Final Report

EXPERIMENTAL STUDY OF VISUAL ACCOMMODATION

By: H. D. CRANE T. N. CORNSWEET

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA 94035

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ABSTRACT

This is a summary report of the third year of a research effort related to the visual accommodation system. The first year was a theoretical study of the accommodation system. The second year was concerned with the development of instrumentation to perform basic experiments in accommodation control, in particular, the development of an optometer, a visual display unit, and a two dimensional eye tracker. During the third year, the first two instruments have become operational. The eye tracker in its present form has an accuracy on the order of five minutes of arc, still short of the desired accuracy of one to two minutes of arc. The present status of these instruments is briefly described. Also described are experiments in accommodation control using the optometer and display unit.

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ILLUSTRATIONS

I BACKGROUND

This is a summary report for the third year of a study of the human accommodation system. The study initially evolved from the development at Stanford Research Institute of an optical range-finder technique based on a mode of vibration that seemed analogous to an observed vibration in the human lens system. The initial goal was to evaluate the potential role of this vibration in human focus control.

The first year's study (NASA Contract NAS2-2760, 12 April 1965)* was principally theoretical in nature, and resulted in the development of models for

(1) Processing of the retinal image to determine the state of focus, and

(2) The nature of the control system controlling the ciliary muscles.

In particular, that study led to the prediction that strong interaction may exist between eye movements and focus control. As for the observed vibrations, it was tentatively concluded that they are probably not used for defocus measuring but more likely are a result of the normal mode of operation of the accommodation control system.

The second year's work (NASA Contract NAS2-3517, 14 April 1966)† was aimed primarily at the development of the instrumentation to test a number of basic hypotheses generated in the first study. The two key items of instrumentation were a two-dimensional eye tracker and an optometer (an instrument to measure the state of accommodation of the eye in real time).

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*H. Crane, "A Theoretical Analysis of the Visual Accommodation System in Humans," Final Report, Contract NAS2-2760, SRI Project 5454, Stanford Research Institute, Menlo Park, California (January 1966).

†T. N. Cornsweet and H. D. Crane, "Design of an Optometer and Two-Dimensional Eye Tracker," Final Report, Contract NAS2-3517, SRI Project 6009, Stanford Research Institute, Menlo Park, California (April 1967).

During the present contract year substantial advances were made in the instrumentation, which permitted us to start the experimental program on accommodation control. The instrumentation and experimental results are summarized separately below.

II INSTRUMENTATION

A. Optometer

The automatic infrared optometer has now been developed to a point where it operates reliably, with high accuracy, and with relative ease. While it is difficult to evaluate the accuracy quantitatively, we estimate that the readings of the device are correct within one-to-two-tenths of a diopter even during the fastest accommodative responses. The most significant improvements in the optometer that permitted it to reach this stage were:

(1) Changes in the electronics of the Esterline Angus servo driver, which resulted in large improvements in the frequency response of the servo system

(2) Identification of the fact that multiple corneal reflections from the beam splitter were present between the input and output paths. The effects of these reflections were eliminated by the use of a compound corneal stop.

(3) Redesign of the mechanical driver system for the fiber optic bundle, in order to minimize vibration of the whole instrument and

(4) Determining that the low-level signals from the photocell were being contaminated by tribo-electric signals in the coaxial cable, due to the vibration. This contamination was cured by using specially designed vibration-insensitive cable.

B. Focus Stimulator

The servo-controlled focus stimulator has also been brought to a state of reliable and easy operation. This instrument was described in Quarterly Report 2. When a subject looks at any object, test pattern, or other form of visual display through this device, the optical distance between the target and subject's eye can be changed rapidly in accordance with an electrical control signal, without changing in any other way. For example, if the subject is correctly focused on a test pattern, and the optical distance to the pattern is then changed by the present device, the pattern will appear to blur in the subject's eye. If the subject correctly refocuses to the new distance, the pattern will then look exactly the same as it did originally, in both intensity and size. A very useful feature of the device is that the subject can view the target pattern through a pupil of arbitrary size and shape. All of the experiments that we have thus far undertaken, except for the focus movie noted below, were carried out using stimuli presented through this device.

C. Eye Tracker

We have continued development of a device to track eye position in two dimensions with precision good enough to detect involuntary eye movements (approximately one to two minutes of arc). The device that we are developing basically measures the two orthogonal components of the distance between the first and fourth Purkinje images formed in the subject's eye. At the present state of development, the precision of the device is approximately five minutes of arc; but we are considering a much more efficient technique for scanning the Purkinje images that we believe will improve the precision by a factor of 5 to 6.

Technical details of the development of this instrument are documented in Quarterly Reports 1, 2, and 3. The first major improvement over the original device came with development of an on-axis input and output optical system, which is discussed in detail in Quarterly Report 1. This led to a very significant improvement in the optical quality of the Purkinje images and corresponding improvement in electrical signals from the scanning disc, although the signal from the low-intensity fourth Purkinje image was still very noisy. Further improvement in the signal/noise ratio was obtained by a novel electronic averaging technique, which was described in Quarterly Report 2. The electronics were subsequently simplified as noted in Quarterly Report 3. It was with this last electronic processing system that we achieved two-dimensional tracking records with an accuracy on the order of five minutes of arc.

In order to verify that the five-minute noise level was not due to mechanical vibrations in the optical system, a new, mechanically sturdy version of the eye tracker was built. The new version also included the facility for rotating the entire device about the eye axis, in order to align the cross-shaped input pattern with the ax . of any lens astigmatism that may be present, in case that should be shown to be important. With this new device it was readily determined that mechanical vibrations were not the source of the noise and that the problem, in fact, was noise-in-signal.

The next logical step is consideration of a scanning technique that, though mechanically somewhat more complex, offers a large potential increase in signal level without any change in the basic optics. A limitation of the present scanning disc is that it utilizes only about 1/80 of the available light. (This results from 5-mil transparent slits spaced approximately every 400 mils.) Significant improvement in utilization of available light, and corresponding increase in the signal/noise ratio, can be achieved by replacing the scanning disc with a pair of servo-controlled crossed-slits that vibrate continuously across each image and are maintained centered on the image. The techniques for such two-dimensional servoing are relatively straightforward. If this provides the expected increase in signal/noise ratio, this would then be the last basic step in development of the eye tracker.

Each of these instruments, as well as the signal-averaging technique noted above, is believed to be novel and has been reported as "New Technology." A patent application has been filed on the automatic optometer (Serial No. 673,680, filed 9 October 1967), and an application is being prepared on the focus stimulator.

III RESULTS

A. Experimental Results*

During this year, a number of experiments have been conducted using the focus stimulator and the optometer. In these experiments, the target is a pattern viewed through the display system. The apparent distance of the target is varied, either under control of a special waveform generator or from the output of the optometer. The experiments that we have performed so far fit into the sequence of experiments described in our second research proposal (SRI ESU 65-82). These experiments will first be described in a context that we believe makes them easy for the reader to assimilate. Then, their relationship to the sequence in our original proposal will be pointed out.

1. Measures of the Response

The latency (i.e., the time between the onset of a target displacement and the beginning of the resulting change in accommodative strength) seems to be very constant at approximately 0.4 second among all subjects, regardless of the direction or the magnitude of the displacement. A typical response is shown in Fig. 1.

The velocity of the response (i.e., the rate of change of refractive strength) can be very different, depending upon the direction of the response. For example, in Fig. 1, the initial velocity of response when the target is moved toward the subject is about 4 diopters per second, while the initial velocity when the target is moved toward infinity is greater than 12 diopters per second. Figure 2 shows the response to a step-target displacement that was recorded from the eye of a 31-year-old commercial pilot. His response velocities are even more strikingly different in the two directions. The fact that the velocities are different in the two directions means that the system is nonlinear. Therefore, ordinary techniques of linear systems analysis are not appropriate. For example, a Bode plot cannot be used to predict the response of the system to arbitrary inputs. (We hope to find

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*The discussion of results included here is essentially that which was included in our proposal for continuing support (SRI ESU 68-37).

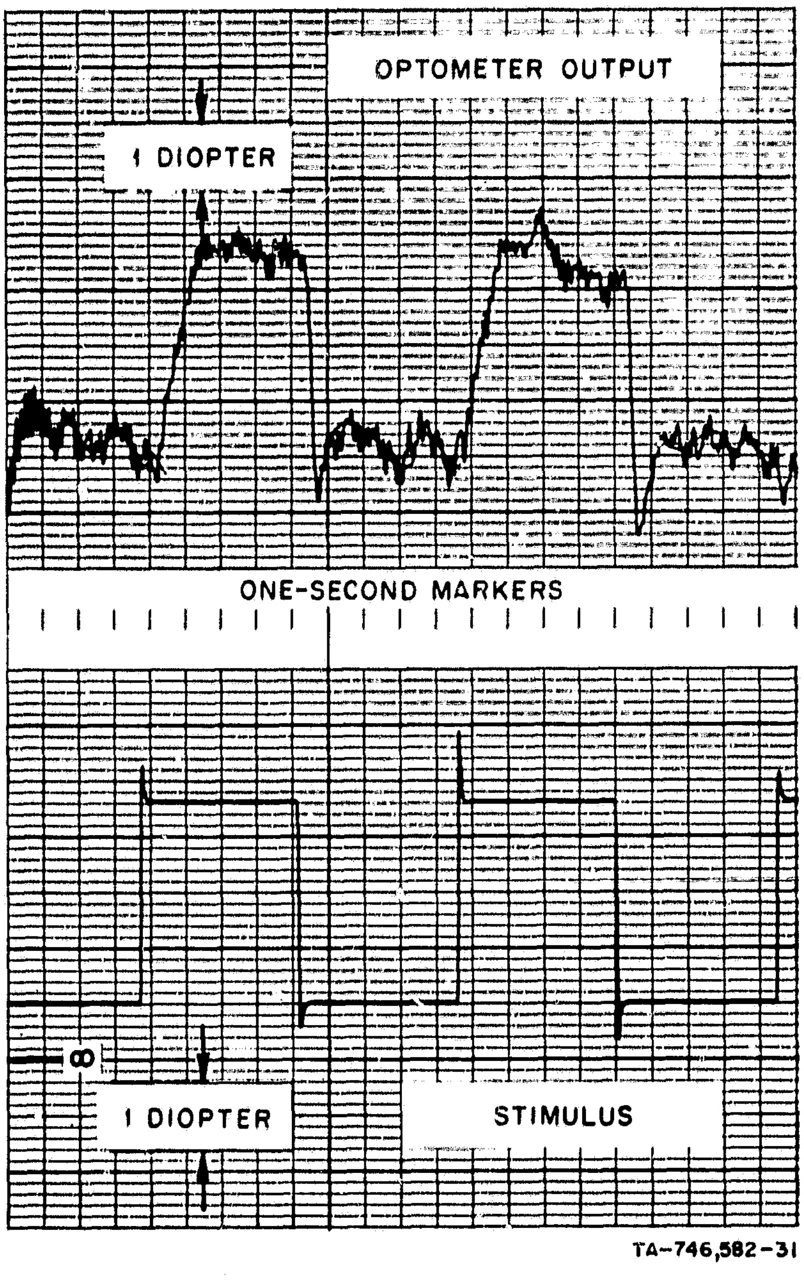

FIG. 1 A TYPICAL SET OF RESPONSES TO STEP DISPLACEMENTS OF THE TARGET

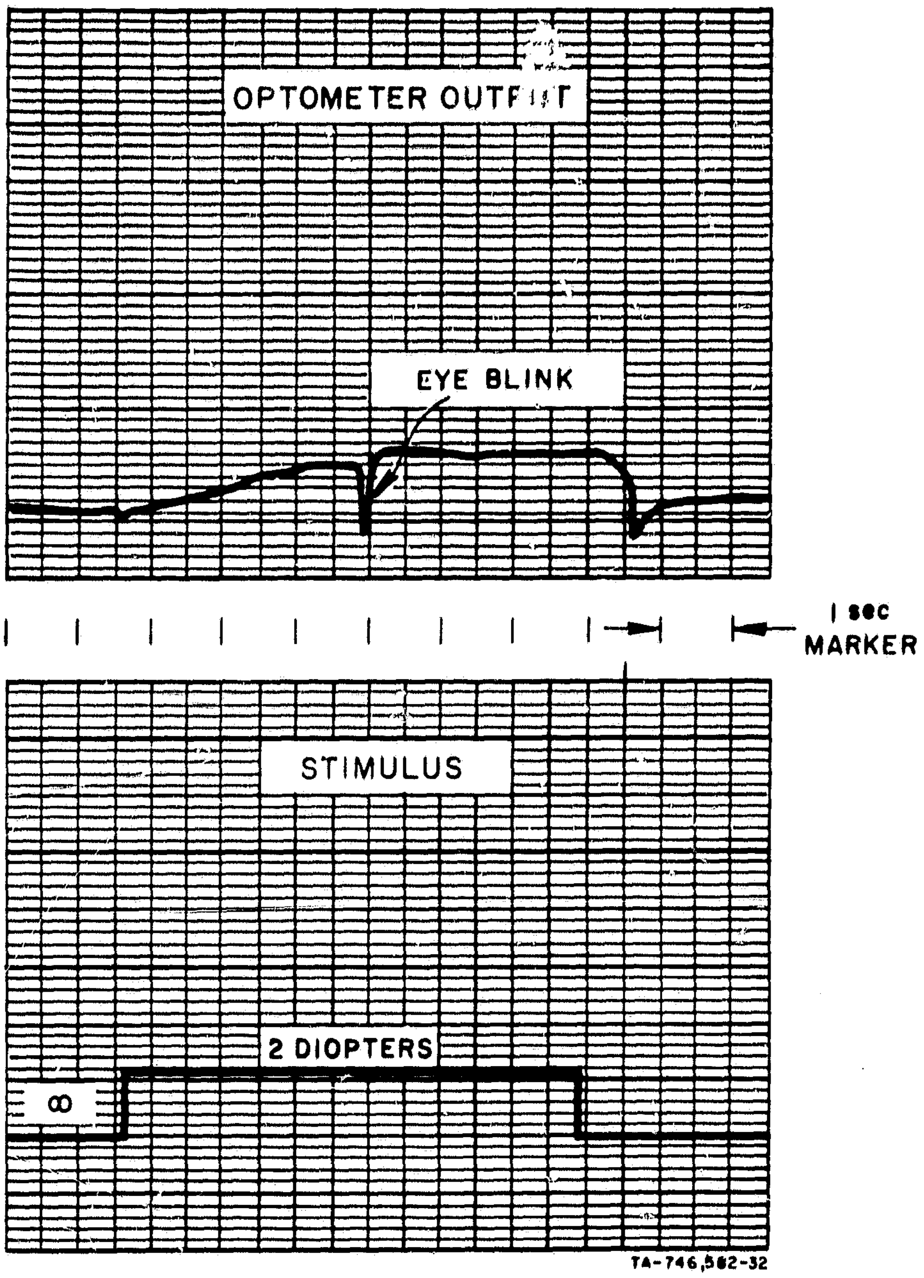

FIG. 2 A RESPONSE TO A STEP DISPLACEMENT BY A 31-YEAR-OLD COMMERCIAL AIRLINE PILOT

conditions and/or techniques that will permit us to perform a servo analysis.) The nonlinearity is especially evident for large sine wave inputs, such as in Fig. 3.

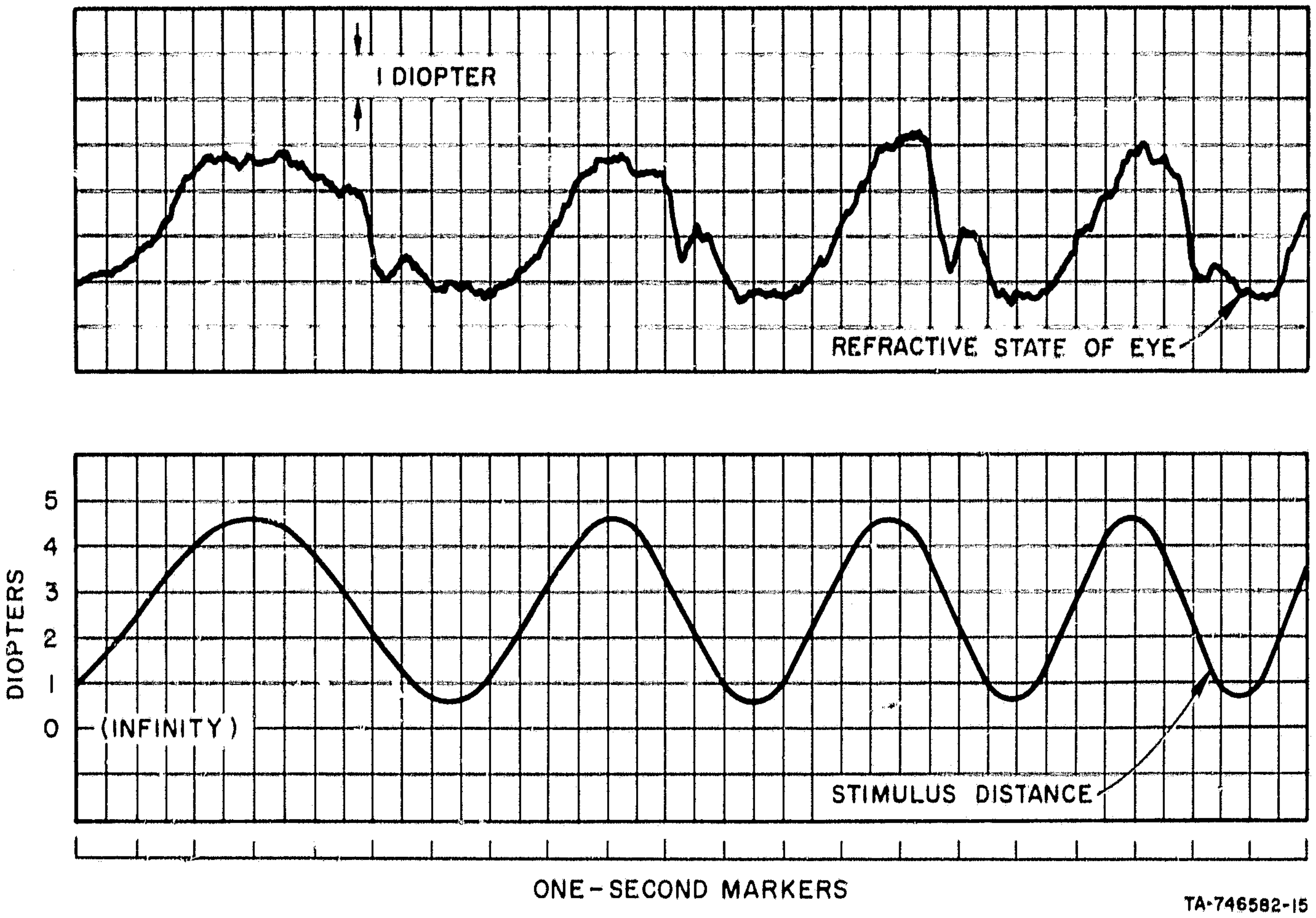

FIG. 3 RESPONSE TO A LARGE-AMPLITUDE SINUSOIDAL TARGET DISPLACEMENT

In spite of the nonlinearity of the responses, Bode plots may be used to make predictions under certain limited conditions. We have therefore measured the responses to sinusoidal stimuli of fixed small amplitude and variable frequency. A typical record is shown in Fig. 4. Note that as the input frequency increases, the response amplitude becomes smaller, and the phase lag increases (there is a fixed delay of about 0.4 second at all frequencies). In particular, the response is 180° out of phase with the stimulus at a frequency of about 1.0 Hz and the amplitude of the response at this frequency is about one-third of the amplitude at very low frequencies. These properties are seen in the Bode plot of Fig. 5.

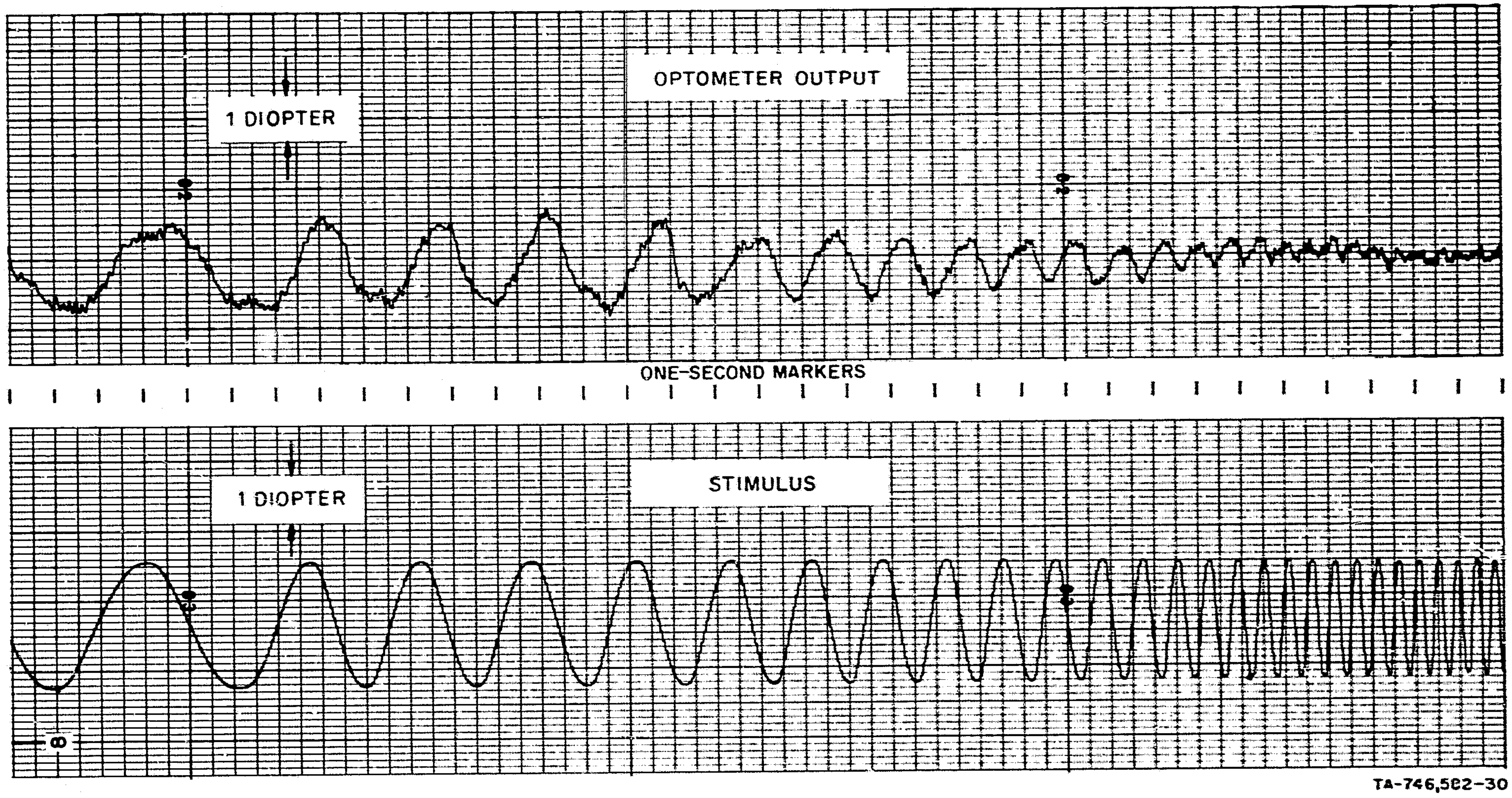

FIG. 4 RESPONSE TO A SMALL-AMPLITUDE SINUSOIDAL TARGET DISPLACEMENT

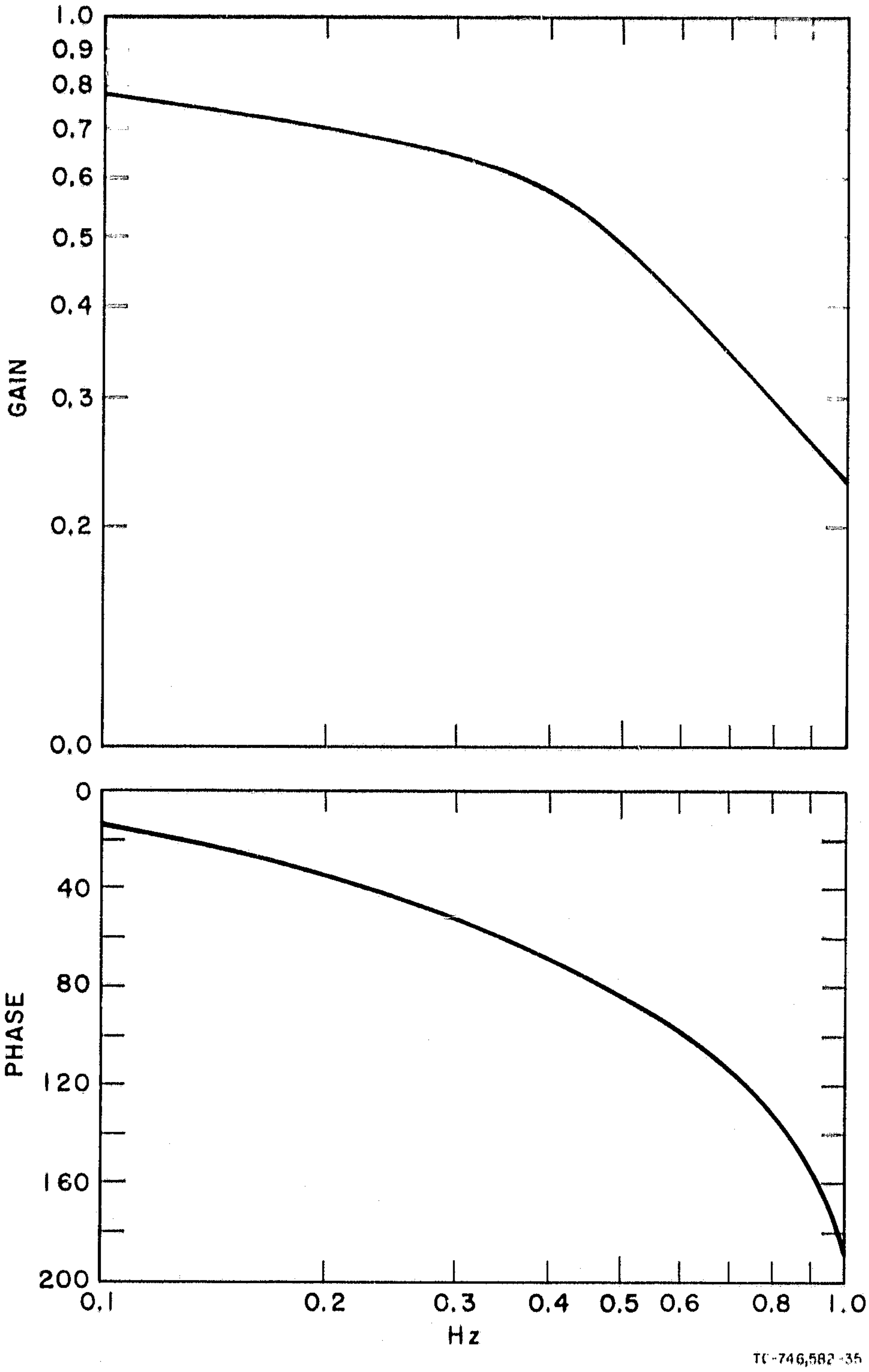

FIG. 5 BODE PLOT OF RESPONSES TO SMALL AMPLITUDE SINUSOIDAL STIMULI

Figure 6 is a representation of the responses to a set of stimulus pulses of varying duration. As the stimulus duration decreases, the response amplitude becomes smaller and smaller. We have also made measurements of the responses to fixed error under open-loop conditions.

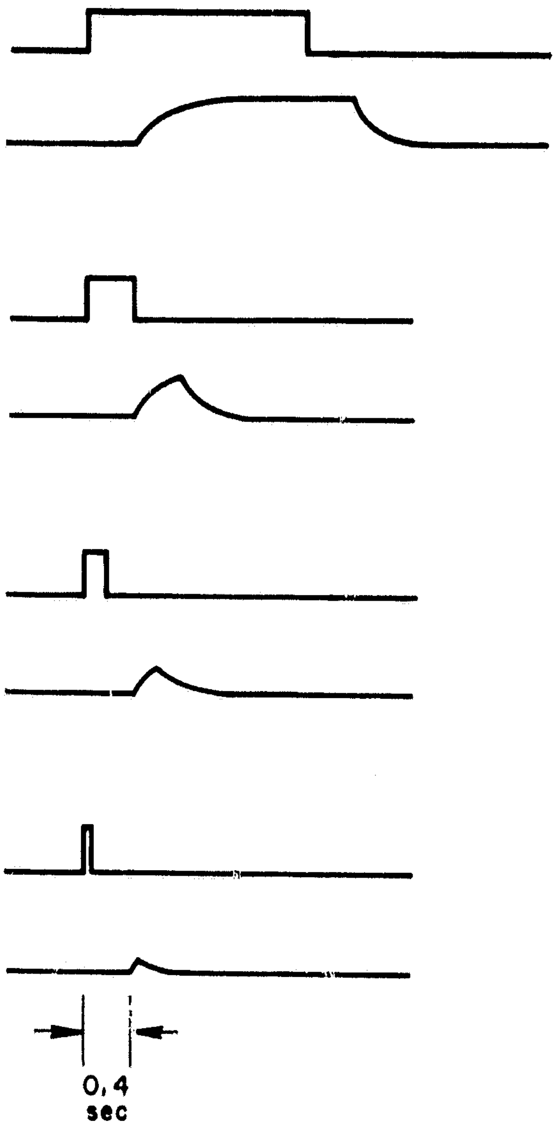

FIG. 6 DIAGRAMATIC REPRESENTATION OF RESPONSES TO SHORT PULSE TARGET DISPLACEMENTS

Here, the focus stimulator was driven by the output of the optometer in such a way that any change in refractive strength produced an exactly corresponding change in target distance, so that the state of focus of the retinal image was unaffected by changes in the refractive state of the eye. When a refractive error is then introduced, the response is a relatively constant velocity of accommodation, which continues until some limit is reached, the limit being either the limit of tracking of our instrument or the limit of the subject's accommodation system.

Both of these findings, and all of the normal responses that we have examined, suggest a continuous rather than a sampled-data control system. The data are consistent with the relatively simple rule that the velocity of refractive change depends upon the magnitude and direction of the refractive error that was present 0.4 second earlier. One of the most striking features of the responses that we have recorded is the fact that, while the latency to the beginning of the response is extremely constant across many different conditions and subjects, the response velocity varies dramatically from subject to subject. For example, we have measured the accommodation responses of commercial airline pilots under the age of 35 to two-diopter-displacements of a target. Their responses are shown in Fig. 7. While all of them completed their responses to targets moving toward infinity within 1.5 seconds, the time taken to bring a target into focus when it moved two diopters toward the subject varied from less than one second to more than six. If such differences are also manifested under more normal viewing conditions (e.g., binocular viewing), they are of obvious importance in the selection of pilots.

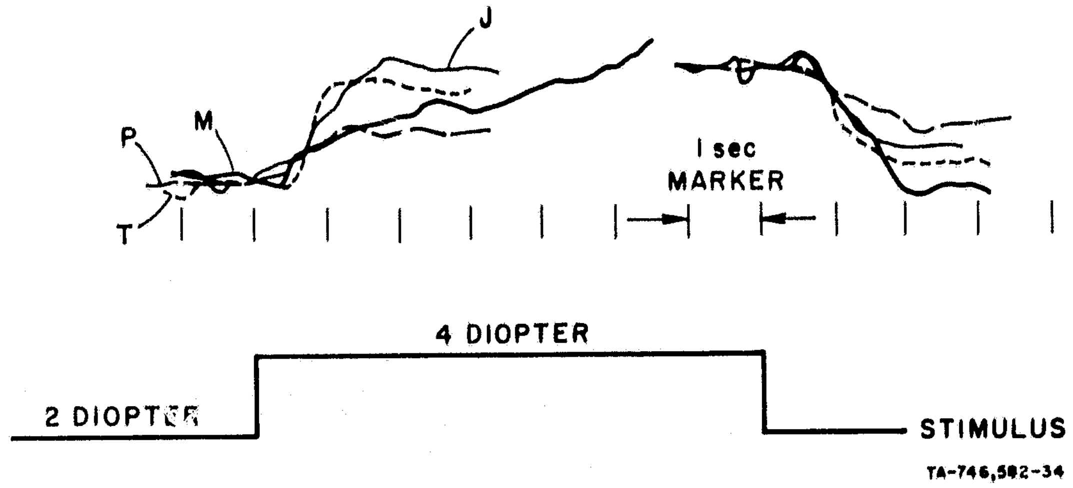

FIG. 7 THE RESPONSES OF FOUR YOUNG AIRLINE PILOTS TO A STEP DISPLACEMENT OF THE STIMULUS. The responses are superimposed for ease in comparison.

2. Measures of the Stimulus to Accommodation

A defocused pattern on the retina is a sufficient stimulus to accommodation. Binocular vision, change in target size, change in pupil diameter, and any other events (aside from blurring of the image) that may ordinarily accompany changes in target distance do not seem to be necessary cues for accommodation, at least for the subjects thus far tested. The subjects virtually always made correct accommodative responses to stimuli produced by our stimulator, which produces changes in retinal image blur only. In our observations thus far, we have never seen an unequivocal error--that is, a response that clearly begins in the wrong direction--when the stimulus was a displacement of the target. (We have recorded "errors" under special conditions, e.g., when the field was dark and the target was suddenly presented several diopters beyond infinity.)

The "blur" in the defocused image is a sufficient stimulus. With all subjects tested so far (approximately 20), there are no noticeable differences in the responses to targets illuminated by white light and by monochromatic light. Therefore, for these subjects, at least, the effects of chromatic aberration are not necessary for proper accommodation.

Responses of normal latency in the correct direction are reliably produced (by the one subject we tested in this way) even when the stimulus is a brief presentation of a new, monochromatic, target four diopters out of focus, that lasts only 0.1 second. Therefore, information about the direction of the focus error is either drawn directly from some aspect of the defocused image on the retina (note that to a first order, the light distribution on the retina should depend only upon the absolute magnitude of the defocus, and not on its direction), or drawn during a very short "testing" period, during which the refractive state undergoes small changes, and the resulting effect on the blur is measured to determine which direction is correct.

The second of these alternatives is very unlikely for two reasons. First, the amplitude of any "testing" would be so small (since there is only 0.1 second during which to test) that it seems unlikely that the direction of a four-diopter error could be evaluated. Second, the direction of responses is also correct in the open-loop experiments described above, and, to the extent that our apparatus is accurately tracking the refractive state of the eye, "testing" cannot be done under open-loop conditions.

We therefore conclude that the information about the direction of focus error is contained in some as yet unknown aspect of the defocused image on the retina.

3. Relation of Experiments to the Plan in Our Original Research Proposal

In our initial proposal[*] we suggested a possible set of experiments to be performed. The first experiment that we proposed (Experiment 1) was to measure the accommodative response under open-loop conditions. That experiment and a closely related one are described on pages 12 and 15 above. The results indicated that "the accommodation control system does not require axial movements, such as by lens virbration, or any sort of axial 'hunting.'"[†] Therefore, the experiment labeled 1A in the proposal was undertaken; measurements were made when the stimulus was illuminated with monochromatic light (page 14, above). Under those conditions the responses were essentially identical to those under broad-band illumination. We conclude that "there must be some as yet undiscovered property of the defocused retinal image which provides the error signal ...".[†] This finding led us to perform the experiment labeled 1D in the proposal.[§] We measured the magnitude of the response under open-loop conditions as a function

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[*] T. N. Cornsweet, H. D. Crane, and J. C. Bliss, "Experimental Study of Monocular Visual Accommodation," SRI ESU 65-82, Stanford Research Institute, Menlo Park, California (7 October 1965) pp. 5-10.

[†] Cornsweet, Crane, and Bliss, op. cit., p. 6.

[§] Cornsweet, Crane, and Bliss, op. cit., p. 7.

of the magnitude of the error signal (page 12). The results indicate that the "velocity of the accommodation response is linear with the magnitude of the error signal"* over a moderate range of error signal.

We have not yet been able to perform Experiments 2 or 3, because our eye-tracker is not operational.

4. Empty Field Myopia

When there is nothing in the visual field on which to focus, the eyes of the two subjects so tested focus at about one meter (one diopter). Since the optometer cannot operate unless the direction in which the eye is looking is restricted to within about 5 degrees, accommodation measurements cannot be made over extended periods of time unless a fixation point is present in the subject's visual field. Therefore the field cannot be completely empty. However, it is possible to provide a fixation point that gives no focus cues by causing it to be viewed through a very small artificial pupil, i.e. through a "pinhole." Thus, in our measurements, the fixation target was an illuminated point that was seen through a pupil 0.1 mm in diameter. The rest of the field was dark.

Under these conditions, the subject manifests what has been called "empty-field myopia." That is, he accommodates for a distance short of infinity. One result, related to empty-field myopia, was unexpected. Suppose a target is seen through the natural pupil at some distance other than the distance at which the eye focuses in an empty field. If the eye is correctly accommodated for that distance and the target is then turned off (so that the field goes dark except for a fixation point that is seen through the 0.1-mm artificial pupil), then the refractive state does not slowly drift to its empty-field state, but it moves there very rapidly. In other words, the response to this "stimulus" appears to be essentially the same as the response that would have occurred if the target had been abruptly shifted to the empty-field distance.

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*Cornsweet, Crane, and Bliss, op. cit., p. 7.

D. A Movie on the Effects of Visual Defocus

There are many situations in which it is important for a human observer to gain precise information from a visual display. A large number of studies have been performed to determine the effects of various conditions on visual acuity, and from them it has been possible to optimize such factors as the illumination on a display, its location in the field, etc. However, most of these studies have been made under conditions in which accommodation is not considered per se. Clearly, improper accommodation yields greatly reduced visual acuity, but the factors that optimize accommodation are largely unknown. At least part of the reason for this neglect of the accommodation mechanism stems from the fact that targets whose retinal images are actually blurred somewhat by poor accommodation usually do not appear to be blurred. A relatively small amount of defocusing of the retinal image can severely limit visual acuity, and yet some of the mechanisms in the eye are such that, while detail is lost optically, the lack of detail is not consciously noticed until the blurring is very severe. Therefore, even though from casual observation it seems that the retinal images are usually in fairly sharp focus, it may well be that they are not, and that acuity suffers without our noticing it.

To demonstrate the loss of visual detail that accompanies ordinary changes in accommodation, we have made a moving picture that displays the blurring of a scene as it is imaged on a subject's retina. The movie was made in the following way. A subject is shown a picture (of an aircraft runway) that is at optical infinity, and his refractive state is continuously monitored by the optometer. He holds a switch, and when he throws it, the scene at infinity is replaced by one at 0.5 meter (an instrument panel) and he refocuses on the new scene. When he returns the switch to its initial position, the scene at infinity is shown again, and, again, he refocuses. (These are the conditions under which the record in Fig. 2 was obtained.)

During this time, a moving picture camera records exactly the same view that the subject sees (through a partially reflecting mirror), and the focus of the camera is automatically driven by the output of the optometer. (Actually, the camera photographs the scene through our focus stimulator, and it is the stimulator that is driven by the optometer output). Thus, when the target is at infinity and the subject is focused at infinity, the film records a sharply focused image of the target. When the subject throws his switch, the film immediately records the new scene, two diopters out of focus, and then, as the subject's eye lens brings the new target into focus on his retina, the image of the new target is also brought into focus on the film. In this way, the blur or the subject's retina is correctly recorded in real time, and may be observed in its correct time relations when the movie is projected.

IV SUMMARY

In summary, our instrumentation has advanced to the point that the optometer and focus stimulator both work reliably, accurately, and with relative ease. The Purkinje eye tracker has been advanced to where it can now record two-dimensional eye movements with accuracies on the order of five minutes of arc, still short of the desired goal of one to two minutes of arc accuracy. However, we are presently considering a modified image-scanning technique, using the same basic optics, that offers the potential for reaching this goal.

Accommodation experiments conducted thus far, using the optometer and focus stimulator instruments, have demonstrated:

(1) A reaction time of approximately 0.4 second, stable across many subjects;

(2) Very large variability in velocity of response from subject to subject;

(3) Large difference in speed of response towards infinity vs. away from infinity, even for a given subject;

(4) Ability of all subjects thus far tested (approximately 20) to respond equally well to targets illuminated with white light or with very narrow-band monochromatic light over a wide spectral range;

(5) Ability of subjects to respond in the correct direction to "pulse" changes in target distance as short as 0.1 to 0.2 second.

Items (4) and (5) together seem to eliminate chromatic aberration and "hunting" as a means by which the eye determines polarity of error. (We have not seen unequivocal errors in polarity of response under any conditions thus far tested.)

To demonstrate the nature of the defocused images that actually fall on the retina, a movie was made in which the camera is controlled by the optometer in such a way that focus of the image on the film is at all times nominally identical with the image on the retina. The subject alternately sees two scenes that are at different optical distances. Although the subject himself is not particularly aware of the blur that occurs on his retina while he is focusing, this blur is striking when viewing the movie. The movie underscores the need for better understanding of eye focus control, especially in applications in which high acuity is important.