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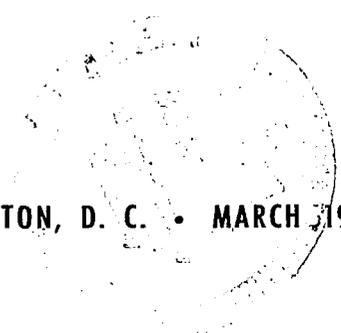
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**EXPERIMENTAL STUDY
OF VISUAL ACCOMMODATION**

by Tom N. Cornsweet and Hewitt D. Crane

Prepared by
STANFORD RESEARCH INSTITUTE
Menlo Park, Calif.
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ABSTRACT

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I BACKGROUND

This report summarizes the past year's study of the human accommodation system. The first year's study was principally theoretical in nature, and it resulted in the development of models for processing the retinal image to determine the state of eye focus. Subsequent work was primarily aimed at the development of specialized instrumentation to pursue this study. The three key items of instrumentation were an accurate eye tracker, an ocular focus stimulator, and an optometer. Details of the optometer and focus stimulator have been described in the literature. The current state of the eye tracker is discussed in this report.

During the previous year of this program we tested experimentally a number of hypotheses regarding human accommodation and arrived at a basic conception of the control system, which is described in Section III-A. Although this model may explain the puzzling ability of the accommodation system to know the polarity of focus error (apparently with no obvious cues available), experimental difficulties prevented us from being able to verify further the applicability of the model.

II INSTRUMENTATION

A. Optometer

The optometer that finally evolved in this program performs very well. During this year, the electronics were completely redesigned so that they are much more compact. Also, an improvement of about 2 to 1 in the signal-to-noise ratio was achieved, mainly by using larger light emitting diodes. The basic optometer design was described in an article in the Journal of the Optical Society of America entitled, "Servo-Controlled Infrared Optometer," April 1970. It has also been covered in a patent (No. 3,536,383) entitled, "Automatic Optometer for Measuring the Refractive Power of the Eye," and described in NASA Technical Brief 70-10401 entitled, "Automatic Optometer Operates with Infrared Test Pattern."

During this past year, we also experimented with the use of a laser beam for purposes of calibration. One of the major difficulties in calibration is what we refer to as the "IR shift." This is the difference in diopters between the visible wavelengths and the wavelength in the near IR at which the optometer works. This shift is composed of two parts: a chromatic aberration part, which accounts for about three-quarters of a diopter shift, and another component that we estimate at between one-half and three-quarters of a diopter. The latter component we suspect derives from the fact that the infrared light is reflected from a different layer of the retina than the light receptor layer itself. At this point, we have no idea how constant this shift is over the population.

The calibration scheme worked reasonably well. For this purpose, a slowly moving surface (either white paper or a painted white surface) was placed in the viewing path and illuminated by a low power neon-helium laser. The subject sees a moving scintillation pattern resulting from interference effects among the rays reflected from the surface of the drum. When the subject's visual receptor layer is exactly conjugate with the surface, the scintillations appear to move at the same speed as the surface, which is very low (e.g., an inch a minute). However, small focus errors produce large changes in the apparent velocity of the pattern. With the surface imaged in front of the receptor layer, the scintillation pattern moves in one direction, and with the image beyond the receptor layer, the scintillations move in the opposite direction. Thus, it is relatively easy for the subject to report when his receptors are conjugate with the paper surface. We can thus obtain an absolute calibration point, at least for the wavelength of the illuminating laser beam. In principle, chromatic aberration curves could be used to correct the calibration for targets illuminated with wavelengths other than that of the laser.

We would estimate that the calibration is good probably to a few tenths of a diopter. The major difficulty that we found is that the scintillation pattern sometimes had a general "swarming" appearance near null so that the region of null was not too sharply defined. At first, we used a surface that rotated about an axis parallel to but shifted from the visual axis. With this arrangement, the velocity of the surface was different at different radii from the center of rotation. We found that this variation in surface velocity over the area being viewed aggravated the general swarming effect. Considerable improvement was achieved by using a uniformly moving surface, which we obtained by driving a closed loop of paper over a pair of spaced rollers.

Any optometer that operates in the infrared (or in fact at any wavelength other than visible wavelengths) will suffer from this calibration problem. We believe that the laser scheme could be usefully adapted to this general problem.

A potential improvement in the range of applicability of this instrument could be made by incorporating circuits to correct, at least in a first-order way, any variations in signal gain during operation; e.g., variations resulting from changes in the subject's pupil size. Such circuits were actually built and verified in another device, referred to as a glaucometer or retinal topograph, being developed at Stanford Research Institute. This instrument is a direct offshoot of the basic optometer scheme. In brief, this instrument is used to trace the physical shape of the retinal surface, particularly in the region of the optic disk, which is most affected in cases of glaucoma. The device is basically an optometer whose beam is caused to sweep across the retina while the subject fixates on a steady target. Variations in physical depth are sensed as different refractive distances. To make this instrument as simple as possible, it was desirable to use a static, nonmoving readout system rather than a mechanical closed-loop servo system. However, it is necessary to be able to correct the effects of any variations in gain in the signal path, as noted above. With a closed-loop tracking system, changes in gain reflect themselves only as a change in the speed of response, whereas in an open-loop mode they reflect themselves as changes in the output reading itself. (This in fact is one of the difficulties with optometers that are run in an open-loop mode.) A first-order improvement in the situation can be obtained by using the sum signal from the two halves of the output split-field detector, in addition to the difference signal, which generally drives the servo. The sum signal is a measure of the total light getting through the system

and therefore is a measure of the total gain. By using this signal to control the electronic gain in the system (through a divider system), a significant improvement in open-loop characteristics is obtained.

The potential significance with respect to optometer instruments in general is the possibility of using a much less accurate servo system, in the following sense. It is always possible to add to the output signal of the mechanical servo some appropriately scaled value of the error signal that drives the servo. In principle, this would accurately reflect the refractive state of the eye even when the servo is not tracking precisely. The problem in this scheme, however, is that the error signal itself, unless corrected in the manner described above, varies in level according to variations in the overall gain in the system. Alternatively, in applications where a wide variation of refractive power is not expected (as in the glaucometer), the need for a closed-loop mechanical servo system may be eliminated altogether. In effect, in a combined system of this type, the role of the mechanical tracking servo may be viewed as that of keeping the system near the region of null. Any disparity from null is then corrected by purely electronic means.

The circuits developed for this purpose in the glaucometer seem to perform well and could readily be incorporated into any future optometer design.

B. Ocular Focus Stimulator

The primary function of the ocular focus stimulator is to vary the effective optical distance to a target over a wide range without affecting either the brightness or angular size of the target. The device also permits the target to be viewed through an artificial pupil if necessary. This device was described in a letter to the editor of the

Journal of the Optical Society of America entitled, "Ocular-Focus Stimulator," April 1970 and was also described in NASA Technical Brief 70-10568 entitled, "Visual Focus Stimulator Aids in Study of the Eye's Focusing Action."

C. Two-Dimensional Purkinje Eye Tracker

Earlier in this project, we developed a two-dimensional eye tracker that tracked the eye over a two-dimensional field of about 6 x 12 degrees, with a noise level of between 5 and 10 minutes of arc. This instrument was loaned by NASA to Prof. Leon Festinger of the New School for Social Research, New York, for conducting certain visual experiments that required the use of a two-dimensional eye tracker. The instrument has been used successfully for almost two years. Although it is an involved procedure to align a subject in the instrument, once such alignment is completed, the instrument performs well for extended periods.

During the past year, we developed a greatly improved version of the eye tracker, which, although it operated in only a single dimension, had much greater accuracy and sensitivity. It was also much easier to align a subject for use. In brief, the scanning disk of the original device was replaced by two split-field photodetectors, each mounted on a separate mechanical driving device and servo-controlled to track one of the two Purkinje images. This new device tracked the horizontal components of eye movements over a range of about 1.5 degrees, with a noise level of less than 1/2 minute of arc, peak to peak. The accuracy of this device was tested to be on the order of 1 minute of arc, which compares favorably with the accuracy of tracking achieved even with so-called tight-fitting contact lenses.

During the current year, we developed a two-dimensional version of this eye tracker that performs in basically the same way except that it operates over a two-dimensional field of between 5 to 10 degrees in diameter. The two-dimensional version of the eye tracker is described in detail in the Appendix. Inasmuch as we believe that these eye trackers represent a substantial improvement in the state of the art, we plan to submit the basic material of the Appendix for publication in the Journal of the Optical Society of America. These eye trackers are covered under the NASA patent application entitled, "Eye Trackers" (SRI file number P-228).

III ACCOMMODATION STUDY

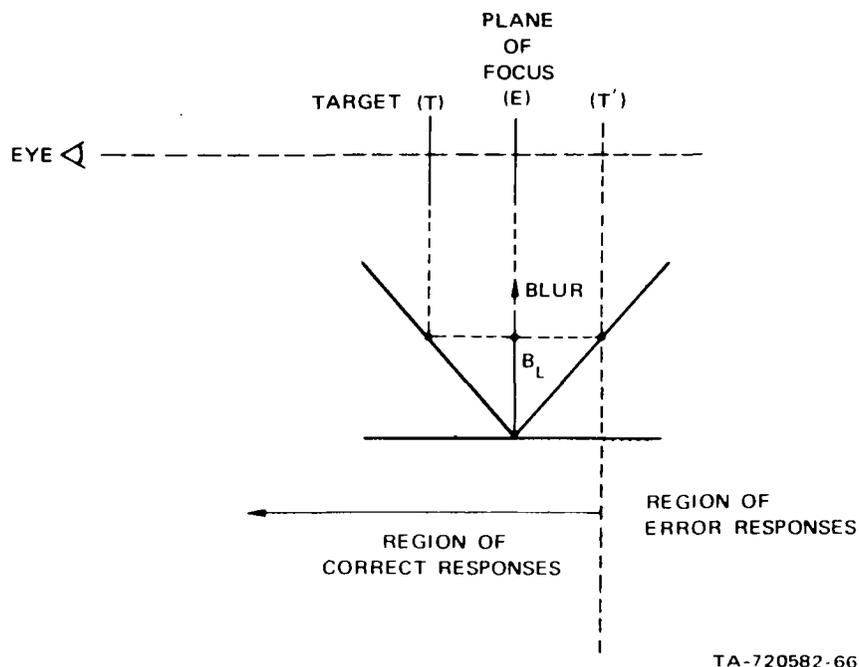
A. A Model of Accommodation Control

Our experiments have shown that subjects can accommodate properly without the benefit of chromatic aberration, spherical aberration, hunting, large field patterns, visual cues in the target itself (such as size changes or intensity changes), or even continuity in the image (in the sense that proper response is obtained even when switching abruptly from one target to a completely different target). We have recently proposed a novel model for accommodation control that we have called an "accommodation lag" model. This model permits the polarity of the response to a focus error to be correct even when the basic relationship between defocus and optical distance from the plane of best focus is an "even function." Accommodation lag, in effect, biases the system away from dead center, and thereby eliminates the need for an "odd function."

The basic hypothesis of the accommodation lag model can be described as follows. A central mechanism, possibly under conscious control, establishes some blur level that is acceptable to the system. (This level may depend on the nature of the visual task.) The control system then produces just enough contraction of the ciliary muscles to achieve that blur level, according to the following algorithm: "If the blur is greater than the criterion level, increase accommodation; if it is less (i.e., sharper), relax."

Following this algorithm, an emmetropic subject would always accommodate on a plane farther from him than the target (except when the target is at infinity), which agrees with the well-known accommodation

lag. For example, when the target is at plane T in Figure 1 and the eye is focused at plane E, beyond T, the retinal image would be blurred by some amount " B_L ." Under these conditions, the algorithm would produce

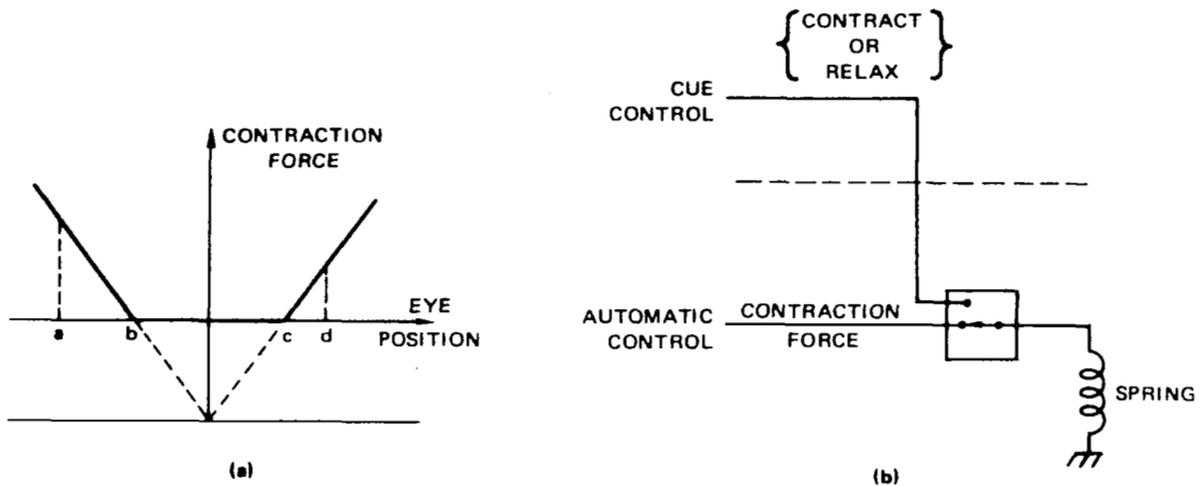


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FIGURE 1 ACCOMMODATION LAG MODEL

accommodative responses in the correct direction for any axial displacement that moves the target closer to the subject, and also correct responses if the target moves away from the subject, so long as it does not move "too far." Specifically, responses would always be correct unless the target abruptly moves farther away than about twice the accommodation lag (i.e., beyond plane T').

There are many forms that an accommodation lag model might take. For example, in Figure 2, we assume a form from which we would deduce that there might be two different forms of contract and relax "responses." Here it is assumed that, whenever blur is greater than criterion, a steady level of contraction force is applied to the ciliary muscle, the magnitude



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FIGURE 2 ALTERNATIVE ACCOMMODATION LAG MODEL

of the force depending only on the excess of blur over criterion, as suggested in Figure 2(a). In the range between positions "b" and "c," the contraction force would be zero and the restoring (i.e., spring) force of the lens would relax the eye toward infinity. Accommodation would thus tend to stabilize in the region "b," since as soon as the eye relaxed beyond that level a contraction force would be applied. Equilibrium would occur where the contraction force equaled the relaxation (i.e., spring) force. (This type of model would predict increasing lag with accommodation, if we assumed that the "resting" level of the lens was near infinity--i.e., near zero diopters.)

In this conception, there is an underlying machinery (which may be controlled by the autonomic nervous system) that simply applies a contraction force proportional to the level of blur over criterion. With only this much mechanism, the eye could always focus properly, if we assume just one other property--i.e., that with no visual pattern at all the eye relaxes to or near infinity. (Our subjects consistently relax

to about one diopter when the stimulus field is dark.) Thus, whenever the eye was closed (i.e., blinked), the eye would relax toward infinity. On opening of the eye, the contract mechanism would bring the accommodation to the proper level, without ever passing through the range where the response polarity is wrong. (Recall that the eye is in that range only when contracted to a plane closer than the plane of the object.)

In this arrangement, it is assumed that the "automatic" system is always operating except when cues are available, at which time the "cue system" can inhibit, override, or "switch out" the "lower level" system and apply specific contract or relax responses. [If accommodation does, in fact, concern both a lower level system and a higher level system, we would expect to find differential reaction to neural damage. Damage to the higher level system might eliminate only cue control, while the underlying tracking mechanism of the lower level system would remain intact. Furthermore, although the "cue control" system is shown connecting to the same "point" as the lower level system in Figure 2(b), it may well be that the higher level system concerns a separate muscle system. It is still not clear how many ciliary muscle systems participate in accommodation control.]

The arrangement that we used to test this hypothesis is as follows. The subject views a horizontal line at three diopters. Then, instantaneously and silently, the horizontal line is replaced by a vertical one that may or may not contain a short gap, the vertical line and gap appearing at various optical distances, either closer to the subject or farther away than the horizontal line. The gap is small enough that it cannot be detected unless accommodation is reasonably close to correct. The subject is asked to judge whether the gap is present, and accommodative responses are recorded with the optometer. It was hoped that the gap detection task would stabilize the focus criterion. The model

predicts that there will be a range of vertical line positions (at distances greater than three diopters) for which the response will begin in the wrong direction.

With the first subject that we used to test this hypothesis, the results seemed completely unequivocal. Movement of the target closer to the eye than some plane T always caused the eye to increase its power (correctly), even for targets as close as nine diopters. For target locations between T and some plane T', there was no response, a weak relaxation response, or an abrupt relaxation response. Beyond T', the eye also increased its power (incorrectly), as predicted.

Similar tests on subsequent subjects yielded more equivocal results. Thus, even though this novel hypothesis offers a possible explanation of fine-focus control and stability, its validity is not clear. It may well be that our knowledge of the eye movement and accommodation systems, together with the limited state of our instrumentation, is not yet adequate to make more definitive tests. With regard to instrumentation, we suspect that the noise level of the optometer and our limited ability to determine absolute calibration may have made it difficult actually to find the central zone, i.e., the region between planes T and T' in Figure 2. (With regard to the stability of accommodation, a central region only a few tenths of a diopter wide would be adequate to maintain stable focus--i.e., avoid the region beyond T'--even with a peak-to-peak variation in accommodation of a half diopter or even more.)

Added to these difficulties is the fact that almost every subject tested seemed to be variable in performance, some much worse than others. This results either from the nature of the physiological systems concerned or from variable aspects of our experimental facility of which we are not aware.

Subject variability might well be connected with at least two other observations. First, we have shown unequivocally that subjects can in fact be trained to respond to any cue. Second, there may be more subtle interconnection of the eye movement and accommodation systems than previously thought. These topics are discussed further in the following two sections.

B. Relation Between Eye Movements and Accommodation

It has been known for a long time that when a subject attempts to fixate a target steadily his eyes undergo constant motions, the most prominent of which are small, abrupt rotations called saccadic motions, or saccades. These saccades occur at an average rate of about two per second. During steady fixation, there is also a continual fluctuation in the accommodation state of the eyes, with a peak in its power spectrum at about 2 Hz. There are a number of plausible hypotheses that would predict a relationship between the occurrences of saccades and of accommodative fluctuations. Therefore, we performed some measurements to determine what if any relationship exists between them.

These preliminary data were collected in the laboratory of Dr. Robert Steinman at the University of Maryland. Dr. Steinman has developed a simple method for measuring very small eye movements, one that permits the measurement of accommodation on the same eye at the same time. His technique is as follows. The subject wears a tightly fitting contact lens through which a hole has been drilled. A small tube is fitted to the hole, and negative pressure is applied to the other end of the tube, holding the lens firmly on the eye. Also attached to the lens is a short stalk with a plane mirror on the end of it. The light from a low power neon-helium laser is reflected from the mirror and onto a special photo-detector that generates voltages corresponding to the horizontal and

vertical positions of the light spot falling on it. As the eye rotates, the laser spot moves across the photodetector and its outputs are recorded.

Because the laser and the photodetector are both far from the eye, and the incident and reflected light beams lie in a horizontal plane at about 45 degrees to the line of sight, it is relatively easy to place the infrared optometer in a position where it will record the accommodation of the eye, through the contact lens, without interfering with the eye movement recording.

This setup was used to record eye movements and accommodation simultaneously during 1-minute runs of fixation on a visual target. The essential question to be answered was whether there was some temporally fixed relationship between the occurrence of saccadic movements and fluctuations in accommodation. To test this possibility, the eye movement and accommodation records were digitized and directly cross correlated. The result for two 1-minute runs is shown in Figure 3. (The vertical and horizontal eye movements were independently cross correlated against the simultaneous optometer record.) These results are far too preliminary to permit drawing any conclusions, although it is interesting that a peak in correlation occurs with some 0.5-second delay between the records (accommodation lagging), since the typical latency of an accommodation response is on the order of 400 milliseconds.

It is inappropriate to speculate on such preliminary results, although it raises the question of whether there may not also be "accommodation saccades," for adjusting the accommodation system, just as there are saccades in the eye movement system for correcting errors in eye fixation. This notion was discussed in a completely theoretical manner in our original report,^{1*} where it was suggested that accommodation

*References are shown at the end of the report.

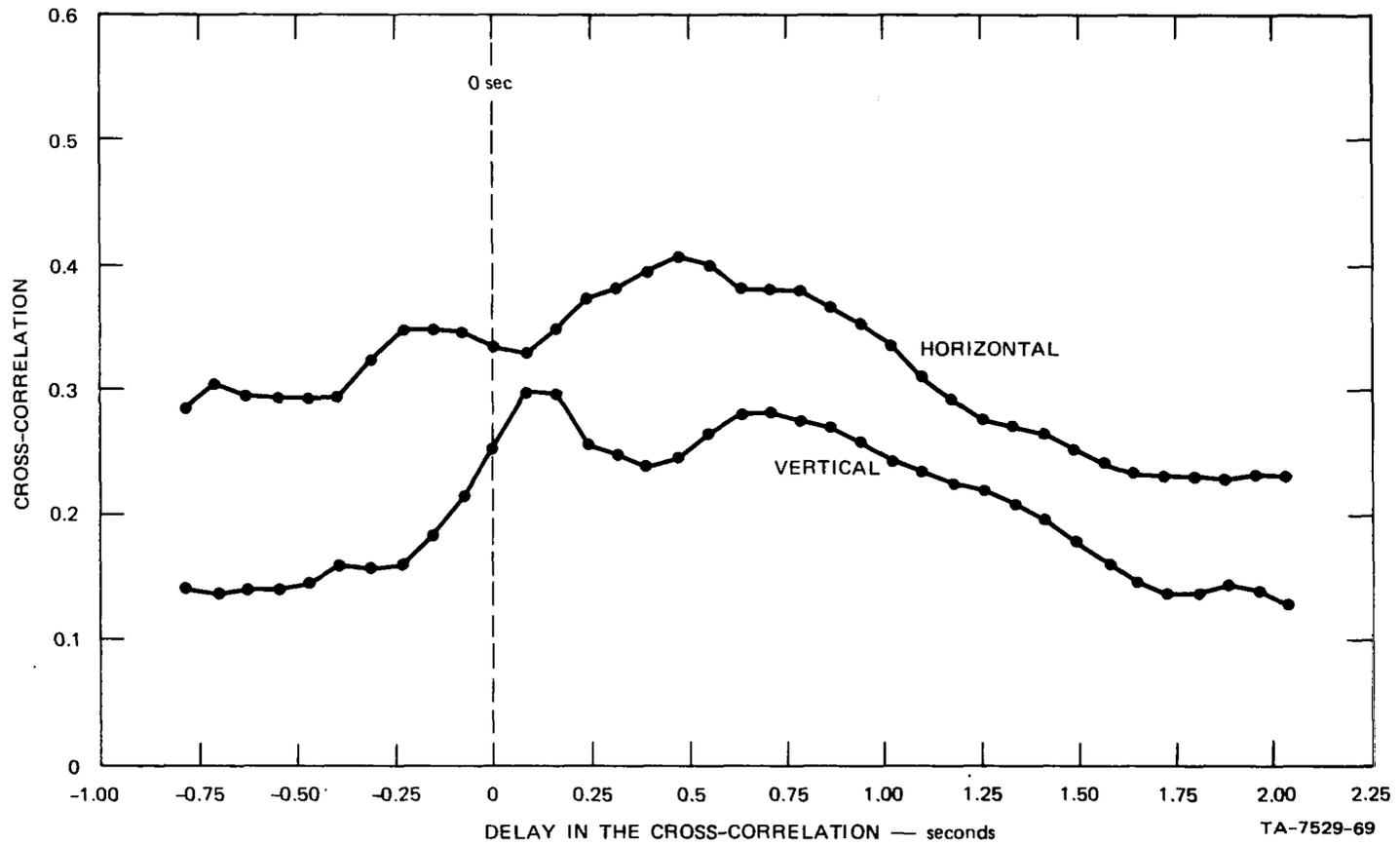


FIGURE 3 CROSS-CORRELATION OF EYE MOVEMENTS AND ACCOMMODATION FOR 1-MINUTE RUNS OF STEADY FIXATION

saccades might be triggered by eye movement saccades, which might account for the strong 2-Hz "vibration" sometimes seen in accommodation records.

It is our opinion that the interaction of the eye movement and accommodation systems is worthy of considerable further study.

C. Training the Visual Accommodation System

Although we concluded earlier that no single cue seemed necessary for accommodative response, we began to suspect that it may be possible that any cue might be sufficient. To test this possibility, we performed the experiment described below, which verifies and extends the results of Robert Randle of NASA Ames Research Laboratory.² We found that it takes only a few hours to train two subjects to respond voluntarily to accommodation stimuli in the form of audible tones; that is, to signals that had no direct relation to visual patterns. In fact, after training, the accommodation responses looked extremely similar, both in latency and form, to otherwise normal accommodation responses (Randle found similar results).

It is our intention to submit the material that follows to Vision Research in the form of a letter to the editor.

When a visible target is suddenly displaced toward or away from a subject, he will, after a latent period of about 0.4 second, respond by changing his accommodation in the appropriate direction. The fact that the direction of the response is correct is puzzling, because, at least to a first order, the blur pattern on the retina has the same characteristics whether the target is too close to the eye or too far from it.

In principle, the change in the size of the retinal image that usually accompanies change in distance could provide the cue for correct

accommodation. Further, in principle, second order effects resulting from chromatic and spherical aberration and curvature of field produce retinal light distributions that have a certain degree of asymmetry as the retina moves through the plane of optimal focus. Therefore, any of them might provide a cue necessary for a correct polarity of accommodative response to a change in target distance. In an extensive series of experiments not described here, we have shown that none of these possible cues is actually necessary for correct accommodation. Further, responses are correct when the target is visible only to one eye, and therefore ocular convergence is not necessary. Another possibility that has been proposed in the literature is that, during the latent period, the small fluctuations of accommodation that continually occur provide information to the system indicating which direction sharpens the image. We have also shown, however, that this "hunting" mechanism can be disabled without perturbing the correctness of the accommodative responses to step changes. In fact, in our own experiments we have demonstrated that responses are correct even when all of these possible cues are simultaneously eliminated.

The experiment described below demonstrates that any perceptible cue that reveals the direction of motion of the target is sufficient to permit the subject to make correct responses. No single cue or particular combination of cues is necessary.

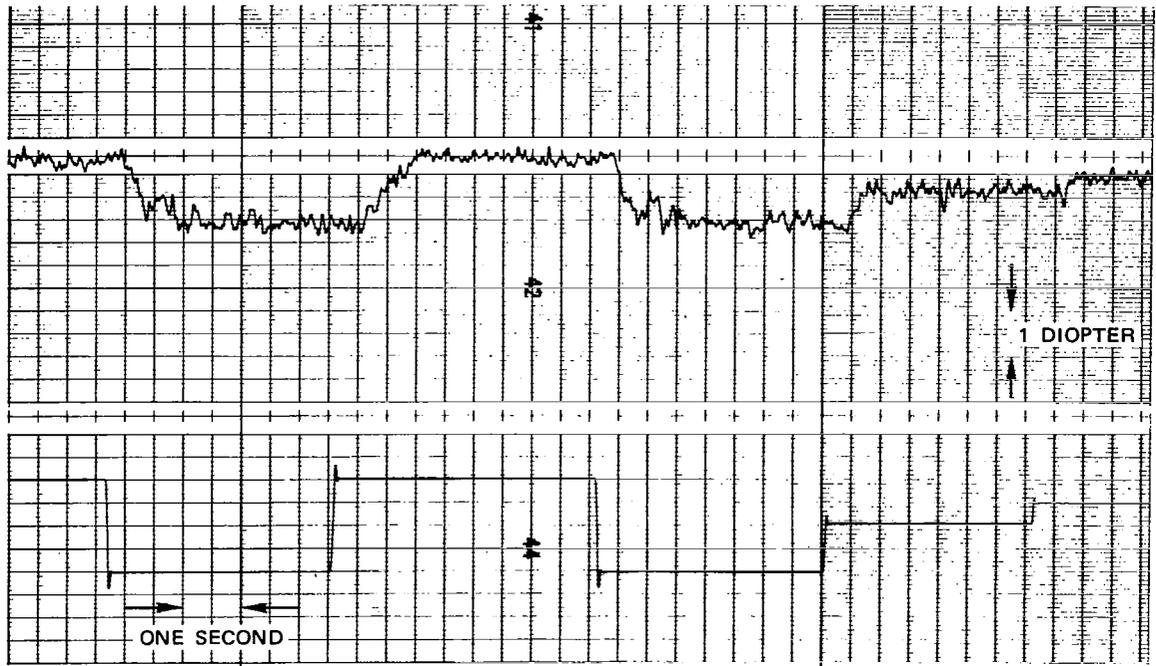
We have previously described an automatic infrared optometer that continuously measures the instantaneous state of accommodation of an undrugged eye, without producing any visual stimulation of its own.³ For the experiment referred to here, we aligned our subjects in this device while they were viewing a dim point source through an artificial pupil 0.1 mm in diameter. With such a target, the eye will remain pointed in a fixed direction so that the optometer will operate properly,

but, because of the large depth of focus provided by the artificial pupil, the retinal image of the target is essentially unchanged even by large changes in accommodation. The subjects were also provided with binaural head phones. A tone was delivered to one ear whose pitch could be controlled either by turning a knob or by delivering any predetermined sequence of voltage levels to a voltage-controlled oscillator. The pitch of the tone in the other ear was controlled by the output of the optometer and therefore depended on the subjects' state of accommodation. The subjects were asked to vary one of the pitches by turning the knob and to change their accommodation to maintain a match between the two pitches.

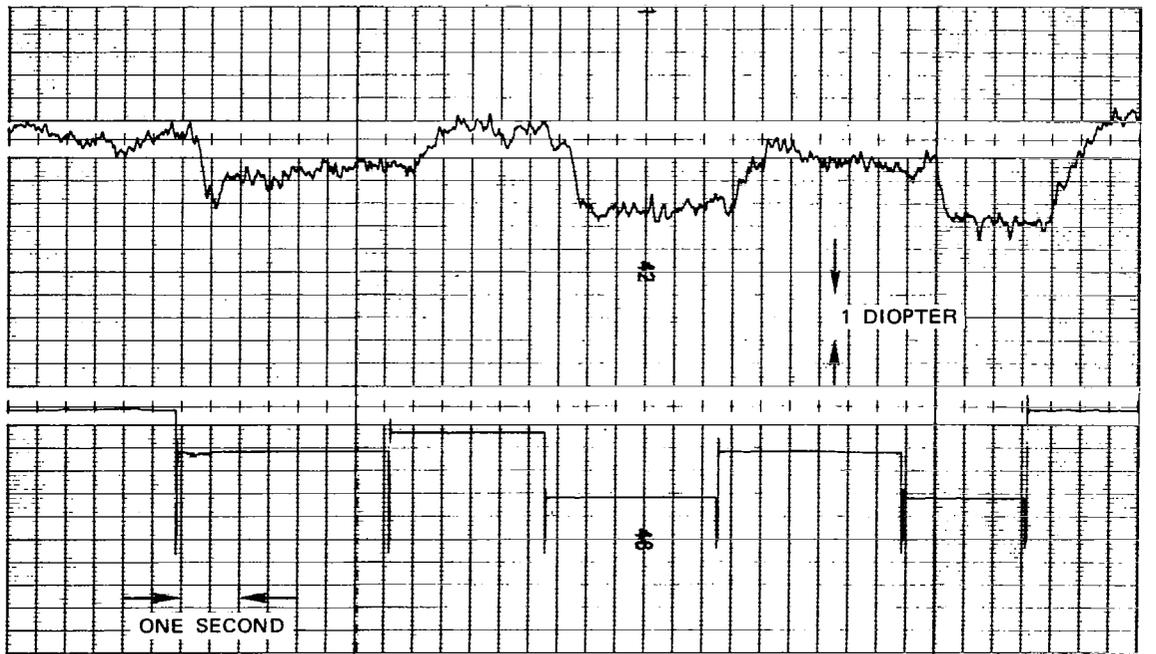
The two subjects were about 20 years old and were emmetropic. Only one of the subjects had previous experience in our accommodation experiments.

When they were first asked to perform this task, both subjects asserted that they simply could not do it; they did not have any idea of how to go about changing their accommodation appropriately. Nevertheless, they practiced, ad lib, and were tested periodically. After a total of three hours of ad lib practice, each of them was fully able to perform the task. As a test, we delivered a series of tones whose pitches were randomly selected, and their accommodative responses, as shown in Figure 4, were indistinguishable in latency and accuracy from those responses that were elicited by random shifts in the distance of a real target seen through the natural pupil.

We then changed the stimulus conditions. The subjects viewed two horizontal lines on the face of an oscilloscope, again through a 0.1-mm artificial pupil. We controlled the vertical position of one of the lines, and the vertical position of the other was controlled by the subjects' accommodative state. The subjects' task was to keep the lines



(a) VISUAL



(b) TONE

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FIGURE 4 ACCOMMODATION RESPONSES:

coincident; that is, when we changed the height of one line, they were to change their accommodation so that the other line fell on top of it. Both subjects could perform this task after just a few seconds of practice. That is, the transfer from the first to the second task is great. It is as if, once the subjects learned to control their accommodation, they could do so regardless of the nature of the command signal.

After the subjects were trained, they were asked how they did it, and neither was able to verbalize what he was doing. They were then specifically asked whether they were imagining that an object was moving toward them or away, and they both said "no."

We conclude that any perceptible cue to the direction of a step displacement of a visual target is sufficient for a subject to make an accommodative response, once he has had training in which he is given immediate feedback about the state of his accommodation.

Because our subjects required three hours of practice for the first task and virtually none for the second, it is evident that even our experienced subject did not possess this skill when he first began as a subject, nor did he acquire it during our earlier experiments, in which we recorded his responses to visual stimuli at changing distances. However, that does not rule out the possibility that our subjects normally use a variety of cues related to the visual image when focusing on visual targets, even without the kind of training described above.

In the training procedures described here, changes in the subjects' accommodation level have virtually no effect on the blur of the retinal image, and the feedback about accommodation is in that sense entirely artificial. On the other hand, during normal visual experience, if some cue such as a change in retinal image size were to elicit an accommodative response, feedback would be provided through changes in the blur of the

image itself, which may be a form of feedback that the visual system is well tailored to accept. In other words, it is possible that subjects may require only a short time to learn to use any given cue for accommodation when the feedback is natural (that is, a change in actual blur) but require considerable practice to learn the different skill of controlling accommodation when the feedback that they must use is artificial, and when, as in our experiments, the feedback provided by blur is erroneous because the blur does not actually change when accommodation does.

These results emphasize the extreme care that is necessary when conducting experiments on the accommodation system where the aim is to try to discover its basic control processes.

Appendix

AN ACCURATE NONCONTACTING TWO-DIMENSIONAL EYE TRACKER

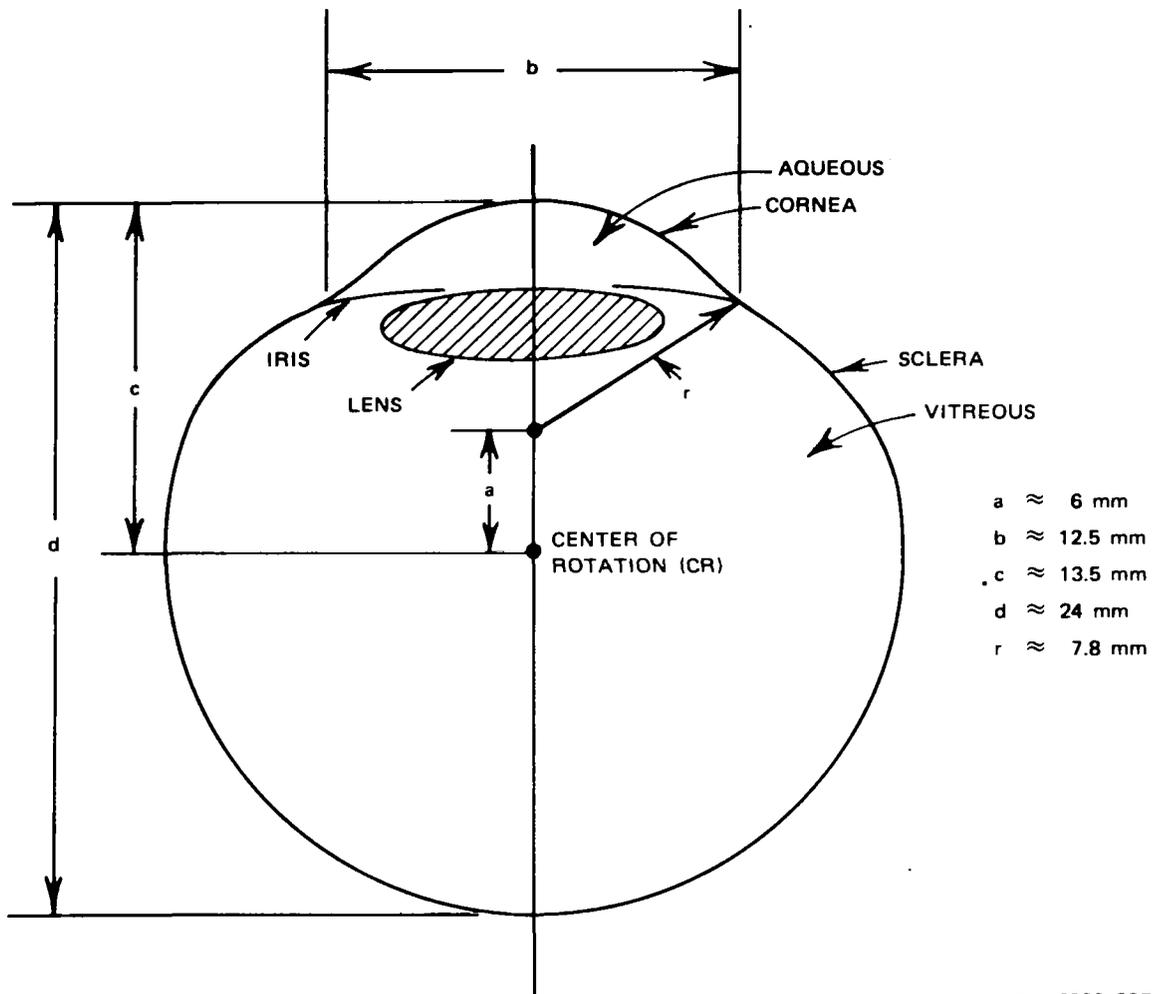
1. Introduction

In this Appendix, we describe a method of eye tracking based on the use of a pair of reflections from the eye. This method requires no attachments to the eye and can provide an accuracy and sensitivity on the order of 1-2 minutes of arc in absolute position over a two-dimensional visual field of between 5 and 10 degrees in diameter.

2. Basic Scheme

a. Translation Artifact

A basic requirement in developing an accurate eye tracker is to be able to differentiate between translational and rotational movements of the eye. Figure 5 is a schematic diagram of an eye with nominal dimensions. Suppose that we attempt to monitor the magnitude of eye rotation by monitoring the position of a spot fixed on the front surface of the eye, say a mark on the cornea. We see from Figure 5 that the distance from the front surface of the eye to the center of rotation is about 14 mm, so that 0.5 degree of eye rotation would cause this spot to move approximately 0.1 mm in reference to the surrounding space. That is a very small movement and in essence is the source of the problem. By monitoring only the position of such a spot, we could not distinguish 0.5 degree of eye rotation from 0.1 mm of eye translation, because both would cause exactly the same shift in the spot position. However, these corresponding rotational and translational movements



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FIGURE 5 NOMINAL EYE DIMENSIONS

have very different effects on the retinal image. For an object at infinity, for example, the position of the retinal image is completely unaffected by translational movements, whereas the shift in retinal position is directly proportional to the magnitude of rotation. If the visual target were one meter from the eye, 0.1 mm of translation would shift the point of fixation 0.1 mm, but a 0.1 mm shift resulting from rotation of the eye would shift the fixation point about 9 mm.

Although we do not know just how much the eye actually "wobbles" or translates in its socket, the combined translation of eye and head, even with the head position carefully fixed, has been reported to be as much as a few tenths of a millimeter. In this event, one could not measure angular position of the eye more accurately than about 1 to 2 degrees of arc by tracking a point on the front of the eyeball. Eye tracker schemes based on the use of tracking a single "mark," say a corneal reflection of a point of light, thus suffer from such translational artifacts. The artifact appears as a wandering base line. The basic approach taken in the instrument described below is to monitor two spots that move together under translation but differentially under rotation. The two "marks" in this case are two particular reflections from the eye.

b. Purkinje Images

As light passes through the eye, reflections occur at every interface at which there is a change in dielectric constant. There are four surfaces where such reflections occur. The images formed by these reflections are well known and are generally referred to as Purkinje images.

The virtual image of the source that is formed by light reflected from the front of the cornea is referred to as the first Purkinje image, or simply the "corneal reflection." A second Purkinje image, formed by light reflected from the rear surface of the cornea, is almost exactly coincident with the first Purkinje image, although more than 100 times dimmer because of the much smaller dielectric change from cornea to aqueous. Light that passes through the cornea passes in turn through the aqueous humor and then the lens of the eye. The third Purkinje image, also a virtual image, is formed by light reflected from the front

surface of the lens. This image is larger and more diffuse than the others and, as we will see later, is formed in a plane relatively far from the plane of the other images. The fourth Purkinje image is formed by light reflected from the rear surface of the lens, where the lens forms an interface with the vitreous humor that fills the bulk of the eyeball. This rear surface of the lens acts as a concave mirror, forming a real image of the source.

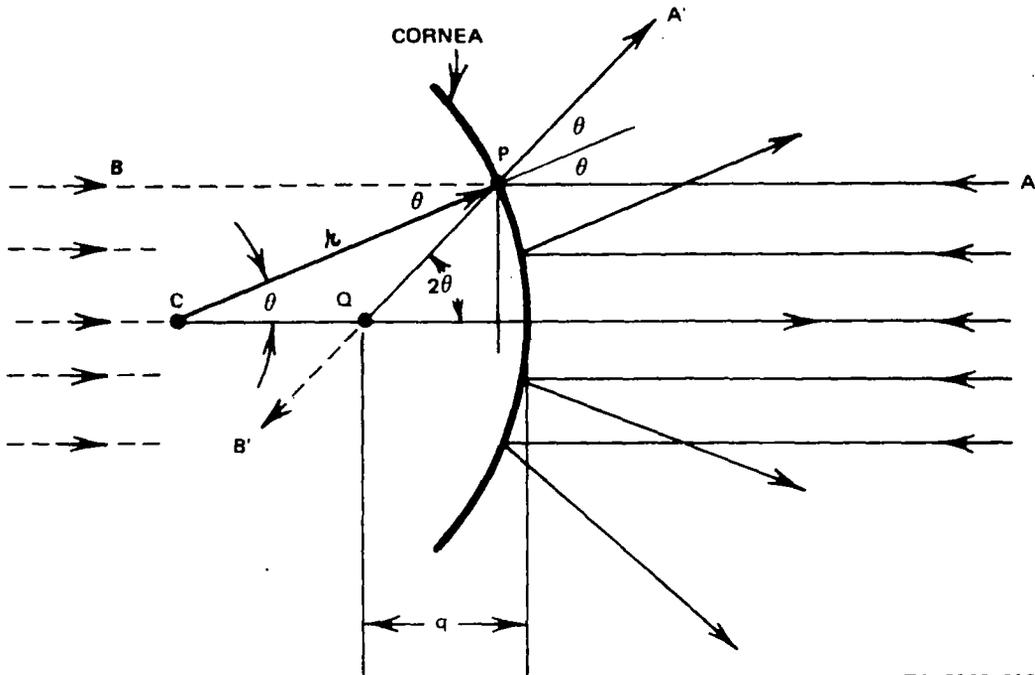
In this instrument, we use the first and fourth Purkinje reflections as the two "marks" to track. These marks move together under eye translation but differentially under eye rotation. Let us consider now some of the basic features of these two images. (Later, we will consider the nature of the third reflection as well, because it is important to be sure that light from this image does not interfere with detection of the first and fourth reflections.)

The basic imaging property of positive and negative mirrors is shown in Figure 6 for the case of a distant source, i.e., collimated input light. Consider first the image formed by a positive (i.e., convex) mirror. (Ignore the incoming rays from the left for the moment.) Input ray A makes an angle θ with the radius drawn to the intercept point P. The reflected ray, A', similarly makes an angle θ with the radius. If this reflected ray is extended backwards, it intersects at an angle 2θ the ray parallel to A and drawn through the center of curvature, C. The intersection point will be at a distance q from the front of the mirror, where

$$q = r(1 - \cos \theta) + (r \sin \theta / \tan 2\theta)$$

or

$$q = r \left[1 - \frac{1}{2(\cos \theta)} \right] \quad (1)$$



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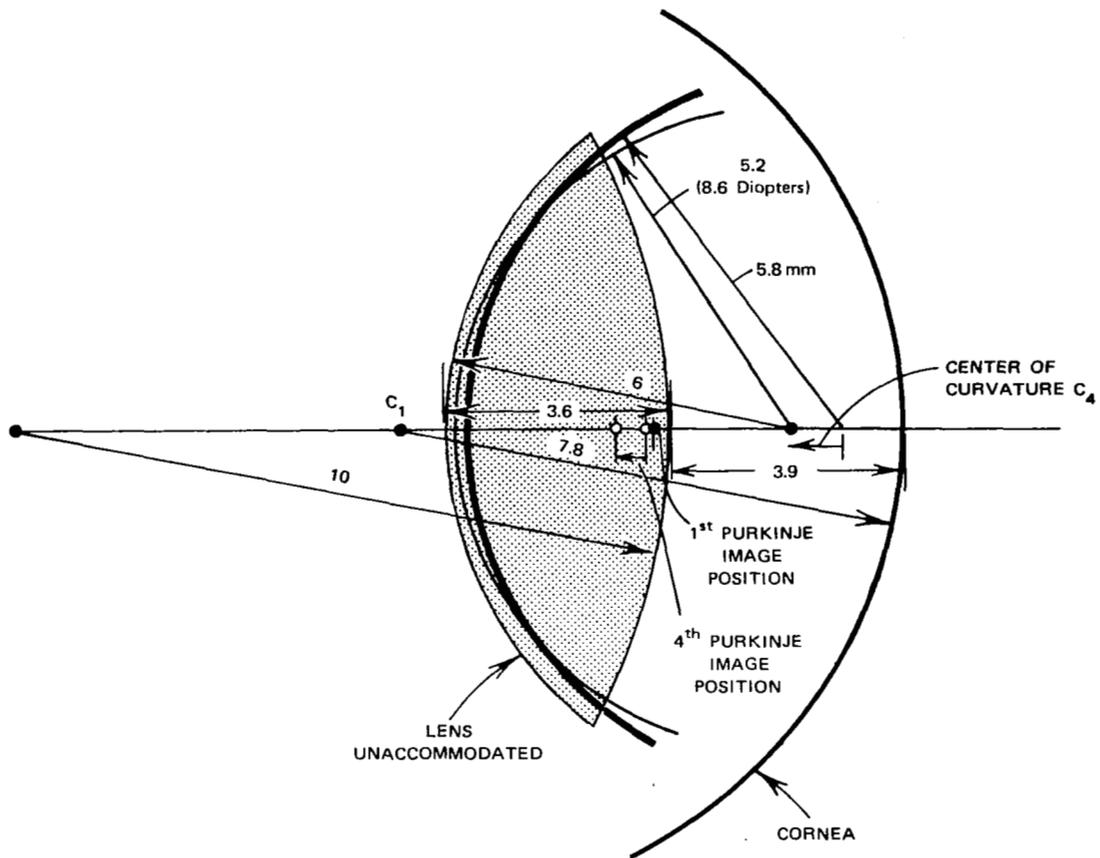
FIGURE 6 REFLECTION OF A DISTANT SOURCE IN A POSITIVE AND NEGATIVE MIRROR

For small θ , we have $q \approx r/2$, which is the well-known focal length for a mirror, and this represents the image plane for a distant object. This " $r/2$ plane" is the paraxial focal length, that is, for rays near the axis. For off-axis rays (i.e., for large θ), q decreases rapidly with θ (e.g., $q = 0$ for $\theta = 60^\circ$), which accounts for the "spherical aberration" of a spherical mirror surface (i.e., a spherical surface is not the proper shape for perfect imaging of a collimated bundle of rays). However, the details of the aberration are beyond the scope of the present discussion, and in any case are not critical to the operation of the device.

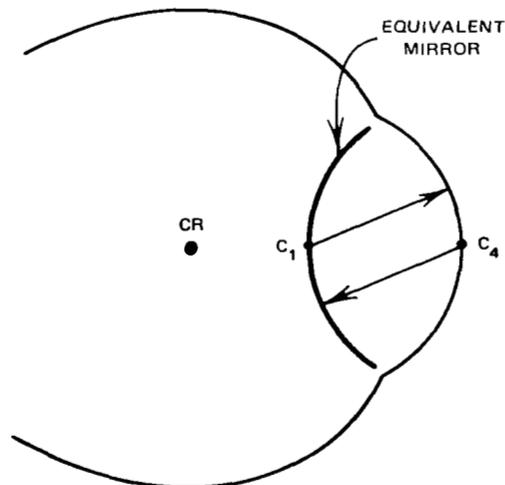
Ray tracing with a negative (concave) mirror is similar to that with a positive mirror. The same mirror of Figure 6 serves as a negative

lens for the dashed rays impinging from the left. For example, ray B, which is along the same line as ray A, is reflected as ray B', which is along the same line as ray A'. Thus we see that the same relations hold for a negative mirror as for a positive one.

Let us consider next the positions of the first and fourth Purkinje images in the eye. The first Purkinje image is formed by light reflected from the front surface of the cornea. For a distant source, the (virtual) corneal image would be in the plane indicated by the solid dot in Figure 7(a), i.e., at a distance $r/2 = 3.9$ mm from the front surface of the cornea. The fourth Purkinje image is formed by light that passes back out through the cornea after reflection from the rear surface of the eye lens. An equivalent single mirror that would form the identical real image is shown by the heavy line in Figure 7(a). The radius of this mirror, for relaxed accommodation, is about 5.8 mm (compared with the corneal radius of about 7.8 mm) and its center is close to the corneal surface.⁴ The position of the (real) fourth Purkinje image is shown by the open dot in Figure 7, and we see that in the unaccommodated condition the planes of the first and fourth images are almost identical. For 8.6 diopters of accommodation, which is a large magnitude, the equivalent mirror changes, as shown, to about 5.2 mm radius with its center shifted slightly farther from the corneal surface, although the image plane remains almost constant. We will comment later on this change in image size and position with accommodation. Another effect that we will consider later is the effect of pupil size on the fourth Purkinje image. Note that light contained in the corneal reflection never actually enters the eye. However, light from the fourth image passes through the pupil twice. Thus, changes in pupil size can have a significant effect on the fourth image.



(a) POSITION OF EQUIVALENT FOURTH PURKINJE MIRROR FOR UNACCOMMODATED EYE AND EYE ACCOMMODATED BY 8.6 DIOPTERS



(b) ASSUMING, FOR SIMPLICITY, THAT THE FIRST PURKINJE MIRROR (Cornea) AND EQUIVALENT FOURTH PURKINJE MIRROR FORM A SYMMETRICAL "CLAM-SHELL"

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FIGURE 7 OPTICS OF PURKINJE IMAGE FORMATION

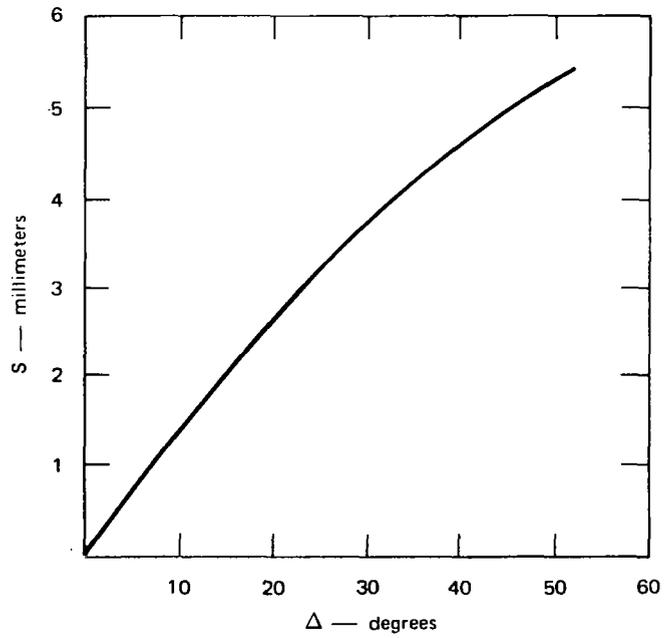
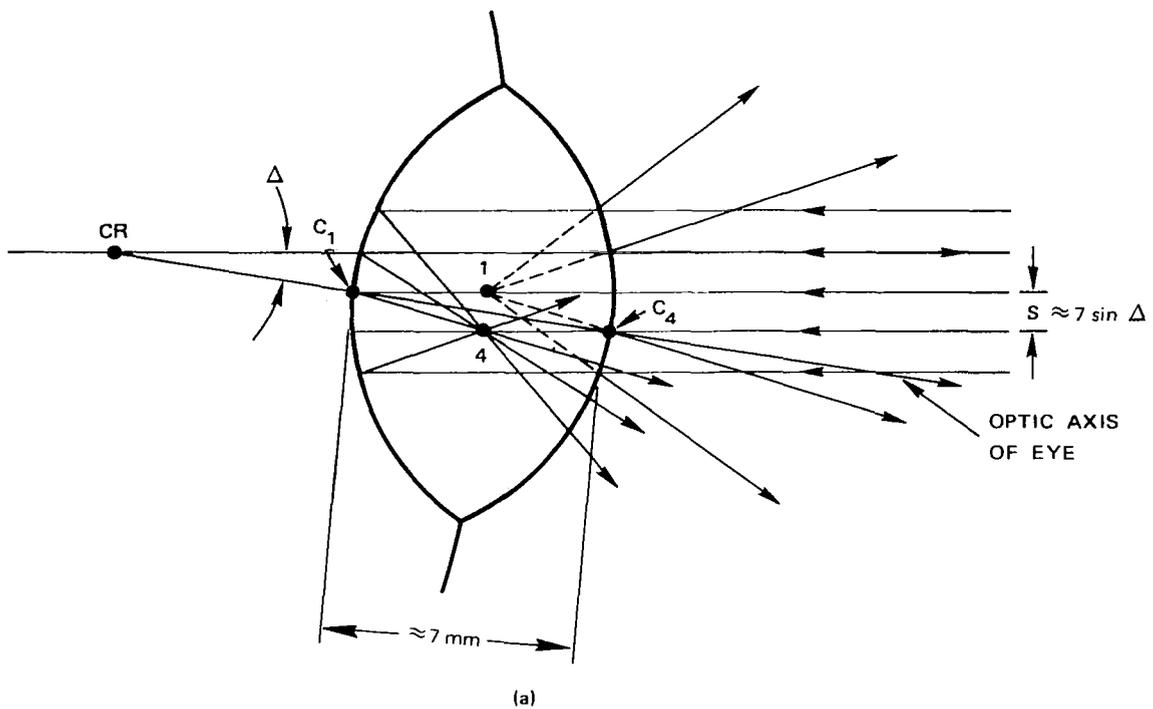
For purposes of explanation, it is often convenient to assume that the equivalent mirror for the fourth Purkinje image has the same curvature as the cornea and that they are separated by exactly their radius of curvature. This configuration resembles the clam-shell arrangement shown in Figure 7(b), C_1 being the center of curvature for the cornea (first Purkinje image) and C_4 the center of curvature for the fourth Purkinje image.

From Figure 8(a), we see that the distance that each image moves as a consequence of eye rotation is directly proportional to the distance from the center of rotation to the center of curvature of the surface that forms it. These distances are approximately 6 mm and 13 mm for the first and fourth images, respectively. Thus, when the eye rotates through an angle Δ with respect to the input axis, the two images, as viewed from the input axis, will separate by a distance

$$S \approx 7 \sin \Delta \quad (2)$$

as plotted in Figure 8(b). These are the magnitudes of movement with respect to absolute space. However, with respect to eye space (i.e., as viewed from the visual axis) the images actually move in opposite directions. This is because one image is in front of, and the other image is behind, its corresponding center of curvature.

In summary, the fourth Purkinje image is roughly the same size and is formed in almost exactly the same plane as the first Purkinje image, although it is less than 100 times as bright. If the eye undergoes translation--e.g., a lateral head movement--both images move through the same distance and direction as the eye. If the eye rotates, however, the two images change their separation in space. The change in separation between these two images yields a measure of the angular rotation



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FIGURE 8 IMAGE SEPARATION WITH EYE ROTATION

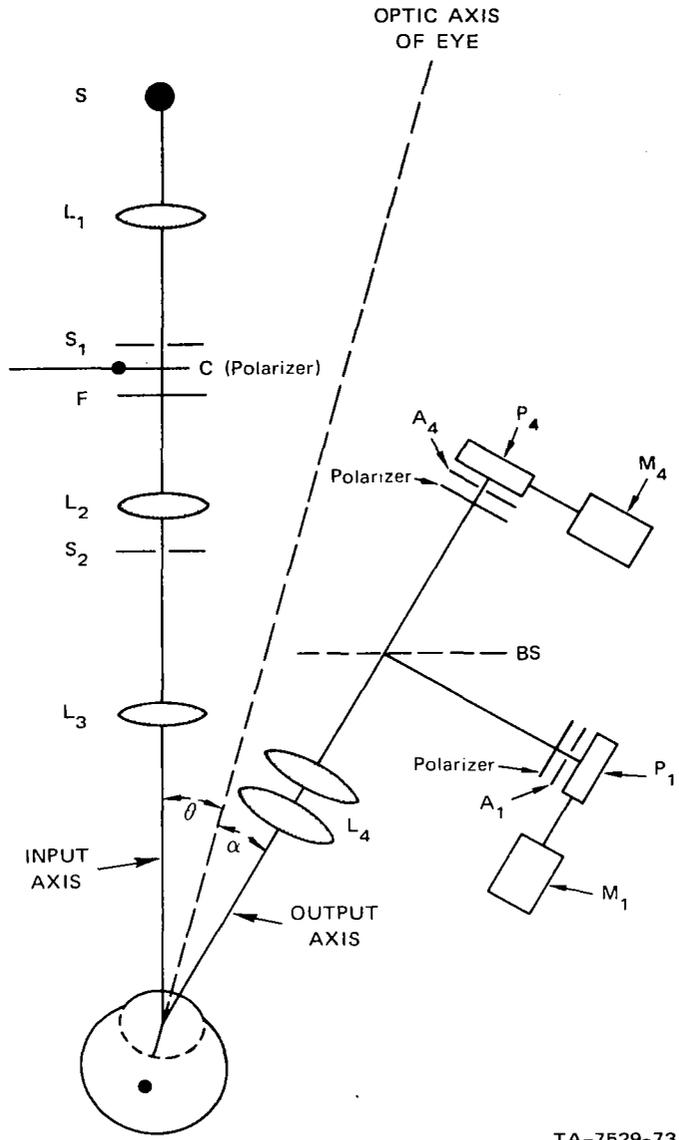
of the eye, and the measure is uncontaminated by lateral movements. The basic function of the eye tracker is continually to monitor the separation of these two images in space.

c. Schematic Diagram of the System

We discuss here some of the gross details of the instrument and show some experimental records and then discuss in more detail certain of the more critical elements of the design. We consider first a one-dimensional version, on which the later accuracy discussion is based, and the conversion to a two-dimensional form.

The basic optical system is shown in Figure 9. Stop S_2 , which contains a 1-cm square hole, is located in the focal plane of lens L_3 and therefore appears to the eye at optical infinity. The optical axis of the eye is rotated horizontally to form an angle θ ($\approx 15^\circ$) with the input axis, which, according to Figure 8(b) results in a separation of about 2 mm in the first and fourth Purkinje images of stop S_2 . These images are reduced by the ratio of the focal lengths of lens L_3 and the respective Purkinje mirror. Thus, the images are about 0.22 mm and 0.16 mm on a side, respectively. These images are in turn reimaged by lens L_4 (a pair of back-to-back, 175 mm focal length, $f/2.5$ aerial camera lenses) and divided by beam splitter BS to form two separate images. Apertures A_1 and A_4 are positioned so that only the first Purkinje image falls on the split-field photocell P_1 and only the fourth Purkinje image falls on split-field photocell P_4 . The beam splitter reflects about 10 percent of the incident light toward P_1 so that only very little light is lost from the much dimmer fourth Purkinje image.

The split-field photocells P_1 and P_4 are servo-controlled so that each image is continually centered on its respective photocell.



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FIGURE 9 SCHEMATIC LAYOUT OF THE OPTICAL SYSTEM

The final output signal is the difference in the electrical signals that are generated in each servo system to maintain a centered, null condition. If the eye translates, both images move by exactly the same amount in space, and the signal increments that are generated in each servo path are nominally identical. Thus, there will be no change in the output signal. However, if the eye rotates the images move differentially and the output signal will change accordingly.

Light source S is a GE DFW Projection Lamp, with a 7-mm square illumination area and a built-in reflector. (Although rated at 120 volts, it is operated at only 80 volts in this application.) The light source is imaged by lens L_1 onto stop S_1 , which is a circular aperture 5 mm in diameter and covered by a tissue paper diffuser. Stop S_1 is in the focal plane of lens L_2 and is therefore imaged in the plane of the pupil of the eye, which is located in the focal plane of lens L_3 . The image of S_1 at the eye is magnified in the ratio of the focal lengths of lenses L_2 and L_3 . Thus, this image is $180/75 \times 5$ mm or 12 mm in diameter, which is adequate to flood the entire corneal region of the eye. In other words, all of the light that appears to emanate from stop S_2 passes through this 12-mm region in the front of the eye.

The input light passes through a near-IR filter F, and is chopped by wheel C of alternating segments of polarizers oriented at 90 degrees to each other. With another fixed polarizer Pol in each output path, the signal light from the highly specular first and fourth Purkinje images are in effect chopped at the frequency of the chopper wheel, i.e., approximately 500 Hz. At this frequency we are above the bad "1/f" noise region of the silicon, split-field photocells. Although an ordinary chopper wheel of open and closed segments would serve this purpose equally well, this method of using polarizers has another advantage. Namely, any diffuse light deriving from the retina or other

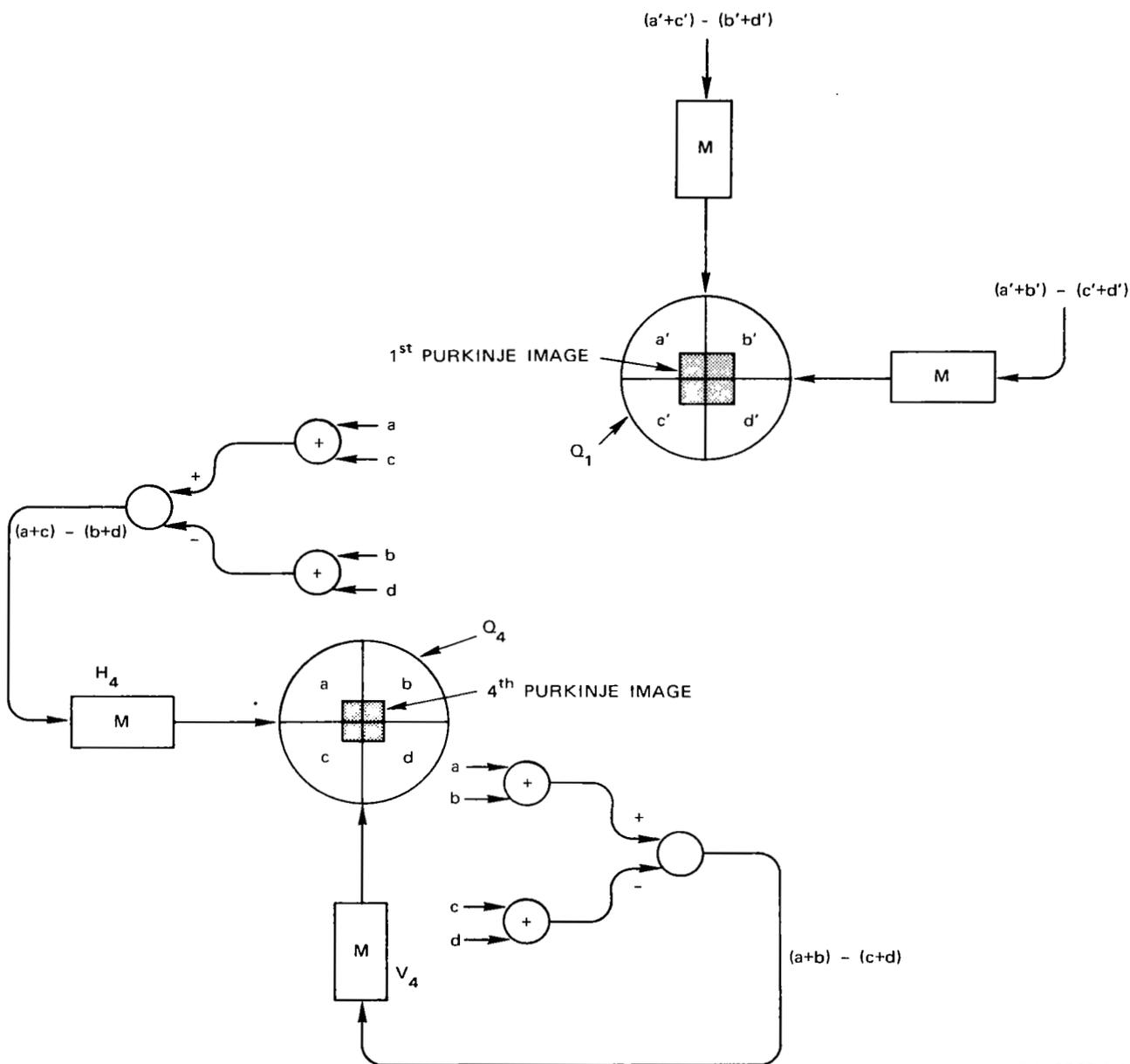
parts of the eye will appear as a dc component and therefore not affect the ac coupled signals from the photocell. This is because the amount of light reflected from a diffuse reflection is independent of the angle of polarization of the input light, whereas, with an open-closed sector wheel, any diffuse reflections would have the same frequency components as the Purkinje images and could not therefore be isolated.

The angular separation θ between the input axis and the optic axis of the eye has been discussed. However, the viewing system is actually on the opposite side of the visual axis, so that the input and output axes are actually separated by an angle $\alpha + \theta$. The main consideration in the choice of angular separation is as follows. The input and output axes could easily be made coincident by means of beam splitters, although this has two distinct disadvantages. First is the fourfold loss in light with double-passage through a 50/50 beam splitter. This would be undesirable from the view of signal-to-noise ratio. A second disadvantage is that although we are really only interested in the Purkinje reflections, an image of stop S_2 is nevertheless also formed on the retina and a significant amount of reflected light from the retina passes back out through the pupil. Thus, viewing directly into the eye, one generally sees a pair of Purkinje reflections (one much brighter and slightly larger than the other) on a generally bright background of light from the retina. In other words, light from the retina makes the pupil area glow. By viewing from off-axis, however, this background retinal light is substantially reduced, with subsequent improvement in the signal-to-noise ratio. This argument is relevant mainly to specular components of the retinal reflection, which are substantial in the near infrared; diffuse reflections are substantially eliminated through the polarizers.

A potential disadvantage of being off-axis is the increased optical distortion of the Purkinje images. The problem that this introduces is difficult to assess, however, since distortion per se does not affect the performance, but only changes in distortion with eye movement. This problem seems insignificant for the relatively small-field tracking that we are currently performing, although it may well be more significant in attempts to make larger field tracking systems. These considerations on angular separation are general, in that the exact angles are not too critical. More constraining considerations on angle are imposed by the requirements for minimizing interference from the third Purkinje image as discussed below.

d. Two-Dimensional Tracker: Sample Records

In the original one-dimensional version of the eye tracker, the input and output axes of the instrument and the optic axis of the eye were in a horizontal plane. The two Purkinje images were thus horizontally separated, and the two photocells simply tracked variations in horizontal position, each with its own individual driver, as shown in Figure 9. In the two-dimensional tracker, however, the cells must track both horizontal and vertical motion. To achieve both vertical and horizontal control both a horizontal and vertical split-field cell for each image are required. This effect can be achieved through the use of a quadrant cell interconnected electrically (through operational amplifiers) to function in both modes. Thus, in Figure 10 each image is shown as falling on a quadrant cell Q interconnected so that the horizontal position is controlled by the difference of the signals from the two right halves ($b + d$) and from the two left halves ($a + c$), and the vertical position is controlled by the difference in the signals from the two top halves ($a + b$) and from the two bottom halves ($c + d$). These signals



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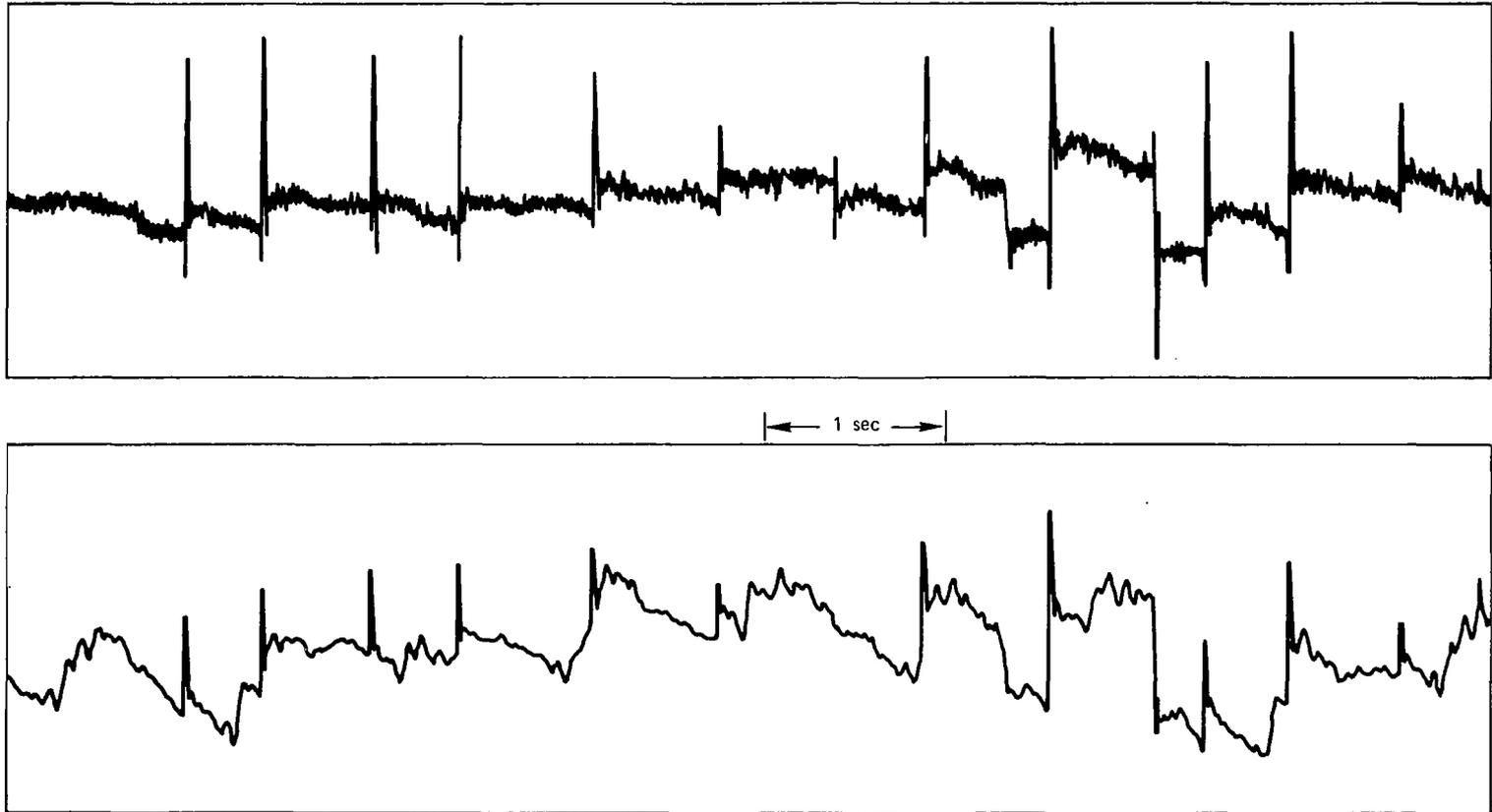
FIGURE 10 INTERCONNECTION OF THE TWO TWO-DIMENSIONAL SERVO DRIVERS

drive motors labeled M. The interconnection scheme is the same for the two quadrant cells. The final output signals are derived from differencing the horizontal position signals and vertical position signals from both cells.

The Purkinje images in Figure 10 are shown displaced at about 45 degrees to each other. This results from raising the optical axis of the eye about 15 degrees from the horizontal. With the input axis already shifted horizontally from the eye axis by about 15 degrees, this results in an effective input angle along a 45-degree axis. This arrangement was primarily for convenience in the optical arrangement and is hardly critical, although with this 45-degree orientation, the action in the horizontal and vertical channels is much more symmetric than, say, with a purely horizontal or purely vertical displacement.

At the time this report was written, the two-dimensional version was not sufficiently advanced to obtain records. Figure 11 shows a record of involuntary eye movements during careful fixation taken from the original one-dimensional eye tracker. In general, the frequency, magnitude, and types of eye movements are typical; i.e., small saccades about 5-10 minutes of arc occurring about twice per second, apparently correcting for slow drifts from the fixation point. However, two atypical response components are seen in the record: a strong overshoot corresponding to about 10-15 minutes of arc following each saccade and a small "anticipatory" response preceding each saccade.

The source of the anticipatory response was traced to the fact that the servoresponse to a saccade occurs about 10 milliseconds earlier in the first Purkinje image tracker than in the fourth. Consequently, when one record is subtracted from the other, the difference in latencies appears as an anticipatory response. There are two possible explanations for this difference in latencies. The first is that the cornea (first



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FIGURE 11 SAMPLE EYE MOVEMENT RECORDS. Top: output of entire eye tracker. Bottom: output of first Purkinje image tracker alone.

Purkinje image) actually moves sooner than the lens (fourth Purkinje image) during a saccade. This is plausible since the lens is coupled to the eyeball through the ciliary muscles, which would filter out the high frequency mechanical components of eye movements. An alternative possibility is that it is caused by slight differences in circuitry and gain settings between the first and fourth servo systems and that the first servo system is simply faster than the fourth. Regardless of the cause, the consequence of this artifact is relatively small, introducing a tracking error of no more than a few minutes of arc.

The overshoot following each saccade may be a serious problem, and we have not yet located its source. The overshoot is about 15-20 minutes of arc, lasts about 20 milliseconds, and shows up as a servo error in both the first and fourth tracking systems. However, the overshoot is considerably larger in the fourth image (\approx 15-20 minutes of arc) than in the first image (\approx 5 minutes of arc). If this effect is not an equipment artifact, it may indicate a real effect in the nature of the eye response. For example, if after a saccade, the inertia of the front of the eye causes the cornea to overshoot by 5 minutes of arc (\approx 15 microns) or the inertia of the lens causes it to overshoot by 15-20 minutes of arc (\approx 45-50 microns), the computed and actual direction of the visual axis must be in error by a substantial amount during this transient overshoot.

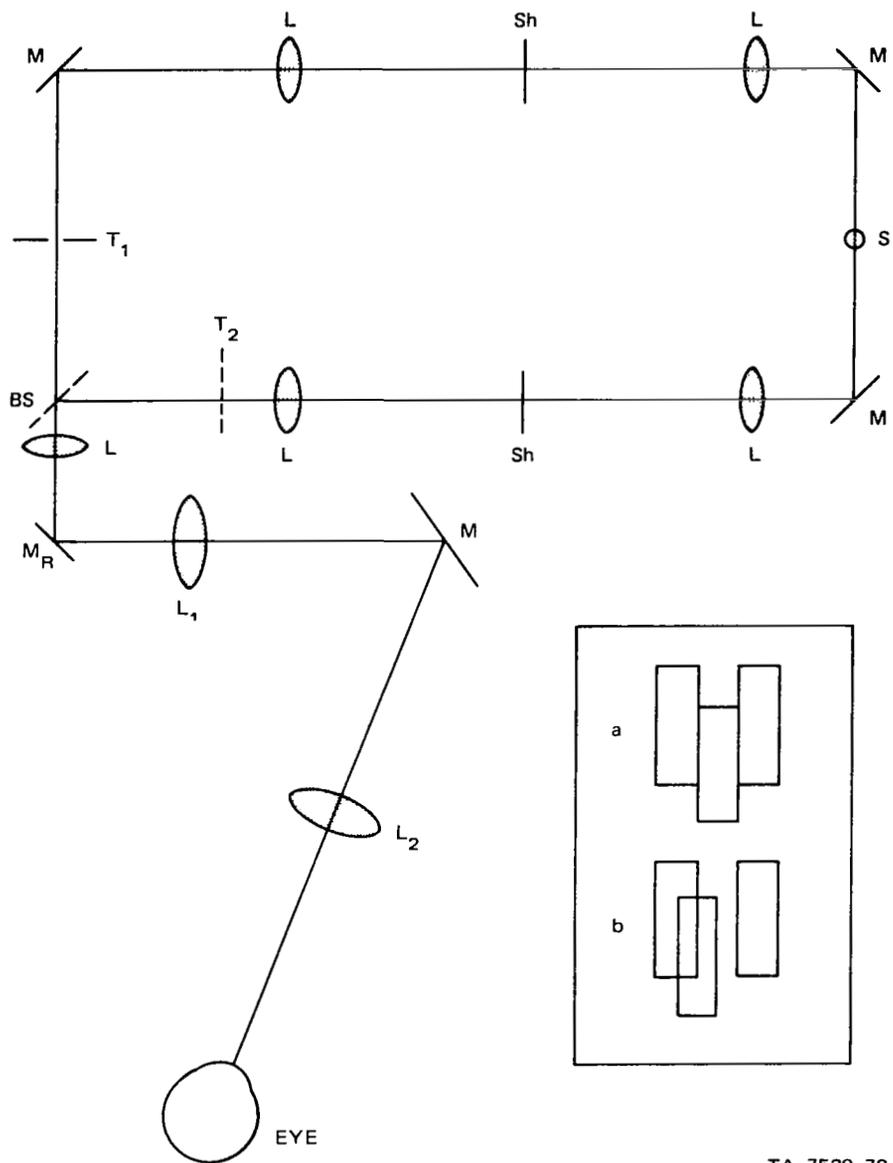
Aside from this large overshoot problem, the eye tracker records are good, i.e., small involuntary eye movements are clearly visible and the record is free from translation artifact, which generally shows up as a baseline drift. The latter point is illustrated in Figure 11, which compares the output of the entire eye tracker (top trace) with that of the first Purkinje image alone (bottom trace). The drifting in the bottom trace is a manifestation of the translational movements of the eye.

e. Accuracy Calibration

To obtain a quantitative estimate of how accurately the eye tracker monitors eye movements, the tracker was used together with an auxiliary system to "stabilize" an image on the retina. (This was done only in connection with the original one-dimensional version.) For this purpose, we measured how well the composite system stabilized the image, using a modification of a technique developed by Barlow.⁵ Because the eye tracker must be at least as good as the whole system, the accuracy of stabilization may be taken as a conservative estimate of the accuracy of the eye tracker itself.

The essence of this technique is to compare the position of an afterimage (which is caused by events occurring within the retina and therefore is perfectly stabilized with respect to the retina³) with the position of an image that is stabilized by means of the optical system. If the stabilizing system does not fully compensate for eye movements, the separation between the afterimage and the stabilized image will vary as a function of time; the magnitude of the change in separation from one moment to the next may be taken as a direct measurement of the system's ability to compensate for eye movements.

The auxiliary optical system used in these experiments is shown schematically in Figure 12. All of the optics above mirror M_R constitute a standard two-channel Maxwellian view stimulating system. Mirror M_R , which occupies that position normally occupied by the eye of the observer, is mounted on a high-quality galvanometer and imaged by means of lenses L_1 and L_2 in the plane of the subject's pupil. Rotation of mirror M_R causes the image to shift laterally with respect to the eye axis. Lenses L_1 and L_2 are separated by the sum of their focal lengths so that the target plane of the Maxwellian view stimulating system is imaged in the



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FIGURE 12 AUXILIARY OPTICAL SYSTEM USED IN STABILIZATION EXPERIMENTS

focal plane of lens L_2 . This optical system, then, images the light source in the plane of the subject's pupil and presents the target to him at optical infinity.

The output signal from the eye tracker is appropriately filtered and amplified and is used to drive the mirror galvanometer. Whenever the subject's eye moves, the voltage at the output of the eye tracker changes by an amount proportional to the magnitude of that eye movement. This voltage change causes the mirror to rotate by the amount necessary to "stabilize" the image on the retina. Because the eye movements being tracked are small (no more than 30'), the front of the eye never moves by more than about 0.1 mm and the image of the rotating mirror remains well centered in the subject's pupil.

With this composite optical-electronic system, the following procedure was used to measure stabilization accuracy. With the subject carefully fixating a point source, a bright vertical slit (4' x 12') was flashed just below his fixation point. Seven seconds later, a pair of parallel vertical slits (both 4' x 12' and separated by 4') was flashed. If there were no errors in tracking or stabilization, the afterimages of the three slits would form the pattern shown in the upper portion of the inset to Figure 12. If there were a tracking or stabilization error, the afterimages would be misaligned, as shown in the lower portion of the inset.

To evaluate the disparity within the afterimage pattern, the subject was provided with a device containing a pair of fixed lines and an adjustable line nominally identical with those presented in the display flashes. After each pair of flashes, the subject got off the bite bar and "projected" the afterimage onto a blank field that was illuminated by a flickering light. After examining the afterimage in this

manner, he adjusted the position of the single line until the relationship between the single and double lines in the device matched the afterimage. [The subject's ability to make this type of judgment was measured independently by offsetting the single and double lines in the stimulating system by a fixed amount (e.g., 1 min) and flashing the single and double lines simultaneously. The subject then adjusted his device to match the afterimage; the adjustment proved accurate to within 0.15'.]

Stabilization measurements were made under two different conditions. In one condition, the subject remained on the bite bar and maintained fixation during the 7-second interval between the two flashes; in the other condition, he got off and then back on the bite bar between the two flashes. The stabilization errors were approximately normally distributed in both conditions. The standard deviations were 1.1 minutes of arc for the first condition and 1.2 minutes of arc for the second.

These results compare favorably with those obtained using other types of stabilization. Barlow⁵ determined that the standard deviation of stabilization errors for a "tightly fitting" scleral contact lens, with optics mounted directly on the contact lens, was about 3-5 minutes of arc. The standard deviation for a small cup applied to the cornea by suction and similarly carrying the optics for stabilization, was 0.6 to 0.7 minutes of arc. Riggs and Schick⁷ determined that the standard deviation for a tightly fitting contact lens with a small plane mirror mounted directly on it was 0.4 minutes of arc. Thus, the Purkinje image tracker in its present form is probably more accurate than most of the contact lens eye tracking and stabilization devices that have been used in the past, and is slightly less accurate than the best ones.

3. Design Considerations

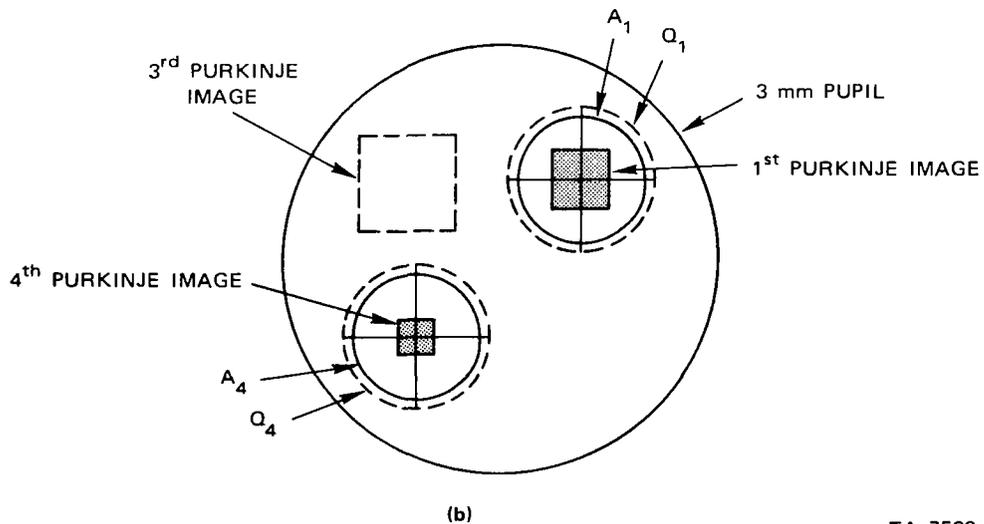
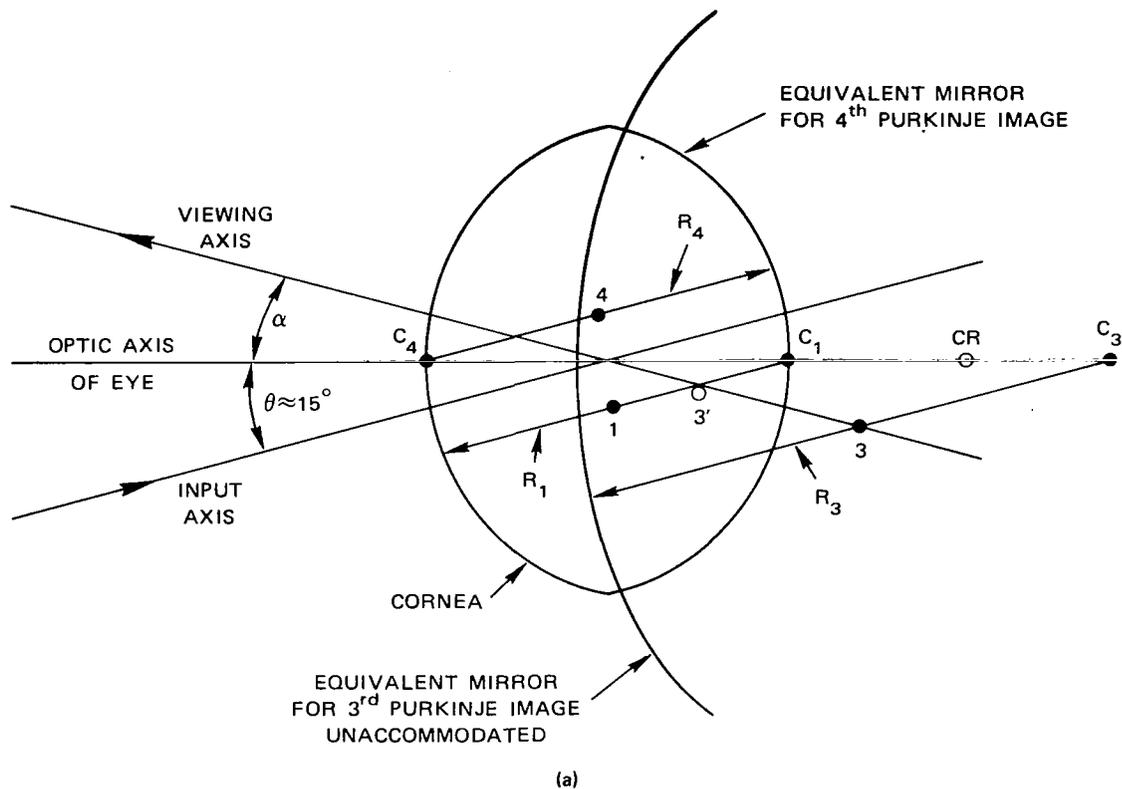
a. Interference by the Third Purkinje Image

The basic eye tracker system operates by measuring the difference in position of the first and fourth Purkinje images, which lie in almost exactly the same plane and are similar in size, although the first is much brighter than the fourth. However, the third Purkinje image is always present, and since it is about as bright as the fourth, it must be properly located so that light from it does not fall onto the photodetectors.

In Figure 13(a), we show the configuration of all these images, assuming a 15 degree angle between the input axis and the optical axis of the eye. The nominal size and position of the equivalent mirror for the third Purkinje reflection are shown for the unaccommodated state. To simplify the drawing, we have assumed that the source being imaged is a point at infinity.

Recall from Figure 6 that the image point of a collimated input beam is located at the $r/2$ position along the input ray passing through the center of curvature of the corresponding mirror. In other words, to find the position of each Purkinje image, we simply pass a line parallel to the input axis through each center of curvature and then mark the corresponding $r/2$ position on each line. This results in the pattern of point images labeled 1, 3, and 4 in Figure 13(a). (The point labeled 3' marks the nominal position of the third Purkinje image with 8.6 diopters of accommodation.⁴)

Note that from the viewing angle ($\alpha \approx 15^\circ$) shown in Figure 13(a), the third Purkinje image in the unaccommodated state (point 3) lies centered between the first and fourth Purkinje images (labeled 1 and 4) and is therefore easily blocked. In fact, even with strong



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FIGURE 13 LOCATION OF THE FIRST (1), THIRD (3), AND FOURTH (4) PURKINJE IMAGES

accommodation, the third image remains fairly accurately centered. The total image formed by the viewing system is shown in Figure 13(b), where we see that (1) the first image is slightly larger than the fourth, (2) the images are separated by about 2 mm (corresponding to the input angle of about 15°), and (3) the images are oriented at about 45 degrees to each other because of the elevation of the eye axis as noted earlier in connection with Figure 10. The third image is larger even than the first and is somewhat out of focus. If all axes were coplanar, the third image would appear between the first and fourth images, but again because of the vertical elevation of the eye the third image is also displaced laterally from the line joining the first and fourth images. Stops A_1 and A_4 are placed around the first and fourth images to prevent as much stray light as possible from reaching the corresponding split-field photocells.

This summarizes the additional constraint on angular separation between the input and output axes noted earlier. We should also note the possibility of viewing from the opposite side of the input axis, so that the third image is to the side of both the first and fourth images, although this possibility has not been studied in detail.

b. Sensitivity to Axial Position

A primary goal of the design is to provide an instrument that is insensitive to lateral, i.e., translational, movements of the eye. However, it is equally important to be insensitive to axial movements of the eye. The basic problem in axial sensitivity can be seen in connection with Figure 14(a), in which we assume that we have a small input bundle of rays, resulting from a small hole in input stop S_1 . For simplicity, we also assume a simple clam-shell arrangement for the first and fourth reflections and a single lens in the viewing system. The

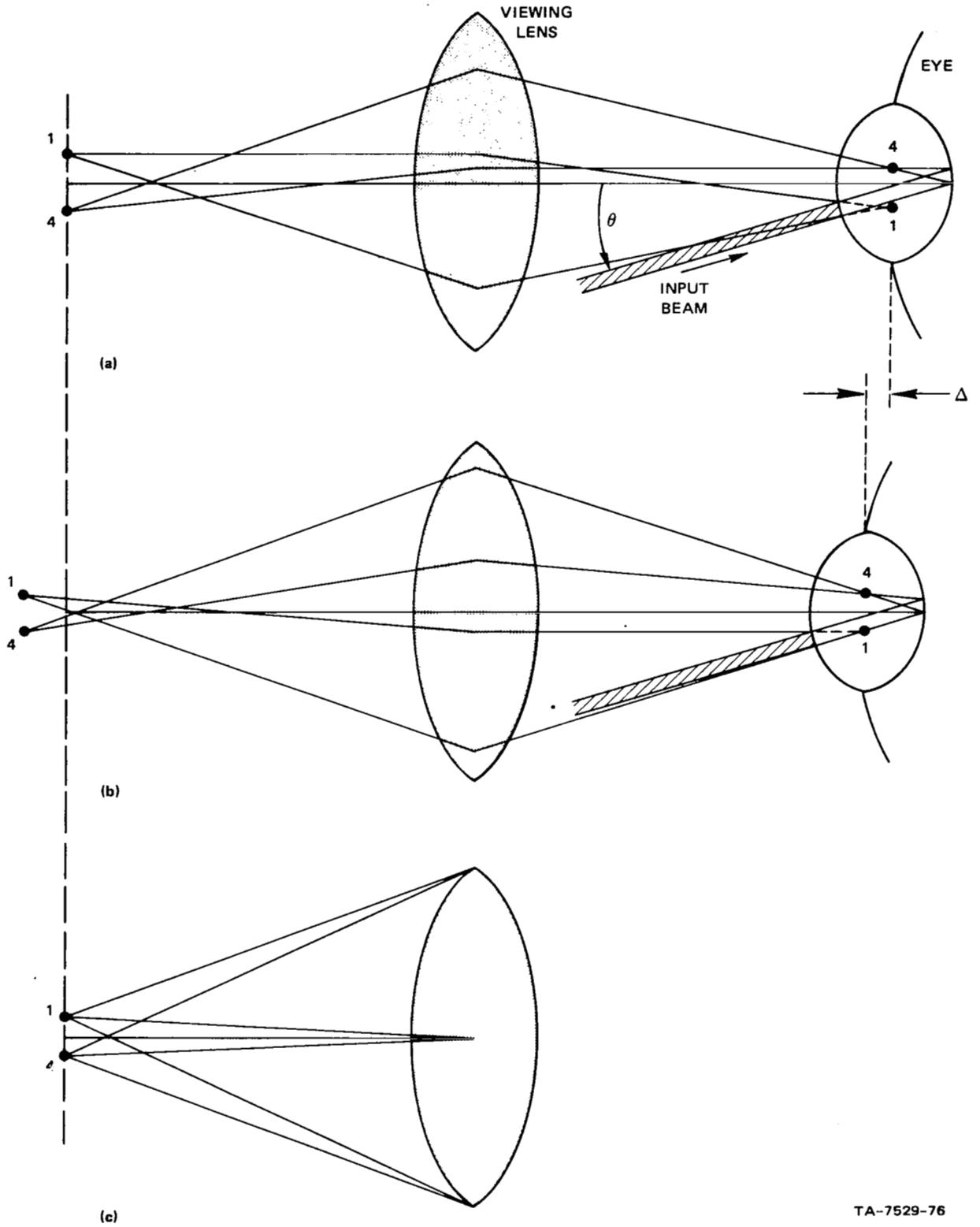


FIGURE 14 EFFECTS OF AXIAL MOTION

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input bundle forms point Purkinje images 1 and 4, as shown, light from the (virtual) first image being reflected from the front (corneal) surface and light from the (real) fourth image being reflected from the rear surface. These bundles are then focused by the viewing lens.

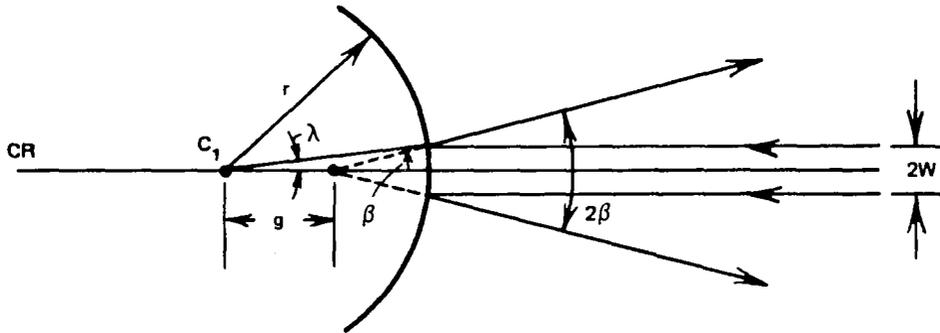
Let us see now the effect of an axial movement in eye position. One fact to be noted is that the positions of the images with respect to the eye will not change in response to axial movement, because the input light is collimated. Thus, the first obvious effect of axial eye movement is that the reformed images 1' and 4' themselves move axially in space and therefore will be out of focus in the viewing plane V by an amount proportional to the actual movement. Even more important is the shift in the angle of the return beams, which can cause a relatively large (apparent) shift in separation of the two defocused images in the (out of focus) viewing plane. Such a shift would be intolerable, since the system would interpret it as an eye rotation. To trace the nature of this problem, assume that the eye moves axially toward the viewing lens as in Figure 14(b). In this case, the return beam from the front mirror (i.e., the cornea) swings to the left (downward in the figure) and the return beam from the rear mirror swings to the right upward in the figure). The amount of angular swing can be determined accurately, though we show only an approximation here. For a change Δ in axial position, the point at which the center input ray strikes each respective mirror moves vertically by an amount approximately equal to $\Delta \sin \theta$. Since the actual image points are fixed in eye space, and the mirror surfaces are a distance $r/2$ from the image points, this vertical movement results in an angular shift of approximately $\alpha = (\Delta \sin \theta)/(r/2)$ radians; or, for $\Delta = 1$ mm, $r \approx 7$ mm (average value between 5.8 mm and 7.8 mm), and $\theta = 15^\circ$, then $\alpha = 4^\circ$. The angular change between the two return beams is actually twice this amount, since one beam swings to the left while the other swings to the right.

As noted above, these large angular swings of the return beams could change the effective separation of defocused images in the viewing plane. This problem is substantially eliminated, however, by increasing the size of the input bundle so that the return beam of light from each point of the image is larger than the viewing lens, i.e., so that the viewing lens is itself the limiting aperture. In this case, the effective separation between the defocused images, with axial movement of the eye, depends only on the focal length of the viewing lens, as indicated in Figure 14(c). With large return beams (i.e., with a large aperture S_1), we have in fact found little interference from axial movement artifact.

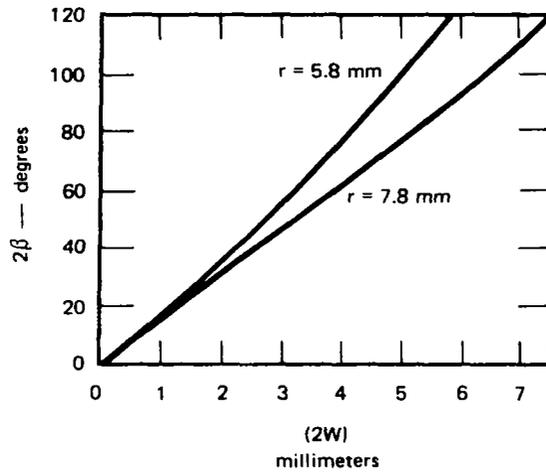
The actual relation between the width of the input beam $2W$ and the angular size of the return beam is shown in Figure 15 for radii of curvature 5.8 mm and 7.8 mm, corresponding to the fourth and first reflections, respectively. Actually, it does not take a large input beam width to generate relatively large return cones, although to ensure that the output lens is completely filled for all eye positions a larger output cone is required than would be inferred simply from the effective f-number of the output system. (The return cone from the fourth image is also limited by the eye pupil, as discussed in the following section.) In fact, to ensure complete filling of the output optical system under all conditions, we have found it useful to flood the front of the eye, which explains why the input optics were arranged so that the image of stop S_1 at the eye was as large as 12 mm.

c. Effect of the Eye Pupil

Although the light forming the first Purkinje image is reflected from the cornea, light from the fourth image is reflected from the back of the lens and therefore passes twice through the pupil of



(a)



(b)

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FIGURE 15 RELATION BETWEEN THE INPUT BEAM WIDTH AND THE ANGULAR SPREAD OF THE RETURN BEAM

the eye. (Light in the third image is similarly limited by the pupil.) This has two effects. First, the pupil limits the effective width of the input beam, as indicated in Figure 16(a), which in turn limits the effective angle of the return cone. Minimum pupil size, according to this constraint, depends then on the required cone size in the return beams, which can be determined from Figure 15.

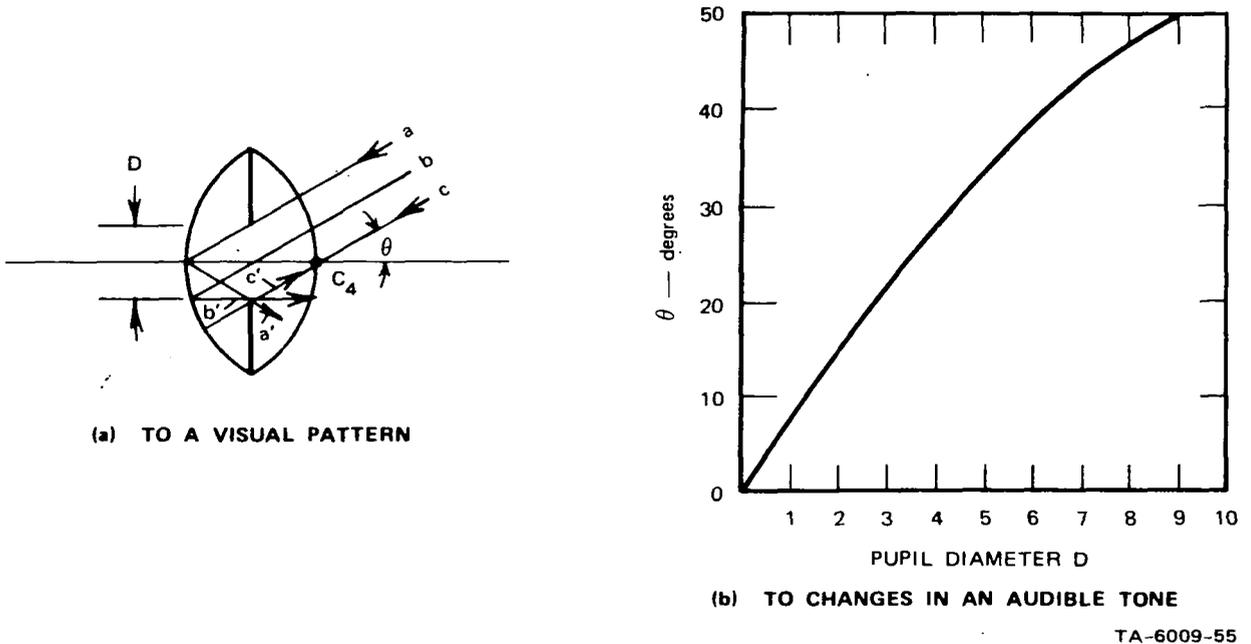


FIGURE 16 EFFECT OF REAL PUPIL ON THE FOURTH PURKINJE IMAGE

Second, the pupil can block part of the image. For the angle θ of input rays drawn in Figure 16(a), the corresponding image point lies near the edge of the pupil. As θ increases, the image point moves closer to the pupil until, beyond some critical angle θ_c , the image point would fall behind the pupil and be completely blocked. Figure 16(b) shows the relationship between θ_c and pupil diameter. Thus, as the pupil

closes, the ends of the fourth image would eventually begin to be cut off. This is not the case for the (virtual) first image, however, which would appear superimposed on top of the iris.

In this instrument, the pupil must actually be larger than the critical magnitude noted above, since if any portion of illuminated iris gets into the field of either photocell, the servo can easily get trapped in an erroneous position. With the present form of the instrument, we have found no difficulty so long as the pupil is at least 3 mm in diameter.

4. Summary

A two-dimensional eye tracker is described that operates on the first and fourth Purkinje reflections from the eye. The basic principle of operation depends on the fact that these two reflections move together under eye translation although differently under eye rotation. As a result, the instrument can easily discriminate translation from rotation, which is critical for achieving a high degree of accuracy. The resulting instrument has a sensitivity and accuracy on the order of 2 minutes of arc over a two-dimensional field between 5 and 10 degrees in diameter. The basic principles underlying the formation and development of the Purkinje images is traced, as well as the basic configuration of the instrument. Certain key features in the design are also considered.

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