

## DYNAMICS OF ACCOMMODATION RESPONSES OF THE HUMAN EYE

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It is not till recently that an optometer has become available (Campbell, 1956; Campbell & Robson, 1959) that enables one to obtain continuous, high-resolution records of changes in the refractive power of the human eye. Using this optometer we have investigated the nature of the accommodation responses when young emmetropic subjects were presented monocularly with a variety of focus-stimulating conditions.

### METHODS

#### *Recording*

The recording optometer used in these experiments is a modified version of the instrument described by Campbell & Robson (1959). A diagrammatic representation of the optometer is shown in Fig. 1; it is not to scale.

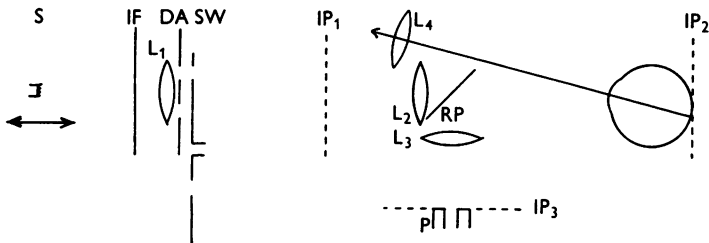


Fig. 1. Schematic diagram to illustrate optical system of optometer (not to scale). S, filament light source. IF, infra-red filter.  $L_1$ ,  $L_2$ ,  $L_3$ ,  $L_4$ , lenses. DA, double aperture. SW, sector wheel.  $IP_1$ ,  $IP_2$ ,  $IP_3$ , image planes. RP, reflexion plate. p, photocells.

The light source (S) consists of a V-shaped filament automobile headlamp. Lens  $L_1$  has a double slit diaphragm (DA) placed immediately before it. Close to this diaphragm is placed a slotted sector wheel (SW) which interrupts the two beams, formed by the slits, alternately at a frequency of 300 c/s. Lens  $L_1$  forms an image of the V-filament in the plane  $IP_1$ . Lens  $L_2$  collects the two beams diverging from this plane and forms an image of the double aperture DA in the plane of the pupil of the subject's eye. If the subject were to look directly into the optometer he would observe a sharp image of the filament S provided his retina ( $IP_2$ ) was conjugate to the image plane  $IP_1$ . If his retina is not conjugate to this

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plane he would observe a double image of the filament. The light source S is so arranged that it can be moved along the axis of the optical system. In this way it is possible to place the image plane  $IP_1$  in such a position that a single image can be formed on the retina, even allowing for abnormal ocular refraction.

By placing a plate RP with a reflexion:transmission ratio of 0.5 before the eye at  $45^\circ$  to the axis of the optometer, it is possible to collect the small fraction of the light reflected from the fundus which passes out of the eye through the pupil. A real image of the reflected fundal image of the filament can then be formed by lens  $L_3$  in plane  $IP_3$ . This real image is allowed to fall on a pair of germanium photodiodes (Siemens Type TP 50) placed side by side. The power of lens  $L_3$  is so chosen that the size of the images of the V-filament is similar to that of the photosensitive surfaces of the photodiodes. The diodes are so aligned that a limb of the V-shaped filament image falls on each photosensitive surface. As the photodiodes are sensitive to infra-red radiation, an infra-red filter (Ilford No. 207) is placed in position IF to render the light invisible. The electronic arrangement is identical with the one already described (Campbell & Robson, 1959). The electronic filter used in most of the present experiments has a corner frequency of 3.3 c/s with a 12 db/octave slope. Critical findings were checked on records obtained with a filter with corner frequency of 33 c/s and a 18 db/octave slope. Except for the presence of high frequency noise the latter records do not differ materially from those shown in this paper. The phase lag of both filters in the frequency range important in the present study is small.

The modifications of the original design of the optometer have resulted in the following advantages:

1. The photodiodes now used do not require cooling with solid  $CO_2$  as did the lead sulphide cells in the original instrument.

2. The internal photoamplification and output from the diodes is higher than that from the lead sulphide cells and consequently the design of the first stage of the amplifier is not so critical.

3. The photosensitivity of the diodes is better matched to the spectral distribution of the source, the transmission of the infra-red filter and the absorption characteristics of the eye media. As a result, the instrument is less sensitive to ambient room light and, indeed, can be used in an undarkened room.

4. The original optometer used a reflexion cube in place of the reflexion plate in the present instrument. The cube was found to allow stray light, arising from interface reflexions of the ingoing beams, to enter the photocell optic system and thus reduce the signal-to-noise ratio of the instrument. The reflexion plate at present in use is of the dielectric type (Barr and Strouds Ltd., Glasgow) with a total absorption loss of less than 2% compared with over 30% in reflexion plates coated with silver or other metals.

5. By using the image of the filament itself in the retinal plane instead of the image of a slit diaphragm, it has been possible to eliminate one lens in the optical system with a resulting further increase in light flux entering the eye.

The optometer was calibrated by requesting experienced subjects with good voluntary control over their accommodation to focus on a series of targets, placed at known distances from the eye, until no trace of out-of-focus blurring could be detected. From these measurements, it was concluded that the optometer and its recording system was linear to within  $\pm 10\%$  over a range of 3 dioptres.

#### *Stimulating*

In addition to the above accommodation recording system, a visual stimulating system (Fig. 2) was placed before the same (left) eye of the subject. It consists of two illuminating beams brought together by a beam splitter K. Each beam has a neon lamp (Hivac Type CC8L) N as a source which illuminated from behind an opal glass screen T limited by an aperture A. On each opal glass screen a black disk was printed which subtended  $10'$  at the

eye. Both beams are adjusted carefully to appear exactly in line when viewed by the subject through lens  $L_4$  placed on the subject's side of the beam splitter.

The power  $F$  (in dioptres) and the position of this lens are so chosen that its second focal plane is in the nodal point of the subject's eye. Under this condition, if  $x$  is the displacement of the target from the first focal plane of the lens in metres, we have, by Newton's lens formula,

$$xx' = f^2, \quad (1)$$

where  $f (= 1/F)$  is the focal length of the lens in metres and  $x'$  is the distance in metres between the image of the target and the nodal point of the subject's eye. If we now express this distance  $x'$  in terms of its reciprocal  $D$ , equation (1) becomes

$$D = xF^2.$$

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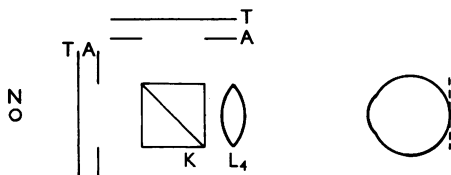


Fig. 2. Schematic diagram to illustrate the optical system used to present targets to the eye (not to scale). Neon lamps  $N$  transilluminate opal glass screens  $T$  each containing a small high-contrast target and limited by apertures  $A$ . The two beams are brought together by beam splitter  $K$  and are viewed by the eye through lens  $L_4$ . One source  $N$ , target  $T$ , and aperture  $A$  can be moved as a unit to vary the accommodation stimulus.

Here  $F$  is the dioptric power of the lens  $L_4$ —a constant under our experimental conditions—and  $x$  is the distance in metres between the target and the first focal plane of the lens.  $D$  is the dioptric distance between the image of the target and the nodal point of the subject's eye and is thus the measure of the accommodation required by the subject to image the target  $T$ , as seen through lens  $L_4$ , sharply on his retina. The advantage of this experimental arrangement is that  $D$  is now a linear function of  $x$ , the target displacement. Another feature of this optical system is that the retinal image size and the retinal illuminance of the target are independent of  $D$ .

The two neon lamps are connected to a high-speed relay and the experimenter can, by means of a switch, change from one beam to the other practically instantaneously. A photocell placed close to one of the neon lamps serves to indicate on one of the channels of the pen recorder the instant of the change-over. The luminance of each of the two illuminated fields as seen by the subject through the beam splitter and the lens  $L_4$  is  $80 \text{ cd/m}^2$ . The neon light source, opal glass screen and aperture of one of the beams can be moved as a unit either by a rack and pinion movement or by an attachment which pulls them against elastic bands by a string fixed eccentrically on a wheel rotated by a variable speed motor.

In some experiments lens  $L_4$  is removed. The subject then views the opal glass screens directly through the beam splitter. In this case when there is a change-over from one beam to the other and there is a difference in distance of the two targets from the eye, there is a change not only in focus but also in apparent size. The dioptric measure of the required change in accommodation is the difference between the reciprocals of the target distances in metres.

The stimulating system is placed at an angle of  $20^\circ$  with the recording system. Thus when the subject has his eyes positioned to view the targets, the optometer light—infra-red and, therefore, invisible—is imaged in the periphery of the retina.

### Procedure

Accommodation responses were recorded in six emmetropic subjects between 20 and 40 years of age. The left pupil was dilated by instilling, about 20 min before the recording session, one or two drops of 1% paredrine into the conjunctival sac. The subject was placed before the apparatus using a bite bar and forehead rest to ensure steadiness of the head. The right eye was occluded. It was ascertained that a change-over from one stimulating beam to the other did not produce any eye movements. The subject was then instructed to keep the target clear at all times. A recording session lasted 10–15 min.

### RESULTS

Refractive changes were recorded in response to the following stimulus changes: (a) instantaneous displacement of a target from one optical viewing distance to another with and without size cues (step stimulus), (b) instantaneous displacement of a target from one optical viewing distance to another with a quick return to the original distance (rectangular pulse stimulus), (c) simple harmonic oscillations of a target through a focus range and (d) gradual change in focus of an object, all other characteristics of the object remaining unchanged. We also recorded voluntary accommodation changes, i.e. accommodation movements initiated voluntarily by the subject without the occurrence of any changes in the visual field.

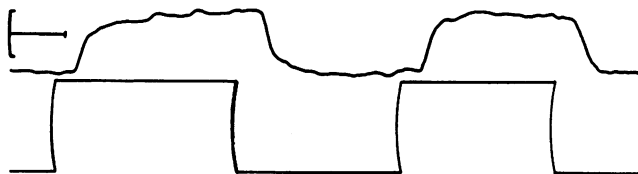


Fig. 3. Record of accommodation responses to a 2D step stimulus and return to zero level of accommodation (subject F.W.C.). Allowance should be made for the arc of the pen. Top line, accommodation (length of horizontal line, 1 sec; height of arc, 1D): upward movement represents far-to-near accommodation. Bottom line, stimulus signal, same scale. This record is an example of single-sweep accommodation responses.

*Steps stimulus.* Two typical responses to this kind of stimulus when size cues were present are illustrated in Fig. 3. There is a reaction time and the response occurs in a single sweep. The same kind of record is also obtained when the subject is asked to accommodate voluntarily. The maximum velocity reached during a 2 D movement is of the order of 10 D/sec. There is an increase in the maximum velocity with increase in the extent of the movement, but we have not yet studied this relationship systematically since we find it difficult to record single-sweep accommodation responses exceeding 3 D, other than voluntary ones.

When the only cue to accommodation is blur, it is more usual to see movements like those illustrated in Fig. 4. There is a considerable vari-

ability in the form of the responses and one can often distinguish more than one step.

All accommodation responses follow the corresponding stimuli after a reaction time. The mean and standard deviations of ten measurements of reaction time for far-to-near accommodation and for near-to-far accommodation in each of our six subjects are shown in Table 1.

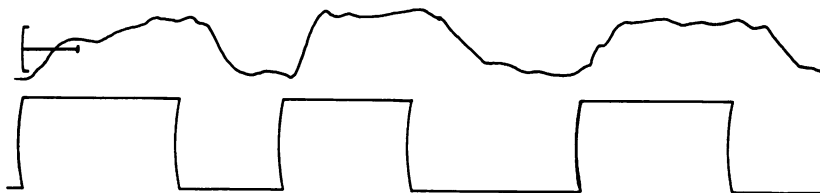


Fig. 4. Typical accommodation responses to a 2D step stimulus and return when targets change only in focus and not in size (subject F.W.C.). Note variability in response form. Length of horizontal line, 1 sec; height of arc, 1D.

TABLE 1. Reaction time (sec) of accommodation responses to sudden changes in focus

Subject	Far-to-near accommodation		Near-to-far accommodation	
	Mean	Standard deviation	Mean	Standard deviation
F.W.C.	0.30	0.09	0.38	0.07
H.C.	0.36	0.16	0.27	0.08
J.G.R.	0.30	0.05	0.33	0.08
R.R.	0.42	0.14	0.46	0.13
P.G.	0.42	0.07	0.42	0.07
D.H.F.	0.36	0.06	0.45	0.06
Average	0.36	0.09	0.38	0.08

When the response is carried out in a single sweep, the movement time appears to be independent of the amplitude of the movement. Average values obtained for movement time are 0.64 sec for far-to-near accommodation and 0.56 sec for near-to-far accommodation. The total time which elapsed between the onset of a stimulus to change accommodation and the achievement of a reasonably stable level of accommodation near the new requirement depends upon the mode of response. When there is a single-sweep response it is about 1 sec, but when the response has more than one phase the elapsed time may be as much as 2 sec or more.

*Rectangular pulse stimuli.* Figure 5 illustrates a series of responses when a far visual stimulus is replaced for various brief periods by a stimulus at a nearer optical distance. It is seen that corresponding to both the ascending and the descending limbs of the stimulus pulse there is an ascending and a descending accommodation change. The interval between the onsets of these accommodation changes is very much the same as the

duration of the stimulus pulse, certainly within the limits of the variability of reaction time shown in Table 1. Since the time course of an accommodation movement is relatively slow, the form of the response pulse depends on the pulse duration, the return action commencing during various stages of completion of the original movement. Pulses momentarily exposing a target more remote than the original and final targets yield responses which on the whole show similar characteristics although there are then occasional pulses without concomitant responses.

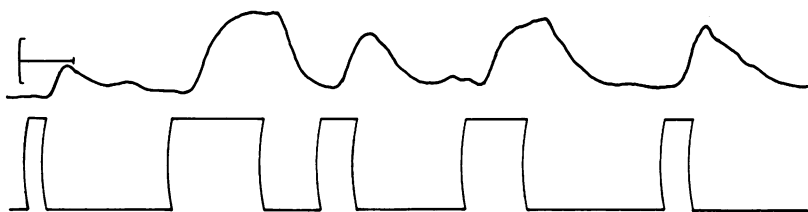


Fig. 5. Accommodation responses when a far visual stimulus is replaced by an identical one at a nearer optical distance for various time intervals presented in random order (rectangular pulse stimuli). Subject J.G.R. Length of horizontal line, 1 sec; height of arc, 1 D.

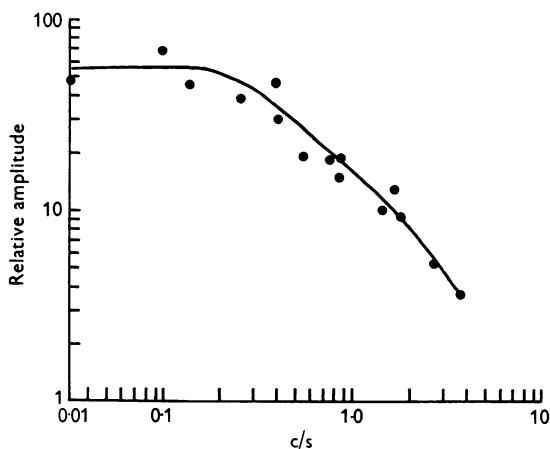


Fig. 6. Graph illustrating change in amplitude of accommodation response when a target is oscillated sinusoidally through a constant focus range of 0.6 D at various frequencies (subject D.D.). Ordinates, relative amplitude of response oscillations; abscissae, frequency of stimulus oscillations. Electronic filter attenuation has been allowed for. Log scales.

When the pulse duration becomes as short as 100 msec or less, responses are small or sometimes even absent. Pulses of duration less than 80 msec were not studied.



Fig. 7. Accommodation response as a target's optical distance is gradually changed (subject F.W.C.). Length of horizontal line, 1 sec; height of arc, 2D.



Fig. 8. Accommodation fluctuations when a subject (H.C.) is unable to return to zero level of accommodation. Height of arc, 1D.

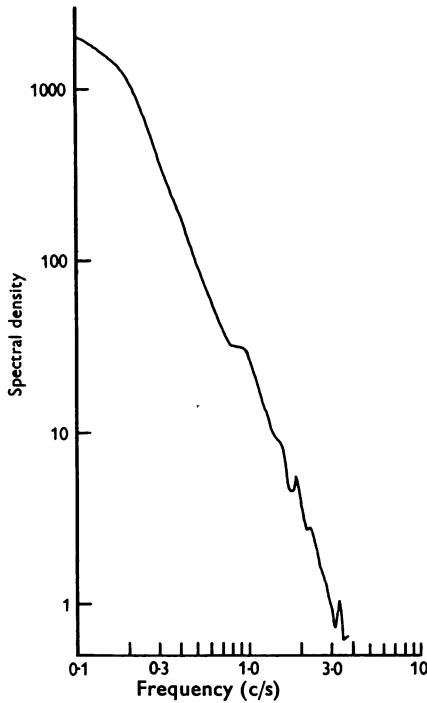


Fig. 9. Spectral density of fluctuations of which Fig. 8 is a short typical section. Ordinates, relative spectral density; abscissae, frequency (c/s). Log. scales.

*Simple harmonic stimuli.* When a visual target is oscillated to produce focus settings (measured in dioptres) varying sinusoidally with respect to time, the accommodation shows oscillations of the same frequency. The amplitude of the response oscillations decreases as the frequency increases (Fig. 6). There is always a time lag between peaks in the stimulus and corresponding peaks in the response and this is found to lie between 360

and 500 msec. The maximum frequency of stimulus oscillation at which there is any evidence of a concomitant response is about 4 c/s. For slow oscillations the response is not smooth; step discontinuities and superimposed fluctuations are evident. Records of accommodation changes in response to sinusoidal focus changes are contained in a previous communication (Campbell, Robson & Westheimer, 1959, Fig. 8).

*Gradual change in optical viewing distance.* A response to such a situation is illustrated in Fig. 7. It usually does not follow the stimulus gradient smoothly but contains discontinuities and fluctuations. The record also demonstrates that a subject may fail to match the target velocity correctly and may make movements in the incorrect direction. Occasionally a subject's accommodation will not relax to infinity when a target is moved from near to optical infinity in our instrument. The accommodation may then fluctuate around a mean level of about 1 D for many seconds. Figure 8 illustrates a section of an accommodation record in such a case and Fig. 9 the spectral density of the fluctuations.

#### DISCUSSION

The reaction time for an accommodation response is considerably longer than that for the pupil, 0.26 sec (Kawahata, 1954), or for eye movements, minimum of 0.12 sec (Westheimer, 1954*a*). The high sensitivity of the optometer enables us to determine the onset of a response to better than 0.1 D so that it is unlikely that the values of reaction time given here are over-estimated through the inclusion of some movement time.

Is the difference in reaction time between accommodation and the other oculomotor systems due to a difference in peripheral response mechanism or should it be interpreted as indicating a longer central delay? The pupil response to light is predominantly if not entirely due to contraction of the sphincter muscle of the iris and has a close affinity to the far-to-near accommodation response in the neural and muscular aspects of the effector system. Both responses are mediated by the third nerve parasympathetic pathway via the ciliary ganglion, and a smooth muscle system activated by acetylcholine. The pupil, too, shows a response when the subject looks at a near object—the so-called near reflex of the pupil. There is little doubt that, while the pupillary light reflex follows an uncomplicated pathway involving the pretectal area, the near response of the pupil shares with the accommodation and convergence reaction a central pathway capable of making distinctions between and interpretations of retinal images which we usually associate with cortical areas (Campbell & Westheimer, 1959).

On this basis one would expect the pupillary response to a near target to have a latency longer than that of the simple pupil reflex to light, in fact, a latency comparable with that of the accommodation response to



a near target. We have carried out measurement of the latency of the pupil response to a near target in one subject (F.W.C.) by presenting targets at two optical distances in our stimulus beams and changing over instantaneously from one to the other, ensuring that no brightness differences but only a focus difference existed between the two beams. There was a mean latency of 0.32 sec for the pupil response to a near target, compared with a mean latency of 0.30 sec for an accommodation response to a similar stimulus. Pupil responses to light measured in the same subject at the same session had a mean latency of 0.24 sec. We conclude that the difference in latency of the two kinds of pupil response is an indication that in the pupil response to a near target there is a longer central component, the retinal response time and the peripheral effector time being comparable in both classes of pupil response.

The latency of a convergence response is about 0.20 sec (Westheimer & Mitchell, 1956). Making the assumption that the convergence, accommodation and pupil responses to a near target share the same afferent and most of the central pathways, we conclude that the longer latency of the last two responses is a consequence of a long-latency component in the peripheral accommodation and pupil effector mechanisms.

Comparison of Figs. 3 and 4 makes it clear that the latter includes responses that are not maximal. Several step-like responses may sometimes be made, generally separated by time intervals of the order of a reaction time. A significant observation is that when the targets differed only in focus and not in size, the responses differed from stimulus to stimulus even within a few seconds and no systematic modifications could be detected during the several dozen responses recorded in a session. We have to conclude, therefore, that while the accommodation mechanism is capable of giving single-sweep, relatively rapid responses, even an instantaneous change-over of optical distance of the target does not assure that such a response will supervene. In a study of the mechanics of the peripheral response mechanism attention must clearly be given to this difficulty.

This variability of response is also seen in accommodation from near to far where discrete phases and oscillations may be distinguished. Using a technique of recording the Purkinje-Sanson image to estimate accommodation, Kirshhof (1940) also reported variability in the response form, although he did not demonstrate the details of these variations. His average values for movement time, viz. 0.5 sec for far-to-near accommodation and 0.43 sec for near-to-far accommodation, are of the same order of magnitude as we have found.

The responses to pulse stimuli afford insight into another aspect of the accommodation mechanism. Pulses as short as 100 msec may provoke a

response even though the stimulus then had returned to its original state more than 200 msec before the onset of the response. The upward response to a pulse stimulus will proceed only for a time interval of the order of the pulse length before a return of accommodation commences. We have evidence here that we are dealing with a continuous monitoring system and that an accommodation movement can be halted during its progress. This may be contrasted with the behaviour of the extraocular muscle system where pulse stimuli, if they yield a response, produce saccadic movements which cannot be modified during their progress (Westheimer, 1954*b*).

The fact that information about the state of focus is assimilated during an active accommodation movement is particularly well illustrated in Fig. 10. Here the return of the pulse stimulus occurs during the early stages of the response to the upstroke of the stimulus. Nevertheless, the response return occurs without further delay, a reaction time after the stimulus return.

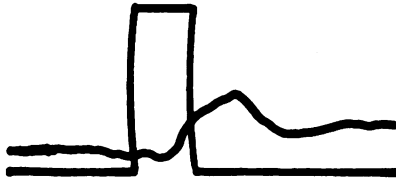


Fig. 10. Accommodation response to a 2D pulse stimulus of 0.32 sec duration (subject H.C.).

The form of the single-sweep accommodation responses is to a first approximation exponential with an average time constant of about 0.25 sec and may, therefore, be regarded as the response of a first-order system (a single stage, resistance-capacitor, circuit model) to a step input. Such a model subjected to an amplitude *versus* frequency analysis would yield a curve similar to that shown in Fig. 6. Working with this simple model one would expect a frequency-dependent component in the phase relationship between stimulus and response in addition to a non-frequency dependent time lag. Unfortunately the magnitude of the frequency dependent delay predicted by this model is too small for our data to establish whether it is incorporated in a constant over-all time delay independent of frequency or whether it is added without interaction to a constant time delay. It is conceivable that this might be achieved by treating a very much larger body of data statistically.

#### SUMMARY

1. Accommodation measurements were obtained with a high-resolution, continuously recording infra-red optometer on six young emmetropic subjects when various focusing tasks were presented to them monocularly.

2. The reaction time of the accommodation responses to a focusing stimulus has an average value of 0.37 sec with a standard deviation of 0.08 sec.

3. Single-sweep responses are obtained during voluntary accommodation and also when a step focusing task is presented with a number of clues identifying the accommodation level required. These responses are to a first approximation exponential with a time constant of about 0.25 sec. Maximum velocities recorded during a 2 D response are about 10 D/sec.

4. The time which elapsed between onset of stimulus and the beginning of a reasonably steady accommodation level near the stimulus requirement is about 1 sec in the case of single-sweep responses. When the response has more than one phase, the time which elapsed may be 2 sec or more.

5. Responses to momentary optical defocusing and to simple harmonic defocusing follow each aspect of the stimulus after a reaction time. It is concluded that information about the state of focus may be assimilated during the act of accommodation and that accommodation movements can be modified during their course.

6. When the accommodation mechanism has to track the focus of a target, it appears to do so usually in steps, but the damping of the system and the superimposed fluctuations make the identification of the tracking strategy or strategies difficult.

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