in terms of feedback theory.

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METHODS

Measurements of the refractive state of normal human eyes were obtained with an infra-red optometer, a brief description of which has already been published (Campbell, 1956). Fuller details of the instrument are given by Campbell & Robson (1959). The principle of the optometer is to direct two narrow beams of infra-red light into the pupil of the eye, one beam entering about 2 mm above and one 2 mm below the visual axis. Each beam forms a real image on the retina of a horizontal slit diaphragm. This diaphragm and the lens forming the narrow beams are so arranged that the images of the slit are superimposed on the retina when the eye is focused at infinity. If, owing to the act of accommodation, the power of the eye increases, the images on the retina separate. This is the basic principle of Young's optometer based on Scheiner's experiment.

The separation of the slit images is detected by collecting the light reflected from the retina after it has passed forward through the pupil. This is then focused by means of a suitable lens on to a lead sulphide photoconductive cell, with two horizontal rectangular photosensitive areas so placed that a real image of the double retinal image straddles the two photosensitive areas of the cell. Separation of the retinal images now results in a separation of the images focused on the photocell. To detect this separation the narrow ingoing beams are interrupted alternately at 400 c/s by means of a suitable rotating sector wheel and the electrodes of the two photosensitive areas are connected in a bridge circuit which gives an alternating output proportional to the separation of the images. The alternating signal is then amplified by means of a narrow-band amplifier tuned to the frequency of modulation. This assists in improving the signal-to-noise ratio of the detecting system. The amplified signal is rectified and passed through a suitable electronic filter to remove the 800 c/s modulation and the resulting d.c. voltage is used to activate a pen recorder after any standing potential has been backed off. The electronic filters used in the apparatus are so chosen that the optometer faithfully records frequencies in the range 0–5 c/s.

Great care is required in the design and adjustment of the optical and electronic systems to ensure adequate sensitivity of the optometer, because only a very small proportion of the light that enters the eye is reflected by the retina and leaves the eye through the pupil. As the lead sulphide photocell is sensitive to infra-red energy in the region of 1 μ, an infra-red transmission filter may be placed in the path of the two narrow beams. The subject cannot then perceive the measuring beams. Because of the balanced type of system used the optometer is insensitive to small movements of the eye, which cause both images to move in the same way upon the photocell, and to stray light, which falls equally on both sections of the photocell.

Tests have been carried out which indicate that eye movements up to 2° in any meridian can occur without producing an artifact on the record. Artifacts due to larger eye movements or to blinking are readily recognized. Pulsatile changes due to the blood flow in the eye or orbit, or slight movements of the head caused by respiratory movements of the neck, might also introduce artifacts into the record in spite of the use of a bite bar. However, if heart and respiration movements are recorded at the same time as the accommodation it can be demonstrated that there is no correlation between them.

With this optometer, records were obtained of the refractive state of young adults when presented with high-contrast targets on a white background at optical infinity and at various near distances. To enable the effective entrance pupil sizes of the eye to be varied, the targets were viewed in the optical system shown in Fig. 1. An iris diaphragm I was placed in front of a ground glass screen transilluminated by light from a tungsten source. The diaphragm was optically conjugate to the pupil of the eye with respect to the two achromatic lenses A_1, A_2. The target T was a small 'C' photographically reproduced on a transparent glass plate. It was imaged on the retina by the lens A_2 and the optical parts of the subject's eye. The subject's accommodation requirements could be altered by moving T back and forth on an optical bench. The apparent distance of target from the subject could be calculated and was expressed in dioptres. The iris diaphragm could be altered in size and its image in the subject's pupil constituted the effective entrance pupil of the eye. It was verified that the depth focus of the eye was changed greatly in the expected direction (Campbell, 1957) when changes were made in the diameter of the diaphragm. Records in 'empty fields' were obtained either by switching off lamp L or by removing I, A_1, A_2 and T and placing close to the subject's eye a plate of calcite between two pieces of polarizing material. The subject then saw one of the typical patterns due to the birefringent material (Ditchburn, 1952). These patterns help to maintain the fixation but do not change in sharpness over a large range of accommodation.

One or two drops of 1% p-hydroxyamphetamine hydrobromide were instilled in the subject's eye and recordings were obtained as soon as the pupil had dilated, i.e. within 15–30 min. With this mydriatic a period of 1–2 hr is available between maximum mydriasis and the onset of a detectable effect on the ciliary muscle. In some subjects it did not appear to affect the ciliary muscle at all.

Analysis of tremor records. The problem of quantitative evaluation of the waviness of a record is often encountered and well-developed techniques are now available for handling it. Basically they amount to finding the amplitudes of the sine waves which when combined in a characteristic manner will give the record. Harmonic analysis of such a record is simplified a great deal by the Wiener–Khintchine theorem which states that Fourier transformation of the autocorrelation function of a record gives its spectral density function, i.e. the square of the amplitudes of the different frequency components making up the original record. Blackman & Tukey (1958) have recently discussed the whole problem fully.

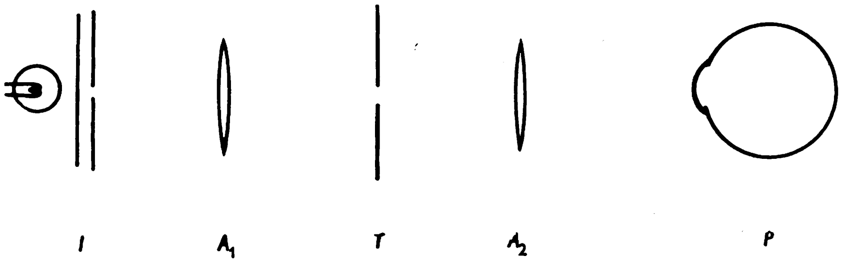

Fig. 1. Schematic diagram to illustrate the optical system used to present a target to the eye. I, iris diaphragm transilluminated by light from a tungsten lamp and passed through a ground glass diffusing screen; A_1, A_2 achromatic lenses. I is in the first principal focal plane of A_1; and P, the plane of the pupil of the eye, is in the second principal focal plane of A_2. T is a target imaged by A_2 and the optical system of the subject's eye on to his retina.

It must be remembered that reconstruction of the original records is no longer possible after the analysis since phase information has been lost in the process of carrying it out. Even so, the analysis is an enormously more valuable tool than the application of simple statistical techniques of finding mean values, average errors or r.m.s. errors, even when associated with such refinements as trend elimination. Many records may have the same values for these statistical parameters yet differ in a fundamental and meaningful way. Visual inspection of a record will give some information, particularly concerning the spectral position of narrow frequency bands that are strongly represented and widely separated. But quantitative information concerning such peaks is never available without harmonic analysis. This will become a yet more valuable tool once adequate statistical techniques become available for gauging the significance level of peaky spectra (Blackman & Tukey, 1958). The second reason for studying spectral density is that it is possible to find out something about the system's characteristics by examining the nature of the rate of change of density with frequency. This is a well-known approach to the study of electrical and other filters.

A major problem in this analysis concerns the question of whether a given record length is typical of the process. Can one be sure that on repetition of the experiment the new record would be merely a different sample from the same population of records as the first one and hence differing from it only within the statistical range of variability of such records? The ergodic hypothesis, which states that for stationary stochastic processes the ensemble of record lengths taken at different times is indistinguishable from the ensemble of similar record lengths taken from a single long record, is presupposed in the present analysis. This is justified in so far as the findings upon which we place emphasis were repeatable in an individual at different times, and in different sections of a single long record.

A continuous strip of record giving a sequence of about 300 datum points at equal and consecutive time intervals was used for analysis. The interval was chosen so that about five datum points were included in a cycle of the highest frequency peak in which we were interested. For example, in the accommodation records an interval of 0·1 sec was used. Autocorrelation curves were obtained up to a maximum shift of 100 unit time intervals and these were subjected to Fourier transformation. The computations were carried out on a digital computer.

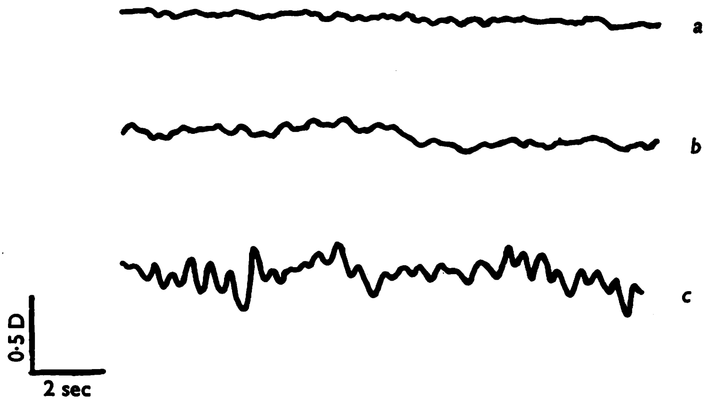

Fig. 2. (*a*) Record of noise generated by optometer with no subject in position. (*b*) Record while subject J.G.R. viewed a small, high-contrast test object placed at his optical infinity. (*c*) Record obtained when subject J.G.R. viewed the target placed at 1 D optical distance with a 7 mm pupil.

RESULTS

Figure 2*a* is a record of the noise generated within the optometer by the photocell and its amplifiers with no subject in position. Fig. 2*b* is recorded at the same gain but with a subject viewing a high-contrast target at his optical infinity. A similar trace is obtained during cycloplegia induced with homatropine. Fig. 2*c* shows a record obtained while the subject (J. G. R.) views the target at an optical distance of 1 D with a 7 mm pupil.

Figure 3 shows the results obtained from eight other young adult subjects while they were viewing a small high-contrast test object at an optical distance of approximately 1 D. Visual inspection of the records shows that there is constantly present a rhythmical component with a frequency of about 1–2 c/s. From inspection of longer portions of such records it appeared to us that the dominant frequency was fairly constant in any given subject but that it might vary from subject to subject.

Figure 4 shows two traces each with the same average accommodation level

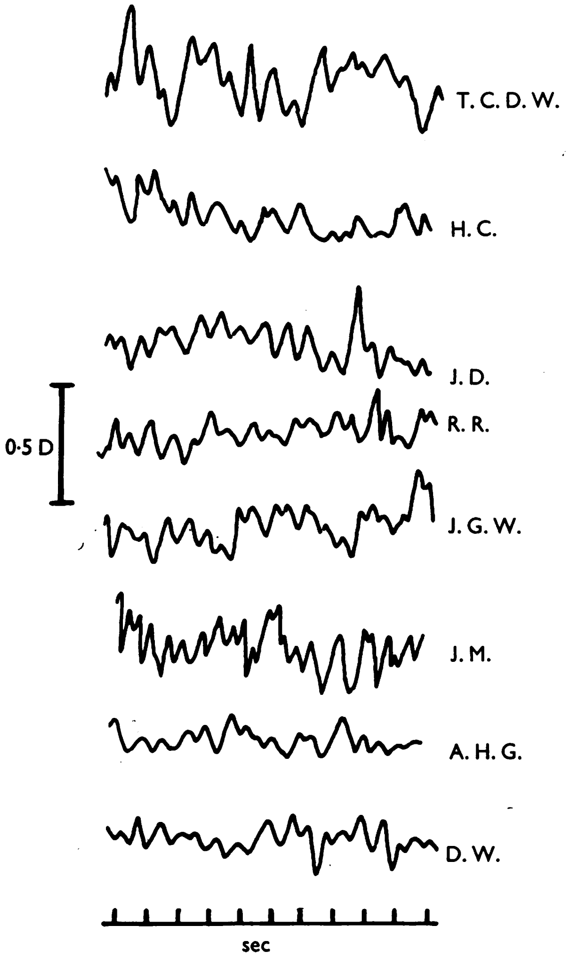

Fig. 3. Records of accommodation response to a stationary test object at an optical distance of 1D from 8 young adult subjects with dilated pupils.

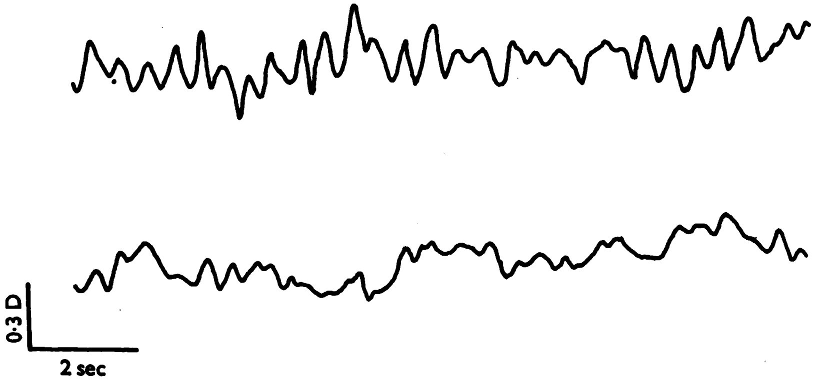

Fig. 4. Accommodation record of subject J. G. R. under normal viewing conditions with a 7 mm pupil (upper) and with a 1 mm effective entrance pupil of the eye (lower). The records have the same average accommodation level.

(about 1D) obtained with subject J.G.R. The upper one was taken under normal viewing conditions of a detailed target through a large pupil and the lower one under conditions of identical retinal stimulation, including retinal luminance, but with a small (1 mm) effective entrance pupil of the eye. The latter has the effect of widening the depth of focus. Figure 5 gives the spectral density of each of these two records. It can be seen that there is a well marked high-frequency component present in the wide pupil experiment in the region of 2 c/s and that this is greatly diminished or absent in the experiment using the narrow pupil. There are also marked low-frequency components present in both records at frequencies less than 0·5 c/s. To ensure that the spectral density distributions obtained in these experiments had not arisen by chance, the experiments were repeated a few minutes later on the same subject under the same conditions and the results of the analysis are shown in Fig. 6. The results obtained are very similar to those shown in Fig. 5, and it may be concluded that the large 2 c/s peaks obtained in this subject with a wide pupil are significant and that the change in the spectral density distribution which occurs when a narrow pupil is substituted is also of significance.

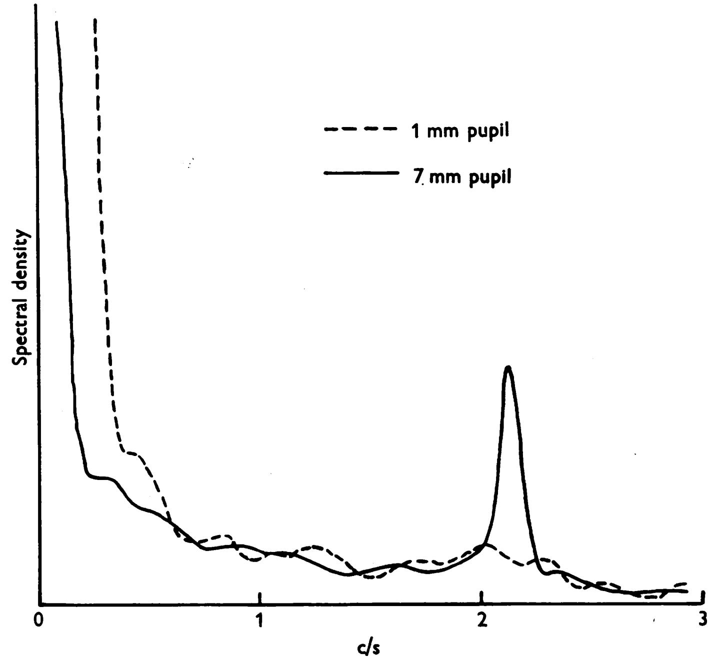

Fig. 5. Frequency spectra of the two records shown in Fig. 4 (linear ordinates).

The high-frequency components shown to be present in subject J.G.R. in Figs. 5 and 6 under wide-pupil conditions appear to be a general feature in other subjects viewing under similar conditions (Fig. 3). We have not, however,

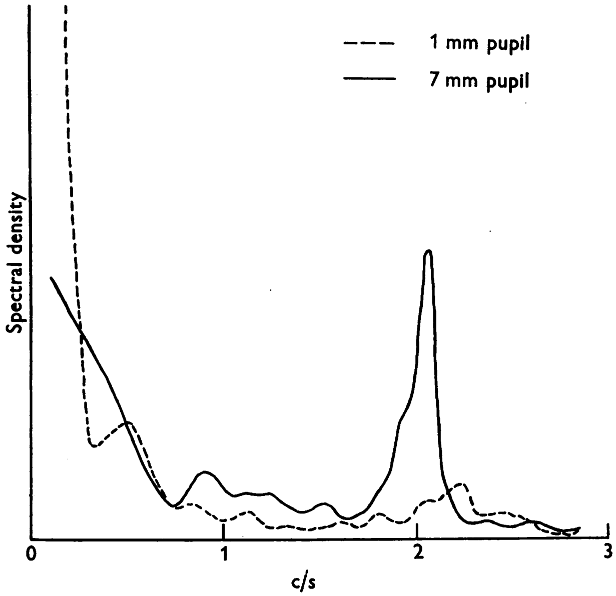

Fig. 6. Frequency spectra of second small–large pupil experiment on subject J.G.R. Results should be compared with those shown in Fig. 5 (linear ordinates).

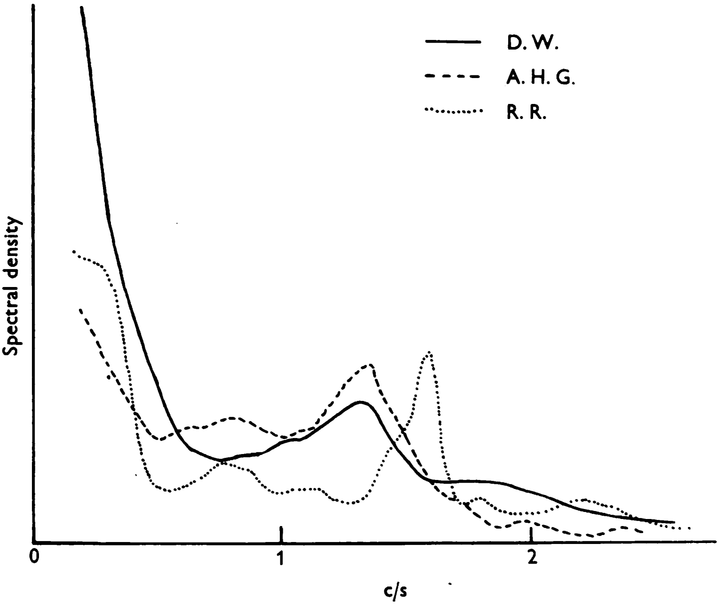

Fig. 7. Frequency spectra obtained from subjects when they viewed a test object at 1D distance with wide pupils. Portions of their original records are shown in Fig. 3 (arbitrary linear ordinates).

attempted to carry out detailed spectral density analysis of all of these subjects on account of the labour involved and also because it would not appear to yield more information than can be obtained from visual inspection of the records, at least as far as judging the presence or absence of a marked high-frequency component. Spectral analyses of the records obtained from three of these subjects are shown in Fig. 7. It can be seen that the position of the high-frequency band varied from subject to subject within the range 1·3–2·2 c/s and that there may be more than one spectral peak. Little significance can be attached to the presence of minor variations in these spectra for it would first be necessary to repeat the analysis on several lengths of record taken from the same subject under the same conditions and to compare these for constant components.

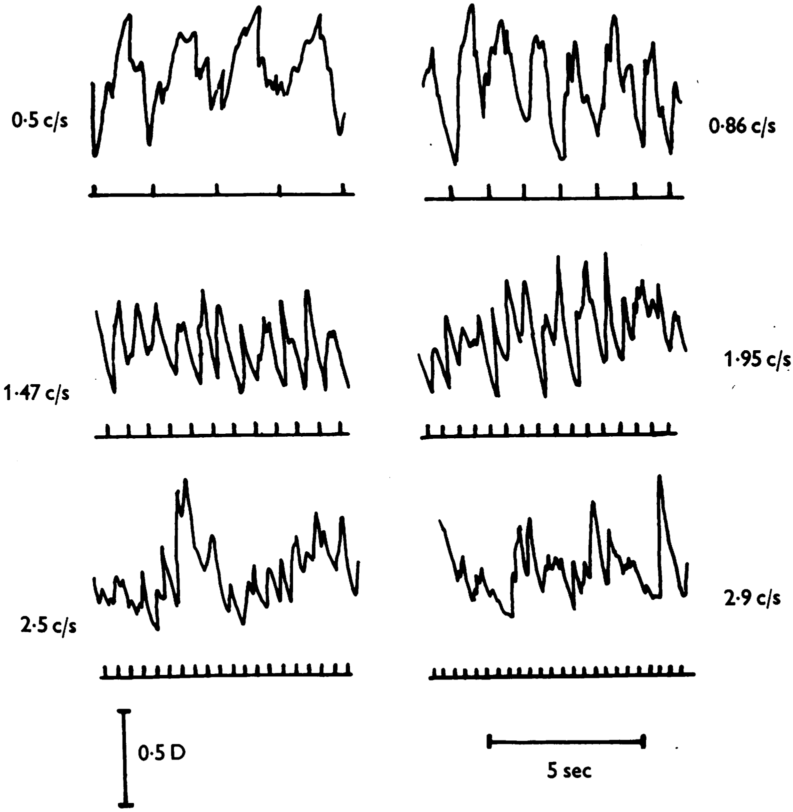

Fig. 8. Responses to an accommodation target oscillating at various frequencies through a range of 0·75 D centred at 1 D. The marks below each record indicate the movement when the sinusoidally moving target was nearest to the subject. Downward movement of record indicates an increase of accommodation. Allowance should be made for the arc of the pen.

When accommodation fluctuations under normal viewing conditions were contrasted with those in an empty field, or in a field with a target unaffected by accommodative changes, a difference similar to that between the two records in Fig. 4 was observed.

In one experiment accommodation was recorded while a subject (J.M.) viewed with a large pupil a small detailed target that oscillated at various frequencies over a range of 0·75D, the range being centred at 1D. The optical arrangement ensured that changes only in focus and not in size or illuminance of the retinal image occurred. Figure 8 illustrates the response at various frequencies.

Figures 9 and 10 show a more detailed study of the ability of an oscillating accommodation stimulus to 'drive' the fast fluctuations. The subject (J.G.R.) was permitted freely to view the target while stationary. The upper record of Fig. 9 was taken during this period. The target was then oscillated at a rate of 2·8 c/s, i.e. faster than most of the spontaneous activity in this subject. The lower record of Fig. 9 was obtained during this period. The spectra, shown in Fig. 10, clearly illustrate that the normal activity at 2 c/s was replaced by a much more marked one at 2·8 c/s.

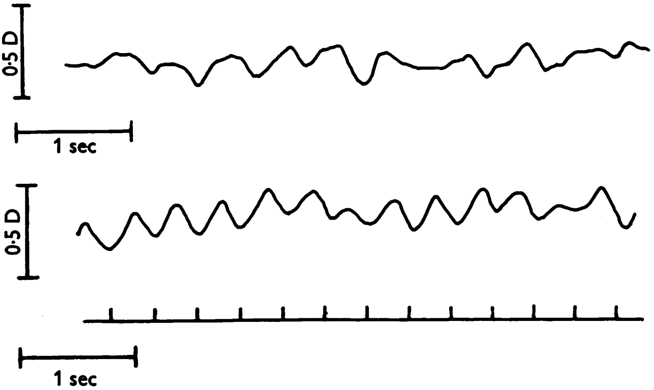

Fig. 9. Normal accommodation fluctuations (upper) and response to an accommodation target oscillating through 0·75 D with a frequency of 2·8 c/s (lower).

A closer study of the records reproduced in Figs. 8 and 9 demonstrates that a time lag of 0·4 sec between stimulus and response is apparently a constant phenomenon in these records. In Fig. 9 this takes the form of a phase lag of rather more than 360°, as would be expected when the frequency is 2·8 c/s. We have not so far been able to demonstrate a phase advance due to prediction as occurs with eye movements (Westheimer, 1954).

DISCUSSION

Before accepting that the small fluctuations recorded by the optometer are due to changes in the refractive power of the eye it would be relevant to inquire whether changes of this amplitude and frequency can be observed by

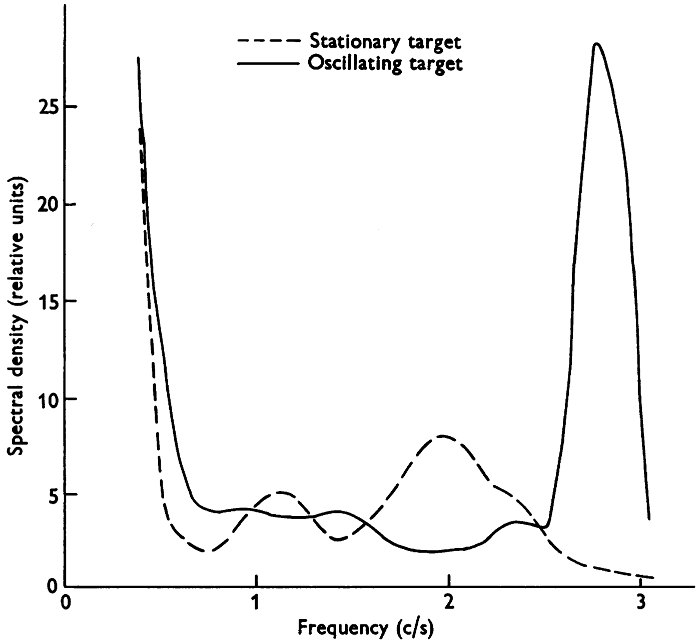

Fig. 10. Frequency spectra of the two records shown in Fig. 9 (linear ordinates).

techniques differing fundamentally in principle from that of the optometer. Several confirmatory pieces of evidence are available.

Records have been obtained by cinephotography at 10 frames/sec of the third Purkinje–Sanson image formed by reflexion of light from the anterior surface of the crystalline lens (Whiteside, 1957). When the eye was focused on a near object continuous small fluctuations in the size of the third image occurred. The dominant component of these fluctuations has a frequency of about 2·5 c/s with an amplitude of about 0·25D peak to peak. It is improbable that these fluctuations are entirely due to errors of recording, for measurements made of the size of the first image (formed by the anterior surface of the cornea) show a scatter of smaller amplitude. Glezer & Zagorul'ko (1955) have also recorded similar fluctuations of accommodation by measuring changes in curvature of the anterior surface of the lens photo-electrically.

Arnulf, Dupuy & Flamant (1955), using an elaborate ophthalmoscopic technique, examined the image of a bright point source formed on the retina. In an eye with active accommodation this image was seen to be constantly undergoing rapid changes of shape which these workers interpreted as being due to astigmatic changes in lens power. The magnitude of the fluctuations in different subjects was estimated to be between 0·04 and 0·14D, but no information has been published of their time characteristics, no doubt because of the difficulty of determining these subjectively. In a personal communication Dr A. Arnulf states that the rate was several per second.

Yet another technique for the detection of these accommodative fluctuations may be used by the reader providing he still retains a reasonable amplitude of accommodation. If a concentric circular pattern (Fig. 11) is examined with one eye, while the head and pattern are rigidly fixed, a series of moving sectors will be perceived. This effect was first described by Helmholtz in 1856 (Helmholtz, 1924). The time course of the movements corresponds to the fluctuations of refractive power described in this paper (Campbell & Robson, 1958). Certain other effects may also be observed which are not connected with accommodation changes (McKay, 1957). As the sectors may appear in any meridian and do not only flick rapidly through 90° we may infer that some at least of the fluctuations are astigmatic.

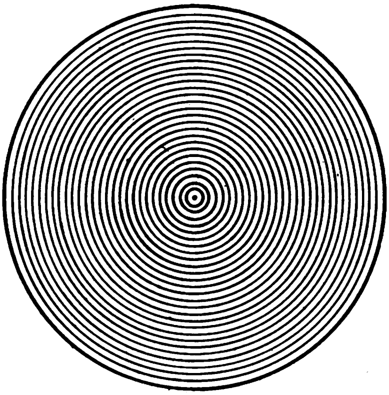

Fig. 11. Concentric ring target of Helmholtz. When the target is viewed with several dioptres of accommodation rotating sectors can be seen. The time course of the movements corresponds to that of the fluctuations of accommodation shown in Fig. 3.

It should be borne in mind that the optometer as at present constructed measures changes in refractive power in only the vertical meridian. A change in power of the horizontal meridian alone would not be detected by the optometer. There have been many attempts to determine whether an astigmatic error could appear, on accommodation for 'near', in an eye which has no astigmatism when focused at infinity. The evidence is against the occurrence of large changes of astigmatism with accommodation (Fletcher, 1951), although the methods used so far have not been sufficiently sensitive to exclude astigmatic changes of less than about 0·2 dioptres. In order to settle this point with certainty it would be necessary to design an optometer which records simultaneously in two meridians at right angles to each other. The technical difficulties of such a method are great and we have not attempted it.

It is interesting to note that Collins (1937) briefly mentioned that accommodation, as measured on his electronic refractionometer, was constantly varying by small amounts at a rate of 1 c/s or even faster, but this observation does not appear to have been followed up.

Figures 5, 6 and 7 show that during natural viewing with a large pupil most of the accommodative activity occurs in the frequency range 0–0·5 c/s, although one or more narrow bands in the high-frequency region may be strongly represented and appear predominant in the original record. Moreover, the activity in the low-frequency region is even greater when the sensory system ceases to convey information of focus position, namely, in the empty-field and small-pupil experiments. These findings suggest that the ability to detect blur is a definite factor in stabilizing the refractive state so far as fluctuations of less than 0·5 c/s are concerned. The presence of these fluctuations in an empty field means that the average refractive level of an otherwise emmetropic eye must be myopic. This probably accounts for the well-known phenomena of night and space myopia (Campbell, Westheimer & Robson, 1958).

The spectrum of the fluctuations of accommodation may be compared with that of other motor systems also studied under 'steady' conditions. Figure 12 shows frequency spectra on a log-log plot of fluctuations in pupil diameter, accommodation, finger displacement and eyeball position (between saccadic movements). All four systems differ in many respects from each other; yet allowing for the differing frequency scale the spectra show close similarity in three respects: (1) a general decrease in amplitude with increase in frequency, the slope in the case of all systems being about the same; (2) a distinct subsidiary peak in a higher frequency region; and (3) a more rapid fall-off of amplitude with frequency beyond the subsidiary peak. The peak occurs at about 75 c/s for eyeball movements, 10 c/s for finger tremor, 2 c/s for accommodation and 1·2 c/s for pupil unrest. However, an analysis over a much wider range of frequencies would have to be made before a more complete analogy could be developed.

The site of the origin of these movements in motor systems is not clear, although in some instances there is sufficient evidence to eliminate several sources that at first sight appear likely. For example, it is known by objective recording of pupil area that spontaneous iris movements are identical in both amplitude and phase in both eyes (Stark *et al.* 1958). Thus the site of origin must be at, or central to, the third nerve nucleus and not peripheral, say in the smooth muscle of the iris. In the case of accommodation it has unfortunately not been possible to record simultaneously the refractive power fluctuations of both eyes, although subjective experiments with the Helmholtz concentric ring target (Fig. 11) suggest that some, if not all, of the accommodation fluctuations are binocularly simultaneous. If this could be confirmed by objective recording it would similarly establish that the site of origin of the movements was nervous and central to the third nerve nucleus. In the case of the fast extraocular muscle tremor (Riggs & Ratliff, 1951) and the 10 c/s finger tremor (Campbell, Robson & Westheimer, unpublished observations) there is no correlation in amplitude or phase between the two sides, so that we cannot similarly exclude certain sites of origin.

Somewhat more can be said about the fast components of accommodation tremor. If we have anywhere, in the sequence of transformations extending from the third nerve nucleus to the lens, a component that acts like a resonant spring device, for example an elastic component in the zonule-lens capsule system, we might expect, in the presence of constant perturbations from the nervous system, that the harmonic analysis of the refractive power fluctuations would contain a prominent band at the resonant frequency. The consequence of such a hypothesis is that quite large oscillations at about the same frequency as that of the subsidiary peak in the spectrum are expected to occur following an ordinary rapid change in accommodation. Since these are not observed one must reject this simple hypothesis.

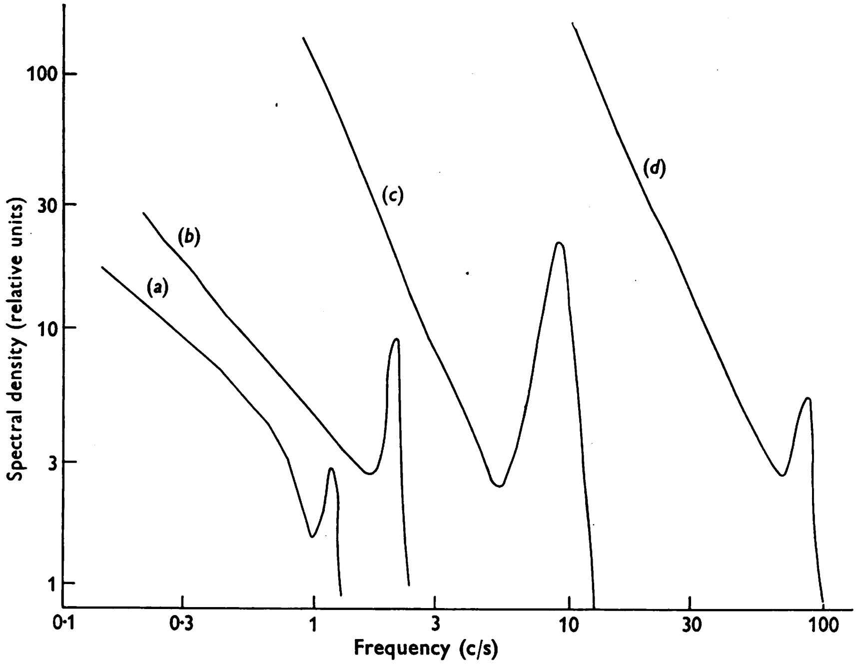

Fig. 12. Frequency spectra of various motor systems in a steady environment, drawn to show principal features (logarithmic coordinates). (*a*) Pupil diameter during steady illumination of the retina; (*b*) accommodation during steady viewing of near target; (*c*) finger displacement during steady pointing; (*d*) eyeball position during steady fixation (between saccadic movements). This spectrum was obtained by analysing a record kindly provided by Dr D. H. Fender.

Hypotheses of quite a different group are those in which we look to the feedback relationship between the retinal image and the accommodation level for the origin of the particular type of output spectrum. Reaction time in the accommodation system is of the order of 0·3–0·4 sec. In addition there is a small dioptric range within which focusing changes cannot be perceived. If one assumes that the normal accommodation posture is near one end of the depth of focus, it is possible to postulate an accommodation oscillation from 'just perceptibly blurred' to 'clear'. Subjective experiments show this range to be about 0·2D (Campbell & Westheimer, 1958). These figures do not permit the conclusion to be drawn that the oscillations in the vicinity of 2 c/s are a consequence of these characteristics, but if we allow a reasonable range of uncertainty of measurements we cannot reject it convincingly without a crucial experiment. Now the behaviour of a system with the described characteristics can be predictably changed by the simple expedient of widening the range of insensitivity to blur. When this is done by using a narrow entrance pupil and thus increasing the depth of focus, the subsidiary peak disappears (Fig. 5). While this means that the 2 c/s oscillations are clearly connected with the presence of a normal feedback loop—they disappear on de-afferentation!—the simple hypothesis of oscillation through a range of insensitivity cannot be upheld. The oscillations do not increase in amplitude when the range is widened.

On the other hand, since the two records of Fig. 4 have the same average accommodation level but quite different oscillation patterns it cannot be postulated that the fluctuations are a characteristic of the motor system merely associated with active accommodation, a hypothesis otherwise favoured by findings that no such oscillations are seen with completely relaxed accommodation or in presbyopic eyes.

While the results published in this paper have sufficed to exclude some specific theories, there remain other possible mechanisms, but in the absence of further experimental evidence it does not seem fruitful to us to speculate about them. The finding that marked changes can be induced in the pattern of fluctuations of accommodation by variations in visual stimulation, e.g. by increasing the range of insensitivity to blur or by oscillating an accommodation target, makes the conclusion inevitable, however, that visual feedback must play a part in its genesis.

SUMMARY

1. When a young adult subject steadily views a near target the refractive power of the eye constantly undergoes fluctuations.

2. These fluctuations disappear when the subject views a target at infinity or when a cycloplegic is instilled.

3. Harmonic analysis shows that the fluctuations have dominant frequency components in the 0–0·5 c/s region, and with a large pupil in one or more narrow bands near 2 c/s.

4. When the retina ceases to obtain information on focus position, e.g. in an empty visual field or in the case of greatly increased depth of focus, the higher frequency components are diminished and the lower frequency ones are increased.

5. Measurements were obtained of accommodation responses to sinusoidal variations in accommodation stimulus. The response follows the oscillation with a time lag and a frequency-dependent amplitude.

6. When the stimulus moves sinusoidally at a frequency near to 2 c/s the natural high-frequency rhythm appears to be suppressed.

7. A comparison of accommodation, pupil diameter, eyeball and finger tremor spectra suggests that spontaneous activity in widely different motor systems is remarkably similar in spite of a differing frequency scale.

8. Several hypotheses concerning the spontaneous activity in the accommodation system are discussed. It is concluded that sensory feedback must play a role.

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