Arch. Soc. amer. oftal. optom. (1962) - 4 - 137

A SERVOANALYSIS OF THE HUMAN ACCOMMODATIVE MECHANISM

BY

JOHN H. CARTER, O. D.

Philadelphia - Penn.

ACKNOWLEDGEMENTS:

This study was undertaken in the laboratories of the Division of Oftometry, Indiana University, Bloomington, Indiana. It was made possible in part by a National Science Foundation Grant, number G - 19302. The author is greatly indebted to Dr. M. J. Allen for his invaluable assistance in the execution of this study as well as for the use of a number of pieces of equipment of his original design.

ABSTRACT

The accommodative mechanism of the eye appears to function as a servomechanism, an error-actuated, self-regulating, feedback control device. Cybernetic approaches were applied to the ocular accommodative mechanism in an attempt to define various system parameters.

The most satisfactory model of the human accommodative mechanism seems to be a first order servo with a time delay of approximately 250 milliseconds and a dead zone. It has a time constant of approximately 275 milliseconds.

Satisfactory open-loop data could not be obtained since gain changed with volition. Repeatable closed-loop data were obtained and an attempt was made to formulate a transfer equation for the accommodative system, utilizing constants consistant with those derived from transient response data. Although an equation was derived yielding a satisfactory fit of the empirical frequency response curve, it defined a regenerative system and therefore had to be rejected.

When, under open-loop conditions, a negative accommodative stimulus was provided, the subject responded with positive accommodation. This suggests that the subject's eye was not able to recognize the polarity of the stimulus.

The influence of volition upon accommodative response and the inability of the subject to respond differentially to pre-focal and post-focal blur (in the absence of accommodative tracking) tend to throw considerable doubt upon the assumption that the accommodative mechanism is purely reflex.

INTRODUCTION

Accommodation is the dioptric adjustment of the eye to attain maximal sharpness of retinal imagery for an object of regard. The present investigation is based upon the premise that the accommodative mechanism functions as a servomechanism - an error actuated feedback control device. As such, it is subject to investigation using servoanalytic methods. Basically, these methods consist of quantitative investigation of the mechanism's transient response (response to a step input) and frequency response (response to a steady-state sinusoidal input).

Indeed, it was found that such methods of testing are applicable to the human accommodative mechanism, although the response of this mechanism does not appear to be fully automatic after the fashion of the pupil.

EQUIPMENT

General Instrumentation:

The present investigation utilized an infrared optometer to monitor accommodation, together with a number of pieces of auxiliary equipment. Figure 1 shows the master control section for equipment used in this study, together with a Tektronix Nº 502 dual-beam cathode ray oscilloscope and its associated Hewlett packard record camera.

The upper deck of the master control unit consists of a section which provides regulated and unregulated voltages to the remaining sections. The second section houses a Tensor Arbitrary Function Generator, Model 5846. In addition, it contains electronic filters and two 50 K precision potentiometers for voltage adjustment. The third section of the master control unit contains two precision resistance decades and gain and zerobalance controls for the Arbitrary Function Badal Optometer.

The fourth deck of the master control unit contains a precision voltage calibrator and a high-impedence voltmeter, used to monitor the action of the Arbitrary Function Badal Optometer target.

Three units for providing accommodative stimuli were utilized with the infrared optometer. The first of these was the Arbitrary Function Badal Optometer unit for the left eye, consisting of a high-speed rectilinear galvanometer which controls the position of a Snellen target with respect to a color-corrected ten diopter lens. It was used in the present study to provide sinusoidal dioptric signals.

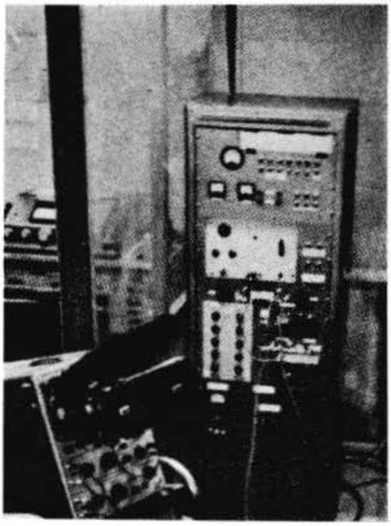

Fig. 1. Master control section for equipment utilized in the servoanalysis of the human accommodative mechanism.

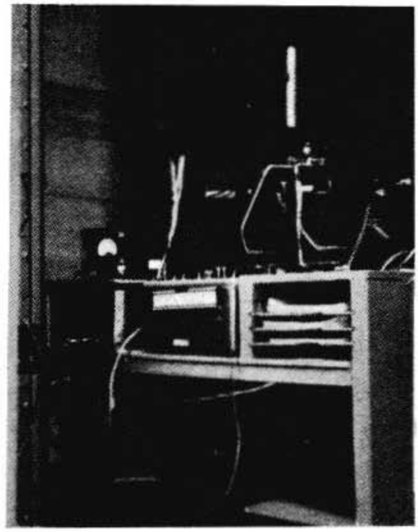

Fig. 2. The Allen infrared optometerhaploscope.

The second auxiliary unit employed was the Badal Step-function Optometer for the left eye. This unit was used for the analysis of the open-loop transient response of the accommodative mechanism.

The third stimulus unit employed was the Badal Step-function optometer for the right eye. This optometer was used in the investigation of the closed-loop transient response of the accommodative mechanism.

The Self-recording Infrared Optometer:

The self-recording optometer [1] used in this study was part of a haploscope designed for the Air Force by Allen [2]. In the present investigation, slight modification of the previously existing instrument was made to render it more suitable for obtaining frequency response information. Figure 2 shows the Allen haploscope-optometer combination and figure 3 shows the transient response of the infrared optometer. Figure 4 is a schematic eye calibration curve and figure 5 is a calibration curve for subject J. S., obtained by fixing the refractive power of the eye by means of cycloplegia and providing incremental changes in effective refractive state by means of trial lenses.

The Step-function Optometer for the Right Eye:

A Badal optometer system capable of presenting alternately two different dioptric stimuli to the right eye was used in studying the closed-loop transient res-

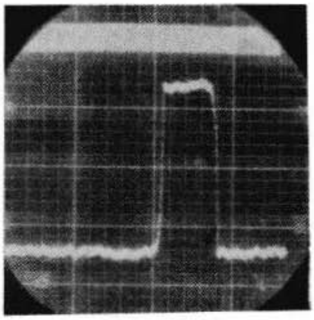

Fig. 3. Transient response of the Allen infrared optometer. 20 c.p.s. time mark.

ponse of the eye, as well as the response of the human accommodative mechanism to an optical rectangular input. Figure 6 is a photograph of the step-function optometer used for the right eye. A dicroic mirror deflects visible (but not infrared) radiation from the stimulus target into the subject's right eye.

The step-function optometer for the right eye contains two separate target systems. The upper systems has a ten diopter range and is used to project a Snellen target into the Badal Optometer below. A removable target in the lower system with a seven diopter range is used to suddenly introduce a stimulus at a different dioptric level. When this second target is brought within the tube of the lower optometer by means of a solenoid, a diffusing screen obscures the projected image from the upper system. The action time of the rotary solenoid controlling the removable target is 20 milliseconds.

When no current is allowed to flow through the rotary solenoid, the projected target is seen. When the solenoid is activated, the lower target moves into place.

Current to the solenoid can be swiched manually, or automatically by connecting the solenoid to a cam-actuate microswitch within the Tensor Generator. A simultaneous voltage presented to one channel of an oscilloscope provides a signal marker.

The Step-function Optometer for the Left Eye:

The left-eye Step-function optometer system provided optical step signals for investigation of the open-loop transient response of the human accommodative mechanism. Figure 7 is a photograph and figure 8 is a schematic diagram of this step-function optometer. In figure 8, C is a ten diopter achromatic lens situated ten centimeters before the entrance pupil of the eye. M is a beam splitter which

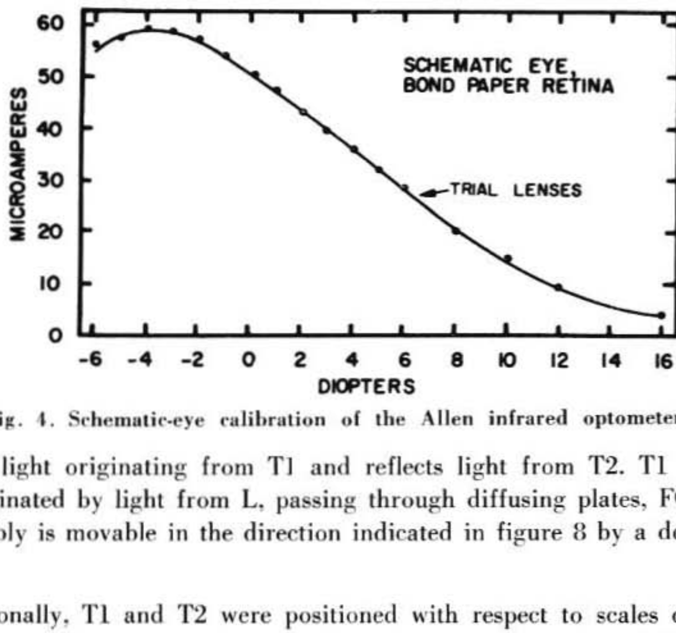

Fig. 4. Schematic-eye calibration of the Allen infrared optometer.

transmits light originating from T1 and reflects light from T2. T1 and T2 are transilluminated by light from L, passing through diffusing plates, FG. Each target assembly is movable in the direction indicated in figure 8 by a double-headed arrow.

Operationally, T1 and T2 were positioned with respect to scales calibrated in diopters, and the stimulus value was changed between two desired dioptric levels by energizing one or the other light source. A low-level current was allowed to pass through the non-illuminated filament at all times, thereby keeping the filament sufficiently warm to be barely visible in an otherwise totally dark room. This, in association with a moderate overvoltage of the filament during its "on" phase, reduced the instrument rise time to approximately 18 milliseconds.

Voltage from across one bulb was fed by way of an attenuating potentiometer to one channel of the Tektronix Nº 502 oscilloscope, thereby providing a signal marker.

The Arbitrary-function Optometer:

The arbitrary-function optometer consists of a front-illuminated Snellen target, driven by an arm connected to the pen of a Massa* rectilinear galvanometer, type, M - 133, having a DC resistance of 1,000 ohms. Figure 9 shows the construction of the Arbitrary function optometer. A supporting structure, which could be clamped to the haploscope table in any desired position, held a laboratory jack. On top of the laboratory jack was affixed a brass plate, milled with a linear groove which in turn was mated to a corresponding projection on the base of the galvanometer carrier. The galvanometer could be moved along a line parallel to the orientation of the left haploscope arm.

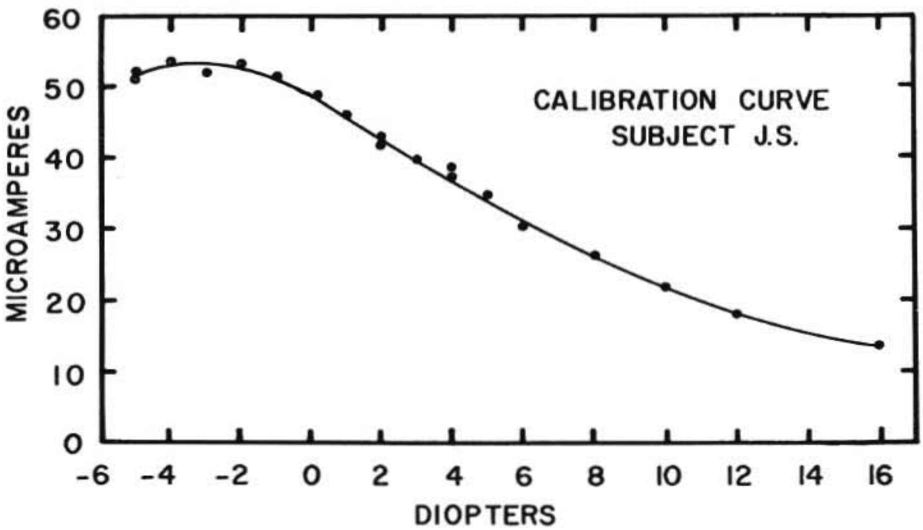

Fig. 5. The infrared optometer calibration curve for subject J. S. To derive this curve, the accommodation of S's right eye was paralyzed and the refractive status of that eye was altered by means of trial lenses.

A small aluminum plate was comented to the side of the galvanometer so that it projected parallel to the galvanometer pen. A hole drilled in the plate adjacent to the pen tip held a sleeve-bearing supporting in turn a thin rod which was attached to the tip of the galvanometer pen. A reduced Snellen chart was attached to a plate mounted upon the free end of the rod. The locus of the pen tip was aligned with the rod and with the optic axis of the left haploscope arm. An acro-

* Massa Laboratories, Inc.
Hingham, Mass.

matic lens of ten diopters was used to complete the optometer, and a millimeter scale (used for calibration purposes) was attached to the lens mounting, parallel to the locus of the reduced Snellen chart. The gross (DC) accommodative stimulus level was obtained by movement of the galvanometer carrier across its specially constructed stage, while fine (DC) accommodative stimulus level adjustment was accomplished electrically.

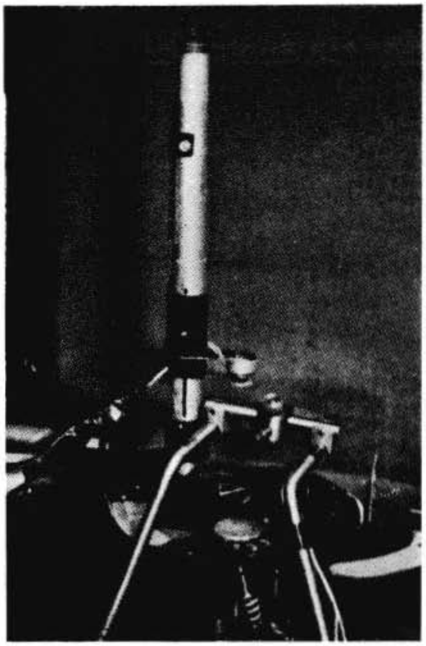

Fig. 6. Step-function optometer for the right eye.

Figure 10 shows the control circuit for the Arbitrary-function optometer. The Tensor* Arbitrary function generator, model 5846, supplies suppressed-carrier modulation of a 1½ KC sine wave. The output is (band-pass) filtered and then amplified by a Heathkit** hi-fidelity amplifier, model EA - 3. It is then fed by way of a step-up transformer into a full-wave bridge and thence to an integrating circuit. The resulting demodulated voltage is applied between the grids of a differential power amplifier with a cathode follower output. The AC accommodative stimulus level is set by means of a vernier gain control on the heathkit amplifier,

* Tensor Electric Development Corp.
Brooklyn, 33, N. Y.

** Heath Company
Benton Harbor, Michigan.

while the DC stimulus level adjustment (fine) is made by means of a vernier-controlled balance adjustment on the differential power amplifier.

Although the Tensor generator can be used to provide any desired function in the frequency range of 0.001 to 10.0 cps, it was used in the pressent investigation only for the purpose of providing sinusoidal and rectangular stimuli.
When used to supply a sine wave, it exhibits maximum harmonic distortion of 3%. Hum distortion is rated as down 45 db.

The output of the Arbitrary-function optometer control circuit was monitored continuously by a high impedence voltmeter, and by one channel of a (vernier-controlled) Tektronix Nº 502 dual beam cathode ray oscilloscope. This Latter arrangement permitted photographic recording of the stimulus to accommodation at a variable (calibrated) scale factor.

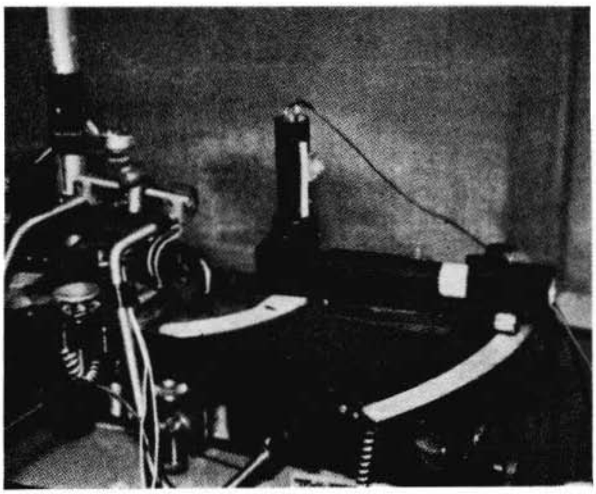

Fig. 7. Step-function optometer for the left eye.

EXPERIMENTAL SUBJECT

It was felt advisable to obtain extensive data with a single subject who could be well trained, rather than to obtain data on a larger number of less well trained subjects. The present study is concerned with general servo-characteristics of accommodation and individual variations were felt not to be important, although they undoubtedly exist.

The subject, J.S., a 22 year old caucasian male, satisfied the criteria established for this investigation. He had a corrected visual acuity in each eye of 20/20, with cycloplegic refractive findings of:

R -1.25 DS c -0.25 DC X 70
R -1.25 DS c -0.25 DC X 125

His ACA ratic (based upon blur points) was 3.6 to 1, and his amplitude of accommodation in each eye was ten diopters, measured by the technique of Donders.

Undoubtedly, human beings use all cues available, including psychic and various binocular cues, in the control of focus of the eye. When an individual is placed in a situation in which most of these cues are absent (Badal Optometer), and only retinal image blur and associated phenomena are present, he frequently is unable to control his accommodation efficiently and must learn to do so.

Prior to actual data taking, the subject was practised in responding to both step and steady-state accommodative stimuli. Three training sessions, each of roughly two hours duration, were undertaken with stimuli presented over a wide frecuency range, but at frequencies not exceding those at which the subject reported difficulty in tracking. It was felt that in the absence of such training, experimental results would be influenced by progressive changes occurring secondary to the learning process. It is true that this approach would be unnecessary if the accommodative mechanism were truly reflex in nature. However, as will be seen

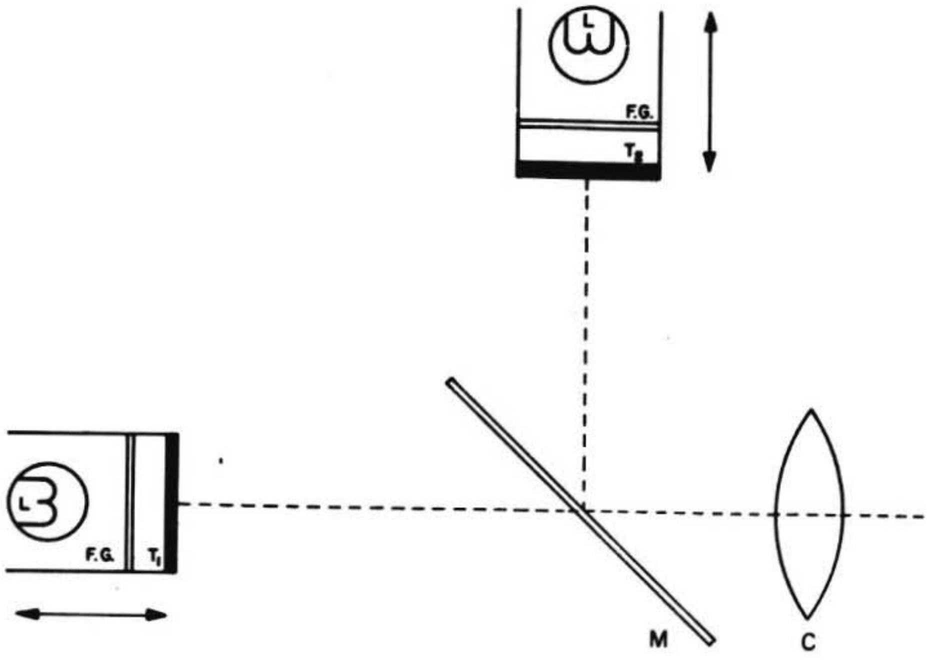

Fig. 8. Construction of the step-function optometer of figure 58.

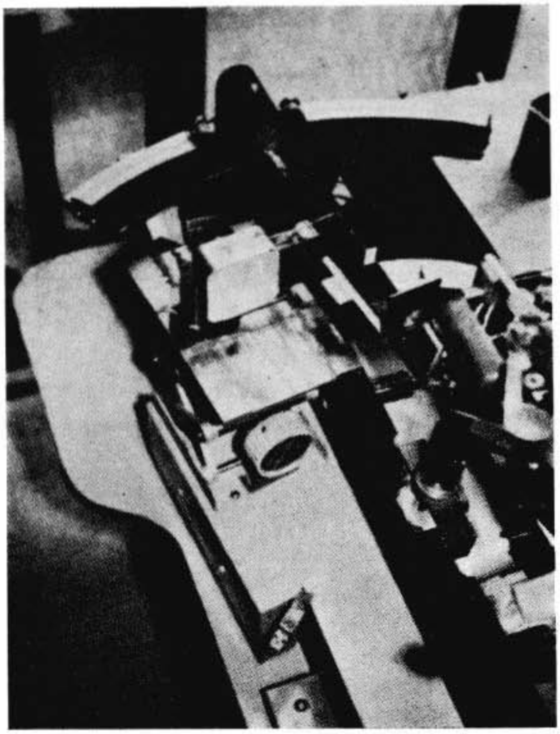

Fig. 9. The arbitrary-function Badal optometer. A brass plate, mounted upon a standard laboratory jack and milled with a linear groove, supports a complementary brass plate affixed to the rectilinear galvanometer. The Snellen target is coupled to the pen tip by means of a moly-coated balsa-wood shaft which is prevented from moving laterally by a close-fitting linear bearing. The bearing is mounted rigidly to a thin aluminum plate which is cemented to the galvanometer body. Although the instantaneous dioptric value is identified in terms of its electrical analog, it can be verified by noting the projection of the Snellen target upon a millimeter scale affixed to the left haploscope arm.

later, there is excellent reason to believe that the higher centers play a significant role in "reflex" accommodation.

METHOD

Open-loop Testing:

The conventional approach to the analysis of servomechanisms is to interrupt the servo-loop, introduce signals at a point adjacent to the break, and record responses on the opposite side of the point of discontinuity. The point of interruption of the serve-loop is unimportant, providing that no sub-loops exist in parallel with the major loop at the site of interruption. It was felt that the most convenient point at which to break the human accommodative serve-loop was at the controller.

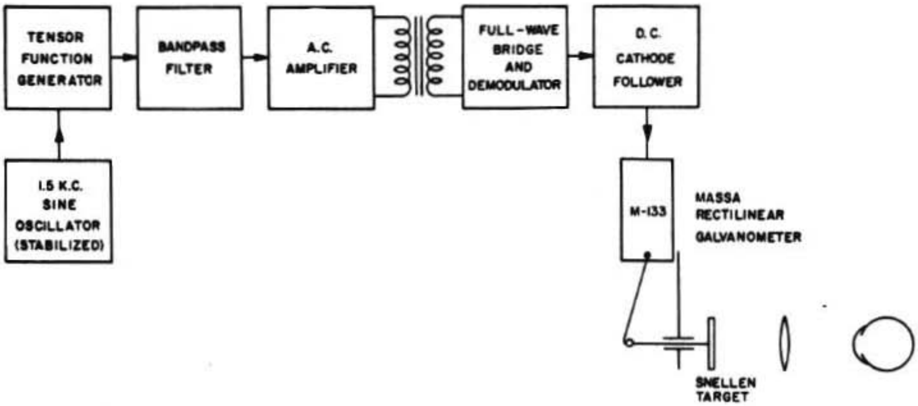

Fig. 10. Control circuit for the Badal arbitrary-function optometer.

With a normal accommodative mechanism, the amount of accommodation in the two eyes is the same. Hence, it was decided to break the servo-loop by atropinization of the left eye. This eye is then incapable of making corrective responses. However, an error-signal due to the blurred retinal imagery in that eye would ascend to the brain and initiate a signal for an accommodative response. Since no difference in efferent signal exists between the right and left eyes, the accommodation measured on the right eye is a correlate of the motor signal to the sinistraocular accommodative mechanism.

For open-loop data, the nature of the accommodative-convergence mechanism is an important consideration since accommodation causes the right eye to turn inward. The infrared optometer is sensitive to vignetting of its beam by the pupillary margin, being unable to distinguish between accommodative activity and decrement of light intensity secondary to absorption by the iris. The subject used in this study exhibits a comparatively low ACA ratio, and vignetting of the optometer beam resulting from an inturning of the right eye proved to be a problem only at the higher accommodative levels.

To obtain valid open-loop data, it is necessary that paralysis of the accommodative mechanism be sufficiently complete to prevent accommodative tracking. The subject was instructed to use 1% atropine sulfate in his left eye t.i.d. for two days preceding the investigation as well as twice during the morning of the day of investigation. Adequacy of cycloplegia was established since blurring of a Snellen target was perceived at equal (dioptric) distances, proximal and distal to the subject's far point.

Following atropinization of his left eye, the subject was placed in his dental bite attached to the infrared optometer. The instrument aligning lights were used

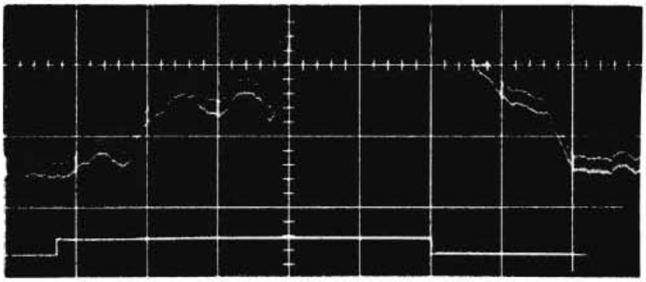

Fig. 11.

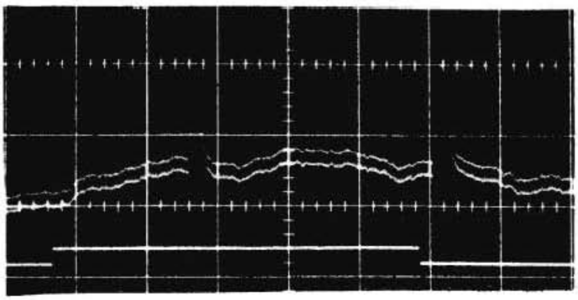

Fig. 12.

Figures 11 and 12 (above): Open-loop step response to a 0.25 D stimulus. In Fig. 11 the subject was instructed to attemp vigorously to clear the perceived blur while in Fig. 12 he was instructed to respond passively. A vertical distance equal to the height of the stimulus marker is 0.4D. The sweep rate is 2 sec./cm.

to align the subject's pupil with respect to the optometer beam. The left-eye Snellen target was placed at the phoria position where the subject saw it centered on the optometer source, made visible by removing the infrared filter. After alignment, all components of the infrared optometer and Badal target systems were secured and checks were made throughout the course of the investigation to insure that proper positioning prevailed.

It was originally intended that open-loop testing would consist of transient response and frequency response testing, and that frequency response testing would be executed over a range of frequencies between 0.01 and 10.0 cps. For reasons which will soon be apparent, investigation through the complete range of frequencies was not undertaken.

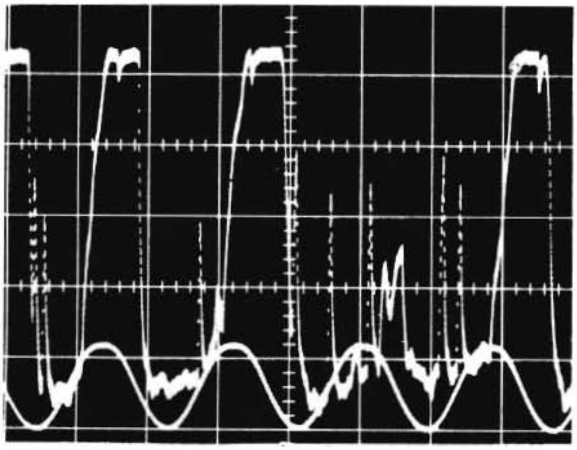

Fig. 13. Open-loop response to a 0.37 D sinusoidal stimulus having a frequency of 0.1 c.p.s. One major scale division equals 3.2 D on the response curve but pupillary vignetting a the higher levels ocurred rendering quantitative analysis inaccurate. In this figure, the subject was instructed to attempt vigorously to clear the perceived blur.

To obtain open-loop step function data, the step function optometer for the left eye was utilized. The vertical arm was adjusted to place the accommodative stimulus at the subject's far point and the horizontal arm was adjusted to place the accommodative stimulus 0.25 D. within his far point. The optometer could be hand-switched from distance setting to near setting, or switching could be accomplished automatically.

Figures 11 and 12 show S's open-loop response to a 0.25 D. accommodative stimulus. The occasional sharp peaks on these and subsequent records are blinks. The height of the stimulus marker is 0.4 D. Removal of the upper segment of the record in figure 11 resulted from the fact that vignetting of the optometer beam occurred, rendering the upper segment of the original record invalid. The breadth of the response line in thes and subsequent records is due to the presence of 60 cycle interference. In figure 11, the subject was instructed to attempt vigorously to clear the perceived blur, resulting when the stimulus target was switched from the far point to a level 0.25 D. within it. In figure 12, the subject was instructed to respond passively to perceived blur. From these figures, it is apparent that the magnitude of the open-loop response is determined, at least in part, by volition.

In figure 11, the positive accommodative response occurred following a dead time. Although the initial response was rapid, the accommodation soon commenced to waver about a drifting baseline until convergence of the right eye caused pupil vignetting and prevented further evaluation. The negative accommodative response followed a dead time, but did not demostrate appreciable instability since the relaxation stimulus was at the zero diopter level.

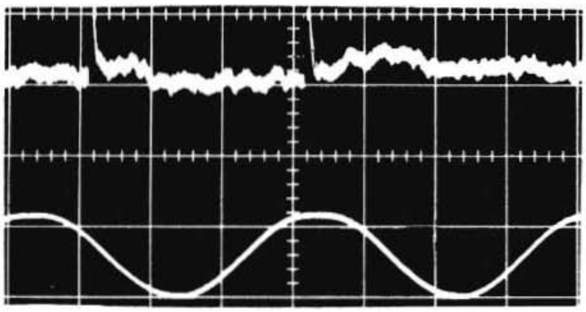

Fig. 14. Open-loop response to a 0.37 D sinusoidal stimulus having a frequency of 0.05 c.p.s. The subject was instructed to respond passively to the perceived blur. One major scale division represents 3.2 diopters on the response curve.

To obtain open-loop frequency response information, the left eye step function optometer was replaced by the arbitrary function optometer system. A procedure similar to that used in open-loop step function testing was utilized to co-align the right and left instrument axes.

By virtue of the variability of open-loop data, it is not possible to measure any systematic frequency dependent relationship between amplitude, phase, and frequency. For this reason, the open-loop data were not subjected to the same sort of analysis as closed-loop data. Open-loop frequency response data may, however, be analysed qualitatively.

On the open-loop frequency response records, one major scale división is equal to 3.2 diopters of accommodation. The stimulus to accommodation for open-loop steady state sinusoidal frequency response testing was 0.37 D., the target lying optically at the subject's far point when in its most distal position. In figure 13 the subject was instructed to attempt vigorously to clear the target when it blurred, whereas in figure 14 the subject was instructed to view the target passively. That these curves were obtained at two slightly different frequencies (see figure legend) is of little significance and the examples presented were selected largely on the basis of photographic quality.

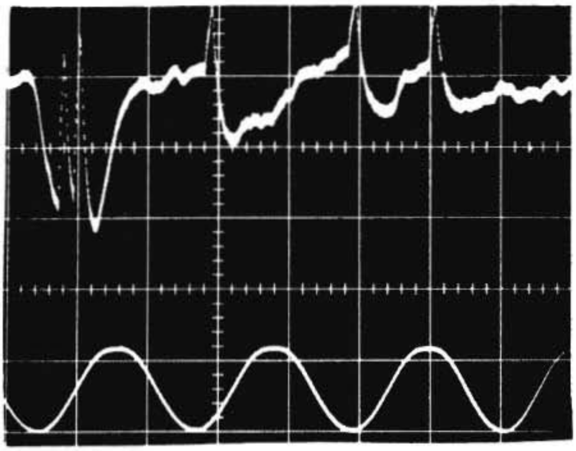

Fig. 15. Open-loop response to a 0.37 D sinusoidal stimulus having a frequency of 0.25 c.p.s. Note the presence of drift. One major scale division equals 3.2 D on the response curve.

In figure 15 it is apparent that the subject responded at a frequency corresponding to that of the accommodative stimulus, although considerable phase lag is in evidence. More important, the amplitude of response to a constant stimulus decreases progressively as a function of time throughout the course of the record. Further, the record demostrates long-term drift toward higher accommodative levels, similar to that seen on the open-loop step function curves.

Campbell and Westheimer [3] conducted a study in which they found that various cues such as chromatic aberration, spherical aberration, and astigmatism could be used to index the required direction of accommodative change. Subjects could utilize these cues after a brief training session in which other cues had been excluded. This suggests that accommodation may not be reflex in the strictest sense of the word, although subtle cues might be utilized under certain conditions to index the required direction and degree of accomomdative response. If certain characteristics of the ligth incident on the retina trigger accommodation reflexly, then a stimulus level beyond the subject's far point should elicit no response, inasmuch as the far point represents the level of maximum accommodative relaxation. If, on the other hand, the subject responds only to blur and is unable to ascertain the direction of blur in the absence of cortical activity, a positive accommodative response would be expected in association with a negative stimulus if accommodative tracking is prevented. To ascertain whether the subject would

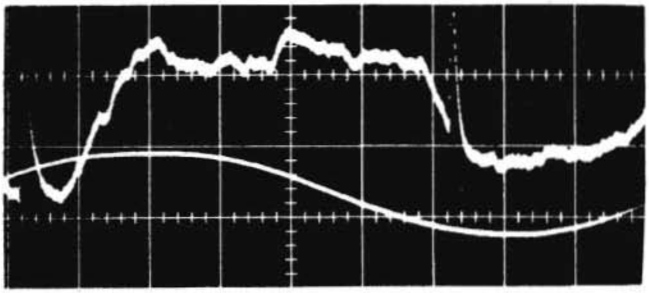

Fig. 16. Positive response to a 0.37 D "negative" accommodative stimulus. The subject was not advised as to the change in stimulus conditions. Polarity of signal input to the oscilloscope has been reversed. Sweep speed is 2 sec./cm.

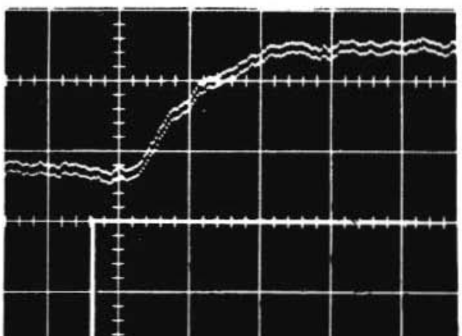

Fig. 17. Closed-loop accommodative response to a 2 D positive step-signal. Sweep speed is 0.5 sec./cm. The signal marker has been retouched.

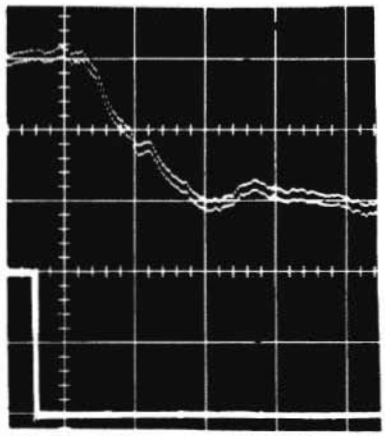

Fig. 18. Closed-loop accommodative response to a 2 D negative optical step-signal. Sweep speed is 0.5 sec./cm. The signal marker has been retouched for better reproduction.

respond differentially to positive and negative blur, data were obtained without the subject being aware of any change in routine. The calibrated dial regulating the zero level of operation for the cathode follower stage in the arbitrary function optometer system was reset so that the target oscillated between the subject's far point and a point (optically) 0.37 D. beyond it, and the polarity of the signal input to the oscilloscope was reversed. Figure 16 is a photograph of the subject's response to this negative accommodative stimulus. It is apparent that the subject responded with positive accommodation.

One factor which could conceivably invalidate the above data with respect to the apparent inability of the subject to discern the directional value of the accommodative stimulus, is that normal oscillations of accommodation were absent during open-loop testing. This investigation does not establish whether such accommodati oscillations do or do not serve as an index of the direction of accommodative error. However, if they normally do play such a role, their abscence in this study would of necessity result in a lessened ability of the subject to appreciate

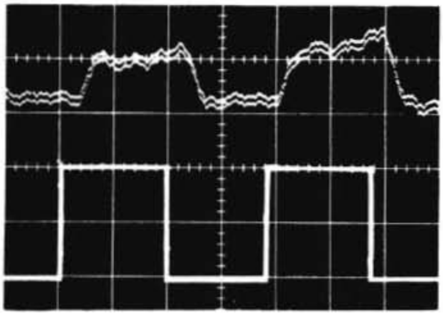

Fig. 19. 0.3 c.p.s.

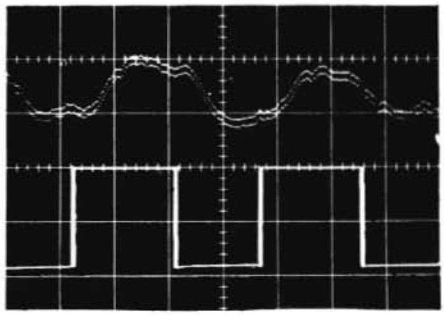

Fig. 20. 0.6 c.p.s.

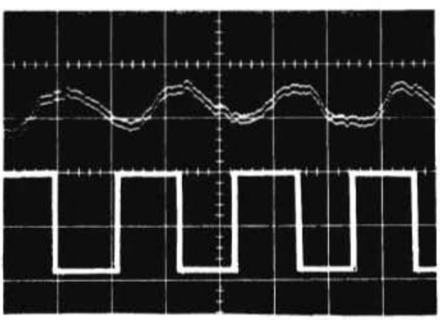

Fig. 21. 1.2 c.p.s.

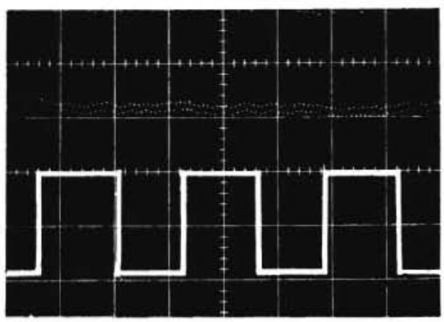

Fig. 22. 2.4 c.p.s.

Figs. 19, 20, 21, 22 (above). Closed-loop response of the eye to a one diopter rectangular stimulus. Note the degeneration of the rectangular waveform and attenuation with increased frequency. The signal markers on the above photographs have been retouched for better reproduction.

directional values. The work of Campbell and Westheimer, previously cited, as well as the fact that normal fluctuations of accommodation largely lie within a sensory dead zone would seem to make such a hypothesis improbable.

Closed-loop Transient Response Testing:

Closed-loop testing of the human accommodative mechanism was undertaken in the absence of cycloplegia. Mydriasis was utilized, however, in the right eye to minimize the possibility of vignetting of the infrared optometer beam, and in the left to minimize depth of focus. A signal amplitude of 1D. was utilized for both transient response analysis and steady-state frequency response analysis. The subject was instructed to respond vigorously to the accomodative stimulus at all times.

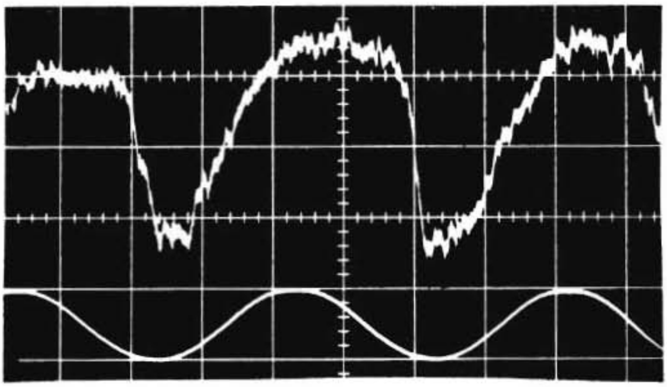

Fig. 23. Closed-loop response of the eye to a 1 D sinusoidal stimulus (0.05 c.p.s.). Note the deviation from sinusoidal form.

In closed-loop step response testing, the optometer system for the right eye was used since its alignment is more readily accomplished than in the case of the step-function optometer for the left eye. The solenoid action time of this optometer is 20 milliseconds. Since this value is negligible compared to the action time of the accommodative mechanism, corrections for optometer action time were not made.

Figure 17 is the accommodative response to a 2 D. positive optical step signal and figure 18 is the response to a 2 D. negative step input. The 1 D. records were unsuitable for publication due to the application of construction lines used to obtain quantitative information. The qualitative aspects of the response to a two diopter stimulus were similar to those for a 1 D. stimulus, save for the fluctuation noted midway along the linear section of the response curve of figure 18 which appeared only on this solitary photograph.

The initial response to a 1 D. optical step signal, either positive or negative, followed a time delay of up to 425 milliseconds but the corresponding value for repetitive data was 240 milliseconds for positive accommodation and 200 milliseconds for negative accommodation. Transient accommodative response appears to be approximately exponential and the time constant for positive accommodation was variously determined as 275 milliseconds (63% of full seale basis) and 325 milliseconds (initial slope basis) The corresponding values for negative accommodation were 250 and 346 milliseconds respectively.

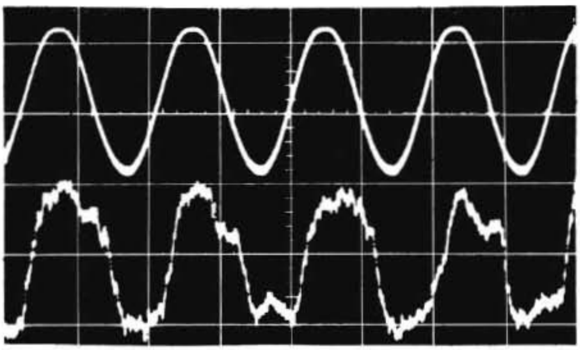

Fig. 24. Closed-loop response of the eye to a 1 D sinusoidal stimulus (0.1 c.p.s.).

If maximum velocity is defined in terms of the steepest slope on the accommodative response curve, the maximum velocity for a 1 D. positive swing was 3.08 D./sec. while the corresponding value for a unit negative excursion was 2.89 D/sec.

If average velocity is defined in terms of the elapsed time between two successive zero-derivative points on the response curve, the average velocity for positive accommodation was 1.01 D./sec. while that for negative accommodation was 2.24 D./sec. The low average velocity for positive accommodation is attributable to the time required to accommodate for the last 10% of the stimulus.

A frequently encountered, but not invariable, peculiarity of the accommodative relaxation curve is noted in figure 18. Based upon a 1 D. negative step stimulus, the accommodation achieves maximum relaxation in 0.446 seconds, then increases to a relative maximum positive level of 0.2 D., attaining this value after roughly

275 milliseconds. The accommodation then drifts slowly toward a state of more complete relaxation.

In attempting to interpret this phenomenon, two points are noteworthy. First, the 0.2 D. value is of the same order of magnitude as the ocular depth of focus. Second, the time interval between attainment of the initial relaxad state and the relative maximum is of the same order of magnitude as the system dead time. Thus, the subject appears to first relax his accommodation to the distal limit of the depth of focus range, this then providing a stimulus for positive accommodation which does not commence until the signal has returned from the brain. When the proximal limit of the depth of focus is reached, the accommodation drifts slowly within a sensory dead zone until a suitable resting level is attained, this level lying in proximity to the distal limit (the lazy lag of accommodation). Such a hypothesis could be better evaluated if the study were repeated employing a null-seeking infrared optometer, capable of more accurately defining the instantaneous DC accommodative level.

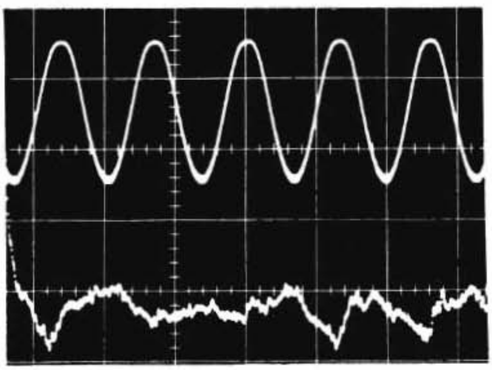

Fig. 25. Closed-loop response of the eye to a 1 D sinusoidal stimulus (0.4 c.p.s.). Note that one entire cycle was skipped.

Closed-loop Response to a Rectangular Input:

It was desired to ascertain the nature of the closed-loop response of the eye to a rectangular accommodative stimulus. It was felt that, due to the presence of system dead time, lag of response behind stimulus should occur, and that at the higher frequencies the response should loose its rectangular form and degenerate into an approximately sinusoidal waveform. Indeed, both of these effects were realized (see figures 19 - 22).

To test the closed-loop response of the eye to a dioptric rectangular wave, the right eye step-function optometer system (employing red-free light), and the accommodation recording system were positioned before the subject. A cam-actuated microswitch provided in the Tensor Generator allowed the dioptric stimulus to alternate between two preset levels.

Figure 19 shows the response of the eye to a one diopter stimulus presented at 0.3 cps. It is noted that of the two cycles completely represented in this figure, the response on one was greater than the response on the other. The degree of difference noted on this photograph was greater than in the case of other pothographs taken under like conditions. The tendency for accommodation to reach an inflection point at near, and the coast slowly toward a higher dioptric level, was encountered for inputs pelow the frequency at which rounding commenced, perhaps representing drift within a sensory dead zone. Figure 20 was taken under similar conditions to figure 19 except for change in signal frequency (0.6 cps). Marked rounding is in evidence.

In figure 21, (1.2 cps.), rounding is more complete and significant attenuation is present. Rounding occurs since the direction of the stimulus alters before the initial accommodative response attains its maximal value. Note the approximately sinusoidal characteristic of the response. Figure 22 was taken under like conditions, save for frequency (2.4 cps). Here, the response is barely distinguishable from noise.

Closed-loop Frequency Response:

In closed-loop frequency response testing, the arbitrary function optometer system was aligned with respect to S's left eye and the accommodative stimulus was allowed to vary in sinusoidal fashion between the limits of 0.75 D. and 1.75 D. within S's far point. The 0.75.D bias was allowed to offset possible effects of instrument myopia.

As in the case of closed-loop transient response testing, the subject was instructed to exert maximum effort at all times. Multiple photographs of stimulus vs. response were made at each frequency setting and phase and amplitude measurements were made from these photographs.

Closed-loop frequency response data revealed a large non-minimum phase shift secondary to system dead time. Figures 23 and 24 are raw data recorded at 0.05 cps. and 0.1 cps. respectively. It will be observed that, at the lower frequency, considerable distortion is in evidence, perhaps secondary to dead-zone effects. The subject expressed considerable difficulty in responding at very low frequencies, and it is interesting to note that at the higher frequencies whole cycles were occasionally skipped (see figure 25).

At any given signal frequency, not all cycles yielded identical amplitudes, nor is phase shift identical for each cycle. Such variation is most pronounced in the case of very high and very low frequencies. This presents some difficulty in interpreting data, since frequency response analysis depends upon a knowlege of the precise value of relative amplitude and phase angle at each frequency. Although the initial approach was to measure the relative amplitude and phase shift for each cycle and to average all of these values, it was found that the data could be plotted more successfully if a procedure were followed in which all obviously anomalous data were rejected and the remainder were averaged.

Figure 26 a is a plot of amplitude ratio against frequency. The line shown on this figure has been constructed to show an attenuation slope of 20 db. per fre-

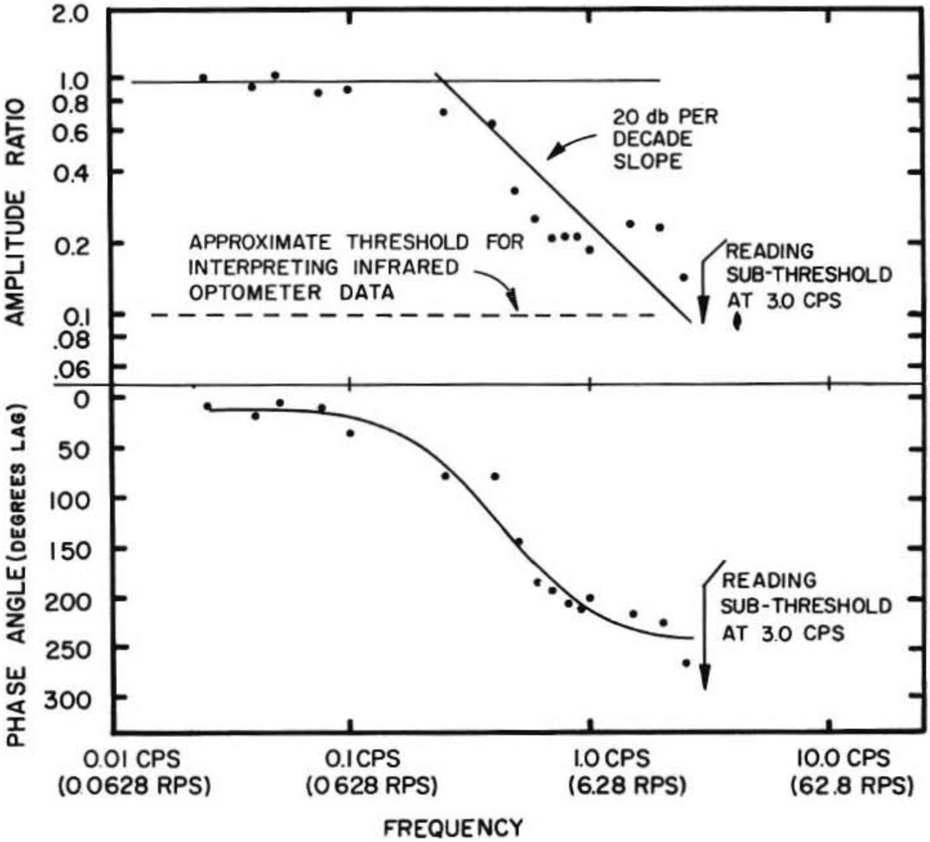

Fig. 26a (above).
Fig. 26b (below).
Closed-loop attenuation characteristic (26a) and closed-loop phase shift characteristic (26b).

quency decade, since this slope (typical of a first-order system) fits the data better than that for a higher order system. Figure 26 b is a plot of phase shift against frequency. The phase shift is largely non-minimum since the maximum possible lag for a linear first order system, free from dead time, is 90°.

In figure 27, the amplitude and phase responses were combined on a complex plane plot in which the radius vector indicates the amplitude ratio at a given frequency while polar angle defines the phase angle. A cmooth curve was drawn which appeared to fit the experimental data. Some of the test frequencies are noted along the curve.

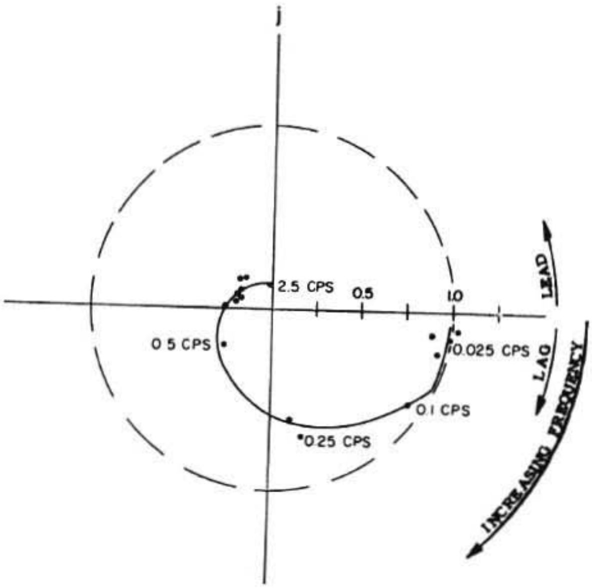

Fig. 27. A complex plane representation of the empirical frequency response of the human accommodative mechanism. The radius vector defines the amplitude ratio at a given frequency while phase lag is defined by the polar angle.

DISCUSSION

The premise upon which the present investigation has been based is that the accommodative mechanism of the eye functions as a servomechanism, an error-actuated feedback control device. It appears that this original assumption was at least partially justified since numerous parameters relating to the mode of action of the accomodative mechanism can be defined in servoanalytic terms. On the other hand, the accommodative mechanism scarcely exhibits all of the automatic properties ascribed to the pupillary mechanism by Stark.[4]

The first suggestion of a strong volitional element in accommodation appeared when the loop was broken by atropinization of S's left eye. It was found that the open-loop gain was very high or very low depending upon the attitude of the subject. This effect was observable with both both step and sinusoidal dioptric inputs.

Further evidence that the accommodative mechanism is not fully automatic appeared when, under open-loop conditions, the subject responded to a negative

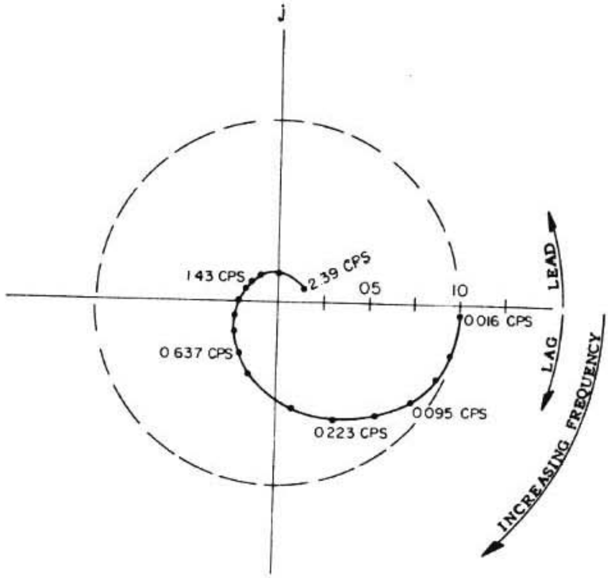

Fig. 28. A complex plane representation of the frequency response of anhypothetical system operating according to the formula:

$$G(w) \frac{0.6\, e^{-j(0.3w)}}{1-0.4(\cos 0.3w)+j(0.27w+0.4\sin 0.3w)}$$

dioptric stimulus with a positive accommodative response. This suggests that the required direction of change of accommodative posture is not coded in terms of the physical characteristics of light incident on the retina. However, it has been shown that a subject can learn to utilize chromatic aberration, spherical aberration, and astigmatism to provide directional cues when placed in an artificial environment such as a Badal optometer. Undoubtedly, under normal environmental conditions, little difficulty attends sensing the required direction of accommodative change since many cues to relative distance are present (eg. monocular and binocular parallax, superposition, direction of convergence change, relative size, etc.)

The availability of open-loop data greatly facilitates servoanalysis since it permits ready idenitfication of certain system parameters, simplifies mathematical analysis, and permits the prediction of closed-loop stability. It is possible, however, to evaluate the performance characteristics of a given servomechanism in the absence of valid open-loop data.

The closed-loop frequency response characteristics measured for subject, J. S., were presented in figures 26 and 27. Under the assumption that the accommodative mechanism can be treated as a first order servo embracing dead time, the general open-loop equation was formulated as follows:

$$(1) \qquad g(w) = \frac{k\, e^{-j w T1}}{1 + j w T_2}$$

where:

$g(w)$	is the open-loop system gain
k	is a gain constant
T_1	is the system dead time
T_2	is the system time constant

The closed-loop response is related to the open-loop response by means of the formula:

$$(2) \qquad G(w) = \frac{g}{1 + g\,H}$$

where:

$G(w)$	is the closed-loop gain
g	is the open-loop gain
H	is the system feedback factor.

Formula (1) was inserted into formula (2) to provide a general equation for the closed-loop response of the eye. H, the feedback factor, was assumed to be a constant defining the attenuation produced by dead zone. It corresponde to a depth of focus of roughly $\pm\, ^1/_6$ D. Values of T_1 and T_2 were selected to be consistent with experimentally derived values and to permit $G(w)$ to define a curve similar to that of figure 27. A value of k was selected which provided unity gain at zero frequency.

Figure 28 is a complex plane plot constructed according to the resultant formula. Although the general form of the curves in figures 27 and 28 are similar, moderate divergence of frecuencies for corresponding sets of point is in evidence.

The equation upon which figure 28 is based is as follows:

$$G(w) = \frac{0.6\, e^{-j(0.3\, w)}}{1 - 0.4(\cos 0.3\, w) \quad j(0.27w \quad 0.4 \sin 0.3\, w}$$

Where: -0.4 represents the product of k and H.

Since kH is negative, the equation above defines a system which is regenerative and, as such, would not be error — correcting. Similarly, the open-loop gain of a regenerative system is less than the closed-loop gain. We have previously seen that the open-loop gain of the human accommodative system exceeds the closed-loop gain when the subject makes a vigorous attempt to clear a perceived blur.

From the above, it is apparent that the cited formula cannot represent the actual transfer function for the human accommodative mechanism. Hence, it is of interest to speculate concerning possible means of obtaining an equation for a degenerative system which is compatible with the empirical frequency response of the human accommodative mechanism.

Conventional servo formulae presuppose that the gain constant, k, does not vary. However, it has been seen that the open-loop gain varies markedly depending largely upon expended effort. If we can assume that the subject "tries harder" in one frequency range than another, it is possible that k may be frequency dependent. The manner in which k, varying as a function of frequency, would influence the closed-loop system gain would not be simple, inasmuch as it appears in the denominator of the closed-loop transfer function as well as in its numerator. Likewise, it might be possible that the accommodative system is higher than first order. Unfortunately, changes in gain with frequency would alter the attenuation slope while the utilization of a second time constant would increase the theoretical slope to 40 db. per decade. Neither of these effects are readily reconciled with the attenuation curve of figure 26. Attempts were not made during the present investigation to utilize equations having more than a single time constant.

One further possibility exists since it is known that a satisfactory fit of the experimental curve can be obtained if the numerical value of the system time constant is increased. A value of 1.5 seconds yields a reasonably satisfactory fit, but this value seems unlikely since it exceeds the experimentally derived value by a factor of five to six times.

Figure 29 is a block diagram of the human accommodative servomechanism showing its relationship to the experimental conditions of the present investigation. Sources of time delay are not noted explicitly on the diagram but are understood to exist throughout the system in the form of nerve conduction and synaptic delays, as well as neuro-muscular lags and delays associated with the muscle-lens dynamics. Under the conditions of open-loop testing, the accommo-

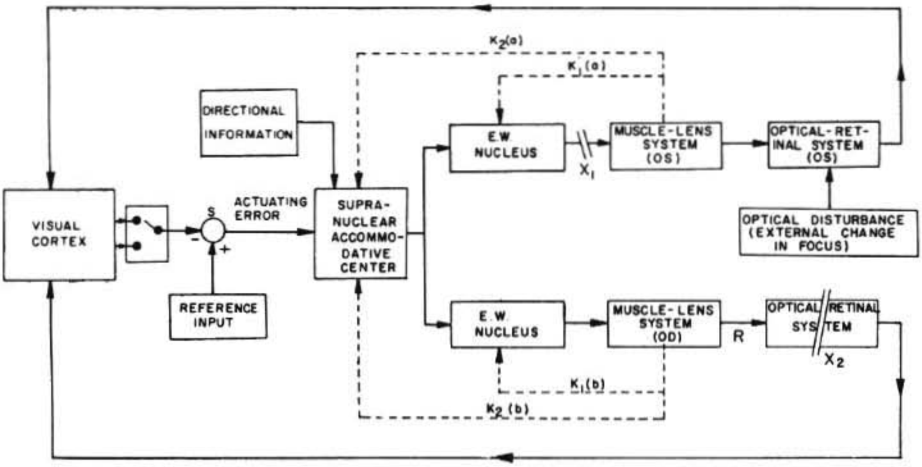

Fig. 29. A block diagram of the human accommodative servomechanism as related to the conditions of the present investigation.

dative servo-loop was interrupted at X1 by atropinization of the left eye, while no light was available to the right eye by virtue of the absence of visible radiation in the infrared optometer system. This had the effect of breaking the servo-loop at X2. Optical readout was taken at R.

In the brain, some parameter of the cortical "image" relating to perceptual clarity is accepted for one or the other eye and compared at summing junction, S, with a reference input. The precise nature of the reference input is unknown. Perhaps the output of the retinal derivative fibers is involved since this relates to the contrast gradient at the image border.

We may assume that gain is acquired in the forward loop while the action of the feedback loop is passive. It may be further assumed that the forward path "inverts" the signal so as to make the system degenerative. Consider the forward path to contain a single operational amplifier and a time delay, and the feedback path to contain only a time delay. It is likely that the time constant of the accommodative system is related to the muscle-lens dynamics, although its precise site is of little importance to the present problem.

Although both the supra-nuclear accommodative center and the E. W. nuclei may be thought of as contributing gain, it is likely that volitional control exists only in the supra-nuclear center. An alternative to supposing that gain varies with volition in a "reflex" system is to imagine that a true reflex system (with constant gain) exists, which can be overridden by impulses originating at a center for voluntary accommodation. The more reasonable assumption, however, would seem to be the former and it is likely that the cortical "image" is in some manner evaluated with respect to clarity and, should a corrective accommodative act be necessary, directional cues are provided from an external source.

Although not anatomically established, the possibility of kinesthetic feedback from the ciliary muscle or associated structures must be considered in the analysis of the accommodative mechanism. Such auxiliary loops, should they exist, could be either regenerative or degenerative. In the former case, they would serve to increase gain while in the later they would tend to reduce gain while expanding the flat portion of the frequency response curve.

The dotted lines in figure 29 indicate possible sites of proprioceptive loops. Under the conditions of "open-loop" testing, loop K1 (a) and/or loop K2 (a) would be deactivated, wile loop K1 (b) and/or loop K2 (b) would be unaffected. Such internal loops could shift the frequency break point and alter the forward gain of the system. Since, however, the constants from such sub-systems would be lumped with those from the remainder of the mechanism, presence or absence of such auxiliary loops could not be inferred.

SUMMARY AND CONCLUSIONS

The purpose of the present investigation has been to analyze the accommodative mechanism as a feedback control device. Accommodative responses to both sinusoidal and step stimuli were recorded by means of an infrared optometer. The responses were, in each case, compared with the stimuli and the data were subjected to servoanalytic techniques.

The more significant findings of the present investigation follow:

1. The closed-loop transient response of the human accommodative mechanism occurs following a time delay and is approximately exponential. With non-repetitive signals, the time delay is approximately 425 milliseconds for both positive accommodation and accommodative relaxation. With repetitive signals, the time

delay averagel 240 milliseconds for positive accommodation and 200 milliseconds for accommodative relaxation.

2. The time constant of the accommodative mechanism was estimated according to two criteria. The results follow:

Positive Accommodation:

63% of full-scale basis:	275 milliseconds
Initial slope basis:	325 milliseconds

Accommodative Relaxation:

63% of full-scale basis:	250 milliseconds
Initial slope basis:	346 milliseconds

3. The closed-loop frequency response data could be fit reasonably well by an attenuation curve having a constant slope of 20 db. per frequency decade. Such a slope typifies a first order system. Phase analysis reveals a very large non-minimum component which is related to system dead time.

4. The accommodative servo-loop was opened by atropinization of S's left eye. A negative accommodative stimulus (i.e. a pre-focal blur) was provided for that eye. The right eye of the subject responded in the manner which would be expected for a post-focal blur. This suggests that directional cues are probably not provided by physical characteristics of the stimulating light. As such, it is likely that a subject, under normal environmental conditions, learns to utilize numerous (including psychic) cues to indicate the required direction of accommodative change.

5. Open-loop gain appeared high under the condition that the subject was instructed to attempt vigorously to clear any perceived blur. Under the condition that the subject was instructed to respond passively, open-loop gain was low. An alternative to assuming that changes in gain can be induced voluntarily in a "reflex" mechanism is the assumption that a reflex mechanism exists which can be overridden by impulses originating at a "voluntary control center".

6. Under the assumption that the human accommodative mechanism is a first order servo embracing dead time and dead zone, an attempt was made to formulate the system transfer equation. When a formula was constructed which provided a satisfactory fit of the empirical frequency response data (using constants compatible with ex experimentally derived values), it was found that the resulting equation defined a regenerative system. Since such a system would not be error-correcting, the equation must be rejected.

7. While it is apparent that volition plays an essential role in accommodation, under normal environmental conditions accommodation seems to be automatic (in the sense that control is not at a conscious level). Many persons placed in an environment in which few of the normal cues to distance are present (eg. Badal Optometer) must learn to respond to different cues than those to which they are accustomed. This accounts for the difficulty often encountered in measuring accommodative changes in the eye of an untrained subject who is attempting to respond to accommodative stimuli presented in a Badal system.

8. Further research is indicated, utilizing a greater number of subjects, to derive a realistic transfer equation for the human accommodative mechanism. A major obstacle in the present investigation has been the fact that the attenuation curve shows a slope characteristic of a first order system, while attenuation commences at a very low frequency. This suggests the presence of a regenerative system (not possible since it would not be error-correcting), or a system having a time constant too long to be reconciled with experimentally derived values. Perhaps voluntary factors enter strongly into frequency response data, or perhaps the mechanism of accommodation is too complex to be accounted for on the basis of a model which is a first order servo containing a single loop and embracing time delay and dead zone.

The Penn, State College of Optometry

BIBLIOGRAPHY

1) ALLEN, M. J., and CARTER, J. H. "An Infrared Optometer to Study the Accommodative Mechanism", *American Journal of Optometry and Archives of the American Academy of Optometry*, Monograph 274, Aug., 1960, 5 pp.

2) ALLEN, M. J., *A Study Corcerning the Accommodation and Convergence Relationship*, U.S.A.F. Contract 33 (616) - 6146, May, 1961, 21 pp.

3) CAMPBELL, F. W., and WESTHEIMER, GERALD, "Factors Influencing Accommodation Responses of the Human Eye", *Journal of the Optical Society of America*, vol. 49 - 6:568 - 571, June, 1959.

4) STARK, LAWRENCE, "Stability, Oscillations, and Noise in the Human pupil Servomechanism", *Proceedings of the I.R.E.*, vol. 47 - 11: 1925 - 1939, November, 1959.

RELATED READINGS

1) ALLEN, M. J. "The Response of the Intra-Ocular Muscles of the Dog and Cat to Electrical Stimulation", *American Journal of Optometry and Archives of the American Academy of Optometry*, June, 1950.

2) ALLEN, M. J., "An Investigation of the Time Characteristics of Accommodation and Convergence of the Eyes", *Abstracts of Doctoral Dissertations Nº 61*, Ohio State University Press, 1951.

3) ALLEN, M. J., "An Investigation of the Time Characteristics of Accommodation and Convergence of the Eyes - Historical Review", *American Journal of Optometry and Archives of the American Academy of Optometry*, February, 1953.

4) ALLEN, M. J., "An Investigation of the Time Characteristics of Accommodation and Convergence of the Eyes, (Subjective Determination of Accommodation and Objective Recording of Convergence.)", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 30 - 8, August, 1953.

5) ALLEN, M. J., 'The Stimulus to Accommodation", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 32, August, 1955.

6) ALLEN M. J., "The Influence of Age on the Speed of Accommodation", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 33, April, 1956.

7) CAMPBELL, F. W., *The Accommodation Response of the Human Eye*. The Physiological Laboratory, Cambridge, England, 1959, 16 pp.

8) CAMPBELL, F. W., *The Depth of Field of the Human Eye*, physiological Laboratory, Cambridge, England, 1956, 5 pp.

9) CAMPBELL, F. W., "The Depth of Focus of the Human Eye", *Journal of Physiology*, vol. 125: 29 - 30, May, 1954.

10) CAMPBELL, F. W., "Twilight Myopia", *Optics*, September, 1951.

11) CAMPBELL, F. W. and GREGORY, A. H., "Effects of Size of pupil on Visual Acuity", *Nature*, vol. 187 - 4743: 1121 - 1123, September, 1960.

12) CAMPBELL, F. W., and WESTHEIMER, GERALD, "Dynamics of Accommodation Responses of the Human Eye", *Journal of Physiology*, Nº 151: 285 - 295, October, 1959.

13) CAMPBELL, F. W. and WESTHEIMER, GERALD, "Sensitivity of the Eye to Differences in Focus", *Journal of Physiology*, vol. 143: 18, May, 1958.

14) CAMPBELL, F. W., ROBSON, J. G. and WESTHEIMER, GERALD, "Fluctuations of Accommodation under Steady Viewing Conditions", *Journal of Physiology*, vol. 145 - 3: 579 - 594, September, 1959.

15) CAMPBELL, F. W., WESTHEIMER, GERALD and ROBSON, J. G., "Significance of Fluctuations of Accommodation", *Journal of the Optical Society of America*, vol. 48 - 9: 669, September, 1958.

16) CAMPBELL, F. W., "The Minimum Quantity of Light Required to Elicit the Accommodation Reflex in Man", *Journal of Physiology*, vol. 123 - 2, 357 ff., 1954.

17) CAMPBELL, F. W., and ROBSON, J. G., "High Speed Infrared Optometer", *Journal of the Optical Society of America*, vol. 49 - 3: 268 - 272, March, 1959.

18) CAMPBELL, F. W., "Correlation of Accommodation Between the Two Eyes", *Journal of the Optical Society of America*, vol. 50 - 7, 738, July, 1960.

19) CHESTNUT, HAROLD and MAYER, R. W., *Servomechanisms and Regulating System Design*, vol. 1, John Wiley and Sons, Inc., N. Y., 1959, 680 pp.

20) CHESTNUT, HAROLD and MAYER, R. W., Servomechanisms and Regulating System Design, vol. 2, Jonh Wiley and Sons, Inc., N. Y., 1955, 384 pp.

21) CROSBY, E. C., and HENDERSON, J. W., "The Mammalian Midbrain and Isthmus Regions: Fiber Connections of the Superior Colliculus, pathways Concerned in Automatic Eye Movements", *Journal of Comparative Neurology* 88: 53 - 91, 1948.

22) DONDERS, F. C., *On the Anomalies of Accommodation and Refraction of the Eye*, The New Sydenham Society, Hatton press Ltd., London, 1952, 635 pp.

23) FINCHAM, E. F., "The Mechanism of Accommodation and the Recession of the Near Point", *Report of the Imperial College of Science*, London, June, 1932.

24) HEATH, G. G., "The Influence of Visual Acuity on Accommodative Responses of the Eye", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 33 - 10, 513 - 514, October, 1956.

25) MARG, ELWIN. "An Investigation of Voluntary as Distinguished from Reflex Accommodation", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 28 - 7: 347 - 356, 1951.

26) MORGAN, MEREDITH W. J., "The Resting State of Accommodation", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 34 - 7, 347 - 353, July, 1957.

27) REESE, E. E., and FRY, G. A., "The Effect of Fogging Lenses on Accommodation", *American Journal of Optometry and Archives of the American Academy of Optometry* 18: 9 - 16, 1941.

28) SISSON, E. D., "Voluntary Control of Accommodation", *Journal of General Psychology*, 18: 195 - 198, 1938.

29) WEINER, NORBERT, *Cybernetics*, John Wiley and Sons, Inc., N. Y., 1961, 212 pp.

30) WESTHEIMER, GERALD, "The Relationship Between Accommodation and Accommodative Convergence", *American Journal of Optometry and Archives of the American Academy of Optometry*, vol. 32 - 4, 206 - 212, April, 1955.