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The Infrared Computer Based Oculometer

by

© Milton W. Petruk

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled The Infrared Computer Based Oculometer submitted by M. W. Petruk in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

The major purpose of this research was to develop a method of measuring and recording eye movements of subjects during various learning tasks. It was required that the method developed for this purpose record simultaneously, as many oculographic characteristics as possible, relatively unobtrusively, with no mechanical attachments and with minimum of constraints placed on the subject. It was also required that the recording speed and sensitivity be sufficient to record all conjugate eye movements in a form readily accessible for computer analysis.

The infrared computer based oculometer system developed consisted of an infrared television camera interfaced with a small computer. The eye of the subject was illuminated with infrared light, and an image of the eye was projected to the face of the infrared television camera. The small computer was used to monitor the video signal coming from the infrared camera via a specially designed interface unit, and to derive and store once every thirtieth of a second, both the pupil dilation and the displacement of the corneal reflection from the pupil center. Analysis of this data to determine and plot eye pointing coordinates was carried out off line, using an IBM 360/67 computer. This study describes and documents the development of the infrared computer based oculometer system.

Operating characteristics of the infrared computer based oculometer are discussed in terms of possible sources of error and in terms of accuracy of the system.

The performance of the infrared computer based oculometer was tested using a small number of subjects viewing a variety of stimulus situations. Plots of observed eye movements in relation to the stimulus situations are presented in this study.

Finally, a number of recommendations for improving the infrared computer based oculometer system are presented. Also further studies of eye movement measurements are recommended to enable additional analysis of error components inherent in the measurements.

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CHAPTER I

INTRODUCTION

The process of learning relies primarily upon sensory information reaching the learner via either or both the auditory and visual channels. While some occasions arise when sensory inputs from the tactile channel are also important to learning, it is much less often that the learner relies upon the remaining senses.

Considering the relative importance of the auditory and visual sensory input channels, it is difficult to determine which of these is more important in learning. A great deal would most certainly depend on the nature of the learning task. Feinstein (1970) identified the visual channel as ". . . our primary sensory input channel".

Considering types of learning that depend on appropriate stimulation of the visual channel, if appropriate stimulation of the visual channel is dependent upon visual response, then one of the factors that affects learning is visual response. It is important therefore that studies of learning involving the visual sensory channel take into account the visual response of the learner.

Educators have recognized the importance of the visual response (eye movements) in learning for nearly a century. The earliest eye movement studies were conducted in relation to reading [illegible] 1, 18[illegible]) and consisted of directly observing and recording the movements of a subject's eyes while reading. One of the most significant discoveries that resulted from this early research was that in reading a line of text, the eye moves in a series of rapid jerks, (called saccades) interspersed with relatively long pauses (called fixations). This discovery replaced the previously held traditional belief that when a person reads his eyes move smoothly and uninterruptedly along the line of print. Tinker (1965) reported that research activity in this area became more vigorous after 1900. He indicated that several hundred investigations of eye movements in relation to reading have been reported and ". . . have contributed much to an understanding of how children learn to read."

The growth of technology during the twentieth century brought about many developments and improvements in methods of measuring and recording eye movements (oculography). By 1971, there were reports (Feinstein, 1970) of as many as seven different methods of oculography and each method included a number of variations in technique. During this same time period, interest in oculography began to spread to a variety of other disciplines, including ophthalmology, biomedical engineering, and psychology. Within education, eye movement research spread to a number of other related fields, including studies of learning in relation to novelty of a stimulus (Berlyne, 1958), familiarity and complexity of a stimulus (Neisser, 1964), size of a visual display (Enoch, 1959), attention (Guilford and Hackman, 1936), problem solving (Teichener and Price, 1966), emotionalism (Luborsky, Blinder and Mackworth, 1963) and perception and information processing (Hebb, 1949; Gould and Schaffer, 1965).

Another result of the growth of technology has been an increase in the importance of the visual sensory input channel in the field of education. The development of offset printing and the subsequent mass distribution and utilization of books by educational institutions; the development of programmed instruction; the introduction of films, trans-p[illegible]ies and educational television into the classroom; the introduction of special education for deaf children and mentally retarded; and most recently, the introduction of computer based instruction all rely heavily on sensory input to the learner via the visual channel.

Instructors responsible for constructing educational materials have relied to a large extent on the generalized findings that have come out of eye movement studies to guide them in designing visual instructional materials. However, frequently there is little similarity between the experimental setting and the educational setting to which generalizations must be drawn. Because most oculography equipment currently available does not readily lend itself to use outside the laboratory, instructors have had no way of evaluating the adequacy of their instructional materials to elicit appropriate visual responses. For example, in an experiment conducted by Wolf, et al. (1970) students were presented with a television scene of an instructor demonstrating the operation of a model airplane. Low IQ students tended to look at the instructor's tie rather than at the model airplane the instructor was demonstrating. This visual response would suggest that the instructor had failed to accomplish the stimulation of the visual channel that he had set out to bring about when he designed the scene. Improvement in visual response and perhaps in learning may be brought about by redesigning existing educational material.

The first purpose of this study is to report and document the development of the infrared computer based oculometer designed for monitoring and recording eye pointing coordinate data and pupil dilations of subjects involved in various learning tasks. The unique features of the computer based infrared oculometer are that it will operate under most normal lighting conditions, and that it will require only a minimum of physical restraint of the subject (chin rest). In addition, it will output data onto 9-track magnetic computer tape that will permit calculation of eye position, eye pointing direction and pupil dilation once every 33.3 milliseconds. This will permit data to be easily analyzed.

The data recorded by the infrared computer-based oculometer system will simply consist of a measure of pupil dilation and a measure of the displacement of the center of the corneal reflection from the pupil center, recorded once every thirtieth of a second. In order to derive the more traditional measures of eye movement such as number of fixations per line of text, mean length of fixation, number of blinks per unit time, etc., further processing of the oculometer output will be necessary. However, because the oculometer output will be available on 9-track computer tape, it will be relatively simple to prepare computer programs that will quickly read the oculometer output tape and output summaries of these more traditional eye movement measures.

A second purpose of this study is to document the reliability, validity, and accuracy of the infrared computer based oculometer. This will be referred to as establishing the proof of performance of the system. This problem is essentially a measurement problem and is necessary when any new measuring instrument is developed.

One way of establishing the proof of performance (reliability, validity and accuracy) of a measuring instrument is to compare the output of the system under test with the output of other systems whose proof of performance is already well established. This approach was not used with the infrared computer based oculometer for several reasons. First, it is difficult to obtain a system with established proof of performance to permit the necessary data to be collected. Second, it is difficult, although possible, to configurate hardware so that two systems, the standard and the system under test, could simultaneously monitor a subject's eye movements. Most important however, it is expected from the design parameters of the infrared computer based oculometer that its reliability and accuracy will exceed the reliability and accuracy of most known available systems. This would mean that determination of accuracy and reliability by comparison would have questionable merit.

An alternative method of establishing proof of performance of the computer based oculometer system, and the one that will be followed in this study consists of documenting the performance of the infrared computer based oculometer system in relation to a series of simple, definable sub-tasks which are known to constitute the overall task that the system is expected to perform. These findings can then be generalized to describe the performance of the complete oculometer system. For example, since the capability of the oculometer to determine where a subject is looking is based on its capability to measure linear displacement (both horizontal and vertical) between two defined points within the image of the eye, one sub-task of the system is to measure small linear distances. Inadequate performance of the infrared computer based oculometer system while measuring small linear horizontal and vertical distances would certainly be one limitation of its capability to determine where a subject is looking. Chapter three of this study includes the identification of other sub-tasks, and documentation of the performance of the infrared computer based oculometer in relation to these sub-tasks, and in turn, in relation to the main task of determining where a subject is looking.

This study will also demonstrate the use of the infrared computer based oculometer for analyzing eye movements during learning by recording and analyzing the eye movements of a small number of subjects involved in three different types of learning tasks. The learning tasks will be selected from available instructional material in the Division of Educational Research Services and will be displayed on the cathode ray screen of an IBM 1500 CAI terminal. The displays will include one display consisting of text only, one display consisting of some text combined with an illustration and one display consisting of a multiple choice question which requires the subject to select a response visually.

Summary

This chapter discussed the importance of the visual sensory input channel to learning and education and discussed the importance of knowing where the learner is looking during various learning tasks. Visual response of learners can be used as a basis for improving visual instructional materials. This chapter also identified the problems to be investigated in this study.

Chapter two of this study will describe the various methods that have been developed for monitoring and recording eye movements and will discuss some of their advantages and shortcomings. This chapter will also present a summary of the findings resulting from eye movement research. The third chapter will describe the infrared computer based oculometer in detail and will present proof of performance data for the system. Chapter four will outline the methodology followed to collect and analyze eye movement data using the infrared computer based oculometer and will present the findings. Chapter five will present a summary of this study together with conclusions and some recommendations for further research.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Since the visual system is one of man's primary input channels, it is important to understand how this system functions. Eye movement research or oculography began during the latter half of the nineteenth century and since then has been taken up by researchers in a variety of different fields with different goals in mind.

Biomedical engineers have studied eye movements in order to better understand the nature of the total oculomotor system and the relationships that exist between the many complex elements that constitute this system. To this end, they have developed computer based simulation models of the oculomotor system. Research by biomedical engineers can ultimately lead to a better understanding of how information is processed in the brain.

Opthalmologists have studied eye movements primarily from a medical standpoint. The development of improved oculographic techniques can benefit the opthalmologists greatly in the diagnosis and perhaps in the correction of certain eye defects.

Eye movement research has been a subject of interest to both educators and psychologists since Huey published his book on the psychology and teaching of reading in 1908 (Tinker, 1965). Since a large proportion of education is presented through the visual channel, eye movement research can provide information to educators about improving the effectiveness of instruction, whether it be by changing the stimulus situation that is presented to the learner, or by modifying the looking behavior of the learner.

This chapter will review the methods that have been developed for measuring eye movements and will summarize the findings of eye movement studies in terms of the kinds of eye movements that have been reported.

Methods of Oculography

Yarbus (1968) and Feinstein (1970) discuss the various methods of oculography that have been developed, each of which will be identified and described briefly here.

Subjective Method

Historically, this method of oculography was the first to be used. It involves an observer who simply looks at the eyes of a subject and manually records his observations of the subject's eye movements. This method has been particularly useful in studying eye movements of infants (Greenberg and Weizmann, 1971) since no external equipment such as head restraints and bite bars is needed. Feinstein (1970) points out that "To this day, direct observation of a patient, while he attempts to follow an object . . . is used as a clinical test to reveal any nystagmus or gross disorders associated with the eye movement system."

Several modifications of this method of oculography have been reported wherein the subject, rather than an observer is responsible for determining and recording his eye movements. One such modification involves the use of "after-images". Several experimenters including Dodge (1907), Helmholtz (1925), Barlow (1952), and others used this method which generally involves having the subject look at a bright wedge of light until the retina is fatigued. After the wedge of light is extinguished, a clear after-image, fixed relative to the retina is visible to the subject. The subject is required to report the position of the after-image he sees while looking at a stimulus target placed within his visual field. Since the after-image is fixed relative to the retina, any displacement of the perceived position of the after-image relative to the target is the direct result of a change in the point of fixation by the subject.

Kaufman and Richards (Richards and Kaufman, 1969, Kaufman and Richards, 1969) used the "Haidinger Brush" technique to enable a subject to determine and record his own eye fixations. This technique uses a slide projector equipped with a blue-light filter and a motorized polaroid filter. The subject is instructed to look at a screen on which slides containing the desired stimuli are projected, using this specially equipped slide projector. Whenever the researcher wishes to have the subject report his point of fixation, he simply turns on the motor which briefly spins the polariod filter. Because the fovea is equipped with thousands of blue-light absorbing radially oriented crystals whose absorption pattern lies along radii from the center of the fovea, linearly polarized light will be absorbed more strongly in some parts of the fovea than others. As a result, the subject sees a "brush" or wedge of light on the screen, perpendicular to the direction of polarization. Because the image thus produced is stable with respect to the fovea, it quickly disappears (stabilized image). However, when the polarizing filter is spinning, the brush is moving relative to the fovea, making it visible to the subject, who reports seeing a "spinning propeller" on the screen. The point on the screen where the subject reports seeing the spinning propeller is the point which the subject was fixating when the polaroid filter was rotated.

Feinstein (1970) describes after-image as offering ". . . one of the largest dynamic ranges of all methods of oculography." However, he goes on to point out the shortcomings of all subjective methods of oculography stating that ". . . subjective measurements, though very useful, give no quantitative record of movement nor can they give any temporal information beyond a crude estimation".

Mechanical Method

The mechanical method of oculography represents researchers' earliest attempts to quantify measurements of eye movements. Feinstein (1970) discussed briefly the work of Delabarre and Huey whose efforts at mechanically coupling a recording apparatus to the eyeball he described as ". . . a remarkable achievement."

One extension of the mechanical method of oculography involved the use of a contact lens, attached to the eye, and linked either optically or magnetically to some recording apparatus. Cornsweet (1956) and others used a contact lens with a tiny mirror mounted on it. The image of a light source, placed before the eye of a subject wearing the lens, was reflected by the mirror to a continuously moving photographic film. This gave a permanent quantitative record of eye movements. Yarbus (1968) developed a number of "caps" designed to be attached to the eyeball by using suction, thus avoiding slippage. The caps which resembled a contact lens reflected a beam of light which traced a record on photosensitive paper. Using "caps" Yarbus conducted many investigations into the nature of eye movements. His findings are probably among the most comprehensive and precise available to this day. Robinson (1964) used a set of coils imbedded in a contact lens to measure eye movements. The coils were exposed to two magnetic fields in quadrature and produced output voltages proportional to both horizontal and vertical eye movements.

While mechanical methods involving contact lenses or caps are by far the most sensitive, it must be pointed out that any mechanical method which necessitates the attachment of foreign objects to the eye suffers from the disadvantage of introducing additional mass on the eyeball. The resulting discomfort for the subject, and altered dynamics of the oculomotor system limit the desirability of this method of oculography.

Direct Optical Methods

Barlow (1952) described a method of oculography that permitted a photographic record of eye movements to be made without the use of caps or contact lenses. He placed a tiny globule of mercury on the anesthesized cornea of the subject's eye and reflected a beam of light from the mercury to a continuously moving photographic film.

A variety of other direct optical methods which did not require the introduction of any foreign object or substance into the eye were eveloped. Dodge and Cline (1901) reflected a point source of light rectly from the cornea and recorded it on a continuously moving photographic film. Tinker (1931) and Taylor (1959) describe applications of this principle of eye movement recording in devices designed to study eye movements during reading. While many different variations of this method of oculography have been developed for studying eye movements, perhaps the one that has been most widely used to this time is that developed by Mackworth (1967). Mackworth developed a stand camera which utilized a beam splitter and which recorded a composite image consisting of the target being viewed with the corneal reflection superimposed on the target, indicating where, on the target the subject was looking. A variety of methods of recording this composite image were developed. These included a polariod camera for fast photographic processing, a 16 mm. movie camera for capturing temporal information or a television camera connected to a video tape recorder. The light source used to create the corneal reflection could be fitted with an infrared filter, provided that the recording device was also modified to record infrared light. This had the desirable effect of minimizing the distracting effect of the light source.

While the Mackworth eye movement camera is likely one of the most commonly used oculographic instruments, it offers two major disadvantages. First, the analysis of eye movement data recorded in this manner is an extremely slow and tedious process. Second, and perhaps most important, in order to insure accuracy, the subject's eye must remain fixed relative to the camera. This is generally accomplished by fitting the subject with a bite bar which he must clench firmly in his teeth throughout the recording session.

Electro-oculography

A standing potential is known to exist between the cornea and the retina of the eye. By attaching electrodes to the left and right of the eye and above and below the eye, the corneo-retinal potential may be recorded. Eye movements are recorded as changes in corneo-retinal potential and are free from interference due to head movement. Yarbus (1968) stated that ". . . electro-oculography is used with fair success by many workers when highly accurate records of eye movements are not required". Feinstein (1970) points out that the main difficulties associated with electro-oculography are electrode polarization, electrical interference or "noise", and data interpretation.

Electronic Measurement Methods

Unlike the direct photographic methods of oculography, which rely on the direction of reflected light to determine where the eye is looking, electronic measurement methods rely on a change in the quantity of light picked up by a photocell. While there are a number of variations, the technique relies on the principle that less light is reflected from the sclera than from the pupil. When a patch of light is directed onto the limbus, (the scleral-pupil boundary), and the quantity of reflected light is projected onto a photocell, the photocell output will vary as the eye moves and varies the position of the limbus relative to the light source. Cornsweet (1956) used this principle in a system which scanned light rapidly across the eye and used a photomultiplier to monitor the level of reflected light. The length of time taken from the start of the scan to a rise in the photomultiplier output was proportional to the horizontal eye position. Rashbass (1968) developed a tracking system consisting of a cathode ray tube and a photomultiplier tube. A spot on the cathode ray tube was projected to the limbus. When the eye moved, the spot moved to the cornea and was reflected to a photomultiplier tube. The photomultiplier tube output was used to reposition the spot to the limbus. The movement of the spot was therefore proportional to the movement of the eye. As was the case with the direct photographic methods of oculography discussed earlier, the subject's head had to be immobilized, since movements of the head would result in displacement of the limbus, thereby giving false readings.

Young (1962) mounted photocells and lamps in a pair of goggles to be worn by the subject, thereby eliminating artifacts that result from unrestrained head movement. Feinstein (1970) also used goggles similar to Young, however, he utilized infrared light sources, thereby eliminating the distraction of visible light. The major advantage of electronic methods of oculography is the ability to measure eye movements without contact with the eye. While the use of goggles limits the amount of head restraint that must be imposed on the subject, some head restraint is nonetheless needed if one is to determine precisely where, within a target a subject is looking. Freedom of head movement would make it possible for the subject to change his point of fixation by moving his head rather than his eyes. Such a change would go undetected unless an additional monitor was added to simultaneously record subject's head position.

The Infrared Computer Based Oculometer

In 1969, Mason and Merchant described a method of oculography which provided relatively unrestrained head movement. The system consisted of an image dissector tube which was made collinear with an infrared light source and which was positioned adjacent to the target area. The infrared light was absorbed by the skin surrounding the eye and by the sclera. Infrared light entered the pupil and was focused on the retina, which tended to scatter the light, backlighting the pupil to some intermediate level of intensity. In addition, the image of the infrared light source was formed as a bright corneal reflection. This image of the eye was focused on the photocathode of an image dissector. An analog computer was connected to the image dissector. The image of the eye was scanned and analyzed by the computer and the output included horizontal and vertical eye position, horizontal and vertical coordinates of eye pointing direction, and pupil dilation. In 1970, Hillsman, Willams and Roe interfaced the image dissector with a digital computer.

The purpose of this report is to document the development of a computer based infrared oculometer which is similar in principle to those reported above but which used a Raytheon television camera equipped to sense infrared and which was fully interfaced to a small digital computer programmed to determine and record horizontal and vertical eye position, horizontal and vertical coordinates of eye pointing direction and pupil dilation once every thirtieth of a second. Applications of the computer based infrared oculometer to educational problems will also be presented.

Types of Eye Movements

Classical eye movement theory identifies three major types or classes of eye movements; conjugate or versional movements, vergence and tremors.

Conjugate or Versional Movements

Conjugate eye movements are movements during which both eyes move in the same direction. There are three kinds of conjugate eye movements.

Small conjugate movements are involuntary and occur during fixation of a stationary target. Feinstein (1970) described small conjugate movement as ". . . a slow drift which tends to displace the image of the target from the fovea, followed by a small, very rapid flick . . . opposite in direction to that of the drift . . . tending to relocalize the target image on the fovea." Mason and Merchant (1969) refer to small conjugate eye movements as "eye noise" or "hunting" and describe them as consisting of displacements as large as two-tenths of a degree away from the point of fixation and recurring at a rate of about five times per second. This angular displacement, expressed as a linear displacement on a target area twenty inches from the eye of the subject would represent a linear displacement of about .07 inches at the target. This means that while a subject is fixating on a point twenty inches away, the eye will actually be looking somewhere within a circle around this point, approximately .14 inches in diameter. Yarbus (1968) conducted a series of experiments using his "caps" and found that the size of small conjugate eye movements is a function of the length of fixation and that it can vary ". . . between 1 and 25 minutes of angle. The minimal dimensions . . . between 2 - 5 minutes of angle. The maximal dimensions . . . approximately 40 to 50 minutes of angle". Yarbus also reported that the duration of small conjugate eye movements depends on their amplitude and is approximately 100 to 200 milliseconds with some lasting as long as several seconds. Referencing these findings to a target area twenty inches from the eye of a subject suggests that small conjugate eye movements could lie in a circle around the point of fixation slightly larger than one-half inch in diameter. West and Boyce (1968) reported that the rate of drift during a small conjugate eye movement was about 5 minutes of angle per second. They found, as did Yarbus that the duration of drift varied from approximately 100 miliseconds to several seconds.

The second type of conjugate eye movement is the saccade, a very rapid movement of the eye whose primary purpose is to move the eye from one point of fixation to another. Saccades can be either voluntary or involuntary. Yarbus (1968) reported that the amplitude of a saccade rarely exceeded 15 to 20 degrees of arc. Research indicates (Feinstein, 1970) that saccades rarely occur more than once every 200 milliseconds, and that the peak velocity of the eye during a saccade can be as high as seven hundred degrees of angle per second. Spache (1962) reported that the shortest duration of an effective saccade was 166 milliseconds and that the minimum time for a saccade to occur was 33 milliseconds. Yarbus (1968) found that the total time taken for a saccade to occur was 10 to 70 milliseconds, depending on its size.

The final type of conjugate eye movement is referred to as smooth pursuit. Smooth pursuit eye movements occur when the eye tracks a smoothly moving target that is moving at a velocity of 35 degrees of angle per second or less (Feinstein 1970). Yarbus (1968) conducted experiments wherein subjects were required to imagine that they were tracking a smoothly moving object. He found that ". . . it always appeared to the subject that the movements of his eyes were smooth and continuous, in fact they consisted entirely of separate fixations, saccades, convergences and divergences." In experiments where the subject was required to view a moving object, Yarbus found that the subject could start or stop visual pursuit of the object at will but could not ". . . interfere voluntarily with the actual process of pursuit and change its speed deliberately." In his analysis of velocities of pursuit, Yarbus found that with angular pursuit velocities of more than five minutes of angle per second, smooth pursuit was possible and was characterized by the presence of small conjugate eye movements. Satisfactory tracking did not seem possible at speeds exceeding 200 degrees of angle per second.

Vergence

Vergence eye movements are movements during which the eyes move in opposite directions. Normally the visual axes of the two eyes intersect at some distance from the subject. Divergence refers to vergence movements that increase this distance while convergence refers to vergence movements that decrease this distance. Feinstein (1970) pointed out that ". . . the amplitude range for vergence movements is much smaller than that for versional [conjugate] movements."

Tremor

Tremor refers to very small, non-conjugate movements of the eyes observed under conditions of fixation (Adler and Fliegleman, 1934). Records of tremor have shown it to consist of angular displacements of a few seconds of angle at frequencies of 30 to 80 displacements per second. Feinstein (1970) states that ". . . it is undecided whether they [tremor eye movements] have any physiological significance or whether they simply represent noise."

Of the three classes of eye movements discussed, it would appear that the ones most relevant to studies of learning and attention are conjugate eye movements. The fact that both eyes move together during conjugate eye movements means that records obtained from one eye are sufficient to describe the subject's looking behavior. This study will document the feasibility of using the infrared computer based oculometer for recording eye movements as they would be used in studies of learning and attention in the field of education.

Eye Movement Research

Dodge (1903) was among the first to begin to analyze eye movements. His distinction between saccadic and smooth pursuit eye movements was investigated further by Westheimer (1954) and Rashbass (1960). Rashbass showed that tasks involving various combinations of displacement and velocity evoke smooth movement responses determined by the task displacement. He concluded that these two different kinds of eye movements were the result of two independent neurological systems.

Volkman (1962) compared vision during saccades with vision during fixations by means of three psychophysical tasks, in an attempt to determine a basis for the lack of apparent blurring during voluntary saccades. He concluded that while vision was not blanked out during voluntary saccades, it was significantly depressed. Matin, Matin and Pearce (1969) sought to further clarify the mechanisms underlying the normal stability of visual direction for stationary objects during voluntary saccades. They used specific points during the occurrence of a saccade as trigger points for the presentation of stationary test flashes to subjects. Subjects reported the perceived direction of motion of a test flash, relative to a fixation target which was extinguished prior to the presentation of the test flash. Classical theory (Helmholtz, 1866; Whitteridge, 1964) suggests that an "extra-retinal" signal occurring outside the retina, and proportional to eye position, acts to compensate for the shift of the retinal image resulting from the movement of the eye, thus a stationary object does not appear to change location during a saccade. Matin, et al. concluded from their findings that there appeared to be an extraretinal signal, but that the extraretinal signal produced was not proportional to eye position. It appeared to be proportional to the elapsed time since the beginning of the saccade. Pearce and Porter (1970) investigated the possibility that a subject's criterion for visual sensitivity was being depressed during voluntary saccades. They developed a criterion-free measure of visual sensitivity and using it to measure saccadic supression, demonstrated that there was a decrease in visual sensitivity as much as 150 to 200 milliseconds prior to the occurrence of a voluntary saccade.

Krauskopf, Cornsweet and Riggs (1960) analyzed horizontal components of eye movements during both monocular and binocular fixation. They found that saccades in one eye seemed to always be accompanied by saccades in the other eye, almost always in the same direction, and about the same size. Drift and tremor of the two eyes are not correlated. Huang and Smith (1970) recorded vertical binocular eye movements and concluded that movements of the two eyes were not exactly conjugate during saccades. They found a time variation of less than 100 milliseconds. Smith, Schremser and Putz (1971) confirmed these findings and concluded that this indicated a possible feedback system between the oculomotor control systems of the two eyes.

Young and Stark (1963) developed and tested a sampled data model to describe the action of the control system of the eye. Robinson (1964, 1965) conducted studies of both the saccadic and the smooth pursuit eye movement systems. He concluded that while the sampled data model of Young and Stark was satisfactory for saccadic movements, it seemed to be inadequate for smooth pursuit movements.

A number of eye movement studies comparing the performance of subjects of various ages have been reported. The aim of such studies is to investigate the developmental aspect of eye movements. Zinchenko, van Chzhi-Tsin and Tarakanov (1963) showed that three year olds tended to fixate longer, made little attempt to search for distinctive features in a display, and stayed within the area of a figure, compared to six year olds. They concluded that eye movements in a growing child develop towards locating distinctive features in visual stimuli.

Vurpillot (1968) studied eye movements of children required to judge stimuli as the same or different. She found that children under six years old tended to make errors in judgement due to insufficient scanning while nine year old children made virtually no errors in judgement.

O'Brien and Boersma (1970) studied the eye movements of 92 female conservers and non-conservers. They found that conservers showed greater perceptual activity in the form of scanning behavior than non-conservers.

Mackworth and Morandi (1967) and Mackworth and Bruner (1970) compared eye movements of adults and children on scanning tasks. Adults showed a greater facility for fixating areas judged to be more informative. They also tended to have longer "leaping" eye movements and shorter fixations.

Miller (1969) recorded eye movement latencies of eight year old children and college students. Subjects were required to change their point of fixation from a central fixation light to one of four randomly illuminated target lights displaced equally in each of four directions from the central fixation light. He found that eight year old children had a longer latency. In addition, he observed that differences in latencies among eight year old children were dependent on the closeness of the target to the central fixation light. No such differences were observed among college students.

Eye movements have been used as the dependent variable in a number of studies of cognitive behavior. Luborsky, Blinder and Mackworth (1963) studied eye movements of subjects during a "search" task. They found that subjects having more fixations were better able to recall the content of perceptual images. Teichener and Price (1966) studied eye movements of subjects given the task of studying a letter sequence in order to determine the next letter in the sequence. They found that a reduction in scanning and an increase in attention to detail resulted in correct solution of the task.

Gould et al. (Gould and Schaffer, 1965; Gould and Brown, 1967; Gould, 1967; Gould and Schaffer, 1967; Gould and Dill, 1969; Gould and Peeples, 1970) conducted a series of experiments to study eye movements of subjects during pattern recognition tasks. They found that subjects spent less time looking at incorrect responses than they did looking at correct or matching responses. They also reported a quadratic relationship between the amount of information contained in a stimulus and the duration of fixation. They concluded that the duration of fixation depended on the amount of cognitive activity required for a specific task.

Faw and Nunally (1967, 1968) reported studies of eye movements of children viewing pairs of pictures differing on a number of different dimensions. They found that subjects spent more time fixating complex and novel stimuli. Children spent more time fixating stimuli having negative affective value while college students spent more time fixating stimuli having positive affective value. Subjects also spent more time fixating stimuli constructed by incongruous juxtaposition, attempting to resolve informational conflict.

Conklin, Muir and Boersma (1968) studied eye movements of "field independent" and "field dependent" subjects given the task of searching for missing parts within a picture. They found that field independent subjects fixated with greater frequency in high-information areas of the stimulus field. They concluded that field independent subjects employed more effective visual search strategies. Boersma, Muir, Wilton and Barham (1969a, 1969b) studied eye movements of field independent and field dependent subjects on "imbedded figures" tasks and "anagram" tasks. On the imbedded figures task, field independent subjects exhibited more shifts between the target figure and the alternatives while on the anagram task, they required less time to scan the 5 letters of the anagram.

Drake (1970) compared eye movements of "impulsive" and "reflective" subjects on the <u>Matching Familiar Figures</u> test. Reflectives tended to look at a larger area of the figure before responding than did impulsives.

Muir (1971) studied eye movements of normal and mentally retarded subjects during directed search tasks and discrimination learning. His results suggested a visual attention deficiency in mentally retarded subjects. Yewchuk (1972) studied eye movements of mentally retarded subjects during a discrimination shift learning task. Eye movement data provided no evidence that individual differences in learning discrimination tasks could be attributed to an attention deficit.

Hess and Polt (1960) and Hess (1965) studied pupil dilation of subjects presented with a variety of stimuli. They suggest that pupil dilation is a measure of interest, emotion, attitude, and ongoing cognitive process. Clark and Johnson (1970) suggested that pupil dilation could be related to cognitive processing. Their results agreed with the findings of Kahneman and Beatty (1966) that the pupil dilates as short term memory is loaded and constricts toward normal size as material is recalled and short term memory is unloaded.

Noton and Stark (1971) suggested that eye movement studies of subjects looking at a variety of stimuli could provide information about whether cognitive processing of visual stimulus information was a serial or a parallel (Gestalt) process. They observed that in scanning a stimulus field, the subject followed a relatively fixed scanpath around a format of features. They discussed the significance of this "feature ring" in terms of recognition of stimuli. They concluded that ". . . the weight of the evidence seems to support the serial hypothesis" and that ". . . the internal representation or memory of an object is a piecemeal affair".

A number of studies of eye movements in relation to learning tasks have been reported. McCormack et. al. (McCormack and Haltrecht, 1966; Haltrecht and McCormack, 1966; McCormack, Hannah, Bradley and Moore, 1967; Hannah and McCormack, 1968; Moore and McCormack, 1968; McCormack, Clemence, Tymm and Malabre, 1969; McCormack and Clemence, 1970) studied eye movement behavior of college students during a variety of paried associates learning tasks. These authors have provided a great deal of evidence in support of Underwood's (Underwood and Schulz, 1960) two stage learning model in which the first stage consists of learning the response and is followed by the second stage, which involves association of the appropriate pairs. They also found that slow learners tend to take longer during the first stage and they experience more difficulty in the second, that eye movements of "high-anxious" subjects differ from eye movements of "low anxious" subjects, and that time spent scanning the response of a paired associate item decreases as learning progresses.

Guba et al. (1964) studied eye movements of subjects during a television lesson. They defined a continuum of eye movements and found that "no observable movements" and "minimovements" were related to intelligence. They also performed density analyses for areas fixated by subjects and found age and intelligence differences.

Nunally, Stevens and Hall (1965) observed eye movements of children after they had learned to associate previously neutral stimuli with rewards. Five days after training, subjects spent significantly more time looking at stimuli previously associated with rewards. Webb, Matheny and Larson (1963) used shock to condition eye movements of subjects. They found that subjects spent significantly less time looking at stimuli previously associated with shock. Schroeder (1970) used reinforcement to train eye movements of college students in a simultaneous discrimination task. He found that subjects fixated stimuli which had previously been reinforced.

Doran and Holland (1969) studied eye movements of subjects studying introductory psychology using programmed instruction. The study sought to determine differences in looking behavior of subjects studying programmed material with high and low "blackout ratios". The blackout ratio was used to provide an index of redundancy. When much material could be left out without affecting the error rate, it was said to have a high blackout ratio. They found that high blackout ratio material resulted in fewer fixations, shorter fixation time and shorter scan time, suggesting that high blackout ratio programs fail to evoke students' attention.

Perhaps no single field of study has shown as much interest in the study of eye movements as the field of reading. The first description of eye movements in reading was presented by Javal in 1879. He reported that the results of direct observation revealed that the eyes move along a line in quick jerks, with pauses between the jerks. Other attempts to measure and record eye movements of subjects while reading were made by Erdmann and Dodge (1898) using a telescope, by Miles (1928) using a "peephole", and by Shackwitz (1913) using a pneumatic capsule attached to the eyelid. A method pioneered by Dodge in 1901 and refined by Tinker in 1931 and Taylor in 1937 based on the corneal reflection principle, led to more than a hundred studies involving eye movements during reading. Tinker (1965) presents a comprehensive review of eye movement studies in relation to reading.

A number of more practically oriented studies involving oculography have also been reported. Such studies have implications for technical and vocational education. Milton and his associates (Milton, Jones and Fitts, 1949, 1950; Milton, McIntosh and Cole, 1951, 1952, 1954; Milton and Wolfe, 1952), Barnes (1970), and Gainer (1964) conducted extensive research on eye movements of pilots under a variety of specified flight conditions. Their findings were used in the design of airplane and helicopter control panels and in the design of pilot training programs. Schroeder and Holland (1968) monitored eye movements of subjects presented with a vigilance task. Subjects were required to visually detect deflection of ammeters arranged in a simulated "control panel" configuration. They concluded that ". . . an eye movement can act as an operant, controlled by its consequences." They suggest that operant control of eye movements has important implications for human factor analysis concerned with attention.

One basic underlying assumption of educators involved in preparing visual instructional materials for students is that students will look at or attend to the appropriate visual material during the learning process. If the learner does not attend to the appropriate visual material during the learning process, then learning may be seriously inhibited. The study of eye movements can provide educators with feedback about the effectiveness of their visual material, whether it be a page or a picture in a text book, an overhead projectual, a test item or a cathode ray screen of a computer assisted instructional system. Such feedback forms one essential part of the basis for producing improved visual materials for instruction. It can also form the basis for teaching students effective looking behavior.

It is apparent from the studies reviewed in this chapter that oculography has been a subject of interest to many researchers in many different disciplines over the past seventy years. The biggest single limitation to more extensive oculographic studies has continually been the limited sophistication of available hardware. Recent developments in electronics and computer technology have now provided some new possibilities for hardware that measures records and analyzes eye movements quickly, easily and unobtrusively. The purpose of this study is to document the development of an infrared computer based oculometer system designed and built with this end in mind. Chapter III describes the infrared computer based oculometer system and documents its performance while the remaining chapters illustrate some applications of this system to oculographic research in education.

CHAPTER III

DESCRIPTION OF THE INFRARED COMPUTER BASED OCULOMETER SYSTEM

Introduction

The importance of oculographic data to many fields, including education has been recognized for more than half a century. During this time, many attempts have been made to develop systems designed to acquire eye movement data. Chapter II briefly describes the basic methods of oculography that have been developed.

Each of the existing methods of oculography was developed to meet a specific need. For example, the Yarbus "cap" (Yarbus, 1968) was a very precise way to measure and record physiological characteristics of the eye, but it would be of little use to a researcher who wished to study eye movements of grade one children while reading. Similarly, the Mackworth camera is an excellent means of determining where a subject is looking, but the need for a bite bar places the subject in a highly artificial experimental situation.

The study of eye movements in relation to learning and attention requires that:

1. The measuring and recording apparatus be relatively unobtrusive.
2. The equipment require no mechanical attachment to the subject.
3. The equipment place as few unnatural constraints (such as restriction of head movement) on the subject as possible.
4. As many oculographic characteristics as possible be

recorded simultaneously.

5. The data be in a form that is readily accessible for analysis by computer.
6. The equipment be sensitive enough to detect, and fast enough to record all types of conjugate eye movements.

Since none of the systems currently being used for oculographic research meets all of these criteria, it is perhaps not surprising that "The number of studies of learning which have employed EM [eye movement] data is disappointingly small" (Fleming, 1969). The infrared computer based oculometer system described here is an oculographic system that will unobtrusively (using infrared light) and with a minimum of head restraint (chin rest) record eye-pointing direction and pupil dilation, once every thirtieth of a second.

The infrared computer based oculometer system is based on the corneal reflection method of oculography. The eye is illuminated with infrared light and the image of the eye is projected to the face of an infrared television camera which is connected via a special interface unit to a small digital computer. The computer rapidly analyzes the signal coming from the camera and calculates and records the displacement of the corneal reflection from the pupil center and the pupil dilation. One such set of data is recorded every thirtieth of a second. This chapter will describe in detail how the infrared computer based oculometer system operates.

The Eye

The human eyeball is approximately sperical and contains optical apparatus which includes two refracting elements, the cornea which is the transparent, curved front portion of the eyeball wall, and the lens which is the refracting element with variable power. The iris, situated between the cornea and the lens acts to control the size of the opening at the front of the eye. (See Figure 1).

The sensory apparatus of the eye is the retina, a thin membrane of photoreceptors. The area of the retina possessing the highest degree of visual accuity is the fovea. (Feinstein, 1970).

The optical axis of the eye lies along a line joining the center of the pupil, the center of corneal curvature, and the fovea. The extension of the optical axis foreward from the eye indicates the point in space being fixated foveally by the eye. (See Figure 2).

The Infrared Image

In order to determine the position of the optical axis of the eye, and thereby determine its point of fixation, it is necessary to make the pupil center and the center of corneal curvature visible. This may be accomplished by illuminating the pupil with infrared light, which is not visible to the human eye. An observer, equipped with an infrared light detector, and situated on an axis collinear with the beam of infrared light being used to illuminate the eye would see the pupil as a bright luminous disc of infrared light against a dark background consisting of the sclera. Within the area of the pupil the observer would see a very small spot of light several times more intense than the pupil -- the corneal reflection. (See Figure 3).

Neither the center of the pupil nor the center of corneal curvature is directly visible as a result of infrared illumination of the eye, however both may be easily determined. Since the pupil appears

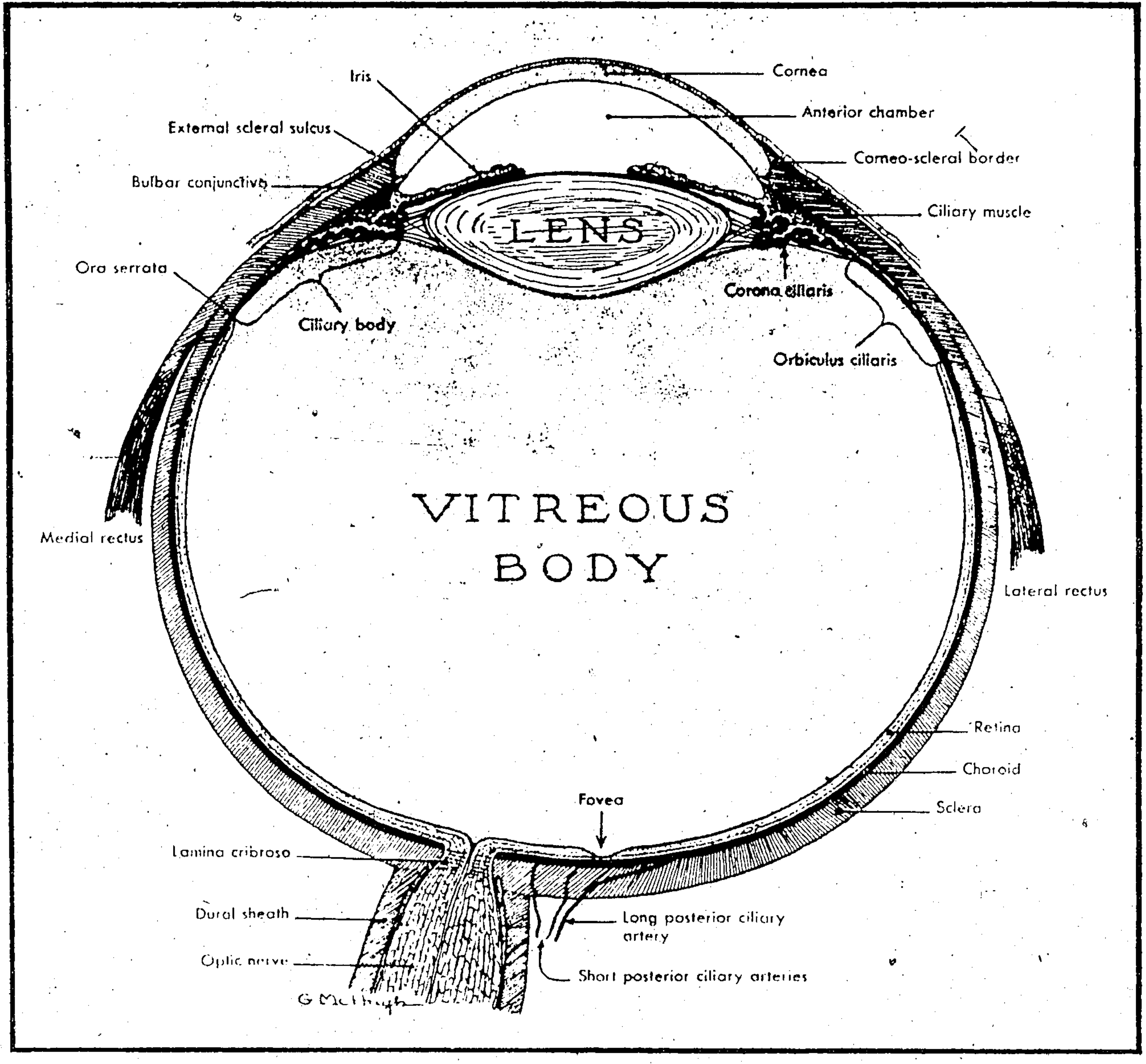


Figure 1

The Human Eye

(From P. C. Kronfeld, 1943)

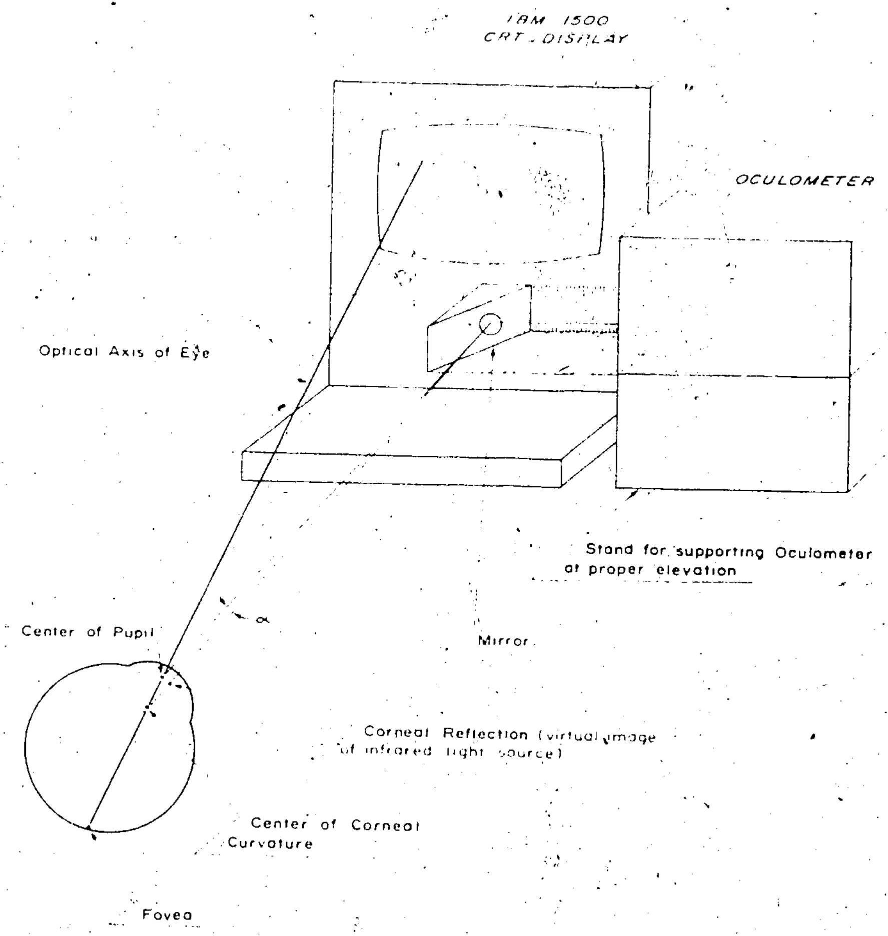


Figure 2

RELATIONSHIP OF EYE POINTING COORDINATES TO CR DISPLACEMENT

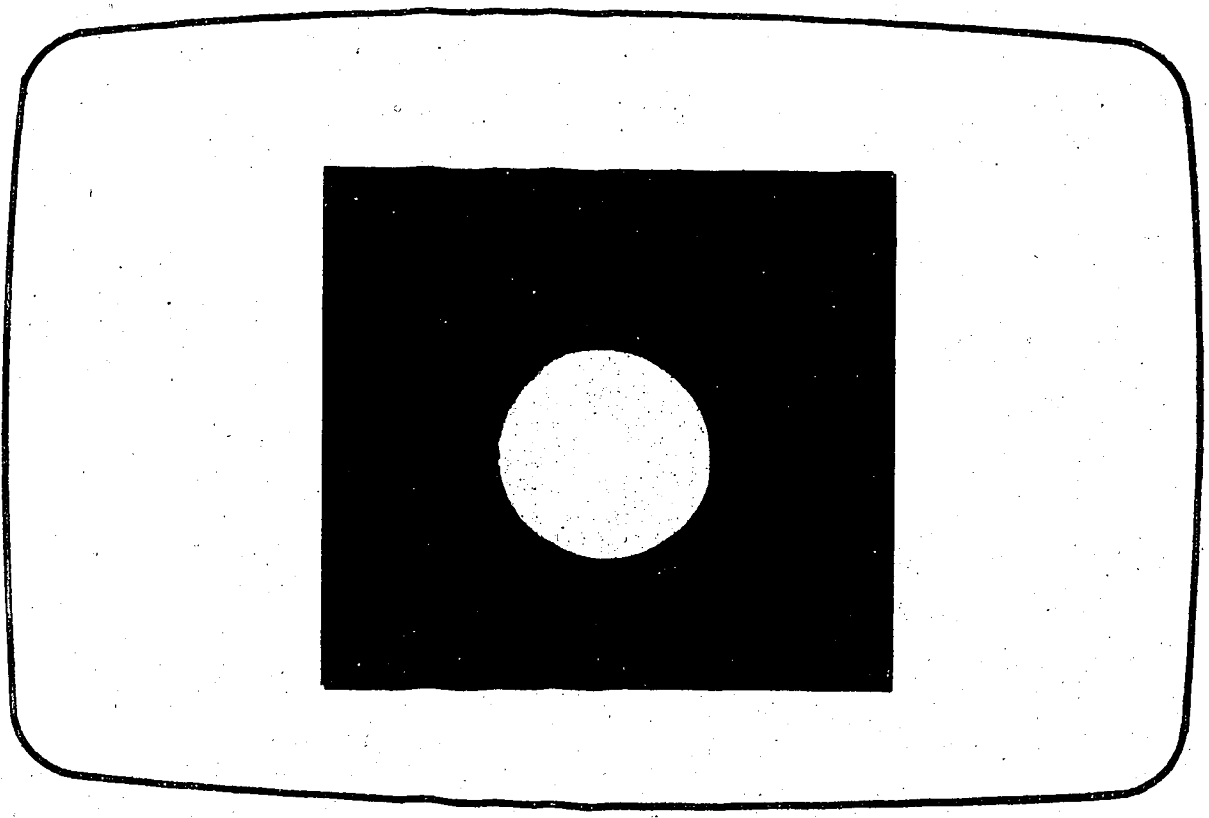


Figure 3

Infrared Image of the Pupil and the Corneal Reflection as a circular disc, the center of the pupil can be located by bisecting the perpendicular to a tangent to the pupil. The cornea, because of its curvature will form a virtual image of the infrared light source as shown in Figure 2. This corneal reflection will lie on a line between the infrared source and the center of corneal curvature, therefore to an observer located at the source of infrared light, the corneal reflection would appear in exactly the same position as the center of corneal curvature (see Figure 2). The center of corneal curvature can therefore be found by bisecting the perpendicular to a tangent to the corneal reflection.

When the optical axis of the eye is pointed directly at the source of infrared light, an observer positioned at the source of infrared light would observe the corneal reflection to be at the center of the pupil. As the optical axis moves away from the source of infrared light, the corneal reflection will be displaced from the center of the pupil. The displacement of the corneal reflection from the center of the pupil is functionally related to the displacement of the point of fixation from the infrared source. Feinstein (1970) indicates that for angular displacements of less than 12 ½ degrees of angle, the relationship between eye pointing direction and relative corneal reflection displacement is linear. Mason and Merchant (1969) state that for movements of the subject's head, either sideways or up and down, ". . . there is only a small second order effect introduced" which may be ignored without appreciable error. It is therefore the displacement of the corneal reflection relative to the pupil center as viewed from the source of infrared light that will be used as the basis for determining eye pointing direction.

The Camera

The complete infrared oculometer camera unit or optical head is shown diagramatically in Figure 4. This unit was designed and supplied by the Honeywell Radiation Center of Lexington, Mass. and consists of a source of infrared light, an infrared television camera and optical equipment that reflects the infrared light so that it is collinear with the pointing direction of the camera. A Sylvania quartz halogen lamp connected to a Superior type 10B variac or autotransformer serves as the variable intensity source of light. It is fitted with a lens and a Kodak type 87C gelatin filter which removes all visible light with the exception of a small amount of red giving it the appearance of a pilot light. A beam splitter directs the infrared light towards the eye of the subject. The image of the eye is projected through the beam splitter and a second infrared filter to the face of a Raytheon model 615 television camera specially equipped with an infrared sensitive RCA 4523A silicon vidicon tube.

The camera converts the infrared image of the eye into a standard 525-line interlaced video signal. The size of the video signal during any given scan line is determined by the nature of the image being scanned. When the black background of the sclera is being scanned, the level of the video produced is about 500 millivolts. When the image of the pupil is being scanned, the video signal rises to about 1.3 volts and when the corneal reflection is being scanned, the video signal exceeds 2 volts. Figure 5 shows the video signal produced by the camera when the various parts of the image are scanned.

HONEYWELL MK1
OCULOMETER

1 RAYTHEON MOD 615 CAMERA E/W RCA 4523A SILICON VIDICON

2 MIRROR

3 36" LENS E/W KODAK 87C FILTER

4 BEAM SPLITTING MIRROR

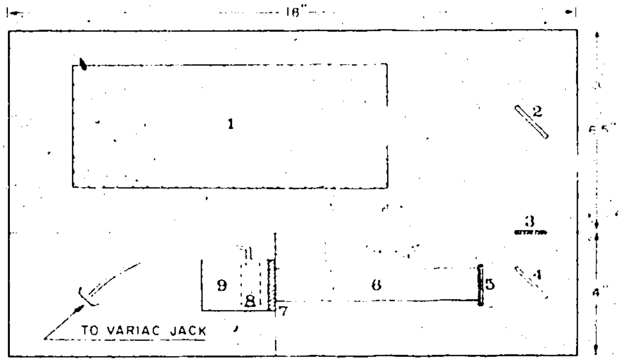
5 INFRARED GELATIN FILTER TYPE 87C

6 COLLIMATING TUBE

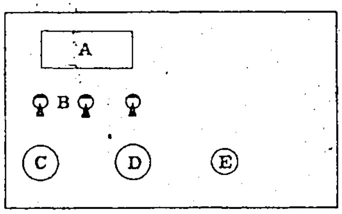
7 LENS

8 SYLVANIA TYPE FCR QUARTZ HALOGEN LAMP

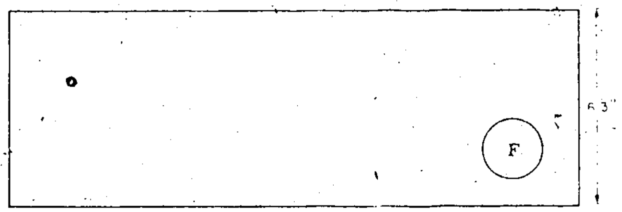
9 PARMOTOR MOD 8500 MUFFIN FAN



TOP VIEW
COVER OFF



SIDE VIEW



FRONT VIEW
COVER ON

A CAMERA ACCESS PORT

B TOGGLE SWITCHES

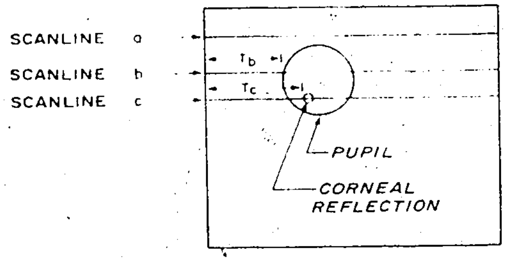
C SYNC OUTPUT JACK

D VARIAC JACK (TO SUPERIOR TYPE 10B VARIAC).

E VIDEO OUTPUT JACK

F PORT

Figure 4



VIDICON FACE

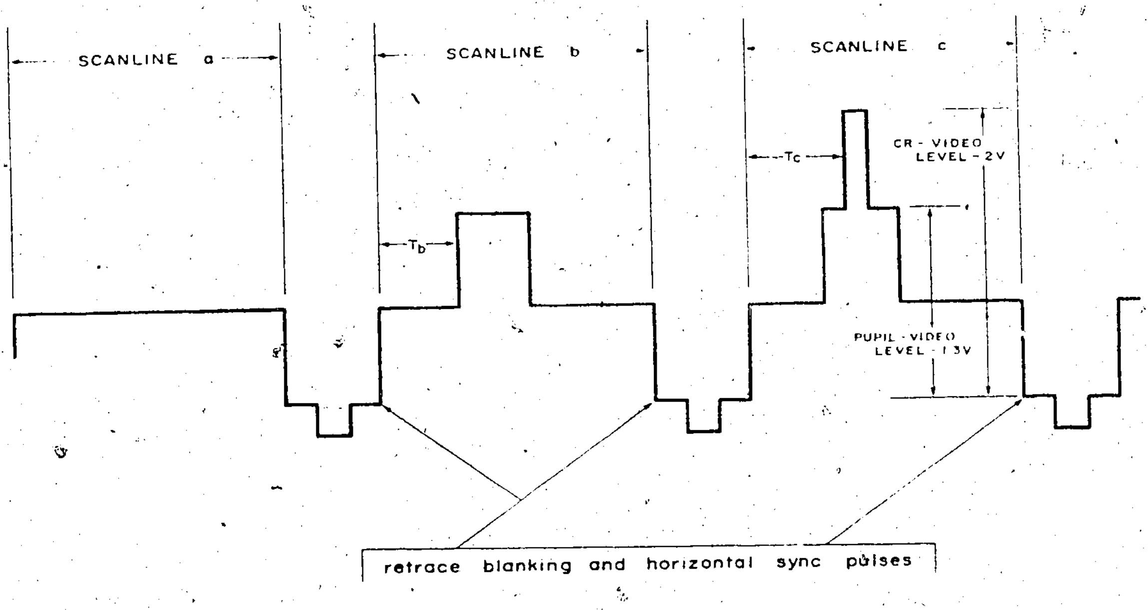


Figure 5

VIDEO OUTPUT WAVEFORM

In addition to the video signal described above, the camera also outputs horizontal and vertical synchronization pulses. A horizontal synchronization pulse is generated at the end of every scan line executed by the camera, therefore there are 15,750 horizontal synchronization pulses generated every second. A vertical synchronization pulse is generated whenever the scanning for one field has been completed and the camera is ready to start scanning a new field. This occurs sixty times per second.

The Computer-Camera Interface Unit

Perhaps the most important element of the entire infrared computer based oculometer system is the computer-camera interface unit. This unit serves two major functions. First, because it is necessary to use the computer to process the camera output, and because the size and shape of the camera output signals are not compatible with the input requirements of the computer, this unit must modify the size and shape of the camera output signals to conform to the input requirements of the computer. Second, the computer-camera interface unit identifies and monitors each scanline generated by the camera. Based on changes it detects in the camera output level relative to a time base it generates, it determines whether a pupil and/or a corneal reflection has been intercepted, the position of the point of intercept relative to its time base, and the instant when a given scanline has reached the end of its scan.

This information is available to the computer to be used as the basis for determining oculometer output.

A simplified block schematic of the computer-camera interface unit is shown in Figure 6. This unit consists of two separate sub-assemblies. One sub-assembly contains the crystal clock which is used to generate a 10 megahertz time base. The time base is derived from a 50 megahertz crystal coupled to a "divide by 5" circuit which is reset at the start of each horizontal scanline. In this way, the starting point of the 10 megahertz time base can be more precisely aligned with the start of the horizontal scanline, thereby improving the accuracy with which pupil and corneal reflection intercept points may be determined.

The second sub-assembly contains all of the remaining circuitry that makes up this unit. It consists of a plug-in printed circuit board equipped with 39 integrated circuits and one transistor.

When a vertical synchronizing pulse comes from the camera, it clears the line count accumulator, indicating that a new field is about to be scanned by the camera. When this pulse is terminated by the camera, there is a time lag of a few microseconds prior to the occurrence of the first horizontal synchronizing pulse. As soon as the first horizontal synchronizing pulse is generated by the camera, it increments the line count accumulator and puts out an interrupt signal to the computer, telling the computer to interrupt whatever it is doing since the interface unit must be serviced. The total amount of time required to service the interface unit and to prepare the interface unit to monitor the next scanline is approximately 18 microseconds. Therefore the horizontal

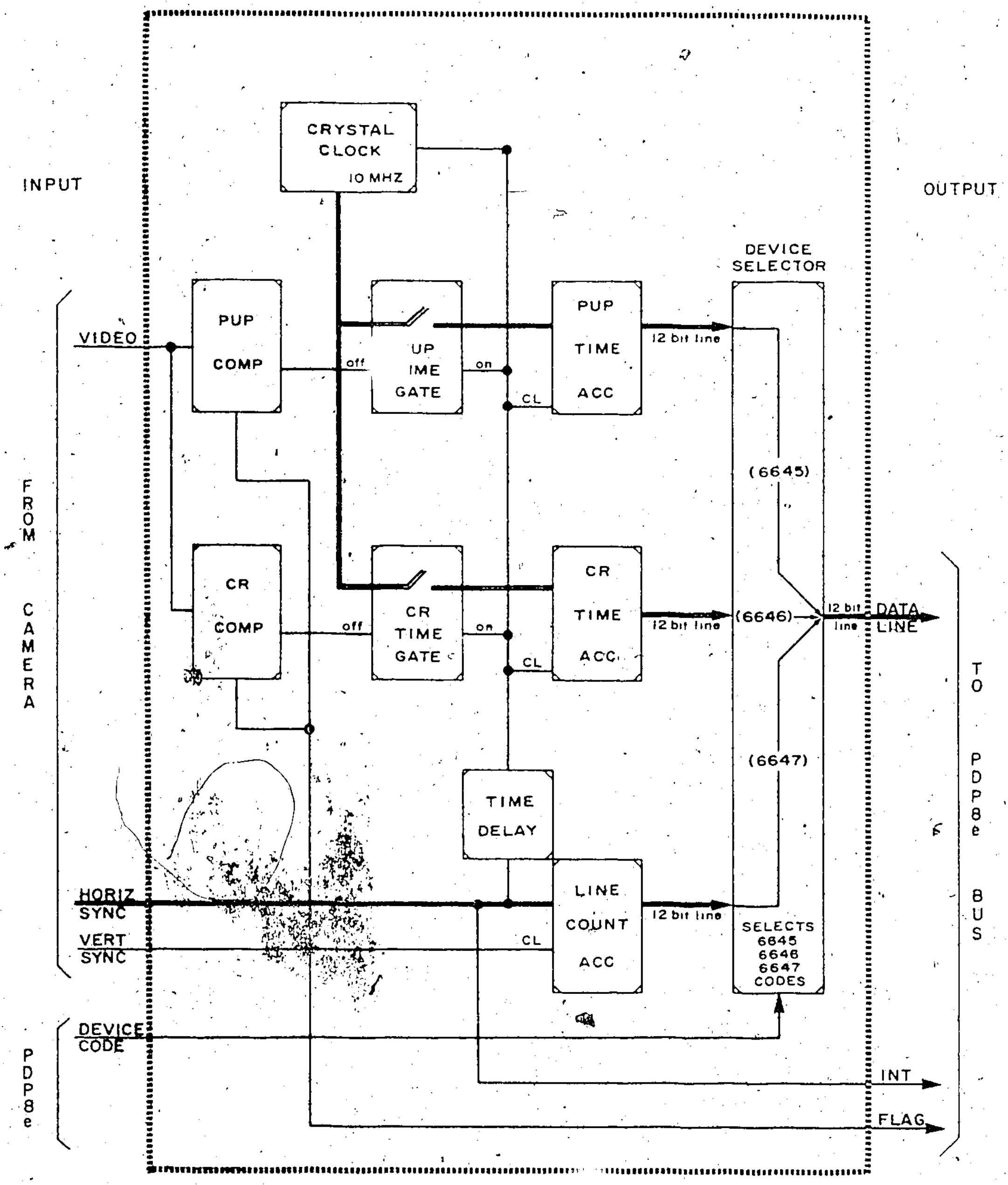


Figure 6

COMPUTER - CAMERA
INTERFACE UNIT
simplified block schematic

LEGEND

ACC	*accumulator*
CL	*clear*
COMP	*comparator*
CR	*corneal reflection*
INT	*interupt*
PUP	*pupil*
VERT	*vertical*
HORIZ	*horizontal*
━━	*primary signal path*

synchronizing pulse is also fed into a variable time delay circuit which is adjusted to 18 microseconds, and the output from the time delay circuit is used to initiate the operation of the interface unit to monitor the next scanline. Since the camera requires only 10.2 mirco-seconds to return the scanline to its starting position and begin scanning the next scanline and the interface unit requires 18 micro-seconds before it begins monitoring the next scanline, the scanline performs the first portion of its scan without being monitored by the interface unit. This occurs for a period of approximately 14% of the total horizontal scan width. Therefore, in positioning the subject before the oculometer, care must be taken to insure that the image of the eye does not fall within this (the leftmost) region.

To initiate the operation of the interface unit, the output pulse from the time delay circuit simultaneously clears the pupil time and CR time accumulators, turns on the pupil time gate and the CR time gate, and zeros the divide by 5 circuit on the crystal clock. This connects the crystal clock to the pupil time accumulator and the CR time accumulator so that these accumulators are incremented by the crystal clock by a count of one every tenth of a microsecond.

If the video signal from the camera is the result of scanning black background, the size of the video signal will be smaller than a preset threshold voltage level at the comparators. As a result, the comparators will not "fire", and the "flag" will not be raised. When the scan is completed, the next horizontal synchronizing pulse occurs, and the process is repeated.

If the video signal from the camera is the result of scanning the pupil, the size of the video signal will be larger than the preset reference voltage level at the pupil comparator, but smaller than the preset reference voltage level at the CR comparator. This means that the instant that the pupil is intercepted the pupil comparator will "fire", turning off the pupil time gate and turning on the "flag", telling the computer that an increase in video signal has been located. At this time, the pupil time accumulator will contain a time measurement which is directly related to the abscissa, and the line count accumulator will contain a scan line number which is directly related to the ordinate of the point where the scan line intercepted the contour of the pupil.

If the video signal from the camera is the result of scanning the corneal reflection, the size of the video signal will be larger than the preset threshold voltage level at the CR comparator. This means that the instant that the corneal reflection is intercepted, the CR comparator will send a signal which will turn off the CR time gate and turn on the flag, telling the computer that an increase in video signal has been located. At this time, the CR time accumulator will contain the abscissa and the line count accumulator will contain the ordinate of that point on the corneal reflection.

The computer-camera interface therefore senses the contour of the semi-circumference of both the pupil and the corneal reflection. The abscissa of each point on the contour is recorded in terms of "clock pulses" where one clock pulse is one tenth of a microsecond. A better indication of the horizontal scale of measure may be attained by expressing this as a linear measure at the eye of a subject positioned

.16 inches from the camera. A horizontal displacement of one clock pulse corresponds to a linear measure at the eye of the observer of approximately .0064 inches. The ordinate of each point in each array is measured in terms of "scan lines". A vertical displacement of one scan line corresponds to a linear displacement of approximately .0048 inches at the eye of the observer.

Figure 7 illustrates the overall time relationship of the signals on this unit relative to the camera output signals. A detailed schematic diagram of the computer-camera interface unit is provided in Appendix A.

The Computer

The computer portion of the infrared computer based oculometer system serves three major functions. First, it monitors the "flag" and stores the contents of the three accumulators on the computer-camera interface unit whenever the "flag" is raised. Second, when the coordinates of all the points on the contours of the pupil and the corneal reflection have been stored, the computer uses this information to calculate the displacement of the corneal reflection from the pupil center and the pupil dilation. Finally, the computer transfers a record of this information onto a 9-track magnetic computer tape. This process is repeated once every thirtieth of a second.

The computer unit will be described in terms of the hardware that constitutes this unit, the software or programming that makes it operational, and the output that comes directly from this unit.

The Computer Hardware

The central process computer used in this research was a rack-

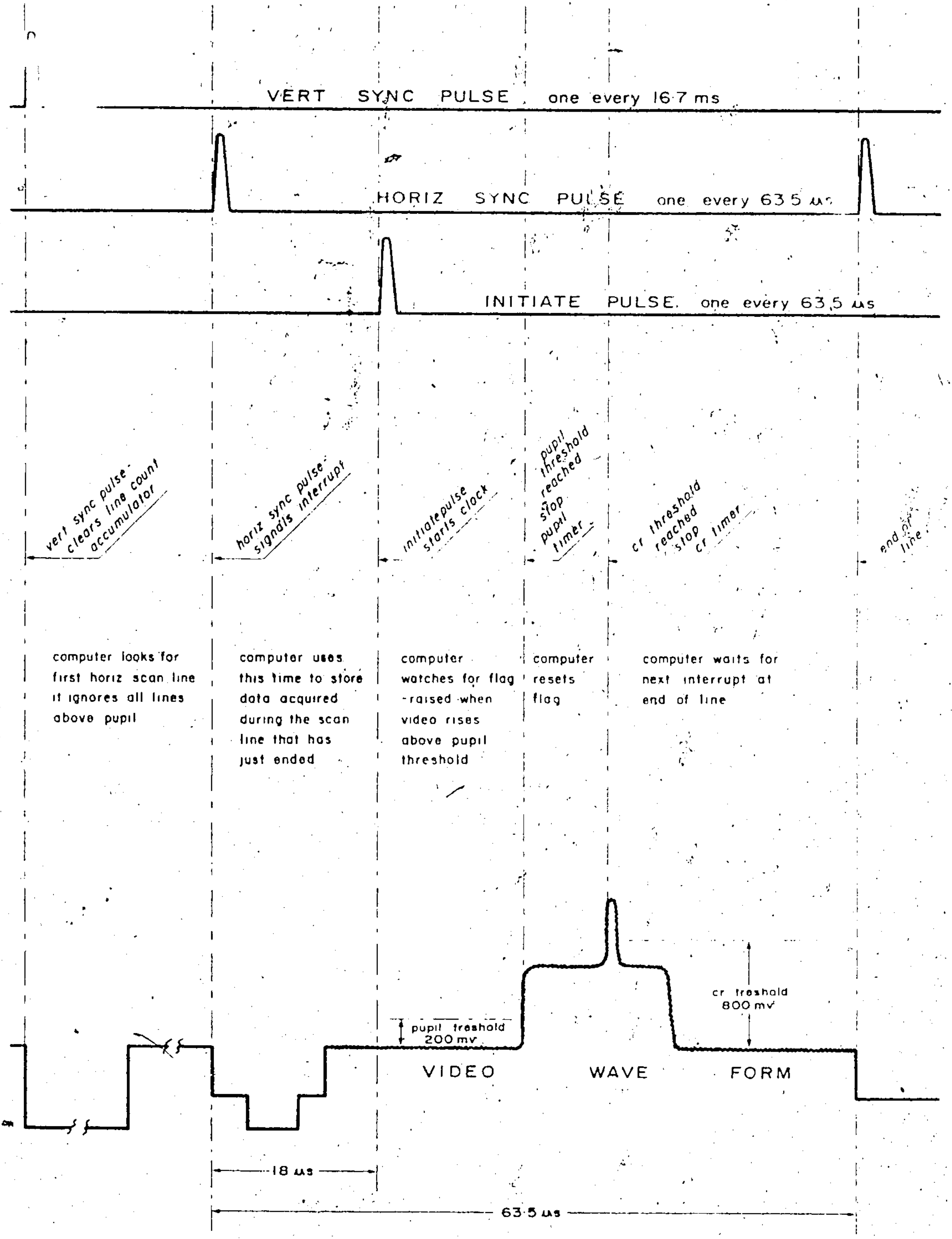


Figure 7

RELATIONSHIP OF COMPUTER FUNCTIONS
TO CAMERA OUTPUT SIGNALS

mounted model PDP-8/e minicomputer manufactured by Digital Equipment Corporation. It was equipped with 8K core, an extended arithmetic element, a two channel D/A converter, a one channel A/D converter, a power-fail and memory protect option, a 9-track magnetic tape unit and a model ASR33 teletype input/output unit. All of the above units were standard equipment supplied by Digital Equipment Corporation. In addition, a CONRAC video monitor, a Telequipment rack-mount oscilloscope and a 5-volt reference power source were also located on the rack. The computer-camera interface unit plugged directly into the bus of the computer.

Appendix B shows the configuration of the equipment on the rack. Appendix C shows a simplified block schematic of the computer hardware unit used in this study.

The Software

All of the programming for the infrared computer based oculometer system was done using machine language. While machine language programming tends to be the most tedious and time-consuming method of programming, it was selected for a number of reasons. First, most of the programming was completed before the magnetic tape unit arrived. This meant that the only way to load system programs such as the assembler was via paper tape and the teletype unit. This is an extremely slow and tedious process. Second, it was felt that more efficient programs could be written by programming in machine language. Finally, since the computer was acquiring information from the camera (via the interface unit) and processing it "on-line", it was more convenient during debugging to work in machine language. These factors, combined with the fact that the overall program was relatively short, led to the decision to use machine language in programming the computer.

Essentially, the program is designed to store the contents of the three accumulators located on the computer camera interface unit whenever a scan line intercepts either the pupil and/or the corneal reflection, and to calculate and store the coordinates of the displacement of the corneal reflection from the pupil center, and the pupil dilation.

Two conditions are received by the computer from the computer camera interface unit; a "flag" that occurs whenever a scan line intercepts a pupil and/or a corneal reflection, and a "interrupt" that occurs whenever a scan line has reached the end of its scan. If during the early part of the scanning sequence, neither the pupil nor the corneal reflection are struck, the flag is not raised, and as each scan line reaches the end of its scan, an interrupt occurs. The absence of a flag means that there is no useful information, which needs to be stored, contained in the accumulators on the computer camera interface unit, so that immediately after the interrupt has occurred, normal program execution resumes as the next scan line begins. When a scan line strikes a pupil, the flag is raised. This means that the contents of two of the accumulators on the computer camera interface unit, namely the line count accumulator and the pupil time accumulator, need to be stored. The program therefore modifies itself so that immediately after the interrupt has occurred, the contents of these two accumulators are stored, and then normal program execution resumes, as the next scan line begins. This process is repeated until a corneal reflection is struck. The program then again modifies itself so that after the interrupt occurs, all three of the accumulators on the computer camera interface unit are stored prior to resuming normal program execution. This process continues so that when the entire pupil has been scanned, the computer has stored the coordinates of every point on the semi-circumference of both the pupil and the corneal reflection.

During the time that the camera is scanning the dark portion of the image below the pupil, the computer calculates and stores the abscissa of the vertical tangents to the pupil and the corneal reflection, the pupil dilation, the diameter of the corneal reflection and the vertical displacement between the pupil center and the center of the corneal reflection. The dilation is measured and expressed in terms of the number of scan lines that actually intercepted the pupil. The ordinate of the pupil center is determined in terms of the absolute number of the scan line that pass through the pupil. This is determined by simply subtracting the absolute number of the first scan line that intercepted the pupil from the absolute number of the last scan line that intercepted the pupil and adding half this quantity to the absolute number of the first scan line that struck the pupil. (See Figure 8). For example, if the first scan line to strike the pupil was line 75 and the last scan line to strike the pupil was line 275, then the pupil dilation would be (275-75)=200 lines, and the ordinate of the pupil center would be located on line (75 + (275-75)/2)=175. The ordinate of the center of the corneal reflection is needed to

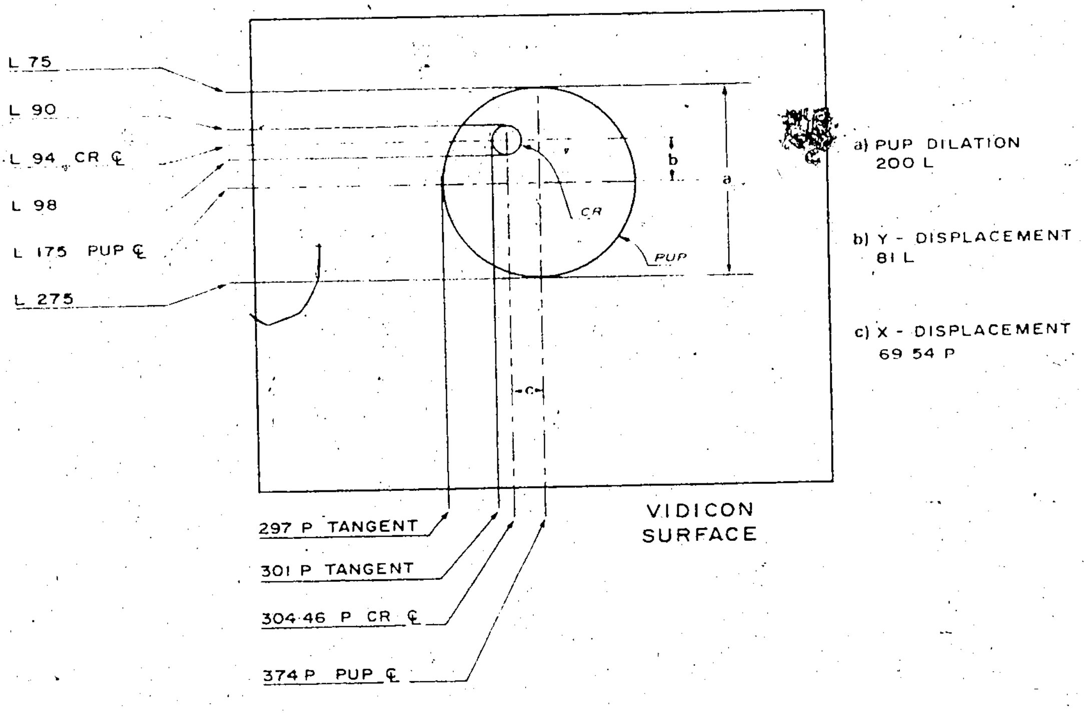


Figure 8

DERIVATION OF DILATION
AND X- & Y- DISPLACEMENT

LEGEND

CR	*corneal reflection*
L	*line(s)*
P	*pulses*
PUP	*pupil*

determine the vertical coordinate of fixation, and is calculated in exactly the same way as the pupil center. Hence, if the first scan line that struck the corneal reflection was line 90 [illegible] the last one was line 98, then the center of the corneal reflection would be located on line (90 + (98-90)/2)=94. The vertical displacement of the center of the corneal reflection from the pupil center, which is a measure of the ordinate of fixation is simply calculated by subtraction, and in the example, is (175-94)=81 lines. Displacements occurring when the eye is looking up were labelled positive (+) and displacements occurring when the eye is looking down were labelled negative (-).

The abscissa of the pupil center and the horizontal displacement of the center of the corneal reflection with respect to the pupil center are calculated in terms of 10 megahertz clock pulses. As explained earlier in this chapter, a 10 megahertz clock begins incrementing the pupil time accumulator and the CR time accumulator at the instant that the scan line is initiated, and incrementing of each respective accumulators ceases when intercept of the pupil and/or the corneal reflection occurs.

To find the abscissa of the pupil center, the abscissa of the vertical tangent to the pupil is located first. The radius of the pupil is then calculated based on the measure of pupil dilation obtained previously. This abscissa of the pupil center is the sum of the abscissa of the vertical tangent to the pupil and the radius of the pupil.

The abscissa of the vertical tangent to the pupil is obtained by calculating the mean horizontal displacement observed over the four scan lines) nearest the center of the pupil. For example, in Figure 8, the center scan line of the pupil was line 175. The mean horizontal displacement of lines 174, 175, 176, and 177 would be used as the basis for determining the abscissa of the vertical tangent to the pupil. If the observed horizontal time displacements of lines 174-177 were 296, 297, 297 and 298 respectively, the abscissa of the vertical tangent to the pupil would be 297.

As explained previously, the dilation of the pupil is determined in terms of scan lines. Assuming that the pupil is circular, this measure of dilation may be expressed in terms of pulses by recognizing that the horizontal-to-vertical aspect ratio in a television system is 4:3, and that the vertical axis is scanned by 519 lines (consisting of 525 lines less 6 lines lost during retrace) and the horizontal axis consists of 533 pulses. The conversion factor for converting length measured in scan lines to pulses is (533/525 x 3/4) = 0.77. Therefore, the diameter of the pupil may be expressed in terms of pulses by multiplying the dilation in scan lines by 0.77. The radius is simply half the diameter. In the example in Figure 8, the pupil dilation of 200 lines is equivalent to (200 x .77) = 154 pulses so the radius of the pupil is 77 pulses. The abscissa of the pupil center is therefore (297 + 77) = 374 pulses.

The abscissa of the corneal reflection is calculated in a similar manner except that the mean abscissa to the vertical tangent is calculated over 3 lines. In Figure 8, the mean abscissa to the vertical tangent of the corneal reflection is 301 pulses, the radius of the corneal reflection is ((0.77 x 9) ÷ 2) = 3.46 and therefore the abscissa of the corneal reflection center is 304.46 pulses.

The horizontal displacement of the center of the corneal reflection from the pupil center, which is a measure of the abscissa of fixation is simply calculated by subtraction and in the example is (374-304.46) = 69.54 pulses. Displacements occurring when the eye is looking to the left were labelled positive (+) and displacements occurring when the eye is looking to the right were labelled negative (-).

Upon completion of the calculations as described, the program stores the results in core memory. The computer then awaits the completion of the scan at which time a new scan is initiated, and the procedure is repeated. After each block of 180 sets of readings (6 seconds) is accumulated in core, the scanning procedure is interrupted for two thirtieths of a second while the readings are transferred to magnetic computer tape.

In the event that a complete scan takes place and no pupil is found, (as in the case of a blink), or no corneal reflection is found ([illegible] may occur when the subject looks away from the target at some extremely large angle), the program outputs a distinct set of characters (7777) in place of the displacement coordinates. This makes it possible to detect when "blinks" occurred and to determine the duration of the blinks.

The Output

Output from the infrared computer based oculometer is stored on 9 track magnetic tape. Included in the output are:

1. the abscissa of the vertical tangent to the pupil center expressed in terms of scan lines,
2. the abscissa of the vertical tangent to the corneal reflection expressed in terms of scan lines,
3. the ordinate of the displacement between the pupil center and the corneal reflection, expressed in terms of 10 megahertz clock pulses,
4. the pupil dilation expressed in terms of scan lines, and
5. the diameter of the corneal reflection, expressed in terms of scan lines.

This provides sufficient data for the calculation of the horizontal displacement between the pupil center and the center of the corneal reflection. The vertical displacement is available directly from the tape.

In order to express this data in terms of absolute target coordinates, it is necessary to calibrate the system to a particular subject. This is accomplished by having the subject look at several specific points in the target area whose physical locations relative to each other are known. By recording horizontal and vertical displacements of the corneal reflection relative to the pupil center for these points, prior to conducting the actual eye movement study, it is possible to express the displacements recorded by the oculometer in terms of physical location within the target area. The process of translating oculometer output coordinates into target coordinates along with other data analysis is carried out on the IBM 360 model 67 computer.

Proof of Performance

One problem that is an inherent part of the development of any new measuring instrument is the problem of establishing validity, reliability and accuracy, or proof of performance of the instrument. The infrared computer based oculometer is not unique in this respect. This section of the study will describe the method that was followed in establishing proof of performance of the system and will present proof of performance findings.

The task of determining where a subject is looking may be broken down into several sub-tasks. First, since changes in the displacement of the corneal reflection with respect to the center of the pupil are related to changes in eye pointing direction, one sub-task is to be able to accurately measure this displacement at any instant in time. This implies that the infrared computer based oculometer system must have the capability of measuring linear distances in both the horizontal and the vertical directions. The first part of the proof of performance will therefore be to establish the existence of this capability.

A second sub-task is to be able to determine the position of the centers of both the pupil and the corneal reflection, since these centers are not made directly readable by the illumination process. Possible sources of error with respect to the performance of this sub-task will be identified and their effect on the determination of where a subject is looking will be discussed.

A third sub-task is to be able to associate an observed displacement (of the corneal reflection with respect to the center of the pupil) with the actual point in space being observed, taking into account both the error due to the oculometer system and error due to uncertainty about where the human eye is actually looking at a given instant in time. Determination of system performance on this sub-task will result in a statement of the system's limits of capability for determining where a subject is looking.

Measurement of Linear Displacement

In order to assess the capability of the infrared computer based oculometer system to measure horizontal and vertical linear displacements, a simulated eye was constructed. It consisted of a black box 3.5" x 4" x 2" deep. On the face of the box was a white circle 0.28 inches in diameter which contained a pinhole arbitrarily positioned in the lower right quadrant of the circle. A 5 watt, 110-volt incandescent lamp was mounted in the box, directly behind the pinhole. When positioned in the field of view of the camera, the image of the simulated eye very closely resembled the image of a human eye, the incandescent light behind the pinhole created an intense 'spot' resembling the corneal reflection, the white circle resembling the pupil, and the black background of the box resembling the face of the subject.

For testing purposes, the simulated eye was positioned in the field of view of the camera unit so that a properly focused image closely resembling the eye appeared on the video monitor. With an intensity setting of 40 on the variac, the camera produced a video output signal closely resembling that shown in solid lines in Figure 7.

The oculometer system was then started, resulting in the simulated eye being scanned over 100 consecutive frames, the results of each scan being stored in the core memory of the computer.

All 100 sets of readings taken were identical, demonstrating the reliability of the system. It was observed that a total of 58 scan lines in the horizontal plane struck the simulated pupil, which was 0.28 inches in diameter. This demonstrated that the approximate vertical resolution rate of the oculometer system is .0048 inches between two adjacent scan lines at the eye. Similarly, it was observed that the difference in horizontal output corresponding to the radius of the simulated pupil (.14 inches) was 22 pulses. This demonstrated that the approximate horizontal resolution rate of the system is .0064 inches between two adjacent pulses at the eye.

Establishing the validity of the oculometer system in relation to measurement of linear displacements was simply demonstrated by placing a lens cover over the camera unit. This resulted in output from the system signifying that a blink had occurred; that is, that the system was unable to locate either a pupil or a corneal reflection. No internal noise which could cause a false identification was evidenced in the electronics of the system.

Determining Centers of the Pupil and Corneal Reflection

Given that the oculometer system is capable of measuring linear displacements as indicated above, once the points between which the measurement must be made are established, it is necessary to consider possible ways in which error might be introduced in the determination of these points. Two types of error will be considered. Error designated in this study as "type A" error occurs when a very small change in pupil diameter or corneal reflection diameter has occurred, while error designated in this study as "type B" error occurs because of the system's inability to resolve dimensions less than one scan line in the vertical plane and less than one clock pulse in the horizontal plane. The effects of each type of error will be considered separately for the vertical and for the horizontal directions.

For measurements in the vertical direction (measured in terms of scan lines) it will be assumed that a target positioned in the space between two adjacent scan lines will be measured to the nearest scan line. That is, if a target extends across lines 20, 21, 22, and beyond line 22, partially across the space between lines 22 and 23, it will be resolved as extending to line 22 if it extends less than half way between lines 22 and 23, and as extending to line 23 if it extends more than half way between lines 22 and 23.

To illustrate the possible effects of type A error on measurement, in the vertical direction, the following example will be considered. Assuming that a pupil was positioned precisely between and tangent to lines 122 and 196. (See Figure 9), simple calculations reveals that the center of the pupil would lie on line 159. Now suppose that the pupil were to remain stationary at this point, but were to undergo a slight dilation. Assuming that the dilation occurred symmetrically around line 159, the pupil might at some point in time extend one-third of the distance towards lines 121 and 197. This in itself would produce no change in the oculometer output. However, if coupled with the change in dilation, the subject were to raise his head by one-

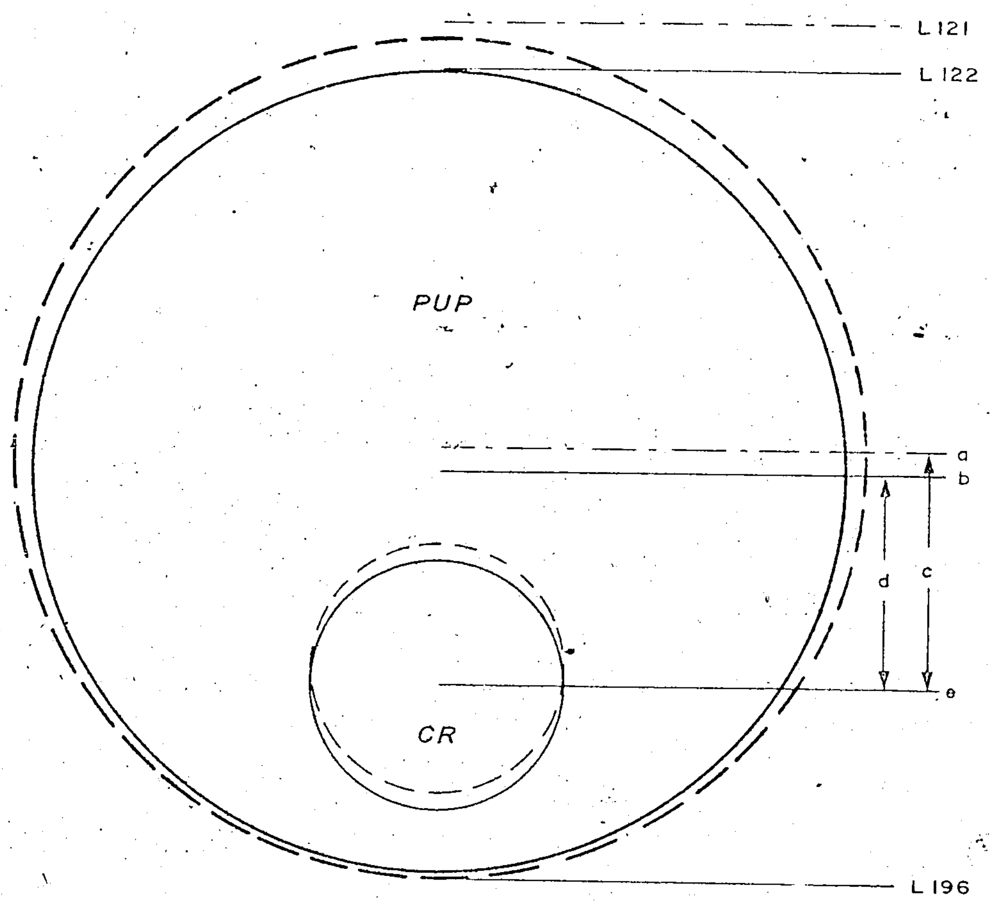


Figure 9

EFFECT OF "TYPE A" ERROR ON MEASUREMENT OF VERTICAL DISPLACEMENT third of a line, the combined effect of dilation and head movement would locate the top of the pupil more than half way toward line 121. The oculometer system would then consider the pupil to be positioned between lines 121 and 196 with its center lying midway between lines 158 and 159. Supposing that in the meantime, the corneal reflection had remained fixed, the oculometer output would show a change in vertical displacement of one-half line even though there was no change in eye pointing direction. Since this apparent movement of the pupil center could occur either upward or downward, the maximum expected variation in the position of the pupil center due to type A error is ±½ line. The same phenomenon could occur in relation to the center of the corneal reflection, hence the maximum expected variation in the position of the corneal reflection center would also be ± ½ line. However, because movement of the pupil center (upward or downward) necessarily implies a corresponding movement of the corneal reflection center, it would not be expected that these two errors would be cumulative. Therefore, the maximum expected type A error for measurement of displacements in the vertical plane would be ±½ scan line.

The possible effects of type B error on measurements in the vertical direction may be illustrated by again considering a pupil positioned precisely between and tangent to lines 122 and 196, whose centerline would be positioned on line 159 (see Figure 10). If there existed a corneal reflection within this pupil such that it was positioned precisely between and tangent to lines 169 and 179 with its center on line 174, the actual displacement between the two centers would be 15 lines, and the oculometer output would indicate this.

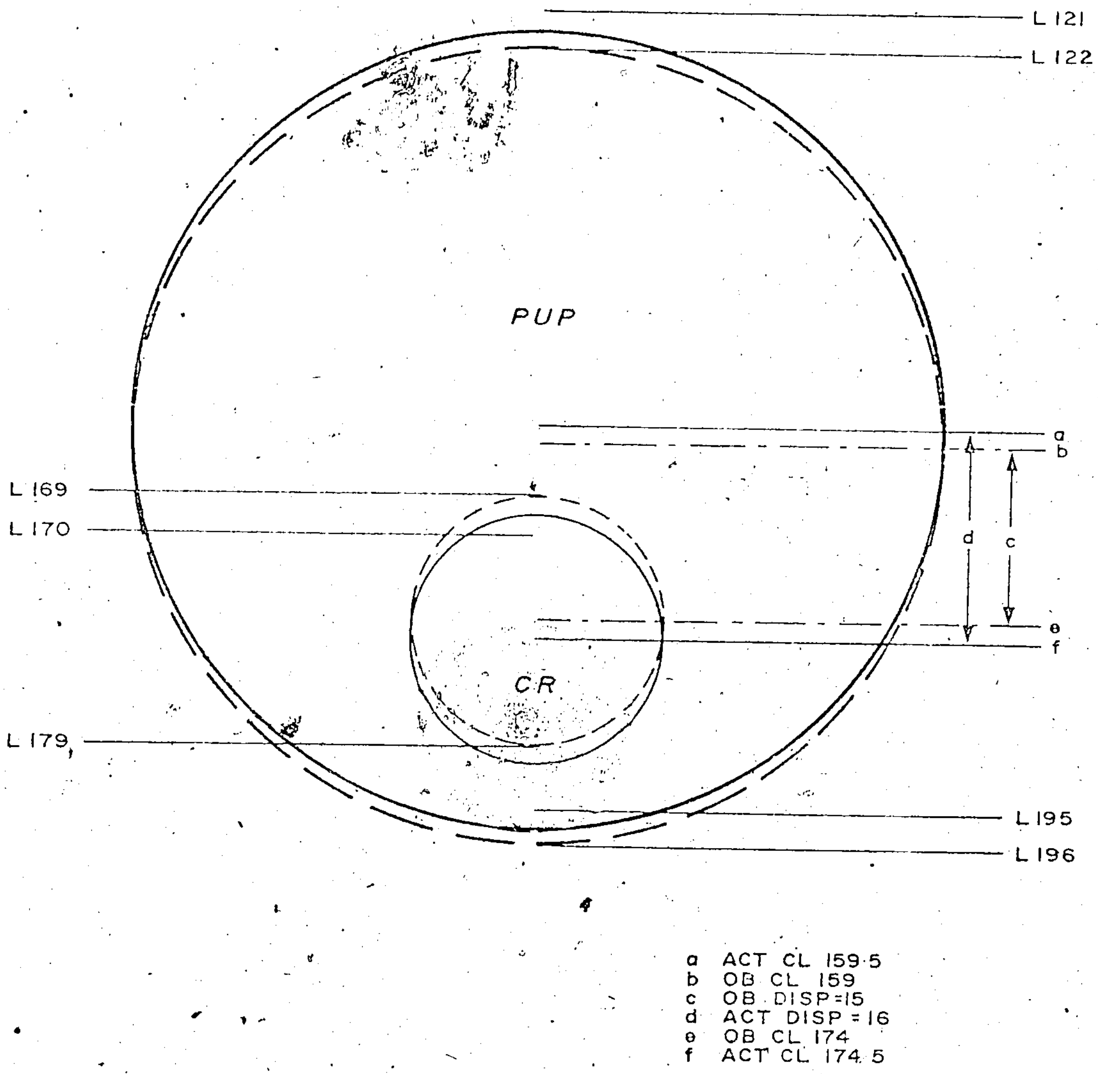


Figure 10

EFFECT OF "TYPE B" ERROR ON
MEASUREMENT OF VERTICAL DISPLACEMENT

However, it could also be possible that the entire pupil was positioned one-half line higher - just below the point that would cause lines 121 and 195 to resolve it. The pupil center would then actually be midway between lines 158 and 159 although the oculometer system would locate it on line 159. At the same instant the corneal reflection could be positioned on-half line lower - just above the point that would cause lines 170 and 180 to resolve it. The corneal reflection center would then actually be midway between lines 174 and 175, although the oculometer system would locate it on line 174. In this case, therefore, the actual displacement between the two centers would be 16 scan lines, but would be recorded by the oculometer system as 15 scan lines. In a similar manner, the pupil could be located as much as one-half line below lines 122 and 196 while the corneal reflection could be located as much as one-half line above lines 169 and 179. In this case, the oculometer system would still record the displacement between the two centers as 15 scan lines even though the actual displacement was only 14 scan lines. Therefore the maximum expected type B error for measurement of displacements in the vertical plane would be ±1 scan line.

For measurements in the horizontal plane, (measured in terms of 10 megahertz clock pulses) it will be assumed that a target positioned in space between two adjacent clock pulses will be measured in terms of the last complete clock pulse that intercepted the target. That is, if a target begins part way between pulse 22 and pulse 23, then it will be recorded as beginning at pulse 22, regardless of how near it exists to pulse 23.

To illustrate the possible effects of type A error or measurements in the horizontal plane, the following example will be considered: Supposing a pupil were positioned so that each of the four horizontal scan lines intercepted the vertical tangent to the pupil just as pulse 150 occurred (see Figure 11). Now, supposing that the pupil were to remain stationary at this point, but were to undergo a slight dilation. If the dilation was less than half a scan line the dilation reading recorded by the oculometer would remain unchanged. However, this slight dilation could be sufficient to cause the mean abscissa of the vertical tangent to the pupil to appear at pulse 149. As a result, an observed change in horizontal displacement equal to one pulse would be recorded by the oculometer when no actual change in eye pointing direction occurred (see Figure 11). Because only the leading edge (left edge) of the pupil circumference is sensed, type A error could only operate in a manner so as to decrease the true value of the horizontal position of the pupil center by one. A similar change could occur in the corneal reflection, resulting in a type A error in the position of the center of the corneal reflection, operating, as in the case of the pupil, to decrease the true value of the horizontal position of the center of the corneal reflection by one. The occurrence of both of these events simultaneously (since they both operate in the same direction) would result in cancellation of the error, therefore the maximum expected type A error for measurement of displacements in the horizontal plane would be -1 pulse.

The possible effects of type B error on measurements in the horizontal plane are illustrated in the example of Figure 12. Supposing

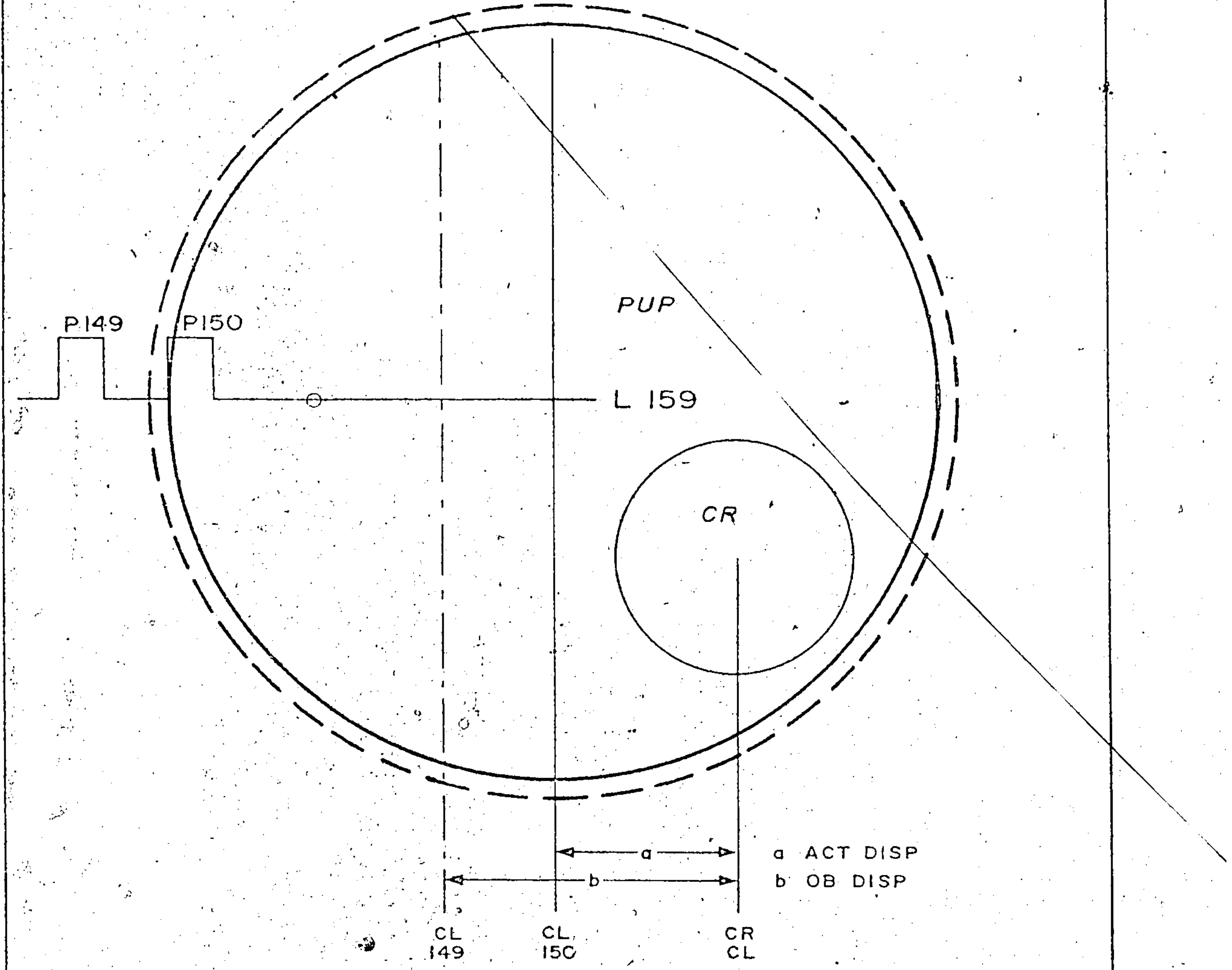


Figure 11

EFFECT OF "TYPE A" ERROR ON MEASUREMENT OF HORIZONTAL DISPLACEMENT a pupil were positioned so that each of the four horizontal scan lines intercepted the vertical tangent to the pupil just as pulse 150 occurred. Now supposing that the pupil were to move to a new position to the right (as shown by the broken lines of Figure 12) by an amount just less than one pulse. Because the movement would not be sufficient to change the observed position of the vertical tangent to the pupil the position of the pupil center would appear unchanged, even though a change of nearly one full pulse had occurred. Therefore the maximum expected variation in the position of the center of the pupil is -1 pulse. The possible effects of type B error on the determination of the horizontal position of the center of the corneal reflection are identical to those just described for the pupil, therefore, the maximum expected variation in the position of the center of the corneal reflection is also -1 pulse. The occurrence of both of these events simultaneously would result in cancellation of the error, therefore the maximum expected type B error for measurement of displacement in the horizontal plane is -1 pulse.

Actual System Performance

In order to assess the actual overall performance of the infrared computer based oculometer system, given the maximum expected errors of measurement for the system sub-tasks, a series of experiments involving both the simulated eye described earlier in this chapter and a human eye were carried out. The purpose of the experiments involving the simulated eye was to gather additional data to demonstrate the reliability and the validity of the oculometer system in a task

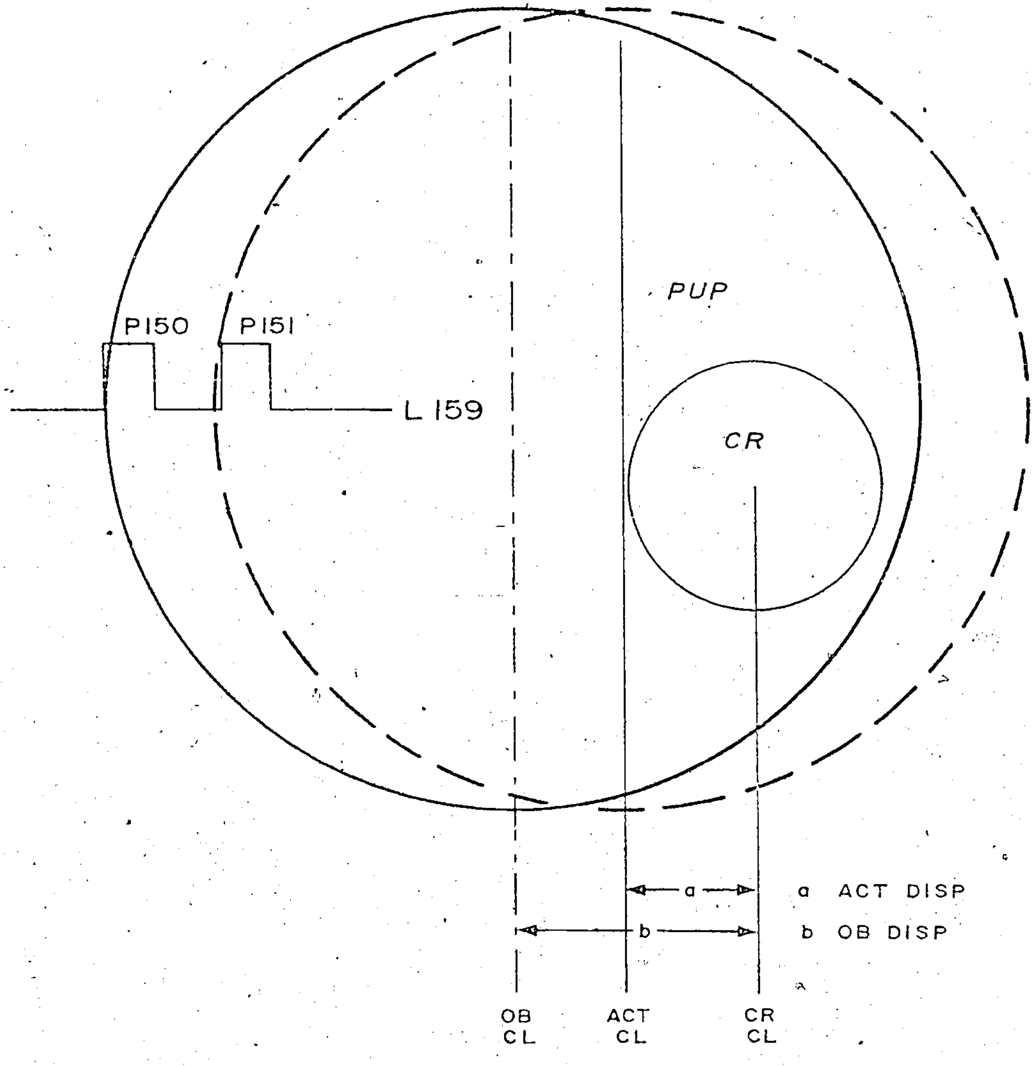


Figure 12

EFFECT OF "TYPE B" ERROR ON MEASUREMENT OF HORIZONTAL DISPLACEMENT involving the determination of the positions of the pupil center, corneal reflection center and pupil dilation, and the calculation of the horizontal and vertical displacements between the pupil center and the center of the corneal reflection for a stationary target. Because the normal human eye does not stay perfectly fixed, even when it is fixating on a stationary target oculometer output obtained from a human eye fixating a stationary target would include error resulting from normal movements of the eye inseparably combined with type A and type B errors. Therefore a statistical approach, presenting frequency distributions of oculometer system output for various tasks involving the human eye will be used to describe overall system performance.

In the second series of experiments, a simulated eye was positioned in the field of view of the camera unit of the oculometer. The video monitor was observed while the camera unit was adjusted to insure that it was properly focused. The intensity of the infrared light source was adjusted so that the video output voltage was as specified in Figure 8 (variac setting of approximately 50). The computer program included in appendix D was used but was modified to stop after 100 consecutive scans were completed. The output consisted of the coordinates of displacement between the pupil center and the center of the corneal reflection as well as pupil dilation. The observed measures of dilation and of displacement were 70 scan lines and 24.5 scan lines respectively. The variance of each of these was 0. The observed measures of X - displacement were normally distributed around a mean of 7.69 pulses with a variance of 0.21. The experiment was repeated two more times, once with the "corneal reflection" pinhole blocked off so that no corneal reflection voltage was present, and a second time with the entire pupil covered by a piece of black construction paper. In both cases, the oculometer system output consisted of 100 identical readings, each denoting that a "blink" had been detected.

These experiments appear to strongly support both the validity and the reliability of the oculometer system. In the first case, identical readings obtained for measures of dilation and Y-displacement strongly suggests that the system provides a reliable measure for these parameters. The observed distribution of measures of X-displacement indicate the relatively high reliability with which the system measures this parameter. In the latter two cases, by eliminating portions of the simulated eye, it was demonstrated that the oculometer output changed appropriately, which suggests that the output from the oculometer system is a valid measure of displacement between the pupil center and the center of the corneal reflection.

In the third series of experiments, an IBM 1500 video terminal was positioned adjacent to the oculometer as shown in Figure 2. A Biometrics model 115 head restraint was positioned in front of the video terminal, so that the eye of a subject whose head was positioned in the chinrest of the head restraint would be 16 inches away from the screen of the video terminal. With a subject positioned in the head restraint, the video monitor was observed while the camera unit was adjusted to insure that it was properly focused. The intensity of the infrared light source was adjusted so that the video output voltage was as specified in Figure 8 (variac setting of 45 to 50 depending on the subject. In various experiments that followed, a target consisting of an asterisk (*) was displayed in a variety of known coordinate locations on the video terminal. Because the movements of the eye are more steady when it is pursuing a smoothly moving object (Yarbus, 1967) the IBM 1500 CAI system was programmed to display a "moving asterisk". For experiments involving vertical displacements, the asterisk was programmed to move back and forth in a pendular fashion horizontally across five columns in specific rows, pausing for 300 milliseconds in each column. For experiments involving horizontal displacements, the asterisk was programmed to move up and down in a similar fashion, across five rows in specific columns, pausing for 300 milliseconds in each row. The subject was instructed to look at the asterisk. For each trial, 100 consecutive oculometer readings were taken. Table 1 is a summary of the displacements observed for one subject under different display conditions.

The mean vertical output displacement between the corneal reflection center and the pupil center was 20.15 scan lines while the subject was looking at the top row of the display and 5.44 scan lines while the subject was looking at the bottom row of the display. This represents a change of 14.71 scan lines resulting from a change in fixation of 4.6 inches, the distance between the top and bottom rows of the display. This means that a change in the point of fixation of .16 inches would result in a change in the vertical displacement output of 0.5 scan line. That is, neglecting error, the oculometer would be

TABLE 1

Oculometer Output for Various Target Locations

Location of Asterisk		Mean Oculometer Output Displacement			
Horizontal Coordinates	Vertical Coordinates	Horizontal Pulses - Variance		Vertical Lines - Variance	
0	17-21			20.15	0.11
30	17-21			5.44	0.13
13-17	0	14.52	0.43		
13-17	39	-7.32	0.45		

N = 100 Readings

capable of detecting vertical changes in eye fixation greater than 0.16 inches on a display positioned 16 inches from the eye of the subject. This corresponds to an angular displacement of 0.6 degrees.

It has already been pointed out that for measurements in the vertical plane, the maximum expected type A error was ±½ scan line and the maximum expected type B error was ±1 scan line. Table 1 shows that the greatest variance of the observed vertical output displacements for the subject tested was .13. This corresponds to a standard deviation of less than 0.4. Because of the possibility of ±½ scan line of error associated with any given reading, and because ½ scan line has been found to correspond to .16 inches at a display 16 inches away from the eye, a given vertical displacement output coordinate defines a region .32 inches high which contains the point on the screen being fixated. Fixations within a region of .32 inches or 1.2 degrees may not be distinguished from each other. In order to distinguish between two points fixated on a display 16 inches from the eye, using the vertical displacement oculometer output, the two points must be separated vertically by more than .32 inches (1.2 degrees).

The mean horizontal output displacement between the corneal reflection center and the pupil center was 14.52 pulses while the subject was looking at the right edge of the display and -7.32 pulses while the subject was looking at the left edge of the display. This represents a change in horizontal displacement output of 21.84 pulses resulting from a change in fixation of 7.9 inches, the distance between the left and right edges of the display. This means that a change in the point of fixation of 0.18 inches would result in a change of 0.5 pulse in the oculometer horizontal displacement output. That is; neglecting error, the oculometer system would be capable of detecting horizontal changes in eye fixation greater than .18 inches on a display 16 inches away from the eye. This corresponds to an angular displacement of about 0.65 degrees.

As in the measurement of vertical displacement discussed earlier, because of this error, it is only possible to define a region which is 0.36 inches wide which contains a point on the display being fixated. Fixations within a region 0.36 inches wide or 1.30 degrees may not be distinguished from each other. In order to distinguish between two points fixated on a display 16 inches from the eye of a subject, using the horizontal displacement oculometer output, the two points must be separated by more than 0.36 inches (1.30 degrees).

In order to assess the linearity of the infrared computer based oculometer system, the numbers one to nine and the letters A and B were sequentially displayed at known coordinate locations of the screen of an IBM 1500 video terminal (see Figure 13). Each character appeared on the screen for exactly six seconds. The subject was positioned in front of the screen as previously described and was instructed to fixate each character as it appeared. Figure 13 shows the positions of the digits on the screen. Of the 180 readings obtained for each point fixated, the first thirty were rejected to insure that the eye had completed its saccade from the previous point being fixated. The next 60 readings were kept for analysis. The last 90 readings were not used since there is some evidence in

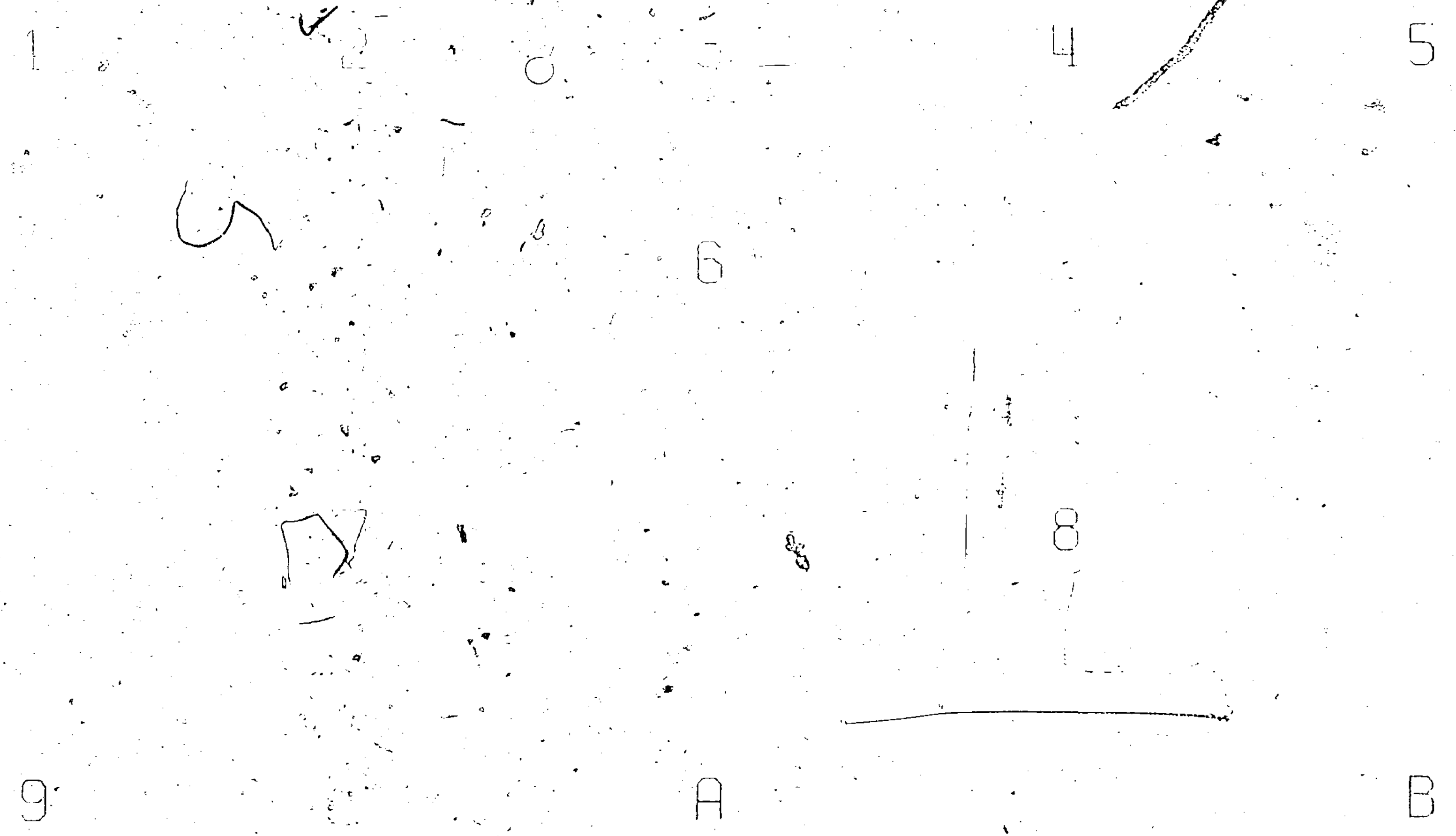


FIGURE 13

Calibration Stimuli

the literature that as the length of time spent fixating an object increases, the size of the drifts away from the point of fixation will also increase.

In order to calibrate the system, the mean observed X - coordinate for points six and A of the display was taken to be the X-distance between point six and A - two points which were three inches apart was used to establish a measure of the vertical resolution. Similarly the mean observed Y-coordinates for points seven and eight of the display was taken to be the Y-displacement for fixations on rows 18 and 19 of the screen and the distance between points seven and 8 - two points which were exactly four inches apart was used to establish a measure of the horizontal resolution. Table 2 shows a summary of calibration data obtained in this manner.

Based on the calibration data of Table 2 and the known locations of the calibration points on the screen, expected coordinate values for each of the eleven calibration points were calculated and compared to the observed coordinate values. Table 3 shows the comparison of expected and observed coordinates for the calibration points.

As indicated in Table 2, the vertical resolution of the system was 3.14 scan lines per inch at the screen of the video display. Since each character displayed on the screen was 0.3 inches high, this represents 0.94 scanlines. Similarly since the horizontal resolution was 2.46 pulses per inch, and each character displayed was 0.2 inches wide, this represents 0.49 pulses per character. Relating this to the error scores in table 3, one Y-displacement (the character B) and nine

TABLE 2

X and Y Calibration Data

Stimulus	Column	Row	Mean Observed X-Displacement	Mean Observed Y-Displacement
6	19	8 and 9	3.34	15.81
A	19	28 and 29	4.66	6.38
Mean			4.00	
Vertical Resolution Scan Lines per Inch				3.14
7	9	18 and 19	8.25	10.73
8	29	18 and 19	-1.59	10.90
Mean				10.82
Horizontal Resolution Pulses per Inch			2.46	

X-Displacement measured in terms of pulses

Y-Displacement measured in terms of scanlines

TABLE 3

X and Y Linearity Errors

Stimulus	Row	Column	Expected X-Disp.	Observed X-Disp.	X-Error	Expected Y-Disp.	Observed Y-Disp.	Error
1	0 and 1	1	13.35	13.52	.17	19.35	19.94	.64
2	0 and 1	9	8.92	8.65	.27	19.30	20.22	.92
3	0 and 1	19	4.00	3.25	.75	19.30	20.13	.83
4	0 and 1	29	-0.92	-3.62	2.70	19.30	19.97	.67
5	0 and 1	37	-5.84	-8.13	2.29	19.30	18.82	.48
6	8 and 9	19	4.00	3.34	.66	15.53	15.81	.28
7	18 and 19	9	8.92	8.25	.67	10.82	10.73	.09
8	18 and 19	29	-0.92	-1.59	.67	10.82	10.90	.08
9	28 and 29	6	13.35	15.52	2.17	6.11	6.09	.02
A	28 and 29	19	4.00	.66	1.66	6.11	6.38	.27
B	28 and 29	39	-5.84	-6.51	0.67	6.11	4.92	1.19

X-Displacements measured in terms of pulses

Y-Displacements measured in terms of scanlines

X-displacement readings (the characters 3-9, A and B) had error scores greater than the size of a character. Only three characters (4, 5 and 9) had an X-error greater than two characters.

Since the angular displacement of the top row and the left edge both exceed 12 ½ degrees, and since earlier studies have suggested that the corneal reflection method is only linear for displacements of less than 12 ½ degrees, these errors can probably be attributed to non-linearity. However, since the remainder of the observed errors are small in relation to the size of the target being fixated, they will be considered negligible for the purposes of this study.

Summary

This chapter describes the infrared computer based oculometer system developed for recording eye movements of subjects involved in various learning tasks. It also provides details on proof of performance of the system. The following chapter will deal with the application of the infrared oculometer system. It will describe the conditions under which eye movements of subjects were recorded during some learning tasks and will present the findings.

CHAPTER IV

DESCRIPTION OF TESTING AND PRESENTATION OF FINDINGS

Introduction

Knowing where a subject is looking under given stimulus conditions is important to many different fields of research. In education, it is particularly important, because failure of stimuli to elicit a visual response from the learner can often inhibit learning. Knowing how the learner responds to a visual stimulus can provide the instructor with feedback, making it possible for him to modify stimulus material in order to elicit the desired visual response from the learner.

This study describes and documents the development of an infra-red computer based oculometer which would provide a means for determining where subjects are looking when presented with visual stimuli. This chapter describes how three subjects' eye movements were recorded while they were viewing visual stimuli presented to them in a simulated learning situation. It also presents the analysis of these eye movements.

Procedure

The stimulus materials used in this study were presented to subjects via a video computer terminal connected to the IBM 1500 computer assisted instruction system in the Division of Educational Research Services of the University of Alberta. A total of five stimulus situations were presented to each of three subjects. The first stimulus situation consisted of the numbers one to nine and the letters A and B as described in chapter three and illustrated in Figure 13. The purpose of this stimulus situation was to obtain data for each subject that would permit calibration of the system to the subject.

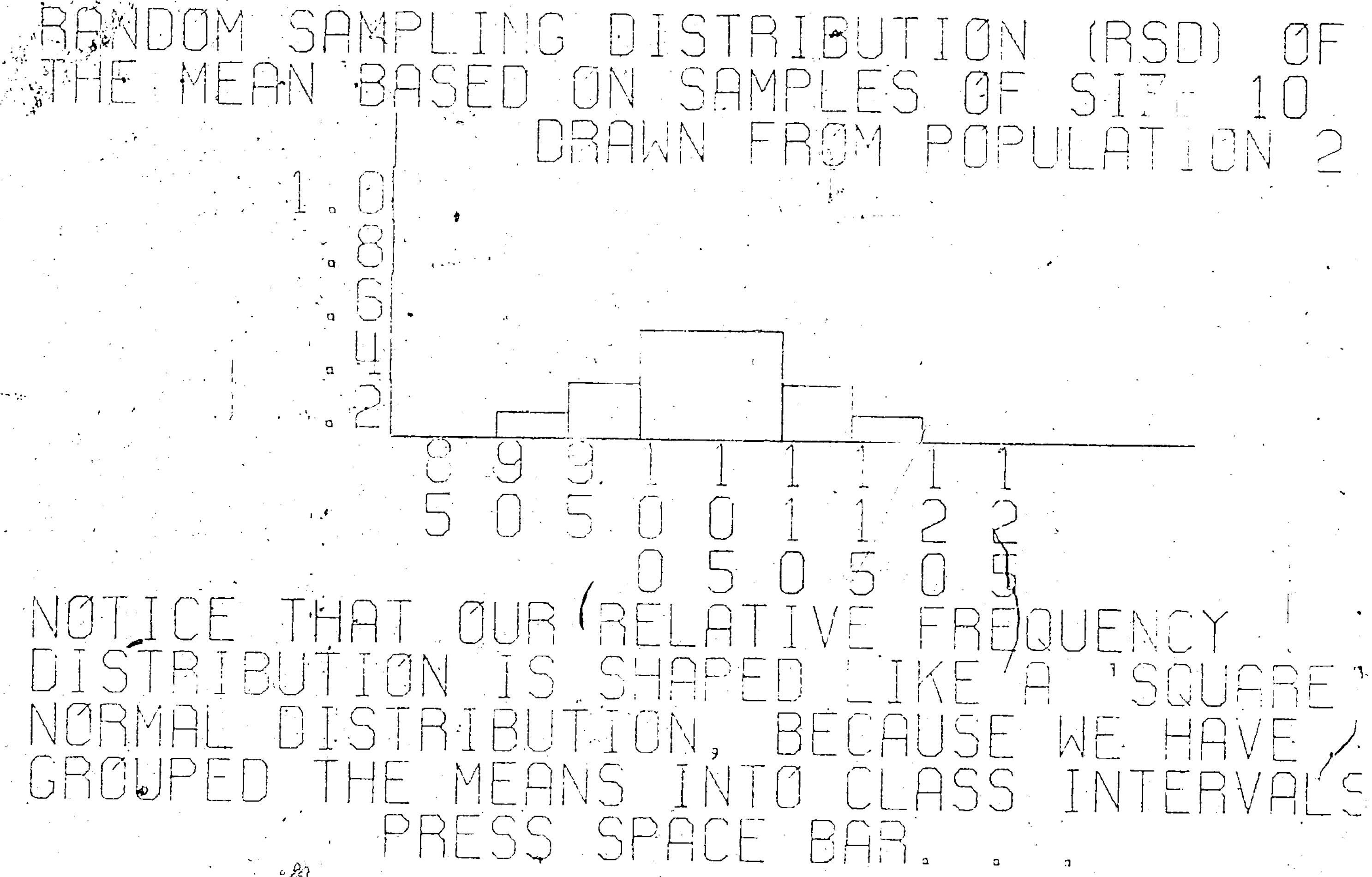
The second, third and fourth stimulus situations are shown in Figures 14, 15 and 16 respectively. These stimulus situations were frames of material selected from a course in inferential statistics developed for use with the IBM 1500 CAT system. One word was deliberately spelled incorrectly in stimulus situation 1 and was intended to provide a calibration check at the end of the test sequence.

The subjects were all mature adults (two male and one female) and all were familiar with elementary statistical terms and concepts and all were familiar with the video terminal. Each subject was positioned in an adjustable chair at a desk on which was located the IBM 1500 video terminal and adjacent to it, the Honeywell optical head. The general testing procedure was explained to the subject, then the subject's head was positioned in the headrest and the chair and headrest were adjusted until a clear, well focused image of the pupil and corneal reflection were visible on the video monitor. The subject was asked to look at various locations on the display while the intensity of the infrared source was adjusted. Finally, the computer was started and the presentation of visual stimuli was

SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LAARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 14

Stimulus Situation 2

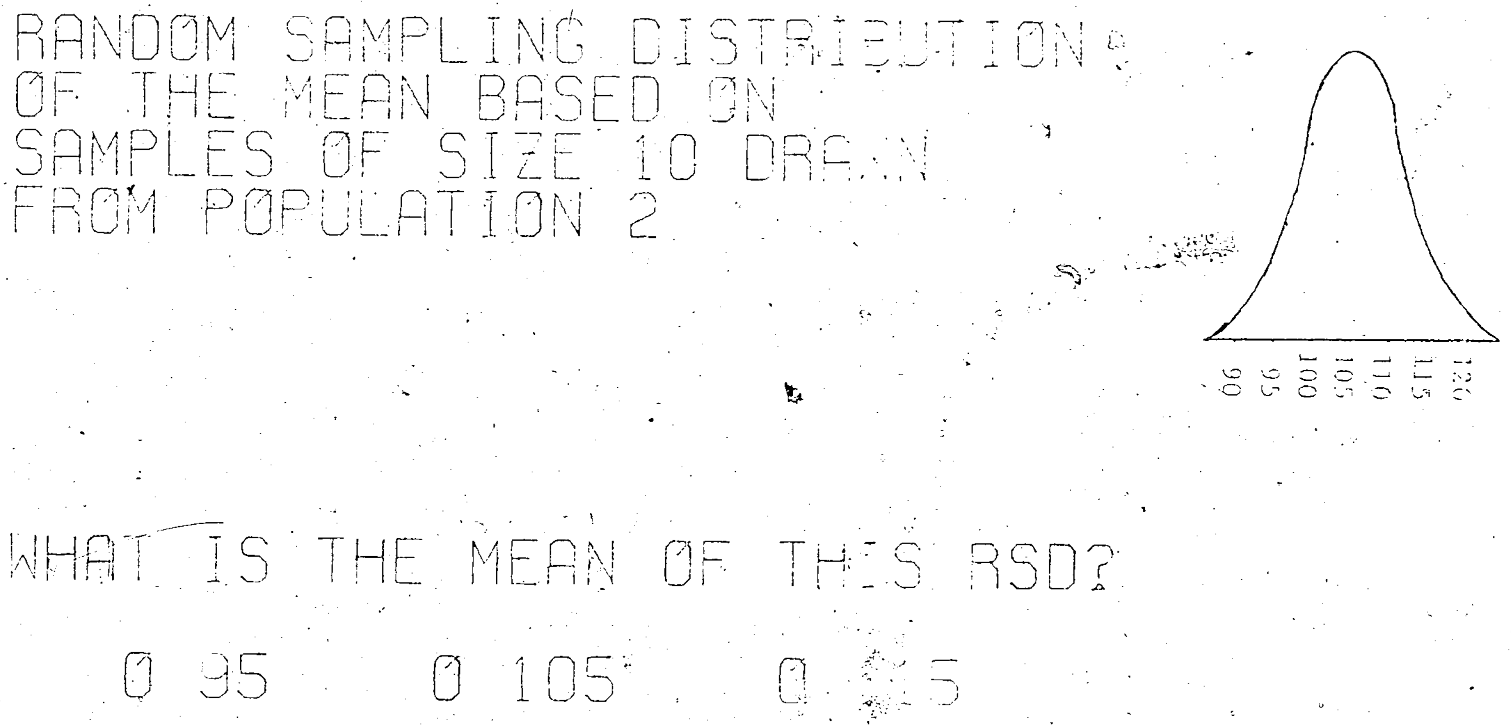


RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2

NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR.

FIGURE 15

Stimulus Situation 3



RANDOM SAMPLING DISTRIBUTION
OF THE MEAN BASED ON
SAMPLES OF SIZE 10 DRAWN
FROM POPULATION 2

WHAT IS THE MEAN OF THIS RSD?

0 95   0 105   0 [illegible]5

FIGURE 16

Stimulus Situation 4

initiated by the researcher. Stimulus situation 1 presented the subject with the numbers one to nine and letters A and B sequentially, each character being displayed for six seconds. At the end of stimulus situation 1, stimulus situation 2 was automatically presented and was kept on the screen for 20 seconds. This was sufficient time for all subjects to finish reading this frame, which, as may be seen from figure 14, consisted of eight lines of text. After 20 seconds, stimulus situation 3 was automatically presented. This stimulus situation consisted of some text combined with a figure depicting a histogram as shown in Figure 15. The subject was required to press the space bar in order to go on to the next stimulus situation. Stimulus situation four consisted of some text and a graph. The text asked a question, such that the subject would have to view the graph, then view three possible answers to the question. The subject was instructed to simply think of the right answer - he was not required to give a response other than a visual response. After 20 seconds, the last stimulus situation, which consisted of the calibration stimuli used in stimulus [illegible] was automatically presented.

At the end of the testing sequence, the magnetic tape containing the data was removed and delivered to the IBM 360 system for analysis. A number of programs were written in Fortran to analyze the data contained on the tape. While in this study, a separate tape was made up containing data for each subject, this, in general would not be necessary since the oculometer system is capable of registering an "end-of-File" mark on the tape. This would insure that each subjects' data would be kept separate.

Analysis

Stimulus Situation 1 - Calibration

The analysis of the data consisted of calculating the X-displacement for each set of readings recorded, summarizing the data, scaling the data to linear dimensions corresponding to the size of the display screen and plotting the data, superimposed on the appropriate text. Each analysis of eye movements will be presented separately for each subject.

Table 4 presents a summary of the calibration data obtained for [illegible] three subjects when they were viewing stimulus situation 1 [illegible] 13). To calibrate the system to each individual, a set of [illegible] running vertically between points six and A and [illegible] between points 7 and 8 were established. These points [illegible] because they were approximately in the center of the [illegible] screen: In this manner, the angular displacement of the eye while fixating these points would likely be small enough so as not to introduce error due to non-linearity (12 ½ degrees).

The position of the mean X-calibration axis, the imaginary vertical line between points 6 and A was determined by calculating the average of the mean observed X-displacements recorded for a period of two seconds (60 readings) for points 6 and A. For example, the mean X-calibration axis for subject one (table 4) was 0.99. This means that the estimate of the X-displacement between the pupil center and the corneal reflection for subject 1, when he was fixating points on a vertical axis joining points 6 and A was +0.99. Similarly, the position of the mean Y-calibration axis, the imaginary horizontal line between points 7 and 8 was determined by calculating the average of the mean observed Y-displacements recorded for a period of two seconds (60 readings) for points 7 and 8. For example, the mean Y-calibration axis for subject 1 (Table 4) was 10.09. This means that the estimate of the Y-displacement between the pupil center and the corneal reflection for subject 1, when he was fixating points on a horizontal axis joining points 7 and 8 was 10.09.

The horizontal resolution for each subject was estimated by dividing the difference between the mean observed X-displacement for points 7 and 8 by the physical distance between these points on the display screen (4 inches), and was expressed in pulses per inch. For example, the mean observed X-displacement for subject one (Table 4) while fixating point 7 was 5.77 pulses while the mean observed X-displacement for this subject while fixating point 8 was -3.98 pulses. The change in X-displacement as the subject changed his point of fixation from point 7 to point 8 was (5.77 - (-3.980) = 9.75 pulses Since these points were four inches apart on the display screen, the horizontal resolution for subject one was (9.75 ÷ 4) = 2.44 pulses per inch. This meant that assuming a linear relationship between the displacement of the corneal reflection from the pupil center and the corresponding change in the horizontal position of the point being fixated, for every inch that the point of fixation moved on the display screen, the observed X-coordinate of the displacement of the corneal reflection from the pupil center changed by 2.44 pulses.

TABLE 4

X and Y Calibration Data

Subject	Stimulus	Mean Obs. X-Disp.	Mean X Calib. Axis	Horizontal Resolution	Mean Obs. Y-Disp.	Mean X Calib. Axis	Vertical Resolution
	6	.61			15.50		
1	A	1.37	0.99	2.44	4.47		
	7	5.77			10.06		
	8	-3.98			10.12	10.09	3.68
	6	9.76			18.10		
2	A	10.26	10.01	2.82	6.37		
	7	15.69			12.12		
	8	4.40			12.13	12.12	3.91
	6	0.05			14.52		
3	A	1.01	.53	2.02	4.47		
	7	4.58*			9.63*		
	8	-3.52			9.63	9.63	3.35

*Estimated Displacements.

The vertical resolution for each subject was estimated similarly except that the mean observed vertical displacements for points [illegible] and A (located three inches apart on the display screen) were used to estimate it. Also since vertical displacement was measured in terms of scan lines, the vertical resolution was expressed in terms of scan lines per inch.

Given the X- and Y- calibration data for a subject, it is possible to calculate the expected values of X- and Y- displacement between the corneal reflection and the pupil center for any point on the display screen. For example, supposing subject one were fixating a point that was one inch above the horizontal calibration axis (points 7 and 8) and one inch to the left of the vertical calibration axis (points 6 and A). Since his horizontal resolution rate was 2.44 pulses per inch, the expected X-displacement between the corneal reflection and the pupil center would be 2.44 pulses greater than it was when the subject was fixating the vertical axis or (0.99 + 2.44) = 3.43 pulses. Similarly, since his vertical resolution rate was 3.68 lines per inch, the expected Y-displacement between the corneal reflection and the pupil center would be 3.68 lines greater than it was when the subject was fixating the horizontal axis or (10.09 + 3.68) = 13.77 lines. Conversely, given a set of X- and Y- displacement coordinates and the calibration data, one can estimate the point on the display screen (with reference to the horizontal and vertical calibration axes) that the subject was fixating.

In order to assess the possible error that was inherent in this method of estimating eye pointing direction, expected X- and Y-coordinates were calculated for each of the calibration points. Observed mean displacement coordinates were subtracted from expected coordinates in order to estimate the error. Tables 5 - 7 show the error scores and Figures 17 - 19 show the plots of the calibration points as they appeared on the display screen together with the plots of calculated eye pointing position for each of subjects 1, 2 and 3 respectively.

Subject 1 had a total of 5 calibration points that were more than one character width away from the calculated position in the horizontal plane and two points that were more than one character height away from the calculated position in the vertical plane. Subjects two and three had three and seven (respectively) calibration points that were more than one character width away from the calculated position in the horizontal plane and two points that were more than one character height away from the calculated position in the vertical plane. Subject two and three had three and seven (respectively) calibration points that were more than one character width away from the calculated position in the horizontal plane and one and no points more than one character height away from the calculated position in the vertical plane. Figures 17 - 19 show the uncorrected plots of the observed eye pointing position relative to the position of the calibration points for each subject.

Conclusions

In view of the fact that previous studies have reported that the corneal reflection method of calculating eye pointing coordinates was not linear beyond 12 ½ degrees of displacement, and in view of the

TABLE 5

Error Table for Subject 1

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	10.26	8.68	1.58*	20.02	19.03	.99
2	5.87	4.06	1.81*	20.02	19.31	.71
3	.99	0.44	.55*	20.02	19.31	.71
4	-3.89	-4.41	.52*	20.02	19.42	.60
5	-8.77	-8.83	.04	20.02	18.69	1.33*
6	0.99	.61	.38	15.61	15.50	.11
7	5.87	5.77	.10	10.09	10.06	.03
8	-3.89	-3.98	.09	10.09	10.12	.03
9	10.26	10.32	.06	4.57	3.96	.62
A	0.99	1.37	.38	4.57	4.47	.10
B	-8.77	-7.01	1.76*	4.57	2.64	1.93*

*Denotes errors greater than one character in size.

TABLE 6

Error Table for Subject 2

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	20.73	20.04	.69*	22.68	21.71	.97
2	15.65	14.18	1.47*	22.68	21.72	.96
3	10.01	8.61	1.40*	22.68	22.18	.50
4	4.37	4.81	.4[illegible]	22.68	22.34	.34
5	-1.27	-1.15	.12	22.68	21.47	1.21*
6	10.01	9.76	.25	17.99	18.10	.11
7	15.65	15.69	.04	12.13	12.12	.01
8	4.37	4.40	.03	12.13	12.13	.00
9	20.73	21.29	.56	6.26	5.77	[illegible]
A	10.01	10.26	.25	6.26	6.37	.11
B	-1.27	-1.49	.22	6.26	6.02	.24

*Denotes errors greater than one character in size.

TABLE 7

Error Table for Subject 3

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	8.21	6.73	1.48*	18.68	17.72	.96
2	4.57	3.05	1.52*	18.68	18.70	.02
3	0.53	-1.58	1.05*	18.68	18.95	.27
4	-3.51	-4.93	1.42*	18.68	18.93	.25
5	-7.55	-9.24	1.69*	18.68	17.84	.84
6	0.53	.46	0.07	14.66	14.52	.14
7	4.57	**		9.56	**	
8	-3.51	-3.52	.01	9.56	9.63	.07
9	8.21	**		4.61	**	
A	0.53	1.01	.48*	4.61	4.47	.14
B	-7.55	-8.76	1.21*	4.61	3.89	.72

* Denotes errors greater than one character in size.

** Denotes missing data.

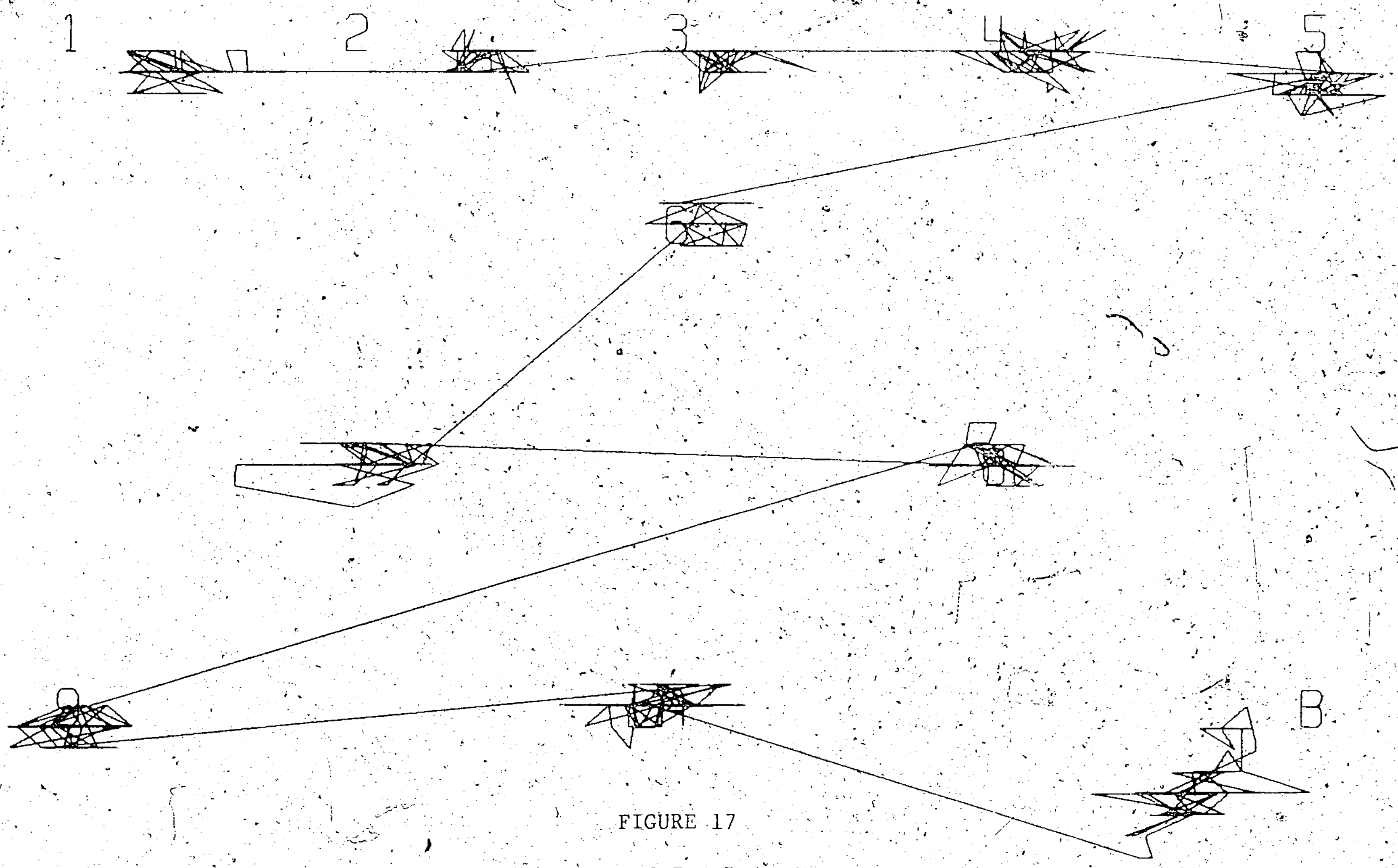


FIGURE 17

Uncorrected Eye Pointing
Positions For Subject 1
Viewing Stimulus Situation 1

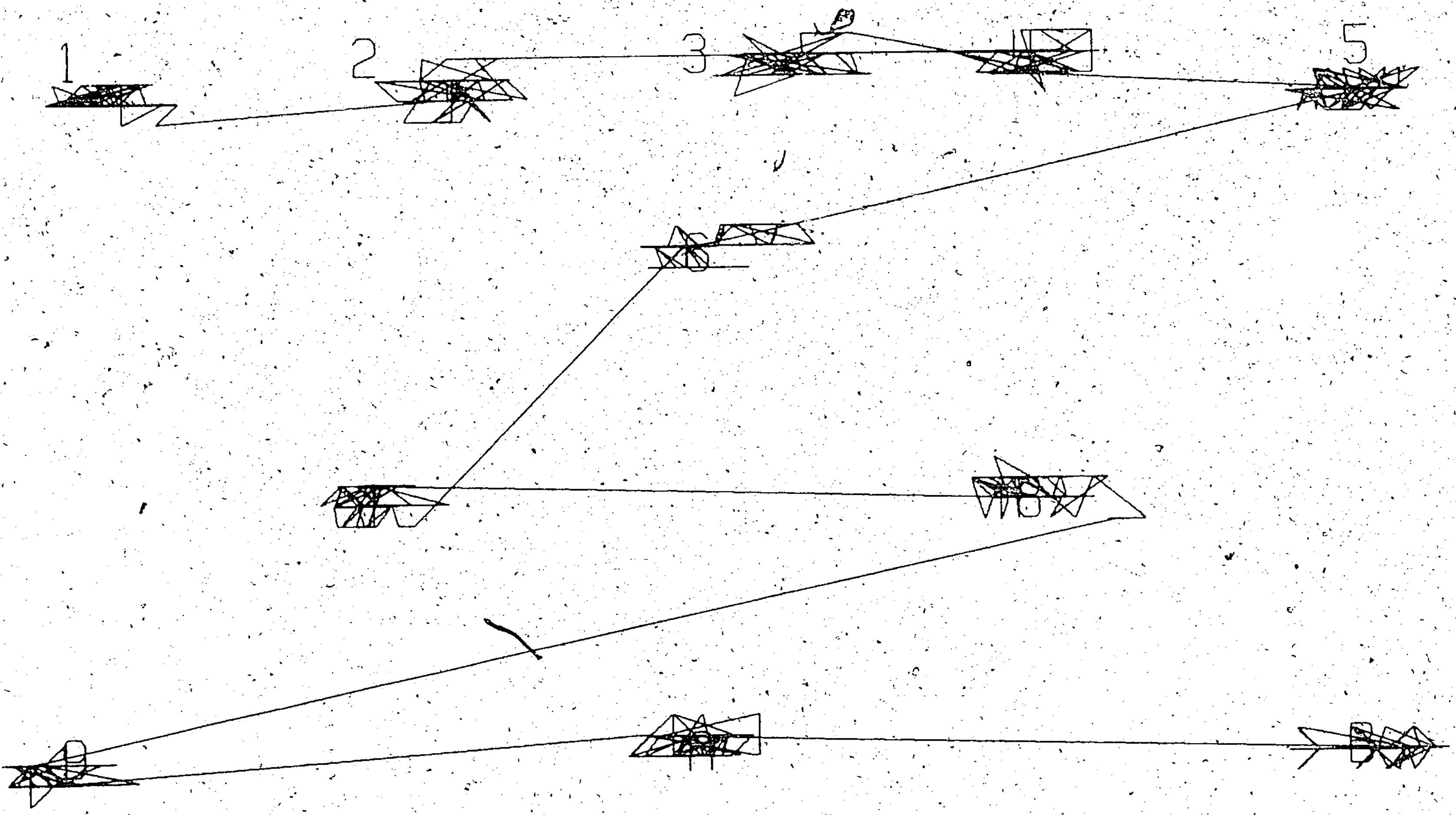


FIGURE 18

Uncorrected Eye Pointing
Positions for Subject 2
Viewing Stimulus Situation 1

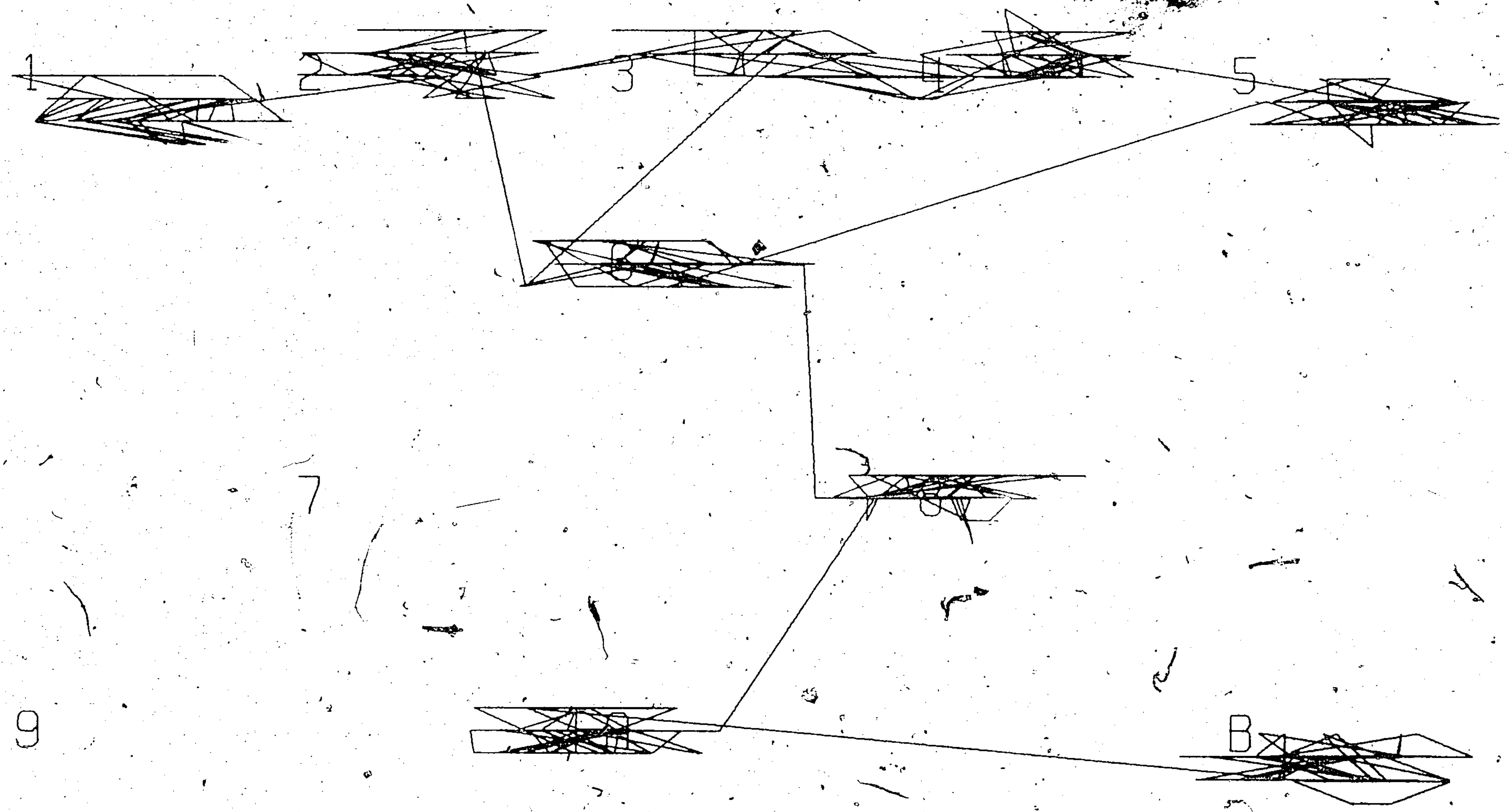


FIGURE 19

Uncorrected Eye Pointing
Positions for Subject 3
Viewing Stimulus Situation 1

fact that some regions within the video display area required angular displacements greater than 12 ½ degrees when being fixated, a procedure was developed for correcting observed eye pointing coordinates recorded when subjects fixated video display regions beyond 12 ½ degrees.

To determine which observed vertical displacements required correction, the vertical displacement ordinate that corresponded to 12 ½ degrees of displacement was calculated. Because the horizontal distance between the subject's eye and the display screen was constant at 16 inches, a vertical displacement of 12 ½ degrees was found to be (16 tan 12 ½) approximately 3 ½ inches. Since the vertical resolution for each subject was previously estimated, it was possible to calculate a critical value of vertical displacement between the corneal reflector and the pupil center, and that observed vertical displacements greater than this amount would require correction due to non-linearity. For example, the vertical resolution for subject 1 was 3.67 scan lines per inch, therefore the critical value of vertical displacement (3 ½ inches) was .5 x 3.68) = 12.85 scan lines.

In order to determine the vertical correction factor, it was assumed that the amount of correction necessary would be a linear function of the amount of vertical displacement greater than the critical value. The amount of non-linearity correction per scan line above the critical line was therefore computed by dividing the difference between the mean expected Y-displacement and the mean observed Y-displacement for calibration points one to five by the number of scan lines between the critical scan line and the mean observed Y-displacement for calibration points one to five. For example, the mean expected Y-displacement for subject 1 was ((19.04 + 19.30 + 19.31 + 19.42 + 18.70) ÷ 5) = 19.15. Therefore the vertical correction factor for subject one was ((20.0 - 19.15) ÷ (19.15 - 12.85)) = 0.122 scan lines per scan line above the critical Y-displacement.

A similar procedure was implemented for determining which observed horizontal displacements required correction: except that for this case, since eye movements both to the left and to the right of the infrared light source were possible, critical values of horizontal displacement for displacements to the left and to the right of the infrared light source had to be calculated. For example, based on a horizontal resolution of 2.44 pulses per inch for subject one, the critical values of horizontal displacement for subject one (3.5 inches) were (3.5 x 2.44) = ± 8.54 pulses. The mean observed horizontal displacement between the pupil center and the center of the corneal reflection at the right edge of the screen was determined by calculating the mean observed X-displacement for calibration points five and eight. This was found to be ((1 - 8.83 + - 7.01) ÷ 2) = 7.92 for subject one. Since this was less than the critical value of horizontal displacement, no correction was necessary for subject one on observed horizontal displacements to the right. The mean observed X - displacement for calibration points one and nine was ((8.868 + 10.32) ÷ 2) = 9.50. Since this was greater than the critical value, corrections to observed X - displacement data to the left of the screen were calculated by determining a horizontal correction factor in a manner similar to that already described for calculating a vertical correction factor. For example, the horizontal correction factor for subject one to be applied to all observed X - displacements greater than 8.54 (left of center) was $(10.26 - 9.50) \div (9.50 - 8.54) = 0.7$ pulses per pulse to the left of the critical X - displacement.

Table 8 shows a summary of X- and Y- linearity correction factors for each of the subjects tested. In order to evaluate the effect of applying these correction factors to the observed data, the observed X- and Y- displacement data for each of the calibration points was corrected.

As was noted on Tables 4 and 7 calibration data for subject three on points seven and nine was missing. The data recorded while this subject was fixating points seven and nine showed one long continuous "blink". This occurred due to the intensity of the pupil suddenly rising to such a level that the oculometer could not distinguish between the pupil and the corneal reflection. Therefore, the horizontal displacement between points six and eight were used in order to determine the horizontal resolution. Also, the displacement for the vertical calibration axis was based on the observed displacement on point eight only rather than on the mean observed displacement for points seven and eight.

Examination of the X-displacement error scores for subject three (Table 8) and the plot of uncorrected eye pointing positions for subject three viewing the calibration points, seemed to indicate that there was a major horizontal misalignment in the calibration for subject three. Therefore, a new horizontal calibration axis was determined for subject three, based on the mean observed horizontal displacement for calibration points five and B. Table 9 shows the error table for subject

TABLE 8

X and Y Linearity Correction Factors

Subject	Critical Y-Disp.	Critical X-Disp.	Mean Y-Disp. Pts.1-5	Mean X-Disp. Pts. 5,B	Mean X-Disp. Pts.1,9	X-Corr. Factor	Y-Corr. Factor
1	12.88	±8.54	19.15	-7.92	9.50	.792	.122
2	13.68	±9.87	21.88	-1.32	20.67	.0056	.098
3	11.72	±7.07	18.43	-9.00	6.73		.037

TABLE 9

Error Table for Subject 3 Based on Corrected Horizontal Calibration Axis

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	6.76	6.73	.03	18.68	17.72	.96
2	3.12	3.05	.07	18.68	18.70	.02
3	- .92	1.58	.64*	18.68	18.95	.27
4	-4.96	-4.93	.03	18.68	18.93	.25
5	-9.00	-9.24	.24	18.68	17.84	.84
6	- .92	.46	1.38*	14.66	14.52	.14
7	3.12	**		9.56	**	**
8	-4.96	-3.52	1.44*	9.56	9.63	.07
9	6.76	**	**	4.61	**	**
A	-	1.01	.09	4.61	4.47	.14
B	-9.00	-8.76	.24	4.61	3.89	.72

*Denotes errors greater than one character in size.

**Denotes missing data.

three based on the corrected horizontal calibration axis. The number of calibration points falling more than one character width away from the mean observed X-displacement was reduced from seven to three as a result of this correction.

The corrected eye movement data for each subject viewing stimulus situation one was again plotted and is presented in Figures 20-22.

Stimulus Situations Two to Four

As described earlier, stimulus situation two appeared on the display screen immediately after the last calibration point. It consisted of eight lines of text as shown in Figure 14. The word "large" was deliberately spelled "laarge" in line six of this stimulus situation.

This stimulus situation appeared on the screen for twenty seconds. All subjects completed reading the material in less than the twenty seconds to finish reading. Since the number chosen to designate a blink was purely arbitrary and of no numerical significance in analysis, all blinks were removed from the recorded data prior to further analysis, although data regarding when blinks occurred and their duration was available. The appropriate corrections for non-linearity were made to the data. Finally, in order to more clearly distinguish between subjects' eye movements while reading and subjects' eye movements while waiting for the next stimulus situation, the data was separated into two parts. In all cases, visual inspection of the displacement coordinates clearly revealed when the subject had reached the lower right corner of the

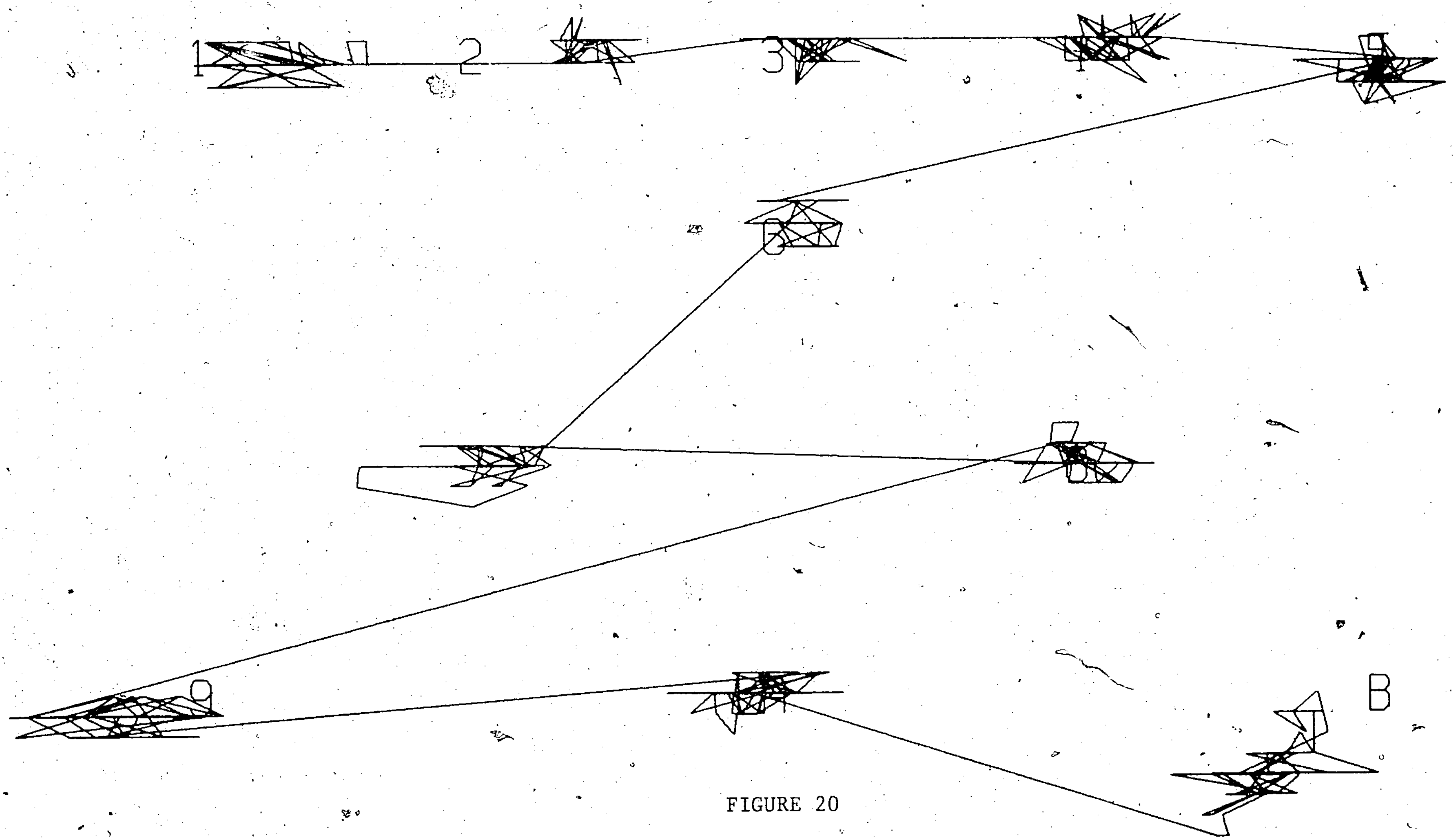


FIGURE 20

Corrected Eye Pointing
Positions for Subject 1
Viewing Stimulus Situation 1

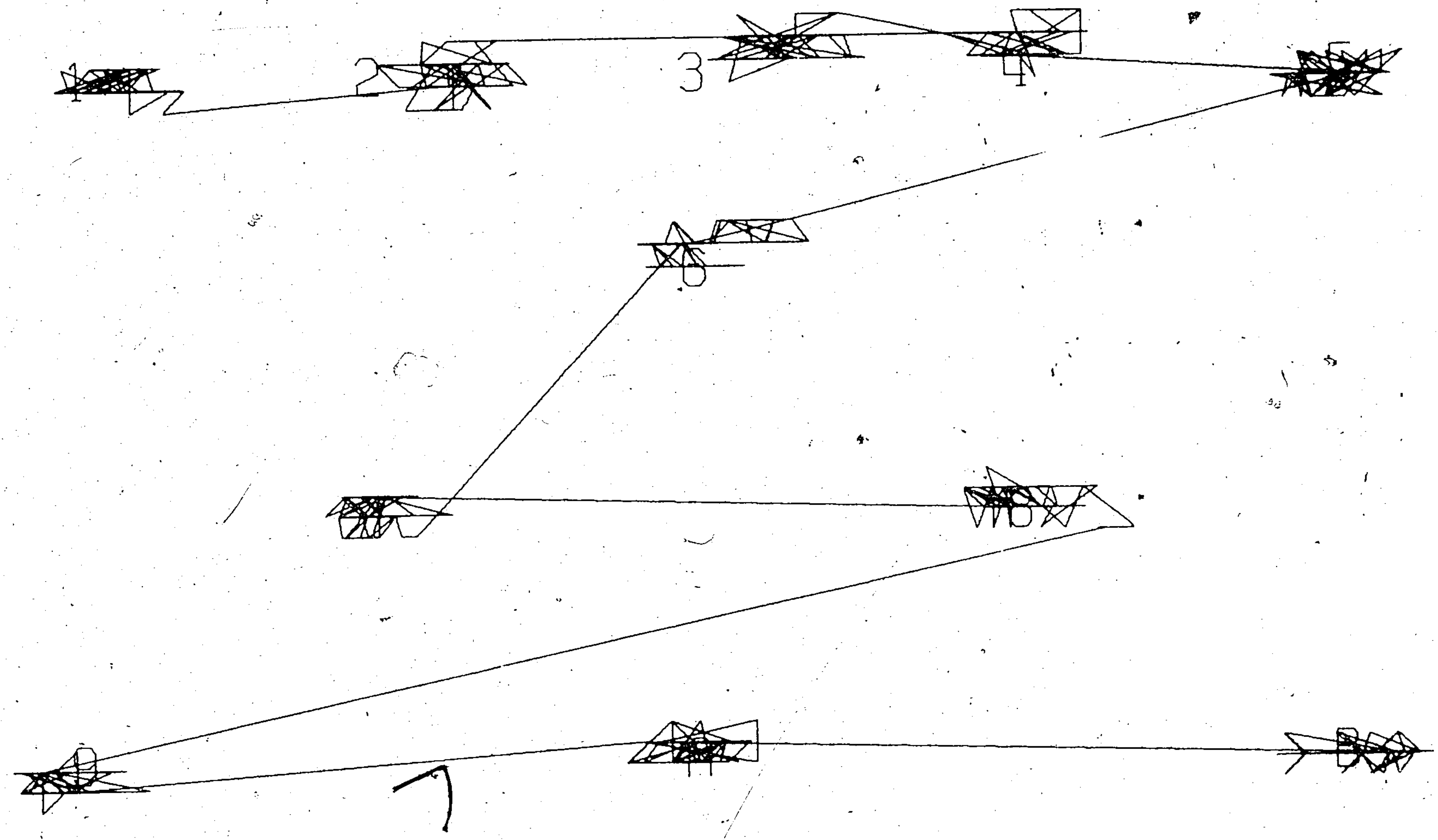


FIGURE 21

Corrected Eye Pointing
Positions for Subject 2
Viewing Stimulus Situation 1

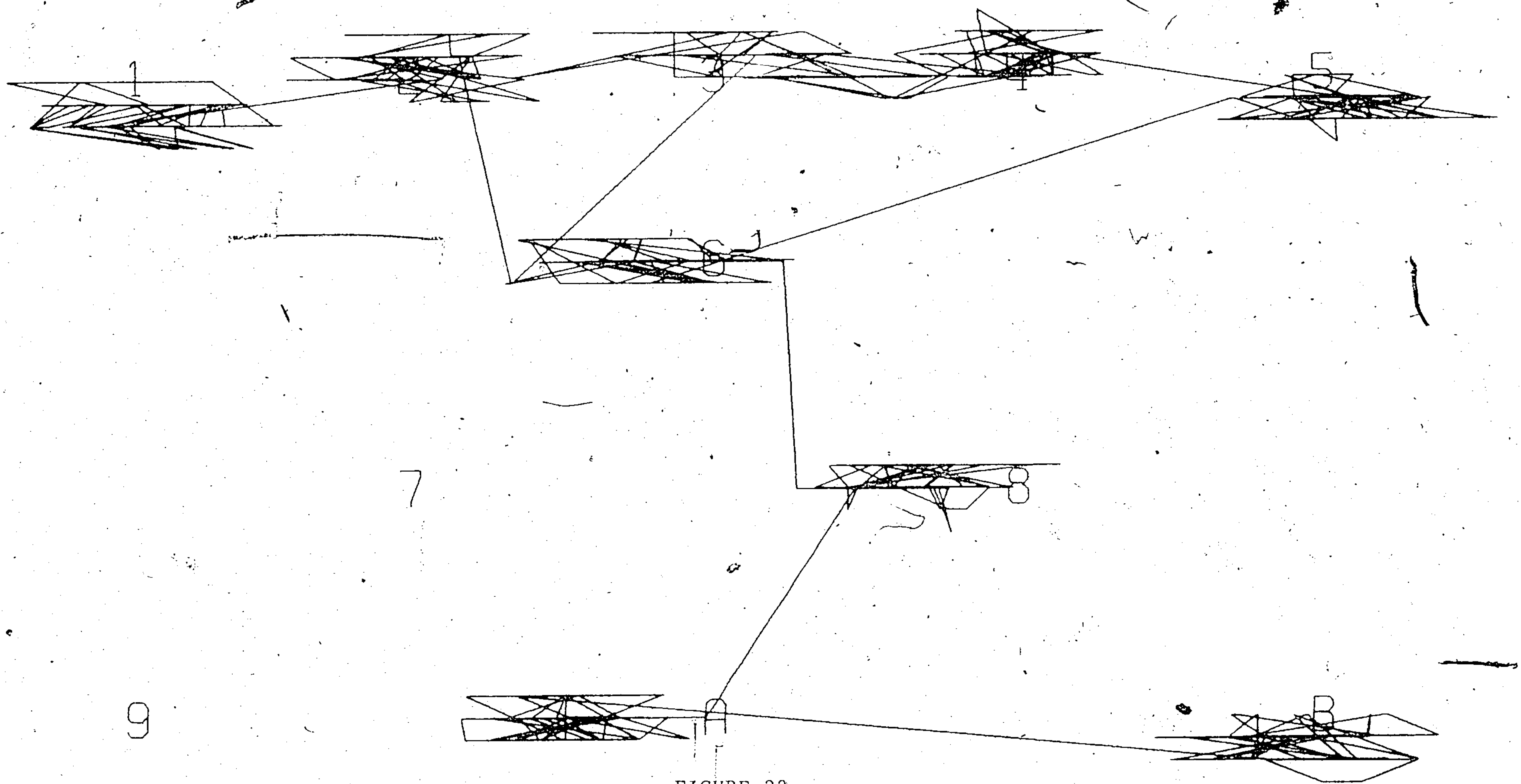


FIGURE 22

Corrected Eye Pointing
Positions for Subject 3
Viewing Stimulus Situation 1

display screen for the first time, signifying completion of reading.

Figures 23,25 and 27 show plots of subjects' eye movements while reading the text presented in stimulus situation one while Figures 24 and 26 show plots of subjects' eye movements after finishing reading the text. Because of the complexity of stimulus situation 4, it was not possible to determine the point at which a subject had finished viewing this stimulus situation, therefore separate plots of eye movements after finishing reading stimulus situation 4 were not made. Readings for stimulus situation 2 and 3 were corrected for non-linearity after removing blinks in exactly the same manner as described above. Plots of eye movements for these stimulus situations are shown in Figures 27 to 37.

Examination of Figures 23, 24, 28, 29, and 33 revealed what appeared to be an increased amount of fixation by all three subjects on the mis-spelled word "large". This correspondence between this increased amount of fixation and the word would certainly suggest that overall calibration of the system had been achieved. However, examination of Figures 28 to 32, the plots of corrected eye movements for subject two seemed to reveal that the vertical registration near the top of the screen was not satisfactory. As a result, the data for subject two was replotted, using only a horizontal correction factor. Figures 38 to 42 show these plots. It appeared that better vertical registration was achieved for subject two without vertical correction of the data.

As has already been mentioned, data regarding the occurrence and duration of blinks was available. Data regarding pupil dilation was also available. Figure 43 shows changes in dilation observed for

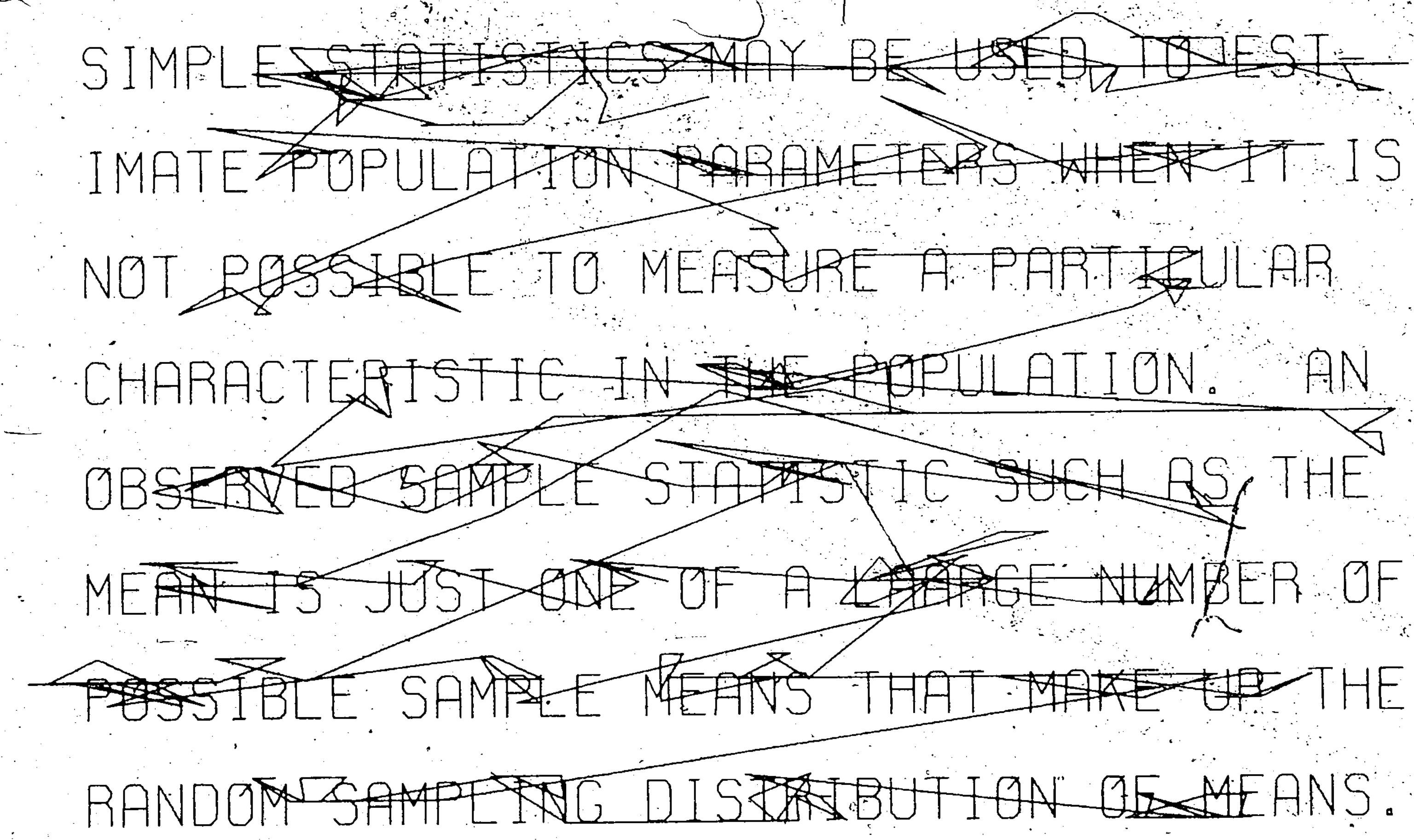


FIGURE 23

Corrected Eye Movements
for Subject 1 Reading
Stimulus Situation 2

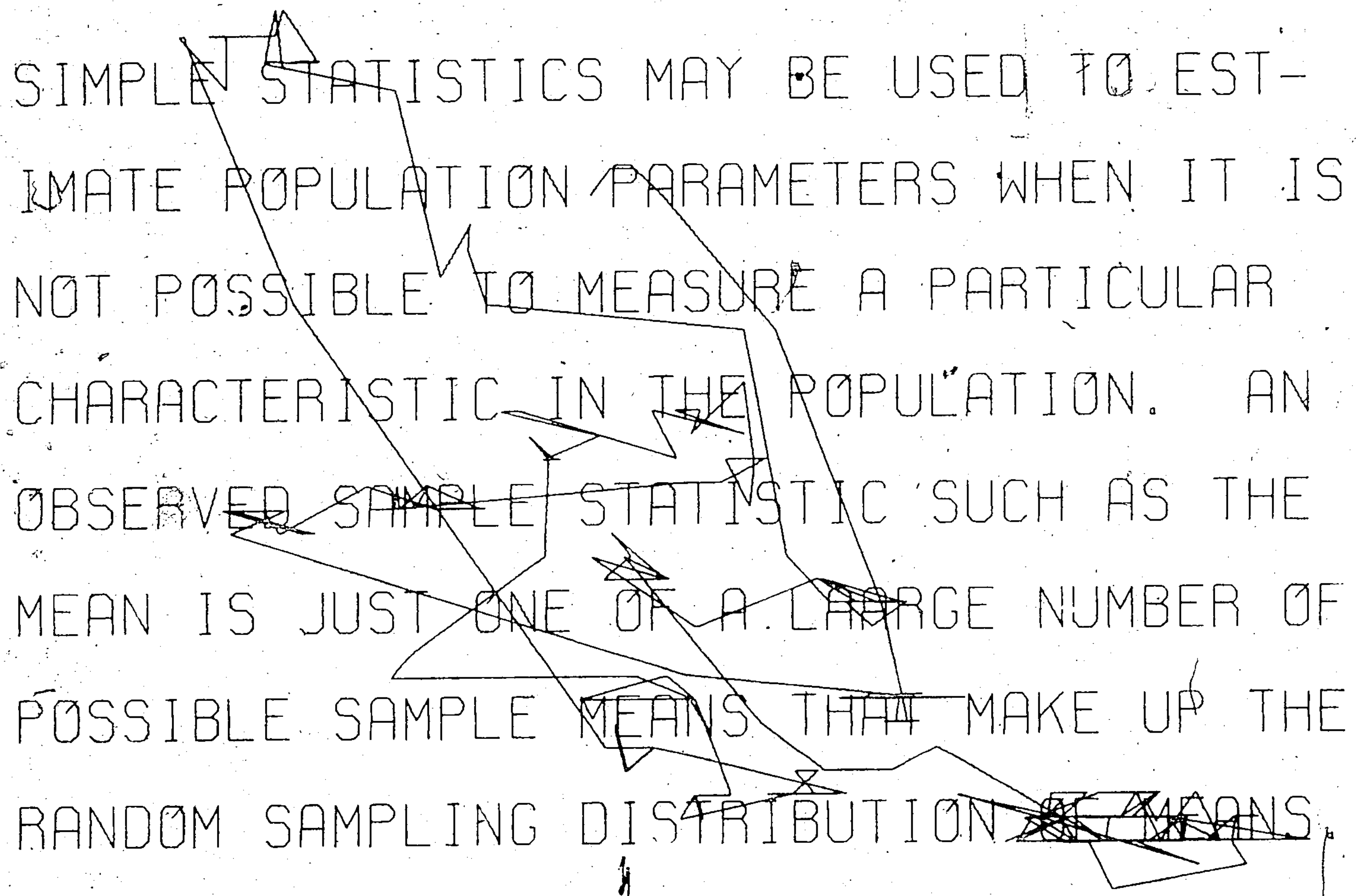


FIGURE 24

Corrected Eye Movements
For Subject 1 Waiting For
Stimulus Situation 3

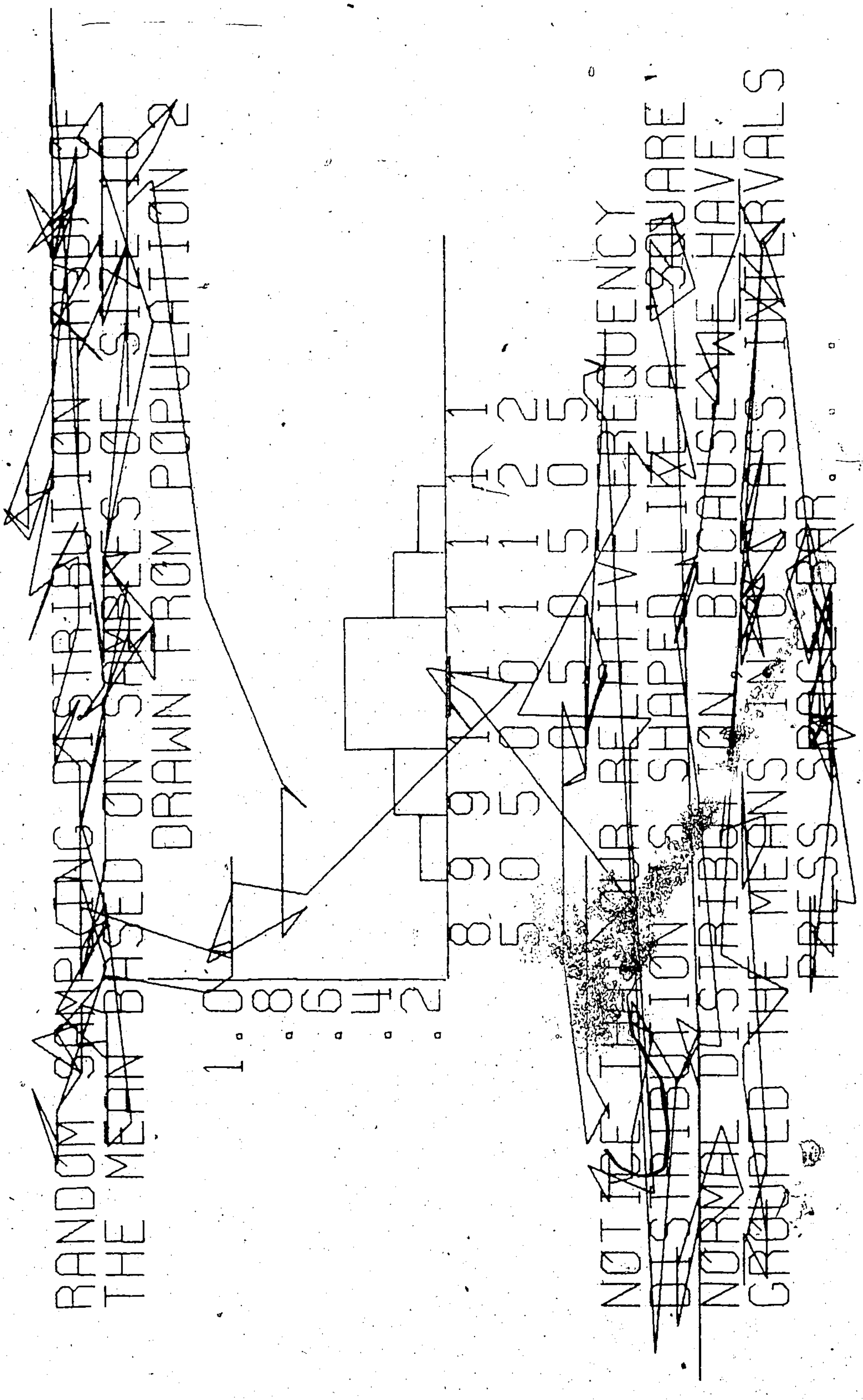
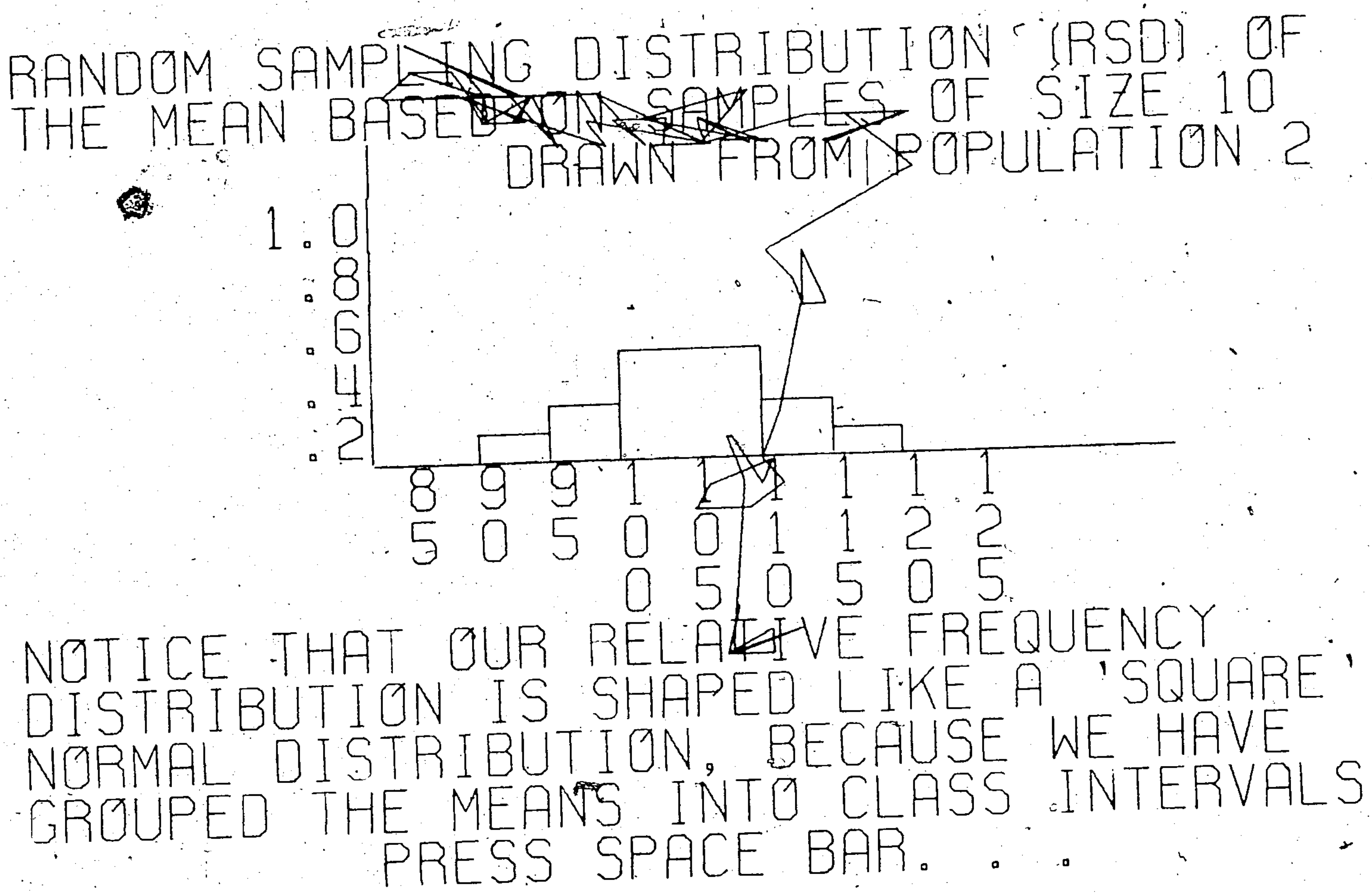


FIGURE 25

Corrected Eye Movements
for Subject 1 reading
Stimulus Situation 3



RANDOM SAMPLING DISTRIBUTION (RSD) OF THE MEAN BASED ON SAMPLES OF SIZE 10 DRAWN FROM POPULATION 2

NOTICE THAT OUR RELATIVE FREQUENCY DISTRIBUTION IS SHAPED LIKE A 'SQUARE' NORMAL DISTRIBUTION, BECAUSE WE HAVE GROUPED THE MEANS INTO CLASS INTERVALS

PRESS SPACE BAR. . .

FIGURE 26

Corrected Eye Movements
For Subject 1 Waiting For
Stimulus Situation 4

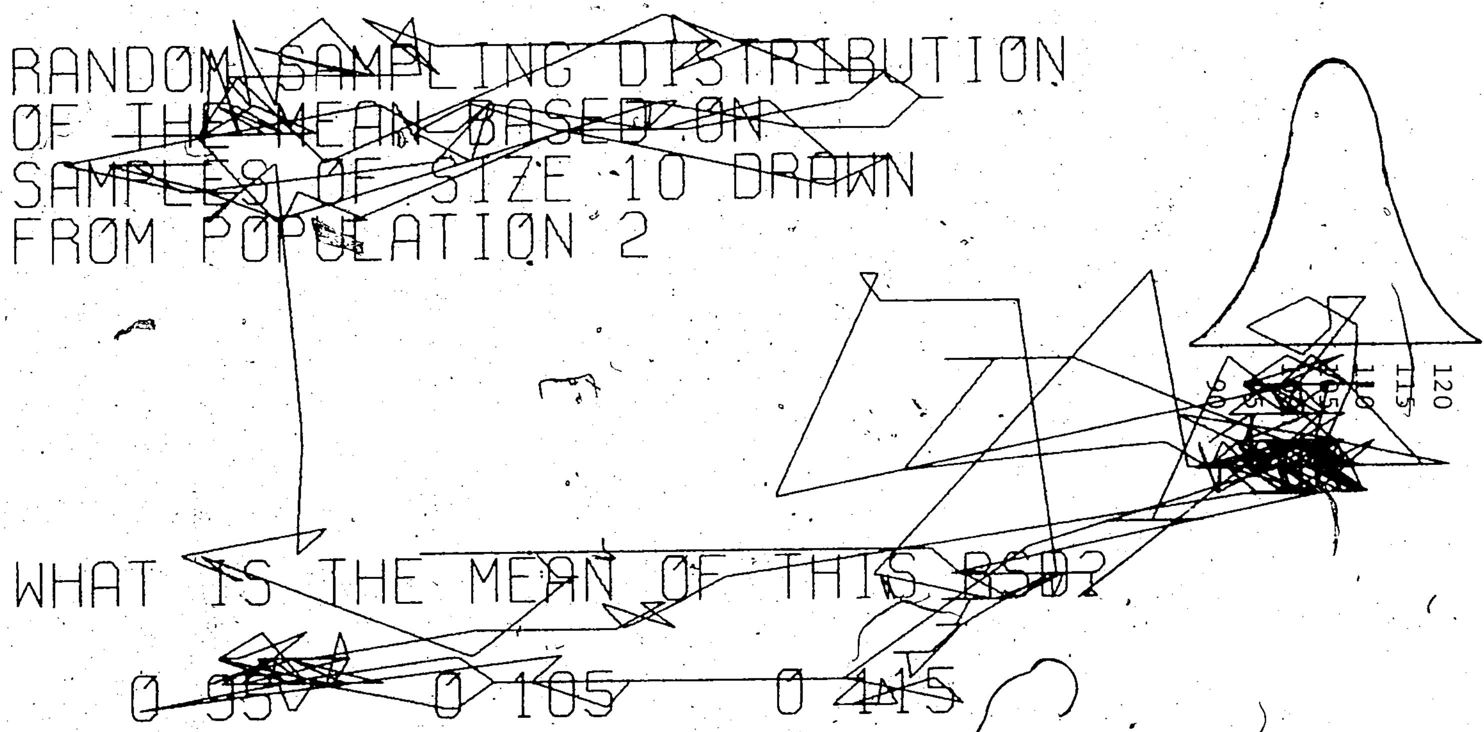


FIGURE 27

Corrected Eye Movements
for Subject 1 Reading
Stimulus Situation 4

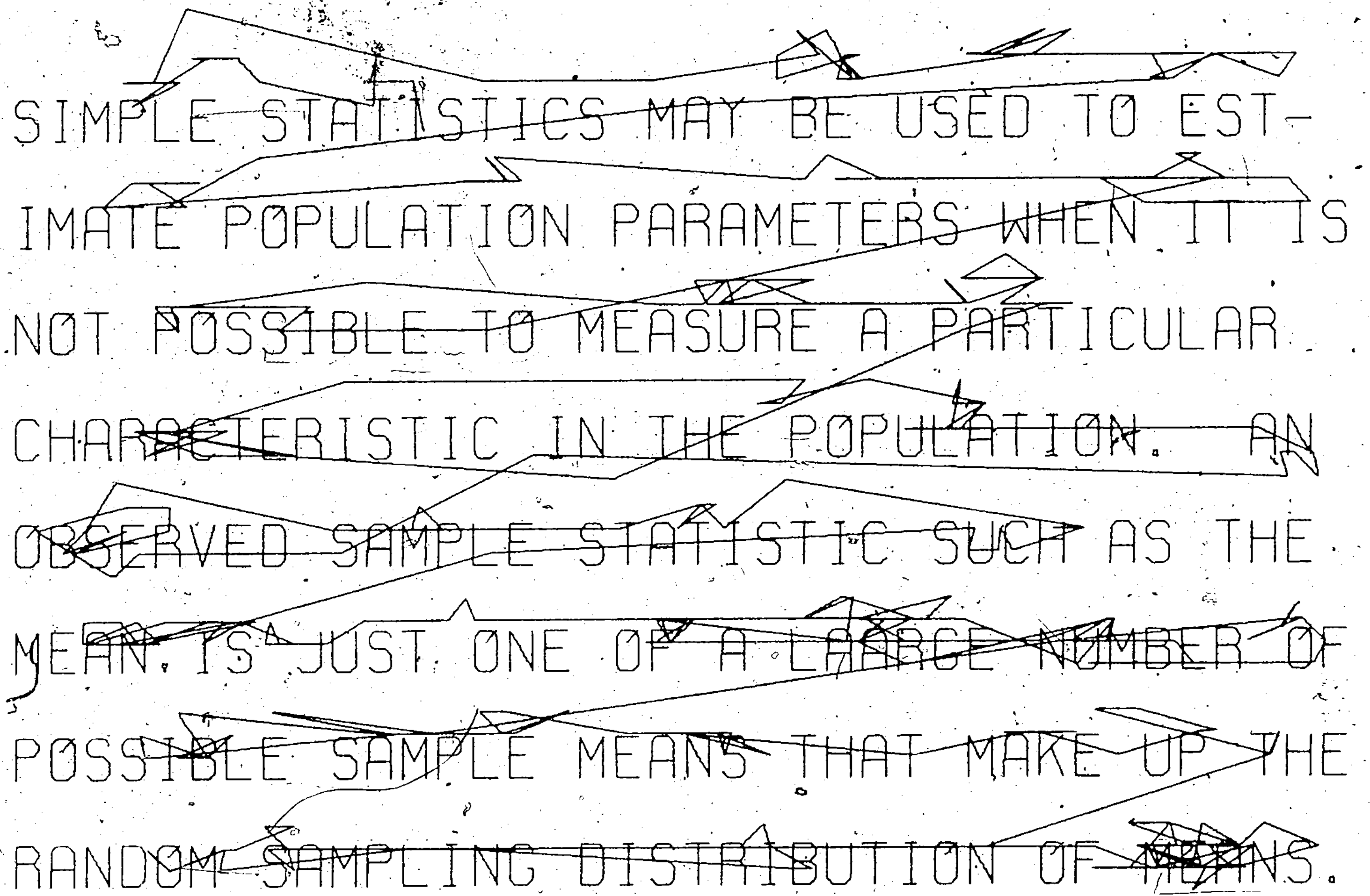


FIGURE 28

Corrected Eye Movements
for Subject 2 Reading
Stimulus Situation 2

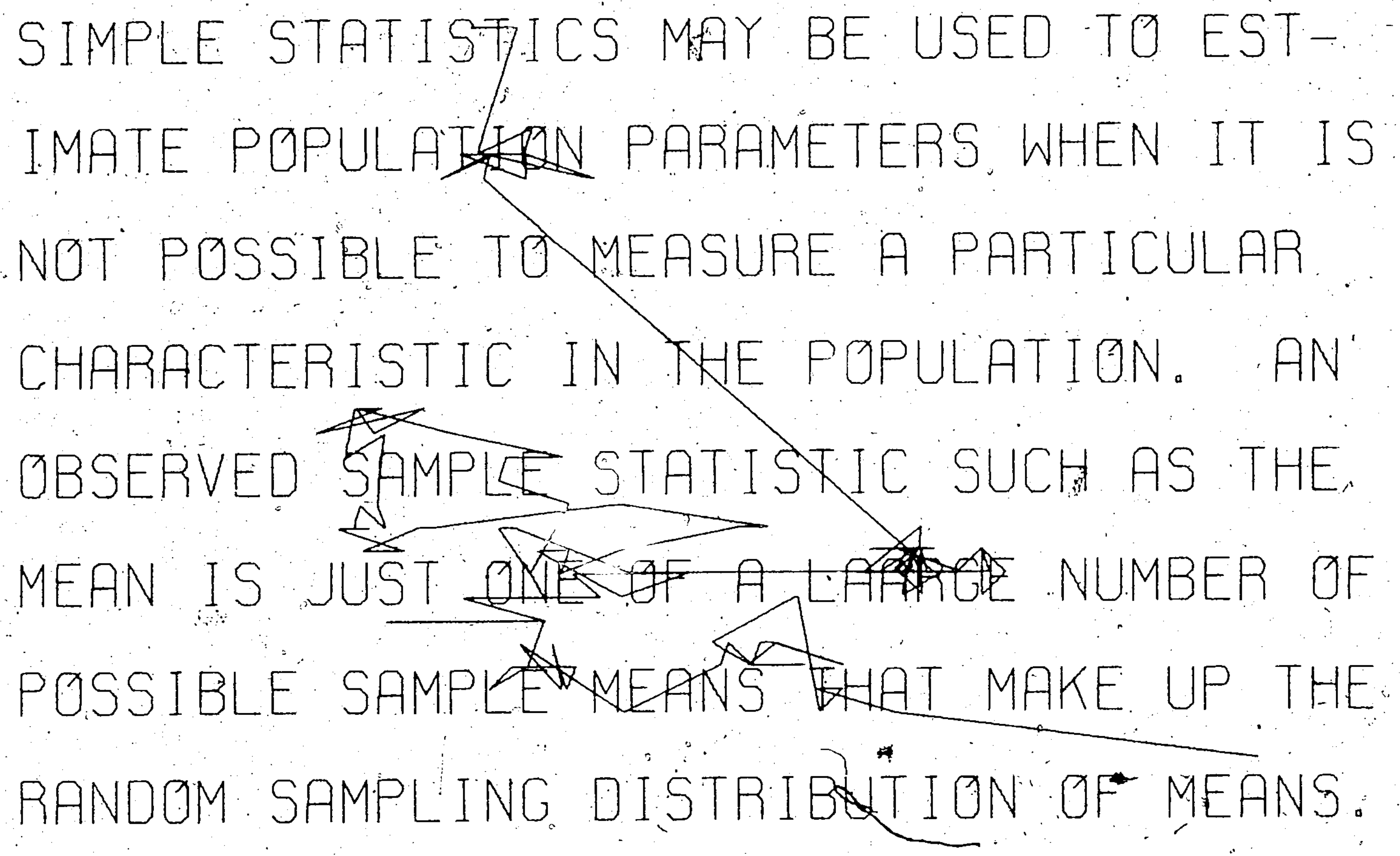
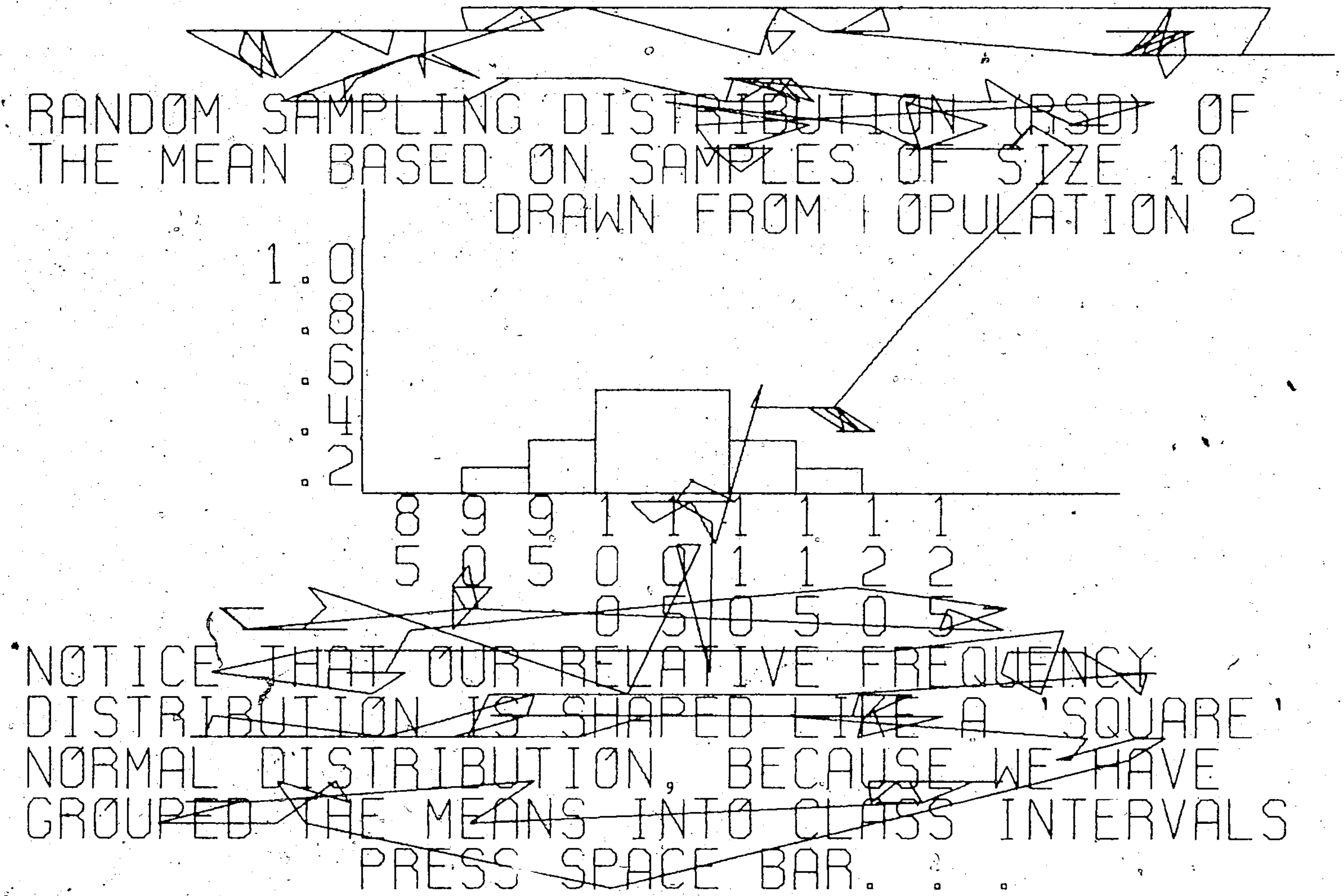


FIGURE 29

Corrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 3

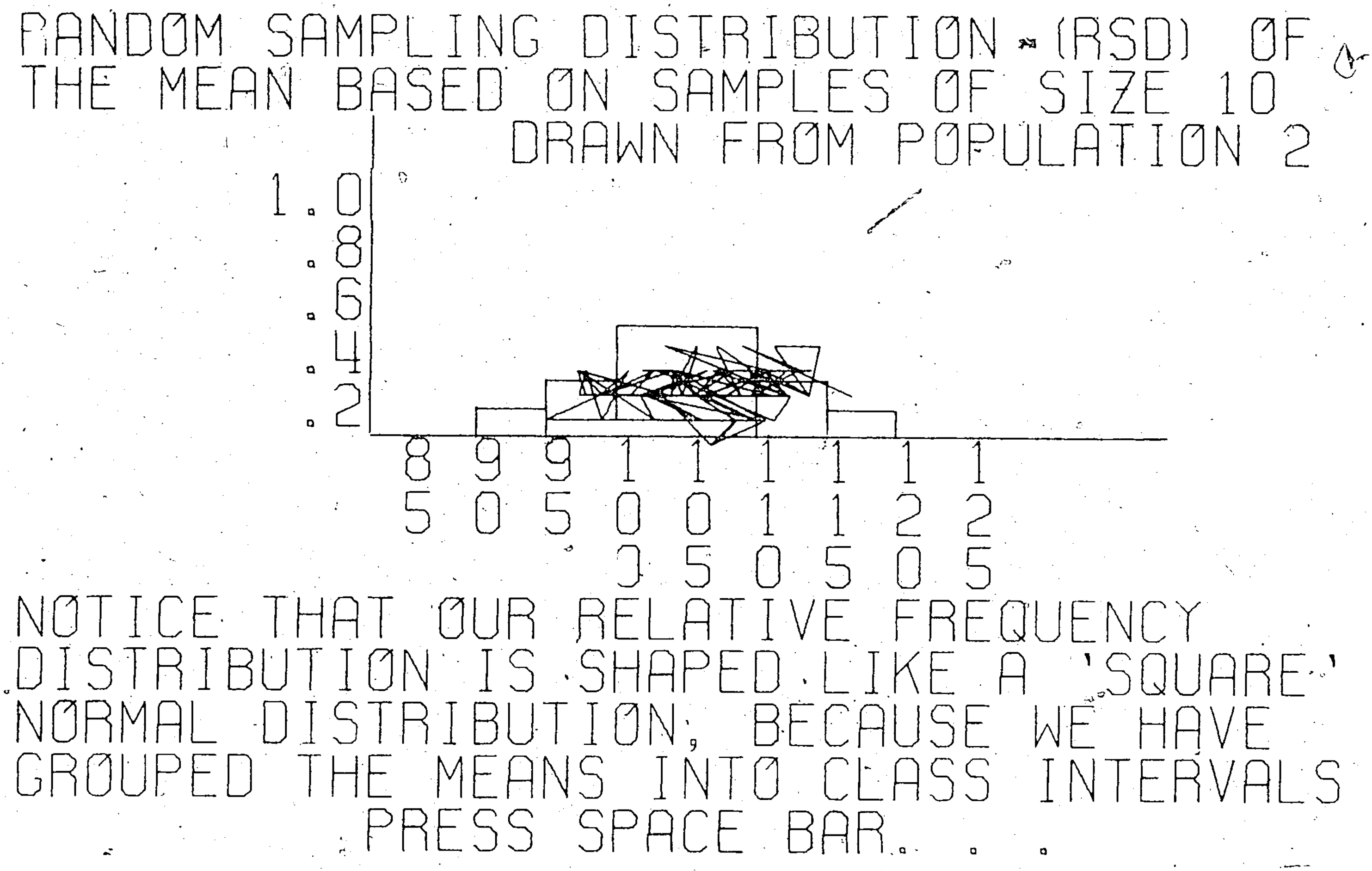


RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2

NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 30

Corrected Eye Movements
for Subject 2 Reading
Stimulus Situation 3


RANDOM SAMPLING DISTRIBUTION (RSD) OF THE MEAN BASED ON SAMPLES OF SIZE 10 DRAWN FROM POPULATION 2

NOTICE THAT OUR RELATIVE FREQUENCY DISTRIBUTION IS SHAPED LIKE A 'SQUARE' NORMAL DISTRIBUTION, BECAUSE WE HAVE GROUPED THE MEANS INTO CLASS INTERVALS

PRESS SPACE BAR. . .

FIGURE 31

Corrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 4

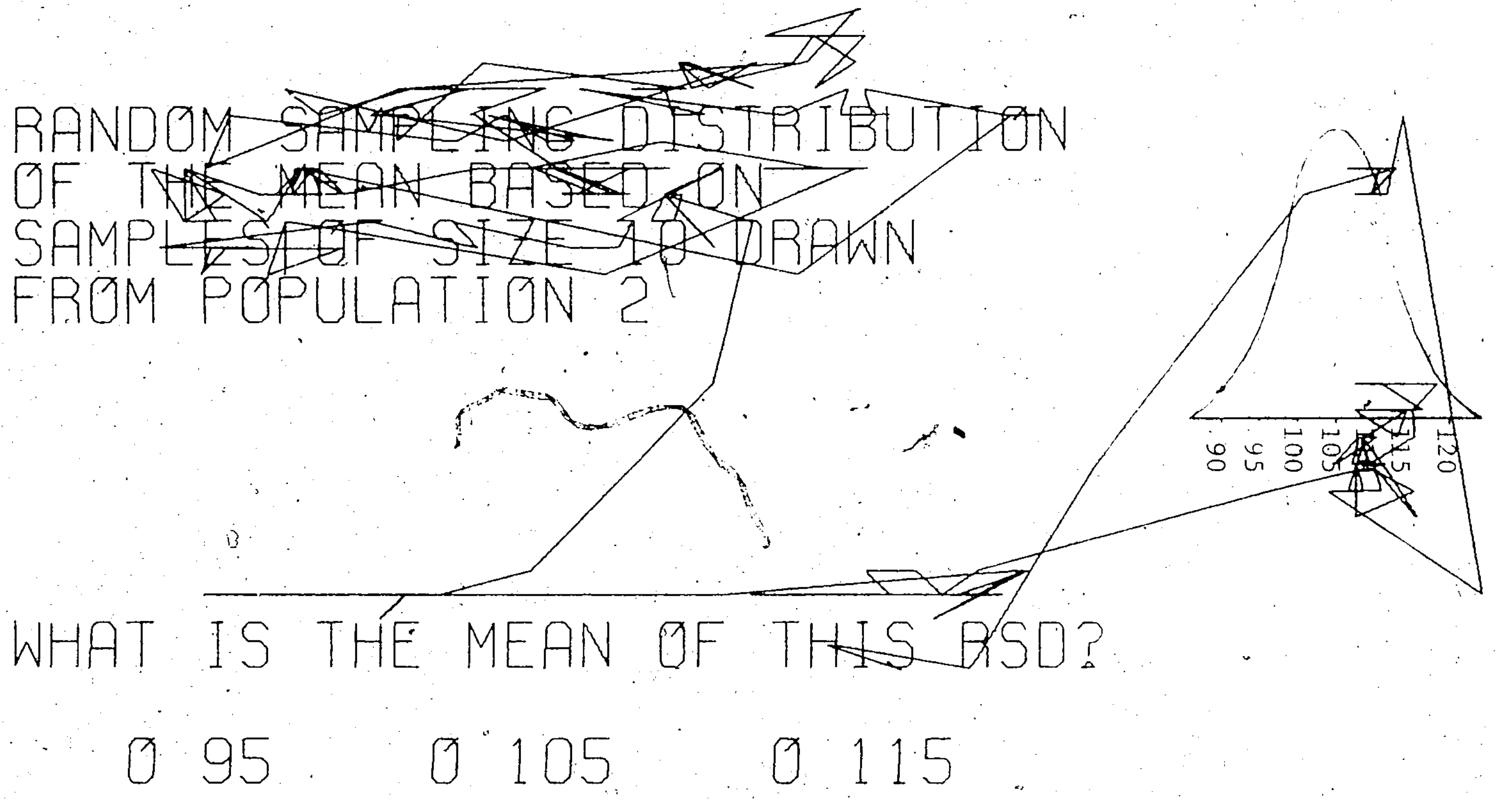


FIGURE 32

Corrected Eye Movements
for Subject 2 Reading
Stimulus Situation 4

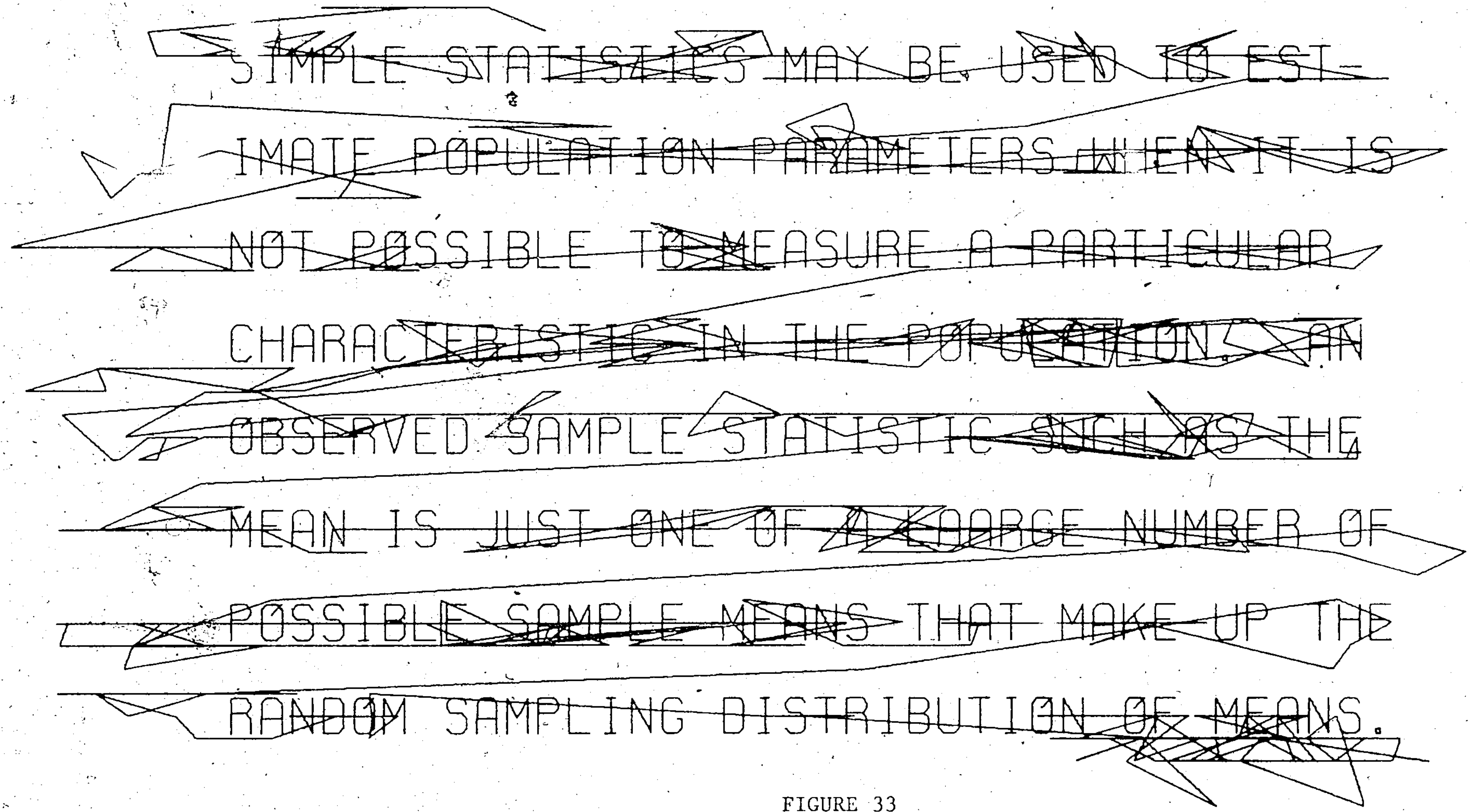
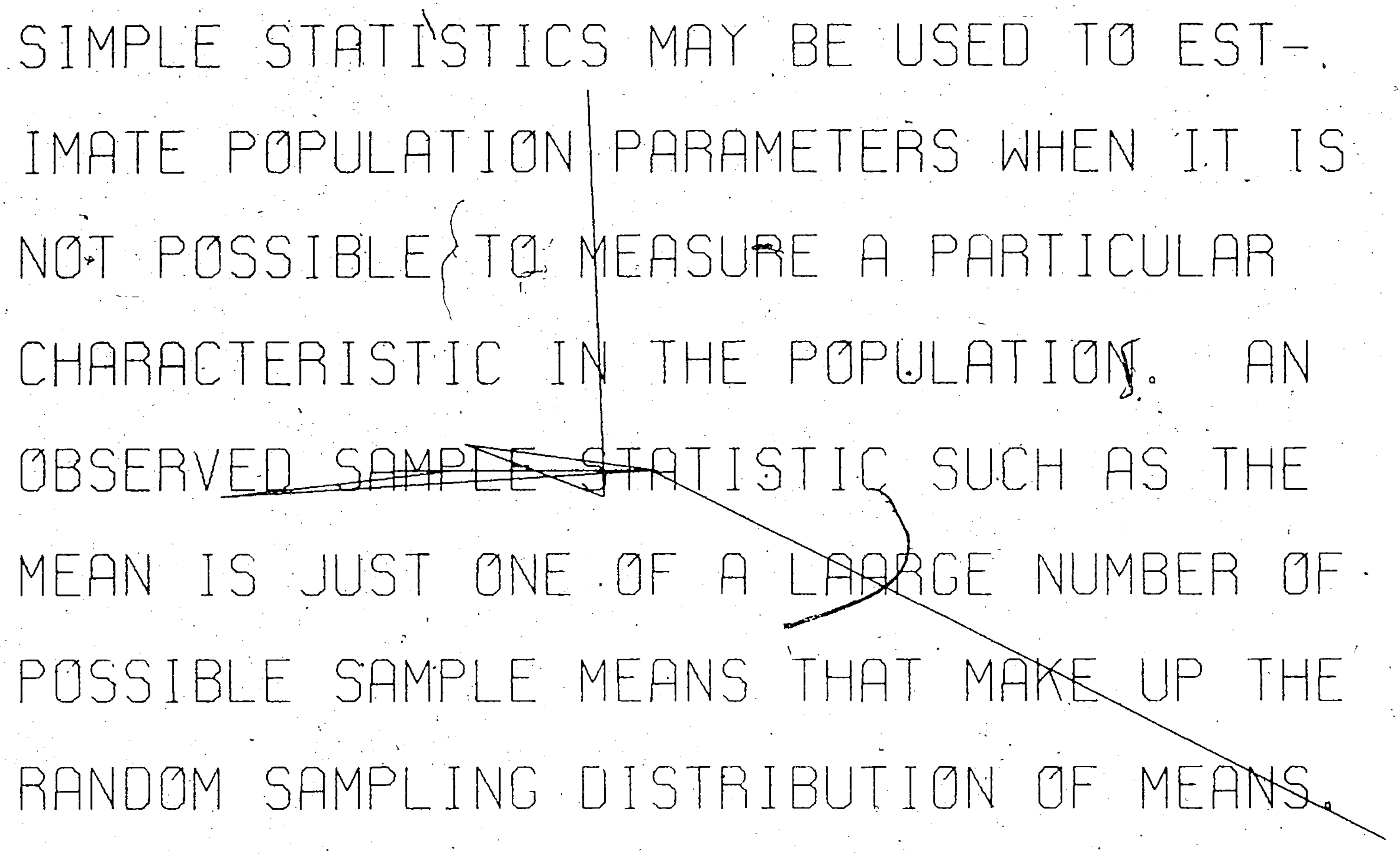


FIGURE 33

Corrected Eye Movements
for Subject 3 Reading
Stimulus Situation 2



SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LAARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 34

Corrected Eye Movements
for Subject 3 Waiting for
Stimulus Situation 3

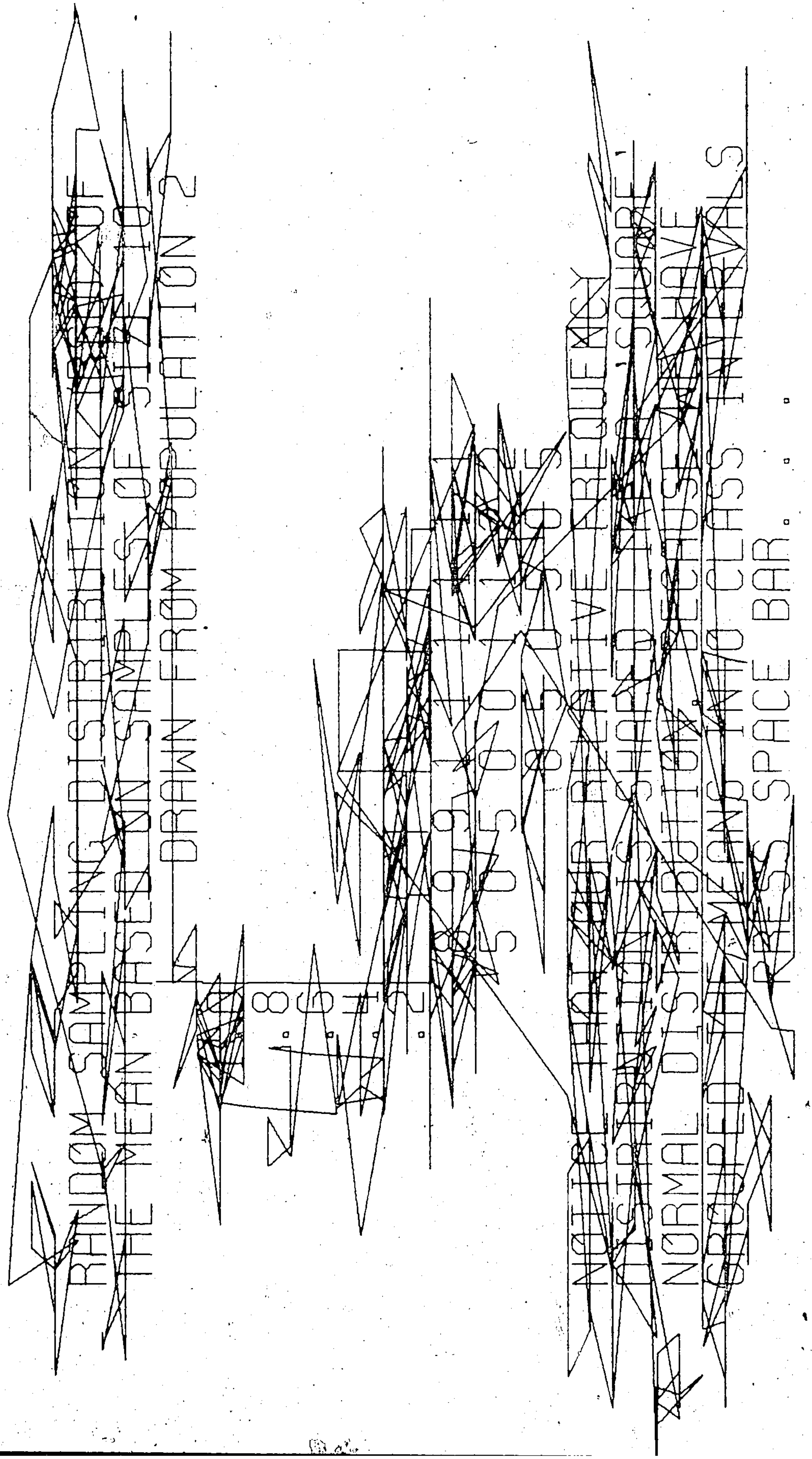
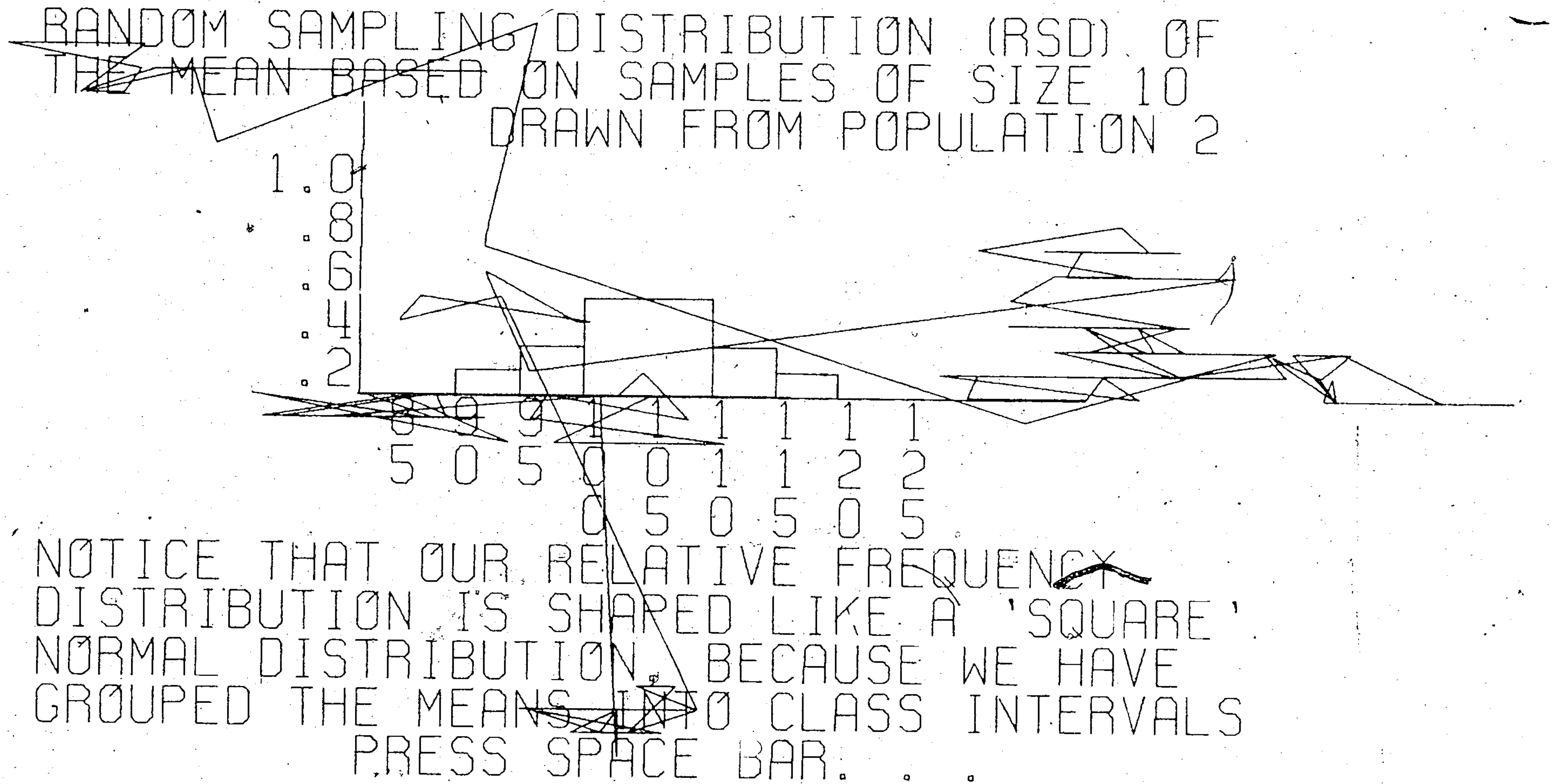


FIGURE 35

Corrected Eye Movements
for Subject 3 Reading
Stimulus Situation 3



RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2

NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 36

Corrected Eye Movements
for Subject 3 Waiting for
Stimulus Situation 4

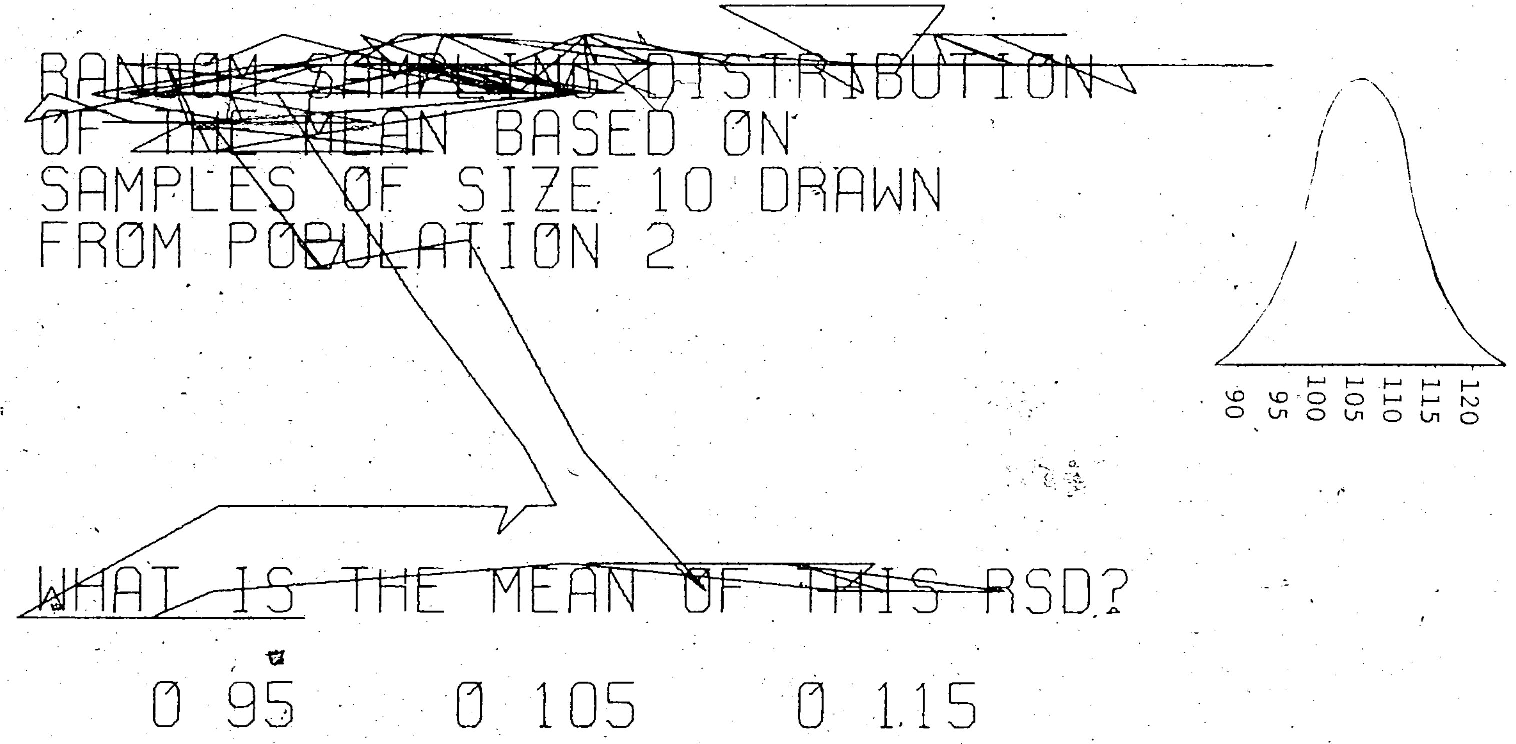
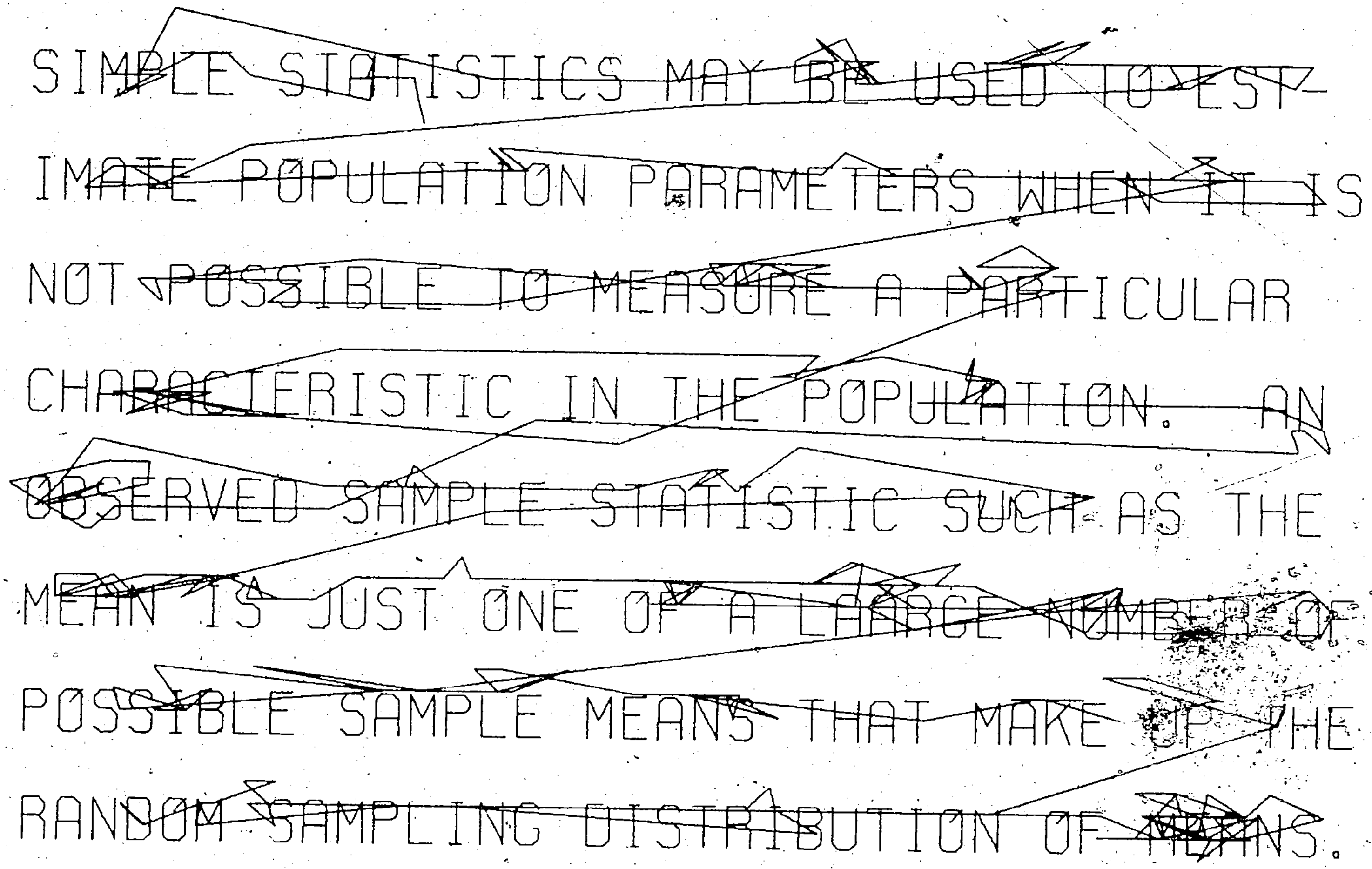


FIGURE 37

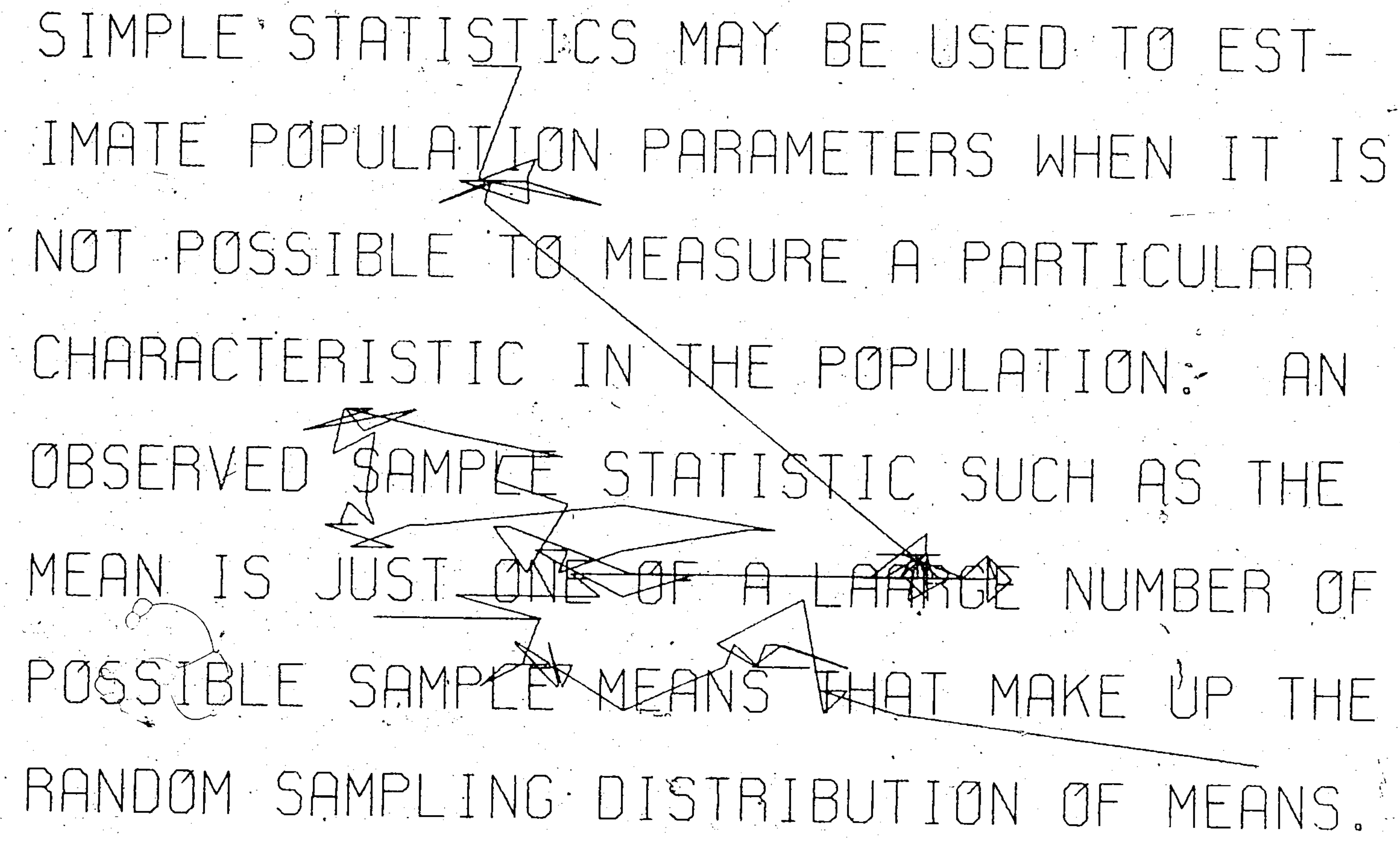
Corrected Eye Movements
for Subject 3 Reading
Stimulus Situation 4



SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 38

Uncorrected Eye Movements
for Subject 2 Reading
Stimulus Situation 2



SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION: AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 39

Uncorrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 3

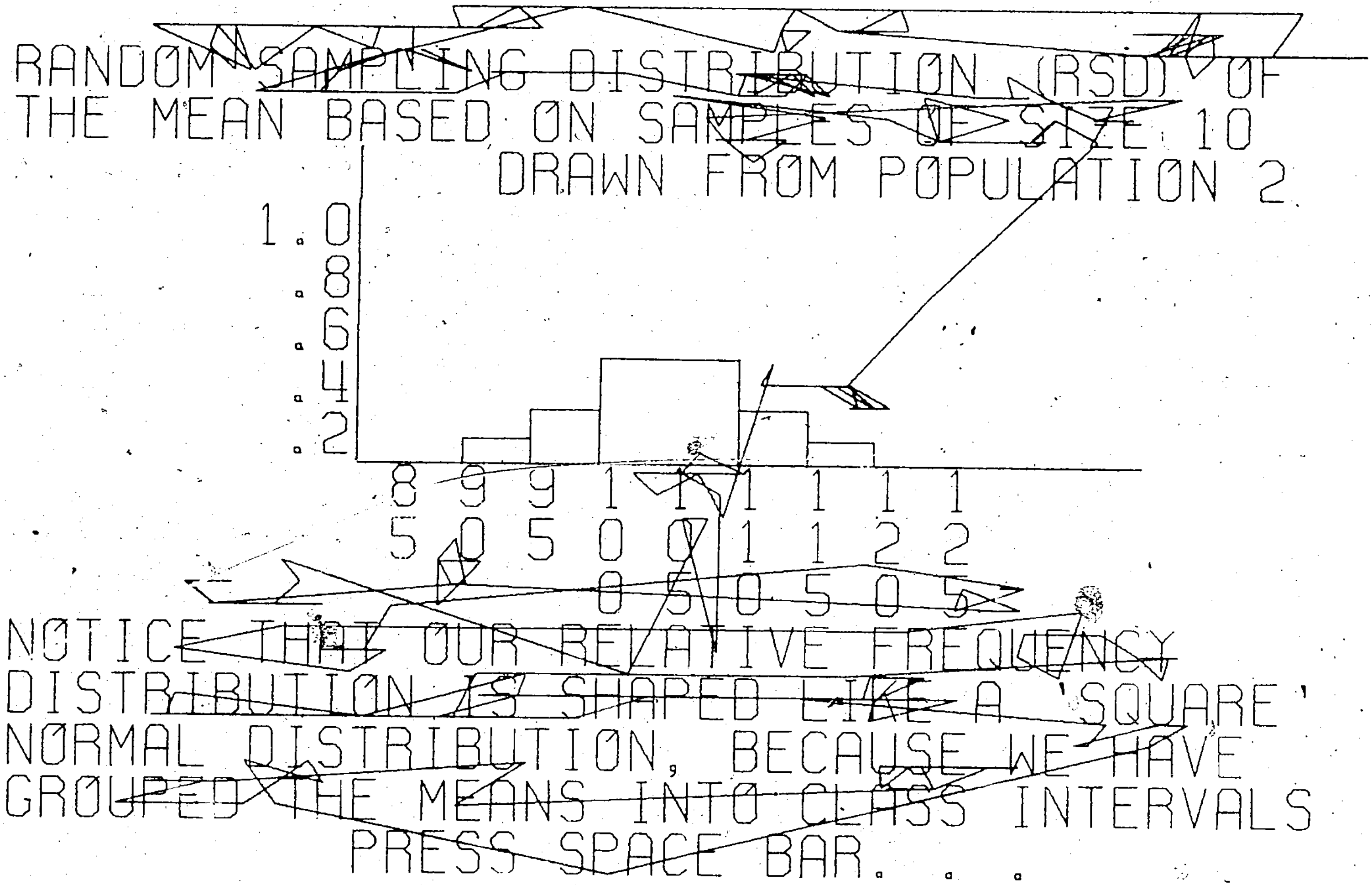
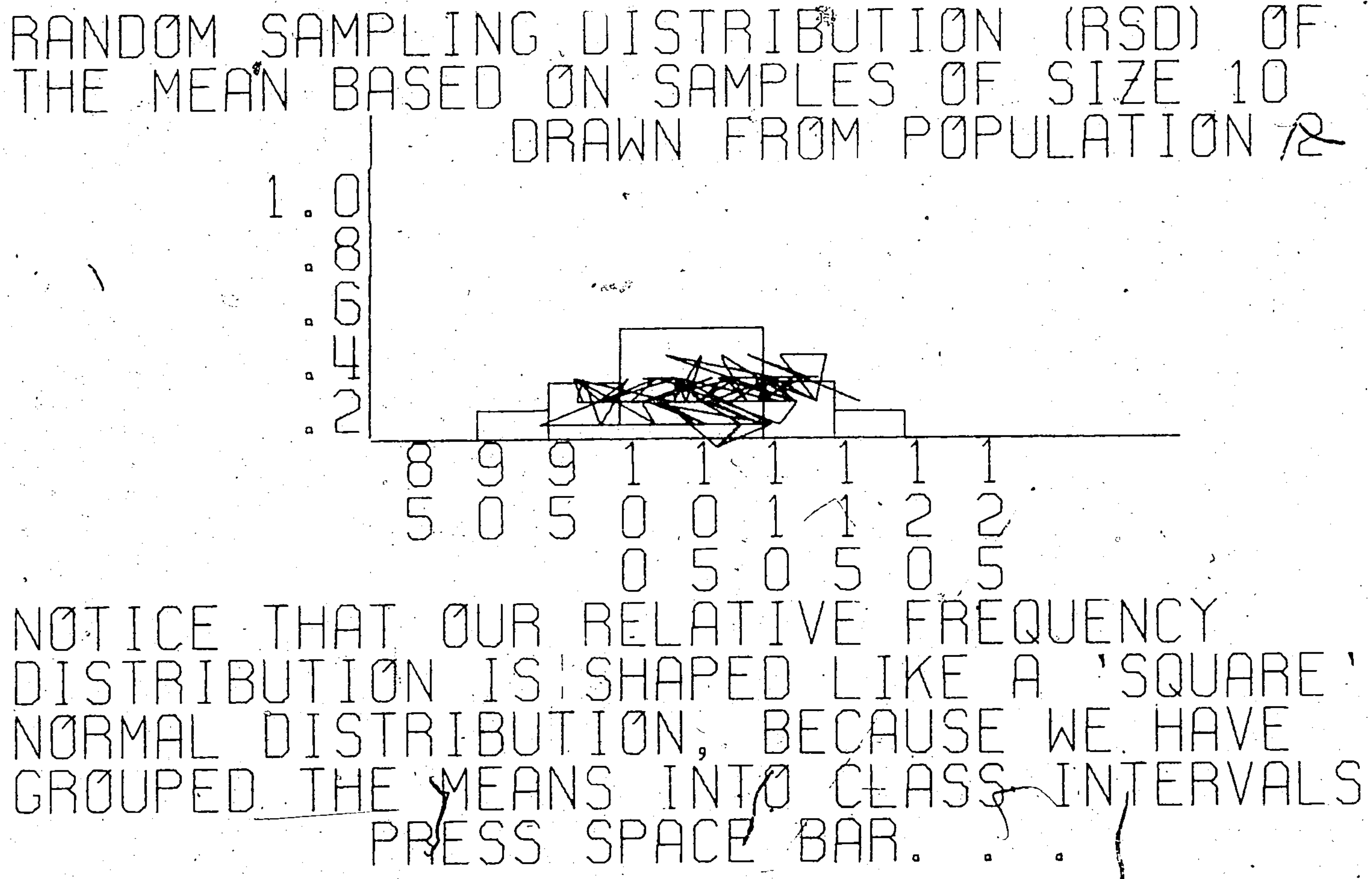


FIGURE 40

Uncorrected Eye Movements
for Subject 2 Reading
Stimulus Situation 3


RANDOM SAMPLING DISTRIBUTION (RSD) OF THE MEAN BASED ON SAMPLES OF SIZE 10 DRAWN FROM POPULATION 2

NOTICE THAT OUR RELATIVE FREQUENCY DISTRIBUTION IS SHAPED LIKE A 'SQUARE' NORMAL DISTRIBUTION, BECAUSE WE HAVE GROUPED THE MEANS INTO CLASS INTERVALS

PRESS SPACE BAR. . .

FIGURE 41

Uncorrected Eye Movements for Subject 2 Waiting for Stimulus Situation 4

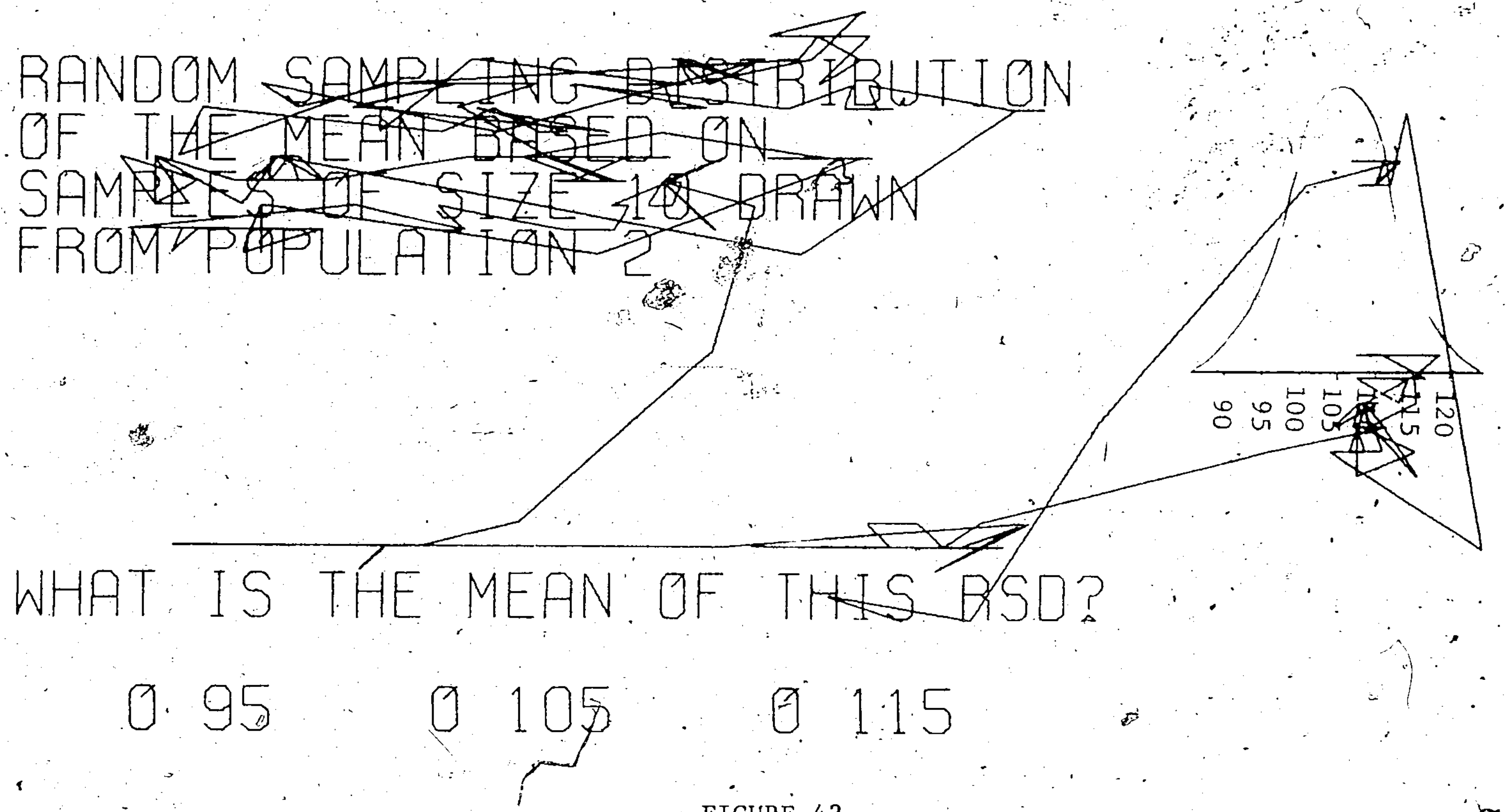


FIGURE 42

Uncorrected Eye Movements
for Subject 2 Reading
Stimulus Situation 4

1 of

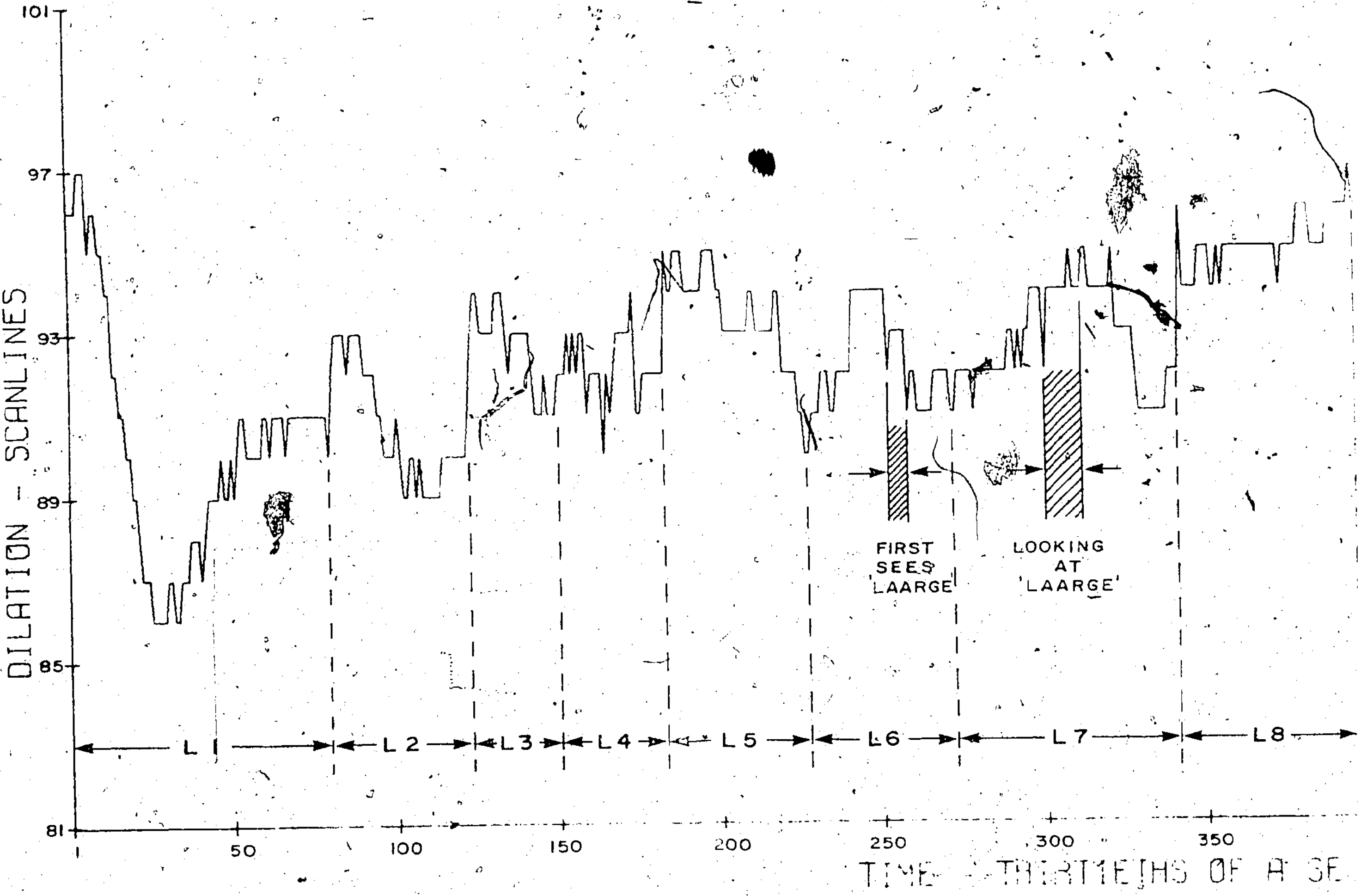


FIGURE 43

Pupil Dilations for Subje
Reading Stimulus Situati

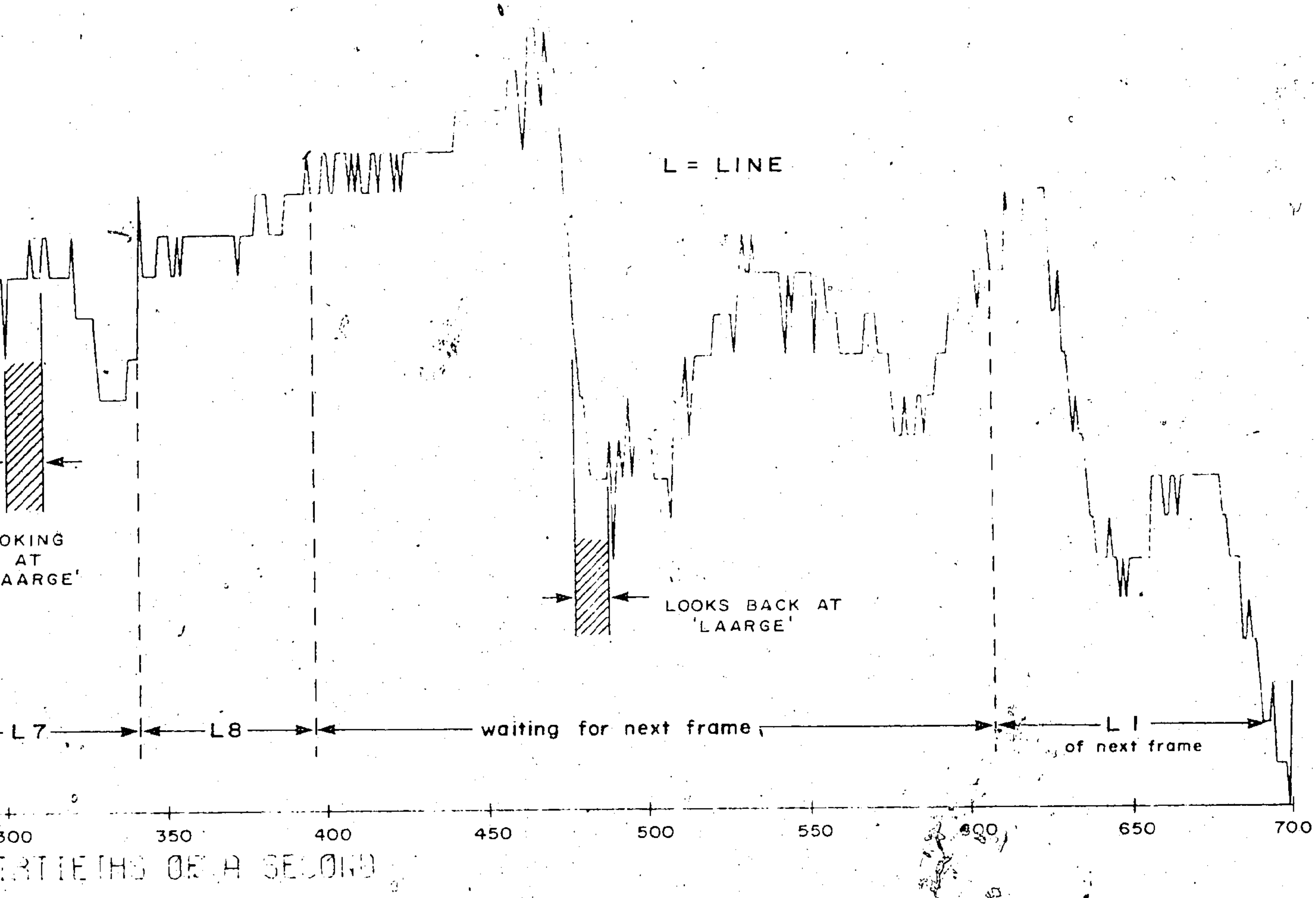


FIGURE 43

pil Dilations for Subject 1
eading Stimulus Situation 2

subject one while viewing stimulus situation two. The dilations for the remaining subjects have not been plotted.

It was noted that approximately eight consecutive seconds of eye movements for subject two were lost while the subject was viewing frame three because of a sudden increase in pupil intensity to a point where the pupil signal level was sufficient to activate the corneal reflection circuits. This was recorded as an eight second blink.

Stimulus Situation Five - Calibration Check

In order to confirm the calibration of the system, the calibration display used in stimulus situation one was presented to subjects at the end of stimulus situation four. The data obtained in this manner proved to be of little value as subjects verbally confirmed that they tended to look at the position on the video display where they expected the next calibration point to appear. This data was therefore not reported in this study.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

Because so much of what a learner learns is presented to him via the visual channel, it is important to educators, particularly those who wish to study learning and attention, to be able to monitor the visual response of the learner. During this century, a number of different methods for monitoring visual response have been used with varying degrees of success. This study described and documented the development of a computer based system for recording eye movements derived from observation of the position of the corneal reflection relative to the pupil center, using an infrared television camera interfaced to a small digital computer.

The infrared computer based oculometer described in this study was developed in order to provide a means of studying eye movements of learners in relation to learning and attention. In Chapter III, six requirements for an effective oculometer system were specified. These were that:

1. The measuring and recording apparatus be relatively unobtrusive.
2. The equipment require no mechanical attachment to the subject.
3. The equipment place as few unnatural constraints (such as restriction of head movement) on the subject as possible.
4. As many oculographic characteristics as possible be recorded simultaneously.
5. The data be in a form that is readily accessible for analysis by computer.

6. The equipment be sensitive enough to detect, and fast enough to record all types of conjugate eye movements.

The infrared computer based oculometer system described in this study is relatively unobtrusive, in that the only part of the system that need be seen by the subject is the faint red glow of the illuminating source of light. The computer and its peripheral devices can be physically located in a separate room. In the event that the red light produced by the system is considered too obtrusive in a given situation, then the addition of a simple inexpensive gelatin filter would eliminate it without otherwise affecting the operation of the system.

The only physical connection between the subject and the oculometer system is the head restraint. While this represents somewhat of an unnatural constraint on the subject, it is necessary in order to insure that the subject's eye remains within the field of view of the camera. While it is somewhat less than the ideal situation of no restraint, it represents a considerable improvement over earlier restraints such as the "bite-bar".

The oculometer system described in this study recorded data in relation to pupil dilation and eye pointing direction at the rate of one record every thirtieth of a second, on 9-track computer tape. Data concerning the occurrence and duration of blinks was also recorded. From the basic data recorded by the infrared computer based oculometer system, it was possible to plot eye movements of subjects while they looked at various stimulus situations presented to them via a cathode ray display terminal connected to an IBM 1500 CAI system. Pupil dilations and Y-displacements were measured in terms of television scanlines, the distance between two adjacent scanlines being approximately .00072 inches at the face of the vidicon. X-displacements were measured in terms of clock pulses occurring at the rate of one pulse every tenth of a microsecond. The distance between two adjacent clock pulses was approximately .00055 inches at the face of the vidicon.

The accuracy of the infrared computer based oculometer system was assessed in relation to a simulated eye which produced an image on the monitor identical to that of a human eye, but which, unlike the human eye could be made to remain perfectly stationary. The variances of both dilation and Y-displacement recorded by the oculometer system using the simulated eye were 0.00. The variance of the X-displacements was 0.21 clock pulses per second squared. The resolution of the oculometer system was assessed by having a subject visually track a moving target displayed at various locations of the display screen. Based on the observed displacements, it was estimated that the vertical resolution was ±0.16 inches on a display 16 inches from the eye of the subject, or ±0.7 degrees of angle, while the horizontal resolution was ±0.18 inches on a display 16 inches from the eye of the subject or ±0.95 degrees of angle.

Relating the observed capabilities of the oculometer system to the types of conjugate eye movements reported in Chapter 2 of this study, it would appear that the oculometer system would be capable of detecting most small conjugate eye movements which occur during a fixation, since these eye movements normally occur less than ten times per second and consist of displacements of about ½ degree of angle. Since saccades are reported to occur no more frequently than five times per second, it would appear that the oculometer system would be capable of recording a minimum of six readings during even the shortest inter-saccadic fixation. For longer fixations, even more readings would be recorded. Also, since satisfactory tracking is only possible at speeds below 200 degrees of angle per second, the oculometer system would be capable of recording an eye pointing coordinate at least once for every seven degrees of angular displacement.

It would appear therefore, that the infrared computer based oculometer system reported in this study would be capable of detecting and recording all types of conjugate eye movements.

While for many studies in education and other fields, the sensitivity of the computer based oculometer system described in this study would be sufficient, greater sensitivity in both the horizontal and vertical directions could easily be accomplished. By using a "non-standard" camera unit, scanning rates of more than 1000 lines could be obtained. This would mean that, compared to the 525-line camera used in this study, the vertical sensitivity could be nearly doubled. Also, by using a faster horizontal time base, for example, 20 megahertz instead of 10 megahertz, the horizontal sensitivity could be doubled.

An oculometer system fully synchronized to a single time base and with better horizontal and vertical sensitivity would certainly reduce the error introduced by the equipment. There is however another source of error, namely error due to the subject. Findings presented in Chapter 4 seem to suggest that even though a subject is looking at a target, his eye pointing direction may not be precisely at the target. Ideally, to assess the capability of the oculometer system to measure eye pointing direction, a plastic model of the eye, mounted on a micrometer head should be used. This would permit accurate pointing of the eye at known target locations, thereby making it possible to assess the capability of the oculometer to measure eye pointing direction without introducing human error. Such a model was reported to have been built at the Massechussets Institute of Technology, however attempts to obtain it have proved fruitless.

One factor which seriously affected the oculometer output was variation in the intensity of the pupil image. As the pupil fixated various coordinate positions of the display screen, the amount of light reflected by the pupil varied sufficiently so that at times, the pupil intensity was as great as the intensity of the corneal reflection. This resulted in the oculometer system recording the presence of a blink even though no blink occurred. In other instances, increased brightness of the pupil was not sufficient to cause the recording of a blink, however it was sufficient to result in an apparent increase in dilation amounting to one or two lines. This could result in an apparent change in eye pointing direction being recorded by the oculometer different from the change that actually occurred. The addition of an automatic intensity control circuit which would sense the video level coming from the camera unit and would control the intensity of the infrared light source making the video level coming from the camera unit constant, would be a relatively simple addition to the system.

The problem of calibration of the oculometer to a particular subject requires that a reference point on the display screen be established and the horizontal and vertical displacement coordinates be noted when the subject is fixating this reference point. In addition, the horizontal and vertical resolutions must be determined in order to establish a correspondence between a given change in displacement between the pupil center and the corneal reflection, and the change in display screen coordinates being fixated. Outcomes of this study were based on the assumptions that for displacements of less than 12 degrees the relationship would be linear. In this study, readings displaced by more than 12 degrees were corrected for non-linearity, the correction factor being determined by the amount by which the displacement exceeded 12 degrees. It appeared however, that for one subject tested in this study, such a correction factor was not appropriate.

In considering the problem of calibration, it was assumed that the characters displayed on the display screen were of uniform size and of uniform spacing. Upon careful examination of the characters actually produced on the display screen, it was noted that characters varied in both size and spacing and that a small amount of non-linearity existed in the columns of the display screen. Perhaps the most pressing need therefore is to conduct further studies into the effects of non-linearity due to large angular displacements, and to establish reliable calibrating procedures that will take non-linearity into account.

Examination of the plots of eye movements presented in chapter 4 reveals that it is rather difficult to distinguish between fixations and saccades. In addition, such plots are further limited in their usefulness since points occurring at precisely the same coordinate location are plotted as a single point. There is therefore a need to develop better methods of analyzing and displaying eye pointing data. Such developments could optionally include analysis of changes in dilation, blinks, and eye fixations and saccades.

Finally, the development of on-line data handling capabilities which could permit subjects to use eye movements to control peripheral equipment would appear feasible and worthwhile. Such capabilities would permit users, who for various reasons are incapable of eliciting a motor response, to perform motor tasks such as typing by fixating on specified target coordinates.

Finally, it is recommended that further research be carried out in order to assess the magnitude of the error component inherent in the oculometer output. This study has presented a discussion of the error which is internal to the oculometer system. Further studies, repeated over subjects as well as over occasions would permit an assessment of the magnitude of the overall error component in eye movement data and would also permit error variance to be separated into that which may be attributed to the oculometer system and that which may be attributed to the subject. Similar studies, carried out using other oculography systems would also be desirable since it would facilitate the comparison of the performance of various systems of oculography without requiring that two systems be used to record eye movements simultaneously.

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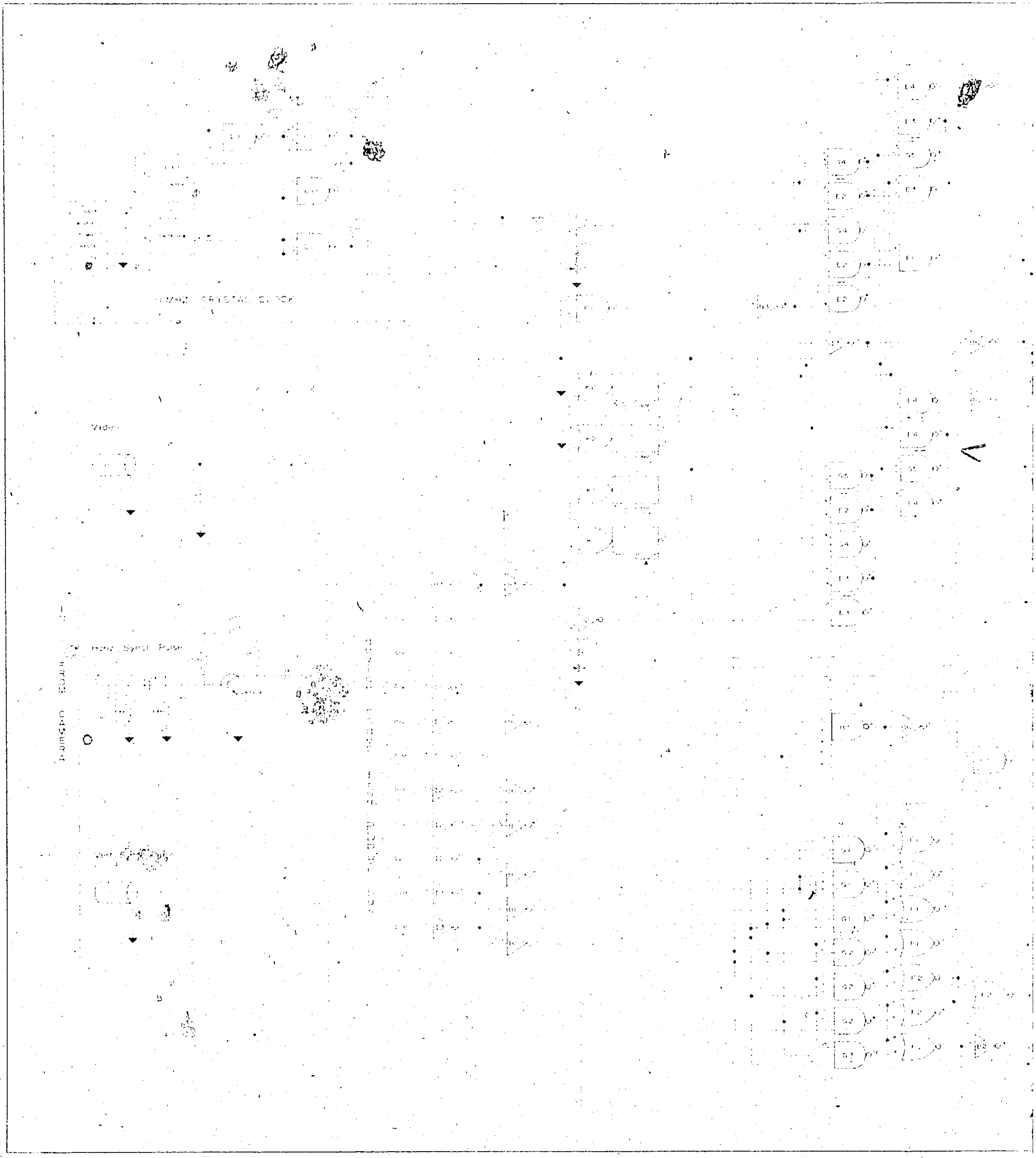
APPENDIX A

1 of



I.C. IDENTIFICATIONS

A • 8881	G • 7410
B • 7404	H • 7430
C • 7493	I • 380
D • 7473	J • μA760
E • 7400	K • 9602
F • 7402	L • MC3004P

NOTES

1) CONTROL FUNCTIONS ARE ASSIGNED AS FOLLOWS

Pin	Code	Function
F1-[illegible]	6641	SKIP ON FLAG
F1-4	6642	SPARE
F1-[illegible]	6643	CLEAR FLAG
F1-3	6644	SPARE
F2-1	6645	READ [illegible] TIME
F2-4	6646	READ [illegible] TIME
F2-[illegible]	6647	READ LINE NO

2) ALL RESISTOR VALUES IN OHMS AND CAPACITOR VALUES IN PICOFARADS

ISSUE	DATE	DWN by	CHK by
[illegible]	Aug 1973	F P	M P

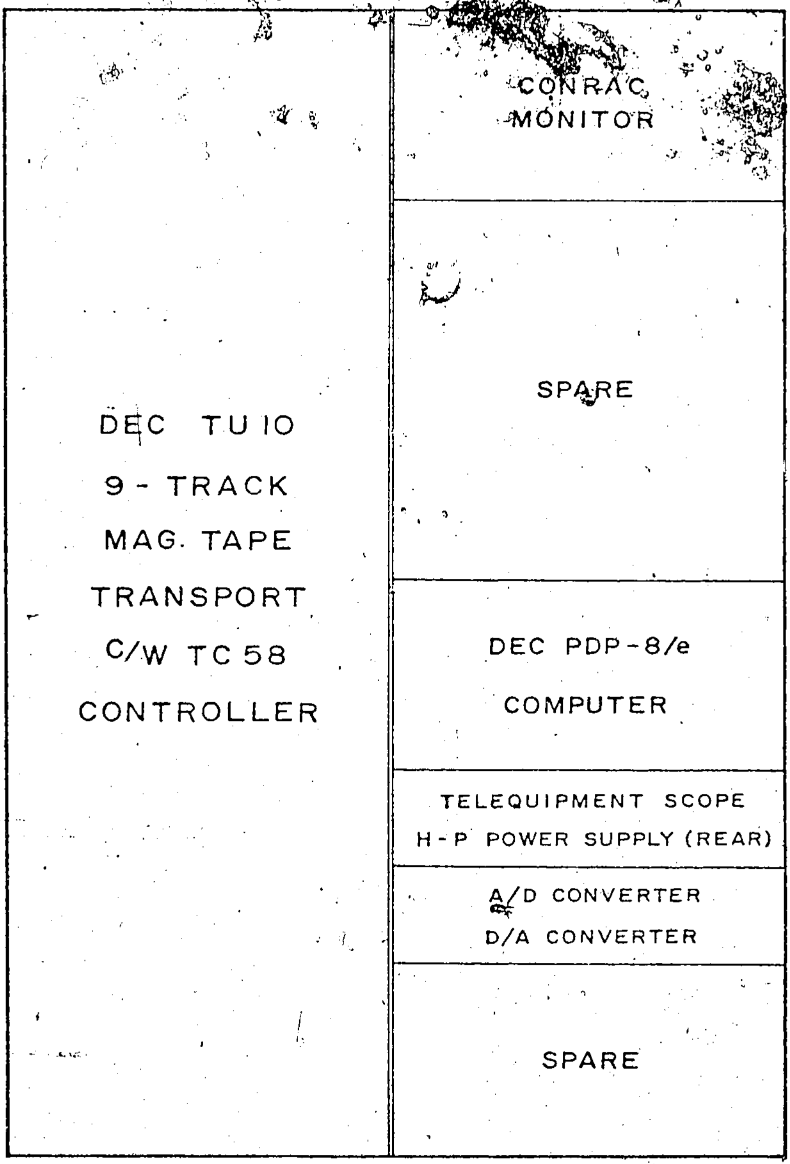
Connected Pin 14 - 13 to Pin: F2 - Clock , Pin 5 - E1 and Pin 2 - G5

ISSUE	DATE	DWN by	CHK by
1	April 1973	F P	M P

COMPUTER - CAMERA INTERFACE UNIT

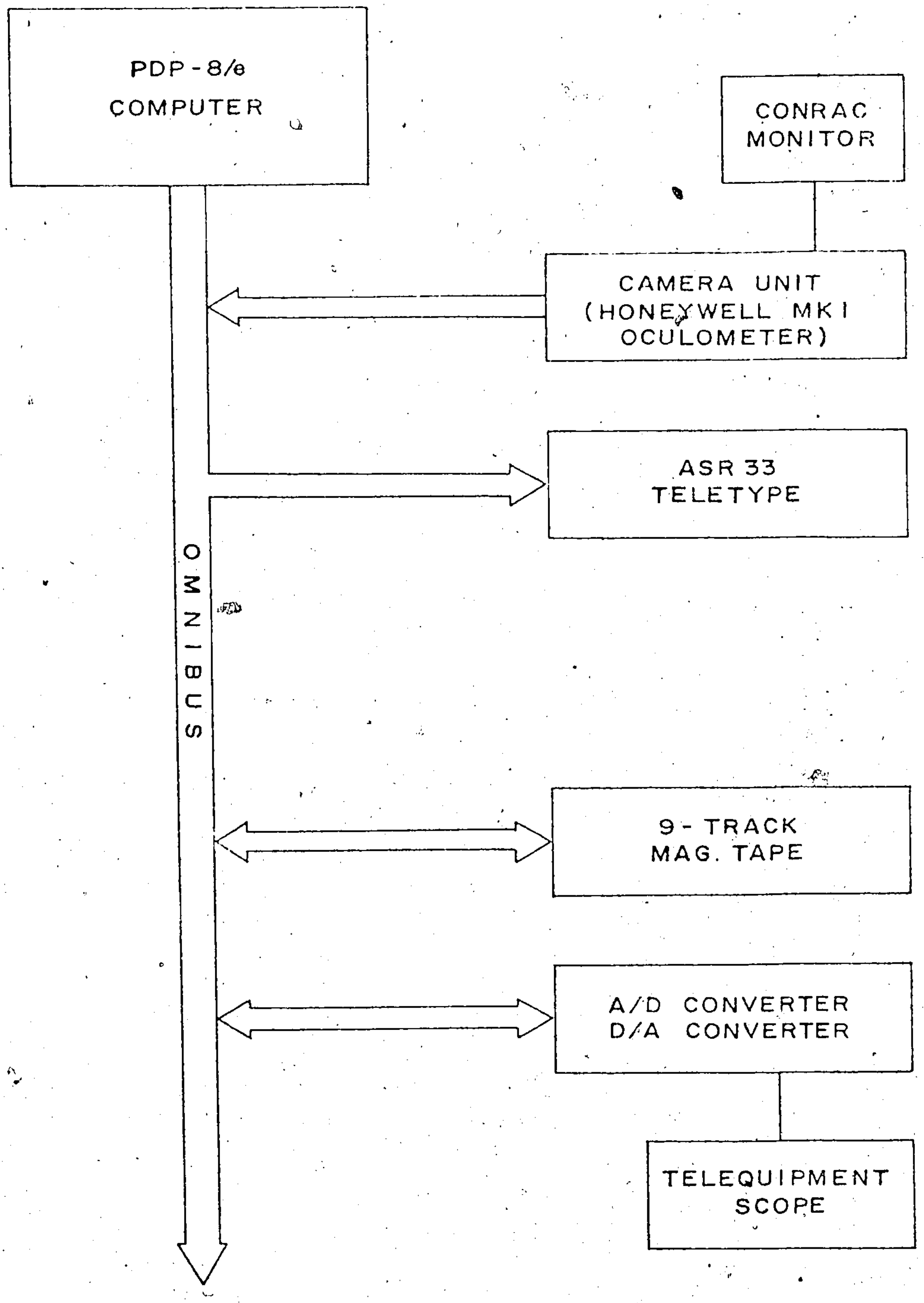
detailed schematic

APPENDIX B



COMPUTER RACK CONFIGURATION

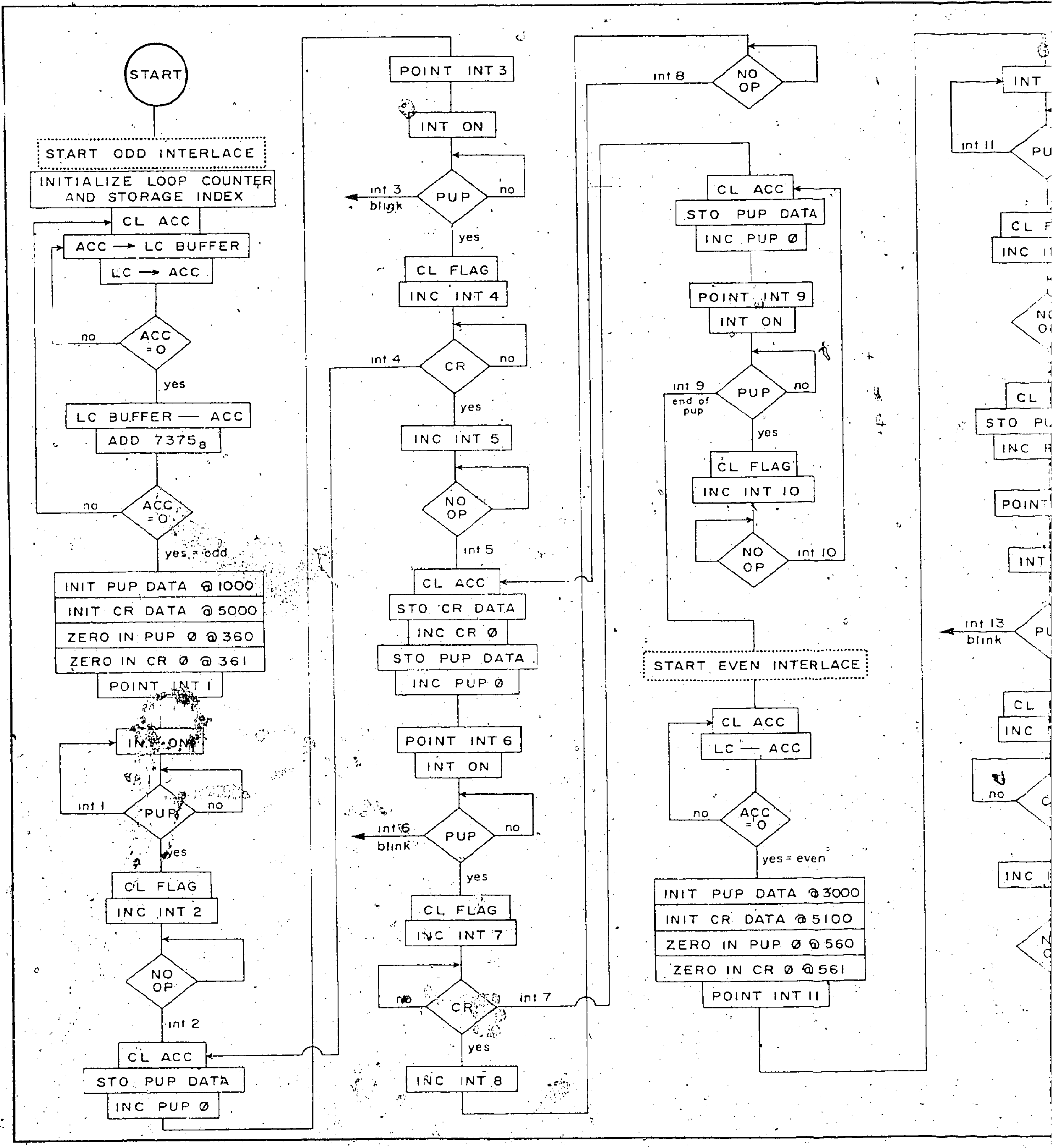
APPENDIX C

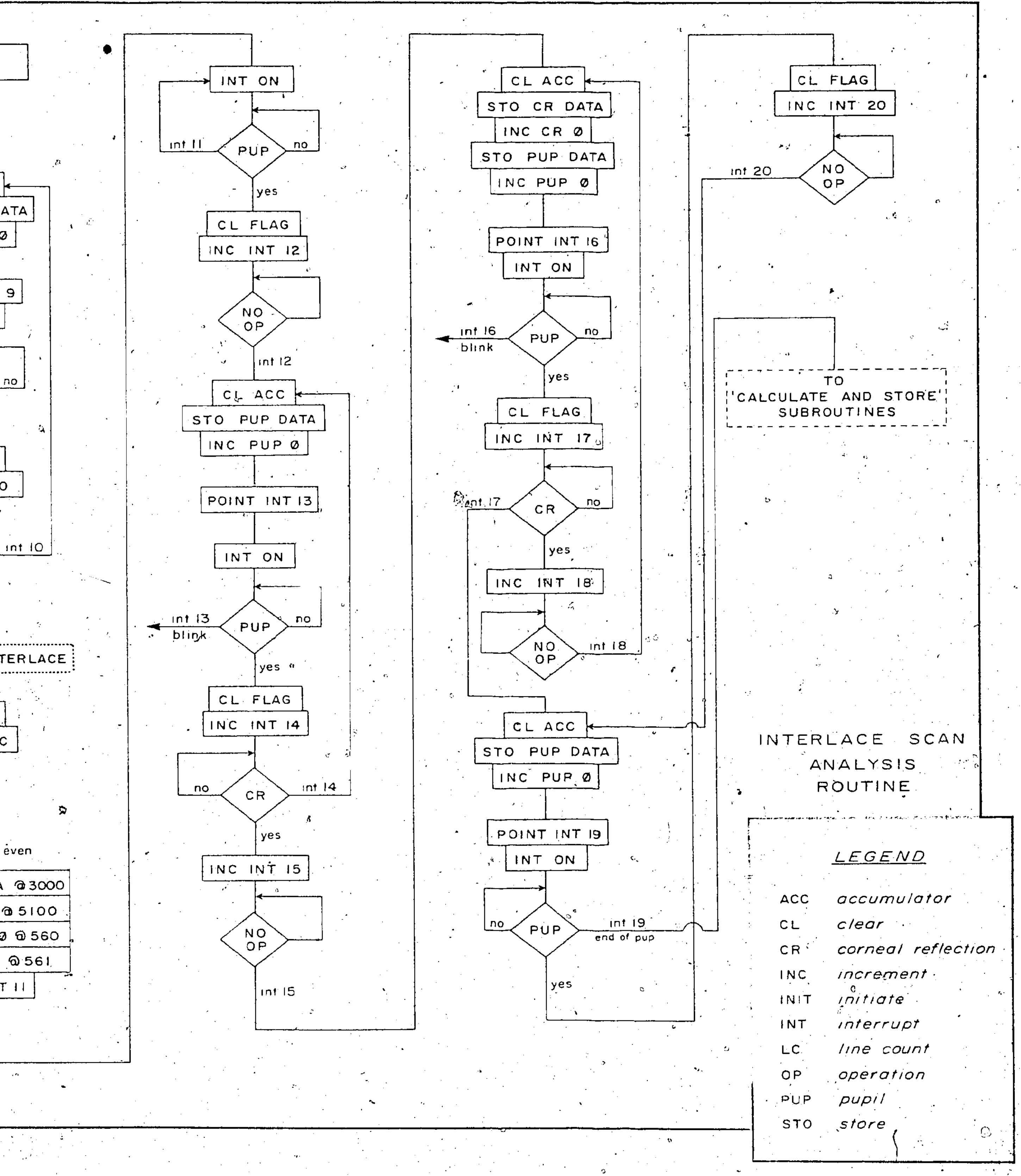


SIMPLIFIED BLOCK SCHEMATIC
OF COMPUTER UNIT

APPENDIX D

1 of


START
START ODD INTERLACE
INITIALIZE LOOP COUNTER AND STORAGE INDEX
CL ACC
ACC → LC BUFFER
LC → ACC
ACC = 0
no
yes
LC BUFFER — ACC
ADD 7375_8
ACC = 0
no
yes = odd
INIT PUP DATA @1000
INIT CR DATA @5000
ZERO IN PUP 0 @360
ZERO IN CR 0 @361
POINT INT 1
INT ON
PUP
int 1
no
yes
CL FLAG
INC INT 2
NO OP
int 2
CL ACC
STO PUP DATA
INC PUP 0
POINT INT 3
INT ON
PUP
int 3 blink
no
yes
CL FLAG
INC INT 4
CR
int 4
no
yes
INC INT 5
NO OP
int 5
CL ACC
STO CR DATA
INC CR 0
STO PUP DATA
INC PUP 0
POINT INT 6
INT ON
PUP
int 6 blink
no
yes
CL FLAG
INC INT 7
CR
no
int 7
yes
INC INT 8
NO OP
int 8
CL ACC
STO PUP DATA
INC PUP 0
POINT INT 9
INT ON
PUP
int 9 end of pup
no
yes
CL FLAG
INC INT 10
NO OP
int 10
START EVEN INTERLACE
CL ACC
LC — ACC
ACC = 0
no
yes = even
INIT PUP DATA @3000
INIT CR DATA @5100
ZERO IN PUP 0 @560
ZERO IN CR 0 @561
POINT INT 11
INT
int 11
PU
CL F
INC I
NO OP
CL
STO PU
INC P
POIN
INT
int 13 blink
PU
CL
INC
no
INC



INTERLACE SCAN
ANALYSIS
ROUTINE

LEGEND

ACC	*accumulator*
CL	*clear*
CR	*corneal reflection*
INC	*increment*
INIT	*initiate*
INT	*interrupt*
LC	*line count*
OP	*operation*
PUP	*pupil*
STO	*store*

```
PDP-8 ASSEMBLER
03-12-73  (01-02-70 VERSION)     PAGE 1

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

                                 1     * THIS PART OF THE PROGRAM SEARCHES FOR THE
                                 2     * ODD INTERLACE AND THEN PROCEEDS TO TRACE
                                 3     * THE PERIPHERY OF THE PUPIL AND CR FOR THE
                                 4     * DURATION OF THE ODD INTERLACE SCAN.
                      00200      5      ORG 200 /BEGIN AT 200
   00200  7300                   6     BEGIN CLA+CLL /CLEAR
   00201  1422                   7      TAD* 22 /INITIALIZE LOOP
   00202  3423                   8      DCA* 23 /COUNTER
   00203  1002                   9      TAD 2      INITIALIZE AUTOINDEX
   00204  3015                  10      DCA 15 /REGISTER FOR DATA STORAGE
   00205  7300                  11     SEARCH CLA+CLL
   00206  3377                  12      DCA 377  ZERO IN LC BUFFER
   00207  6647                  13      6647 /READ LC
   00210  7440                  14      SZA
   00211  5206                  15      JMP SEARCH+1  READ LC BUFFER
   00212  1377                  15.5    TAD 377
   00213  1376                  16      TAD 376 /ADD CONSTANT
   00214  7440                  17      SZA
   00215  5205                  18      JMP SEARCH /RETURN, KEEP LOOKING
   00216  7300                  19      CLA+CLL
   00217  1374                  20      TAD 374 /     INITIALIZE AUTOINDEX
   00220  3010                  21      DCA 10 /STORAGE FOR PUPIL DATA
   00221  1375                  22      TAD 375
   00222  3011                  23      DCA 11 /INITIALIZE STORAGE FOR CR DATA
   00223  3360                  24      DCA 360  INITIALIZE PUPIL DIAMETER COUNTER
   00224  3361                  25      DCA 361 /INITIALIZE CR DIAMETER COUNTER
   00225  1373                  26      TAD 373 /     POINT
   00226  3001                  27      DCA 1 /INTERRUPT 1
   00227  6001                  28     I1 ION /INTERRUPT ON
   00230  6641                  29      6641 /IS PUPIL HIT?
   00231  5230                  30      JMP *-1 /NO - KEEP LOOKING
   00232  6643                  31      6643 /YES CLEAR FLAG
   00233  2001                  32      ISZ 1 /REPOINT INTERRUPT
   00234  7000                  33      NOP        WAIT
   00235  5234                  34      JMP *-1 /FOR INTERRUPT
   00236  7300                  35     I24 CLA+CLL
   00237  6647                  36      6647        READ
   00240  3410                  37      DCA* 10 /AND STORE PUPIL LINE NUMBER
   00241  6645                  38      6645 /      READ
   00242  3410                  39      DCA* 10 /AND STORE PUPIL TIME
   00243  2360                  40      ISZ 360 /INCREMENT PUPIL DIAMETER
   00244  1372                  41      TAD 372 /
   00245  3001                  42      DCA 1 /POINT INTERRUPT 3
   00246  6001                  43      ION /INTERRUPT ON
   00247  6641                  44      6641 /IS PUPIL HIT?
   00250  5247                  45      JMP *-1 /NO - KEEP LOOKING
   00251  6643                  46      6643 /YES CLEAR FLAG
   00252  2001                  47      ISZ 1 /REPOINT INTERRUPT
   00253  6641                  48      6641 /IS CR HIT?
   00254  5253                  49      JMP *-1 /NO, KEEP LOOKING
   00255  2001                  50      ISZ 1 /YES, REPOINT INTERRUPT
   00256  7000                  51      NOP /      WAIT
   00257  5256                  52      JMP *-1 /FOR INTERRUPT
   00260  7300                  53     I58 CLA+CLL
   00261  6647                  54      6647 /READ AND STORE
```

```
 00262  3411               DCA◆ 11 /CR LINE
 00263  6646               6646 /AND
 00264  3411               DCA◆ 11 /CR TIME
 00265  2361               ISZ 361 /INCREMENT CR DIAMETER
 00266  6647               6647 /READ AND STORE
 00267  3410               DCA◆ 10 /     PUPIL LINE
 00270  6645               6645 /AND
 00271  3410               DCA◆ 10 /PUPIL TIME
 00272  2360               ISZ 360 /INCREMENT PUPIL DIAMETER
 00273  1371               TAD 371 /     POINT
 00274  3001               DCA 1 /INTERRUPT 6
 00275  6001               ION /INTERRUPT ON
 00276  6641               6641 /IS PUPIL HIT?
 00277  5276               JMP ◆-1 /NO, LOOK AGAIN
 00300  6643               6643 /YES CLEAR FLAG
 00301  2001               ISZ 1 /REPOINT INTERRUPT
 00302  6641               6641 /IS CR HIT?
 00303  5302               JMP ◆-1 NO, KEEP LOOKING
 00304  2001               ISZ 1 /YES REPOINT INTERRUPT
 00305  7000               NOP /WAIT
 00306  5305               JMP ◆-1 /FOR INTERRUPT
 00307  7300              S710 CLA+CLL
 00310  6647               6647 /READ AND STORE
 00311  3410               DCA◆ 10 /PUPIL LINE
 00312  6645               6645 /AND
 00313  3410               DCA◆ 10 /CR LINE
 00314  2360               ISZ 360 /INCREMENT PU   DIAMETER
 00315  1370               TAD 370 /REPOINT
 00316  3001               DCA 1 /INTERRUPT 9
 00317  6001               ION /INTERRUPT ON
 00320  6641               6641 /IS PUPIL HIT?
 00321  5320               JMP ◆-1 /NO, KEEP LOOKING
 00322  6643               6643 /YES
 00323  2001               ISZ 1 /INCREMENT INTERRUPT 10
 00324  7000               NOP /WAIT
 00325  5324               JMP ◆-1 /FOR INTERRUPT
                00360      ORG 360
 00360  0000               0000 /CONTAINS PUPIL DIAMETER ODD
 00361  0000               0000 /CONTAINS CR DIAMETER ODD
                00370      ORG 370
 00370  5710               5710 /POINT INTERRUPT 9
 00371  5705               5705 /POINT INTERRUPT 6
 00372  5702               5702 /POINT INTERRUPT 3
 00373  0777               0777 /INITIAL ADDRESS FOR PUPIL DATA ODD
 00374  4777               4777 /INITIAL ADDRESS FOR CR DATA ODD
 00375  7375               7375 /CONSTANT FOR FINDING ODD INTERLACE
 00376  0000               0000 /INTERLACE LINECOUNT BUFFER
                00002      ORG 2
 00002  0377               377 /BEGIN STORING DATA HERE
                00022      ORG 22
 00022  6566               6566 /CONTAINS NUMBER OF LOOPS TO BE DONE
 00023  6567               6567 /USED AS COUNTDOWN FOR NO. OF LOOPS
                00100      ORG 100
 00100  0227               227 /INTERRUPT 1
 00101  0236               236 /INTERRUPT 2
 00102  0321               321 /INTERRUPT 3
 00103  0236               236 /INTERRUPT 4
 00104  0260               260 /INTERRUPT 5
```

```
PDP-8 ASSEMBLER
03-12-73  (01-02-70 VERSION)     PAGE 3

     00105  0321          113       321 /INTERRUPT 6
     00106  0307          114       307 /INTERRUPT 7
     00107  0260          115       260 /INTERRUPT 8
     00110  0400          116       400 /INTERRUPT 9
     00111  0307          117       307 /INTERRUPT 10

OPERAND CROSS-REFERENCE LISTING

     BEGIN    000 00200     6
     I1       000 00227    28
     I24      000 00236    35
     I58      000 00260    53
     I710     000 00307    76
     SEARCH   000 00205    11      000 00211 000 00215

ERRORS 0     $CARDS 118     $PRINT 129      $PUNCH 7      $STORAGE 3
$20:08.25 1.394 RC=0
$
```

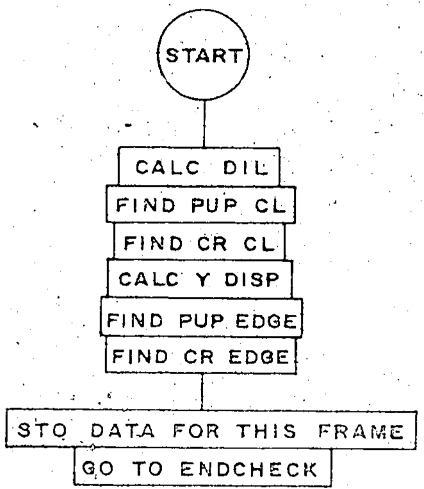
```
PDP-8 ASSEMBLER
03-12-73  (01-02-70 VERSION)   PAGE 1

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)
                              ◆ THIS PART OF THE PROGRAM TRACES
                              ◆ THE PERIPHERY OF THE PUPIL
                              ◆ DURING THE EVEN INTERLACE.
                              ◆ TITLE: SEARCHEVEN
                   00400       ORG 400 /STARTING ADDRESS IS 400
       00400  7300            EVEN CLA+CLL
       00401  6647              6647 /READ THE LINE COUNTER
       00402  7440              SZA /CHECK FOR 0
       00403  5200              JMP EVEN /IF NOT, KEEP LOOKING
       00404  7300              CLA+CLL
       00405  1374              TAD 574 /INITIALIZE PUPIL DATA
       00406  3012              DCA 12 /AT 3000 AND
       00407  1375              TAD 575 /CR DATA
       00410  3013              DCA 13 /AT 5100
       00411  3360              DCA 560 /ZERO PUPIL DIAMETER
       00412  3361              DCA 561 /AND CR DIAMETER
       00413  1373              TAD 573 /INITIALIZE
       00414  3001              DCA 1 /SET INTERRUPT 11
       00415  6001             I11 ION /TURN INTERRUPT ON
       00416  6641              6641 /IS PUPIL HIT?
       00417  5216              JMP ◆-1 /NO, KEEP LOOKING
       00420  6643              6643 /YES, CLEAR FLAG
       00421  2001              ISZ 1 /REPOINT INTERRUPT
       00422  7000              NOP /WAIT
       00423  5222              JMP ◆-1 /FOR INTERRUPT
       00424  7300             I1214 CLA+CLL
       00425  6647              6647 /READ AND STORE
       00426  3412              DCA◆ 12 /LINE COUNTER
       00427  6645              6645 /AND
       00430  3412              DCA◆ 12 /PUPIL TIME
       00431  2360              ISZ 560 /INCREMENT PUPIL DIAMETER
       00432  1372              TAD 572 /REPOINT
       00433  3001              DCA 1 /INTERRUPT 13
       00434  6001              ION /TURN INTERRUPT ON
       00435  6641              6641 /IS PUPIL HIT?
       00436  5235              JMP ◆-1 /NO, KEEP LOOKING
       00437  6643              6643 /YES, CLEAR FLAG
       00440  2001              ISZ 1 /REPOINT INTERRUPT
       00441  6641              6641 /IS CR HIT?
       00442  5241              JMP ◆-1 /NO, KEEP LOOKING
       00443  2001              ISZ 1 /REPOINT INTERRUPPT
       00444  7000              NOP /WAIT
       00445  5244              JMP ◆-1 /FOR INTERRUPT
       00446  7300             I1516 CLA+CLL
       00447  6647              6647 /READ AND STORE
       00450  3413              DCA◆ 13 /CR LINE
       00451  6646              6646 /AND
       00452  3413              DCA◆ 13 /CR TIME
       00453  2361              ISZ 561 /INCREMENT CR DIAMETER
       00454  6647              6647 /READ AND STORE
       00455  3412              DCA◆ 12 /PUPIL LINE NUMBER
       00456  6645              6645 /AND
       00457  3412              DCA◆ 12 /PUPIL TIME
       00460  2360              ISZ 560 /INCREMENT PUPIL DIAMETER
       00461  1371              TAD 571 /REPOINT
```

```
    00462  3001               56      DCA 1 /INTERRUPT 16
    00463  6001               57      ION /TURN INTERRUPT ON
    00464  6641               58      6641 /IS PUPIL HIT?
    00465  5264               59      JMP *-1 /NO, KEEP LOOKING
    00466  6643               60      6643 /YES, CLEAR FLAG
    00467  2001               61      ISZ 1 /REPOINT INTERRUPT
    00470  6641               62      6641 /IS CR HIT?
    00471  5270               63      JMP *-1 /NO, KEEP LOOKING
    00472  2001               64      ISZ 1 /YES, REPOINT INTERRUPT
    00473  7000               65      NOP /WAIT
    00474  5273               66      JMP *-1 /FOR INTERRUPT
    00475  7300               67     I1720, CLA+CLL
    00476  6647               68      6647 /READ AND STORE
    00477  3412               69      DCA* 12 /PUPIL LINE NUMBER
    00500  6645               70      6645 /AND
    00501  3412               71      DCA* 12 /PUPIL TIME
    00502  2360               72      ISZ 560 /INCREMENT PUPIL DIAMETER
    00503  1370               73      TAD 570 /REPOINT
    00504  3001               74      DCA 1 /INTERRUPT 19
    00505  6001               75      ION /TURN INTERRUPT ON
    00506  6641               76      6641 /IS PUPIL HIT?
    00507  5306               77      JMP *-1 /NO, KEEP LOOKING
    00510  6643               78      6643 /YES, CLEAR FLAG
    00511  2001               79      ISZ 1 /REPOINT INTERRUPT
    00512  7000               80      NOP /WAIT
    00513  5312               81      JMP *-1 /FOR INTERRUPT
                   00560      82      ORG 560
    00560  0000               83      0000 /PUPIL DIAMETER EVEN INTERLACE
    00561  0000               84      0000 /CR DIAMETER EVEN INTERLACE
                   00570      85      ORG 570
    00570  5722               86      5722 /POINT INTERRUPT 19
    00571  5717               87      5717 /POINT INTERRUPT 16
    00572  5714               88      5714 /POINT INTERRUPT 13
    00573  5712               89      5712 /POINT INTERRUPT 11
    00574  2777               90      2777 /STORAGE LOCATION FOR EVEN PUPIL DATA
    00575  5077               91      5077 /STORAGE LOCATION FOR EVEN CR DATA
                   00112      92      ORG 112
    00112  0415               93      415 /INTERRUPT 11
    00113  0424               94      424 /INTERRUPT 12
    00114  0321               95      321 /INTERRUPT 13
    00115  0424               96      424 /INTERRUPT 14
    00116  0446               97      446 /INTERRUPT 15
    00117  0321               98      321 /INTERRUPT 16
    00120  0475               99      475 /INTERRUPT 17
    00121  0446              100      446 /INTERRUPT 18
    00122  0514              101      514 /INTERRUPT 19
    00123  0475              102      475 /INTERRUPT 20


 OPERAND CROSS-REFERENCE LISTING

    EVEN      000 00400    62     000 00403
    I11       000 00415    19
    I1214     000 00424    26
    I1518     000 00446    44
    I1720     000 00475    67
```

```
PDP-8 ASSEMBLER
 03-12-73  (01-02-70 VERSION)    PAGE 3

 ERRORS 0     SCARDS 102     SPRINT 111      SPUNCH 5      STORAGE 2
#22:36.47 1.307 RC=0
#
```

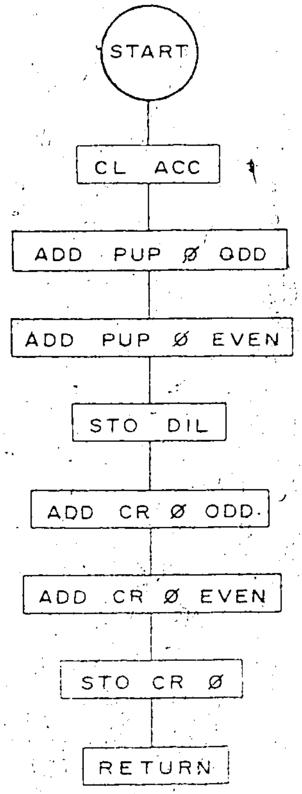
LEGEND

CALC	*calculate*
CL	*centerline*
CR	*corneal reflection*
CT	*centertime*
DIL	*dilation*
DISP	*displacement*
PUP	*pupil*
STO	*store*



CALCULATE & STORE
SUBROUTINE

```
PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

    00000  0000                1   *TITLE: SUBROUTINES
    00001  0001                2   *THIS SERIES OF SUBROUTINES CALCULATES
    00002  0002                3   *AND STORES DISPLACEMENT OF CORNEAL
    00003  0003                4   *REFLECTION CENTER FROM THE PUPIL
    00004  0004                5   *CENTER AND DILATION
    00005  0005                6   *IT IS ENTERED VIA INTERRUPT 10 OF
                                    SEARCHEVEN
                  00514        7   ORG 514
    00514  4740                8  SUB JMS* 540 /CALCULATES DILATIONS
    00515  4741                9   JMS* 541 /FINDS PUPIL CENTERLINE
    00516  4742               10   JMS* 542 /FINDS CR CENTERLINE
    00517  4743               11   JMS* 543 /FINDS PUPIL CENTERTIME
    00520  4744               12   JMS* 544 /FINDS CR CENTERTIME
    00521  4745               13   JMS* 545 /CALCULATES X-DISPLACEMENT
    00522  7000               14   7000 /NO-OP
    00523  4747               15   JMS* 547 /STORES DATA IN CORE 0
    00524  5750               16   JMP* 550 /CHECKS TO SEE IF MORE SCANS
                                    NEEDED
                  00540       17   ORG 540
    00540  0600               18   600 /LOCATION OF DILATION SUBROUTINE
    00541  0613               19   613 /LOCATION OF PUPIL C.L. SUBROUTINE
    00542  0652               20   652 /LOCATION OF CR C.L. SUBROUTINE
    00543  6510               21   6510 /LOCATION OF Y-DISPLACEMENT
                                    SUBROUTINE
    00544  7200               22   7200 /LOCATION OF NEW CR.CT SUBROUTINE
    00545  6600               23   6600 /LOCATION OF X-DISPLACEMENT
                                    SUBROUTINE
    00546  7000               24   7000 /NO-OP
    00547  5650               25   5650 /LOCATION OF DATA STORAGE
                                    SUBROUTINE
    00550  6560               26   6560 /LOCATION OF END SUBROUTINE
OPERAND CROSS-REFERENCE LISTING

    SUB    000  00514          8
```

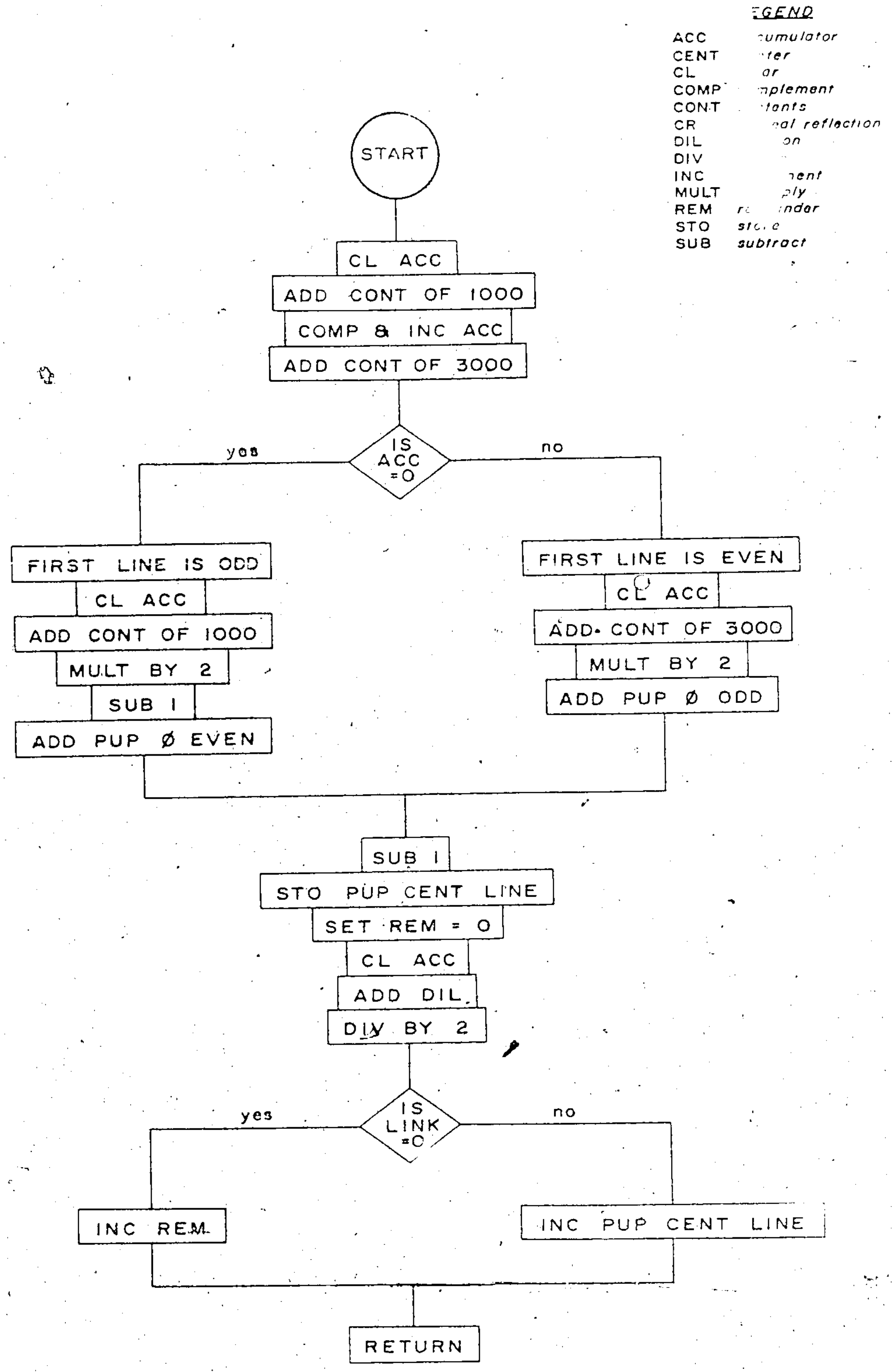


DILATIONS
SUBROUTINE

LEGEND

ACC	*accumulator*
CL	*clear*
CR	*corneal reflection*
PUP	*pupil*
STO	*store*

```
PDP-8 ASSEMBLER
03-13-73  (01-02-70 VERSION)     PAGE 1

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

                             1      ◇ DIAMETER SUBROUTINES
                             2      ◆ CALCULATE DIAMETERS OF PUPIL*
                             3      ◆ AND CORNEAL REFLECTION, GIVEN
                             4      ◆ ODD AND EVEN INTERLACE SCAN DATA
                    00600    5       ORG 600 /STARTING ADDRESS - 600
     00600  7000             6      BEGIN NOP  /SP RETURN POINTER
     00601  1124             7       TAD 124 /LOAD PUP DIAM ODD
     00602  1125             8       TAD 125 /ADD PUP DIAM EVEN
     00603  3140             9       DCA 140 /STORE PUP DIAMETER
     00604  1133            10       TAD 133  LOAD CR DIAM ODD
     00605  1134            11       TAD 134  ADD CR DIAM EVEN
     00606  3137            12       DCA 137 /STORE CR DIAMETER
     00607  5600            13       JMP◆ BEGIN /RETURN

OPERAND CROSS-REFERENCE LISTING

     BEGIN    000 00600     6     000 00607

ERRORS 0     SCARDS 13      SPRINT 17       SPUNCH 2      STORAGE 2
*21:31.36 .285 RC=0
*
```



PUPIL
CENTERLINE
SUBROUTINE

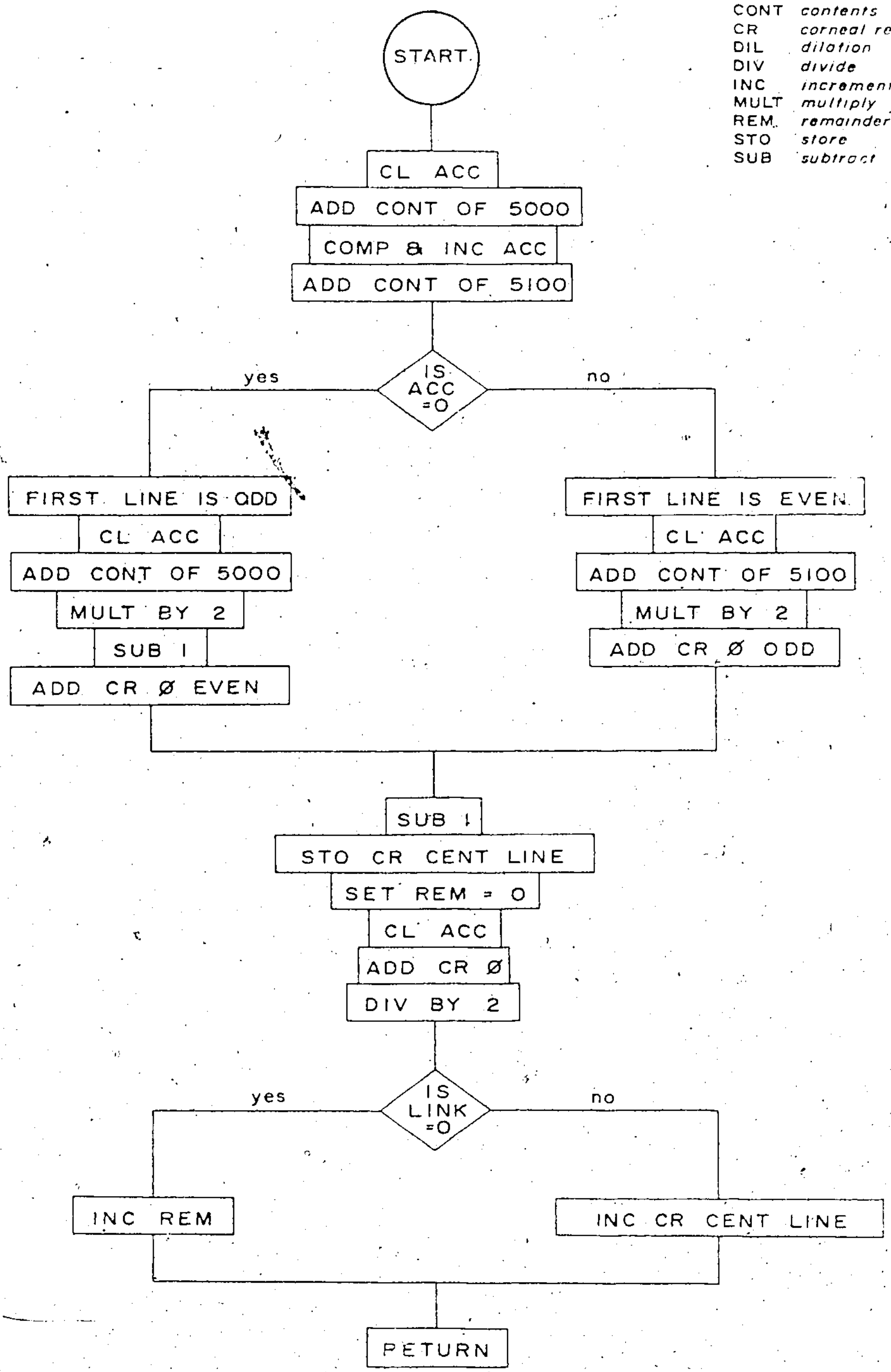
PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                * TITLE: PUPCEN
                                * THIS SUBROUTINE IS CALLED WHEN
                                * THE DILATION SUBROUTINE ENDS.
                                * THIS SUBROUTINE CALCULATES THE
                                * PUPIL CENTERLINE.
                                * THE PUPIL CENTERLINE NUMBER IS
                                * STORED IN LOCATION 141 WITH THE
                                * HALF-LINE REMAINDER IN LOCATION 142
                   00613         ORG 613
 00613  0000                    PUPCEN 0000 /RETURN ADDRESS
 00614  7300                     CLA+CLL
 00615  1526                     TAD* 126 /GET LINE 1 ODD
 00616  7041                     CIA
 00617  1527                     TAD* 127 /GET LINE 1 EVEN
 00620  7440                     SZA
 00621  5243                     JMP L1E /LINE 1 IS EVEN SO JUMP
 00622  7300                     CLA+CLL
 00623  1526                     TAD* 126 /LINE 1 IS ODD SO CONTINUE
 00624  7004                     RAL /DOUBLE
 00625  1132                     TAD 132 /SUBTRACT 1
 00626  1525                     TAD* 125 /ADD DILATION
 00627  1132                    FIN TAD 132 /SUBTRACT 1
 00630  3141                     DCA 141 /STORE PUPIL CENTERLINE
 00631  3142                     DCA 142 /AND HALF LINE (141-142)
 00632  7300                     CLA+CLL
 00633  1140                     TAD 140 /GET PUPIL DILATION
 00634  7010                     RAR /DIVIDE BY 2
 00635  7430                     SZL
 00636  5241                     JMP LK10 /LINK=1, DIAMETER ODD
 00637  2142                     ISZ 142 /DIAMETER EVEN
 00640  5613                     JMP* PUPCEN /RETURN
 00641  2141                    LK10 ISZ 141 /DIAMETER ODD
 00642  5613                     JMP* PUPCEN /RETURN
 00643  7300                    L1E CLA+CLL
 00644  1527                     TAD* 127 /LINE 1 EVEN-CONTINUE
 00645  7004                     RAL /DIVIDE LINE 1 EVEN BY 2
 00646  1524                     TAD* 124 /ADD PUPIL DIAMETER
 00647  5227                     JMP FIN /GO TO STORE
                   00132         ORG 132
 00132  7777                     7777 /SUBTRACT 1 CONSTANT
OPERAND CROSS-REFERENCE LISTING
```

LEGEND

ACC	*accumulator*
CENT	*center*
CL	*clear*
COMP	*complement*
CONT	*contents*
CR	*corneal reflection*
DIL	*dilation*
DIV	*divide*
INC	*increment*
MULT	*multiply*
REM	*remainder*
STO	*store*
SUB	*subtract*

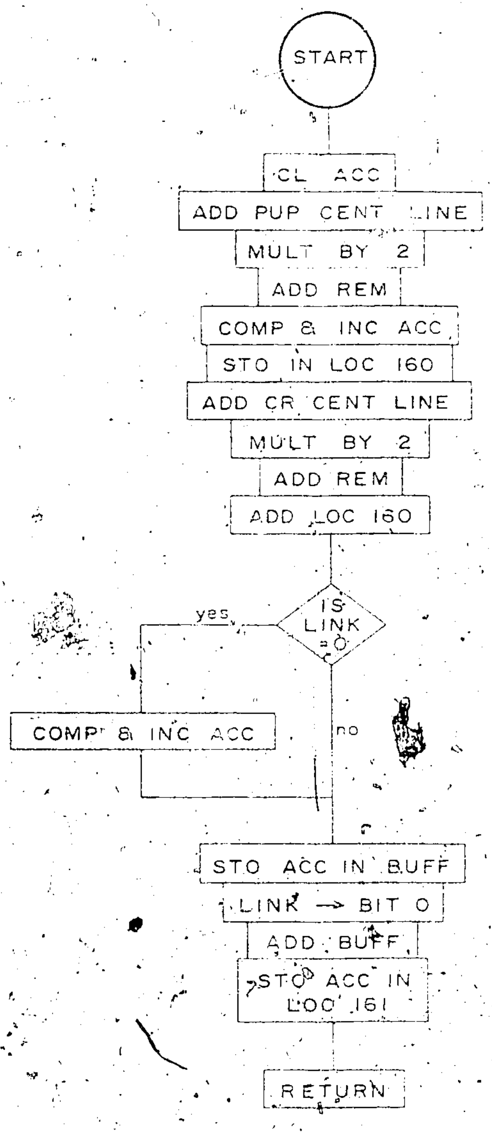


CR
CENTERLINE
SUBROUTINE

```
PDP-8 ASSEMBLER
03-13-73  (01-02-70 VERSION)     PAGE 1

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)
                                    1      ◆ TITLE: CRCENT
                                    2      ◆ THIS SUBROUTINE IS CALLED WHEN THE PUPIL
                                    3      ◆ CENTERLINE SUBROUTINE ENDS.
                                    4      ◆ THIS SUBROUTINE CALCULATES THE CR
                                    5      ◆ CENTERLINE.
                                    6      ◆ THE CR CENTERLINE IS STORED IN
                                    7      ◆ LOCATION 145 WITH THE HALF-LINE
                                    8      ◆ REMAINDER IN LOCATION 146.
                          00652     9       ORG 652.
  00652  0000                      10      CRCENT 0000 /RETURN ADDRESS
  00653  7300                      11       CLA+CLL
  00654  1535                      12       TAD◆ 135 /GET LINE 1 ODD
  00655  7041                      13       CIA
  00656  1536                      14       TAD◆ 136 /SUBTRACT LINE 1 EVEN
  00657  7440                      15       SZA
  00660  5302                      16       JMP L1E /LINE 1 IS EVEN-JUMP
  00661  7300                      17       [illegible]LL
  00662  1535                      18       [illegible]35 /LINE 1 IS ODD-CONTINUE
  00663  7004                      19       [illegible]BLE IT
  00664  1132                      20      [illegible]2 /SUBTRACT 1
  00665  1534                      21       [illegible] /ADD DIAMETER
  00666  1132                      22       [illegible] /SUBTRACT 1
  00667  3145                      23       [illegible]145 /STORE CR CENTERLINE
  00670  3146                      24       [illegible]CA 146 /AND HALF-LINE(145&146)
  00671  7300                      25       CLA+CLL
  00672  1137                      26       TAD 137 /GET CR DIAMETER
  00673  7010                      27       RAR /DIVIDE IT BY 2
  00674  7430                      28       SZL
  00675  5300                      29       JMP LK10 /LINK=1, DIAMETER ODD
  00676  2146                      30       ISZ 146 /DIAMETER EVEN
  00677  5652                      31       JMP◆ CRCENT /RETURN
  00700  2145                      32      LK10 ISZ 145 /DIAMETER ODD
  00701  5652                      33       JMP◆ CRCENT /RETURN
  00702  7300                      34      L1E CLA+CLL
  00703  1536                      35       TAD◆ 136 /LINE 1 EVEN-CONTINUE
  00704  7004                      36       RAL /DIVIDE LINE 1 EVEN BY 2
  00705  1533                      37       TAD◆ 133 /ADD CR DIAMETER
  00706  5264                      38       JMP FIN /GO TO STORE
                          00132    39       ORG 132
  00132  7777                      40       7777 /SUBTRACT 1 CONSTANT

OPERAND CROSS-REFERENCE LISTING

    CRCENT    000 00652    10     000 00677 000 00701
    FIN       000 00664    20     000 00706
    LK10      000 00700    32     000 00675
    L1E       000 00702    34     000 00660

ERRORS 0     SCARDS 40      SPRINT 47      SPUNCH 3      STORAGE 2
◆22:16.42 .586 RC=0
◆
```

LEGEND

ACC	*accumulator*
BUFF	*buffer*
CENT	*center*
CL	*clear*
COMP	*complement*
CR	*corneal reflection*
INC	*increment*
LOC	*location*
MULT	*multiply*
PUP	*pupil*
REM	*remainder*
STO	*store*

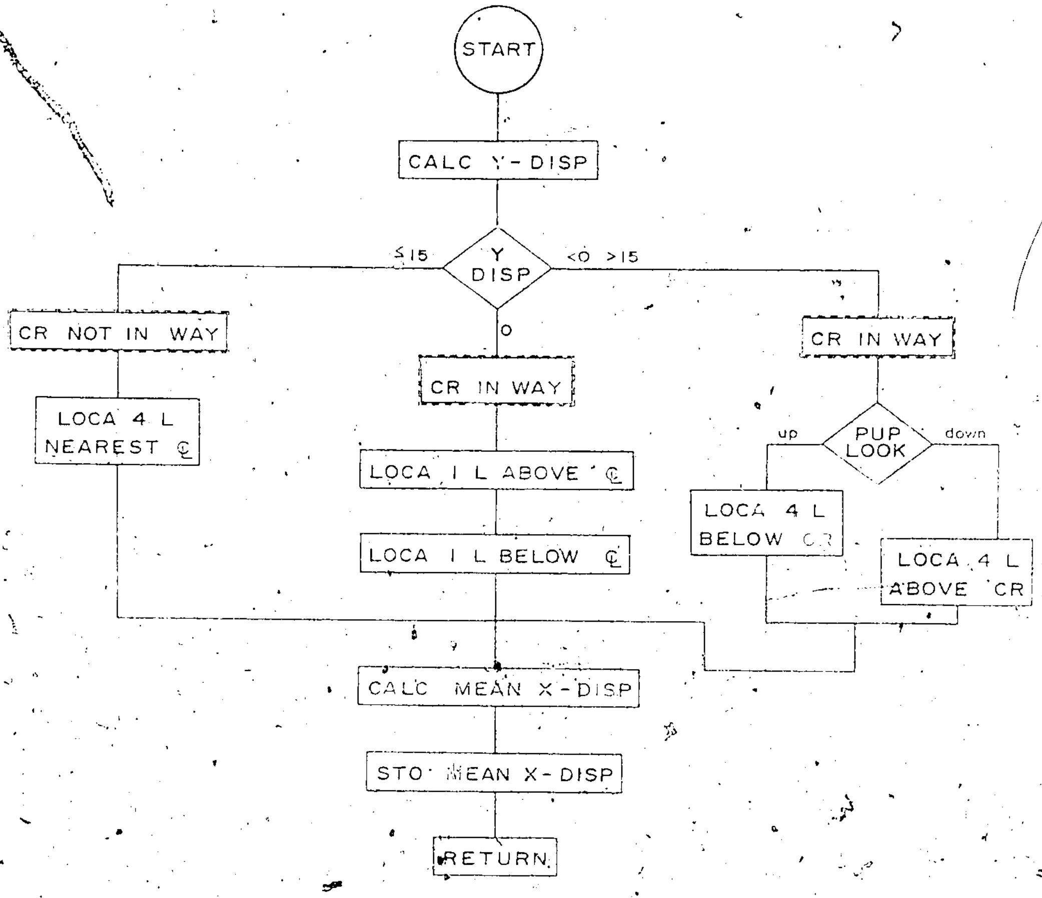


Y - DISPLACEMENT
SUBROUTINE

```
PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE IN OCTAL)

                                  1   * TITLE: YDISP
                                  2   * THIS SUBROUTINE IS CALLED WHEN THE
                                  3   * X-DISPLACEMENT SUBROUTINE ENDS.
                                  4   * THIS SUBROUTINE CALCULATES THE
                                  5   * Y-DISPLACEMENT BETWEEN THE PUPIL
                                  6   * CENTER AND THE CR CENTER AND STORES
                                  7   * IT IN LOCATION 161.
                                  8   * THE UNITS OF MEASURE ARE HALF-LINES.
                          06540   9    ORG 6504
    06504  7440                  10   ZERO SZA /IS ACC 0?
    06505  5326                  11    JMP STOR
    06506  7300                  12    CLA+CLL
    06507  5326                  13    JMP STOR
    06510  0000                  14   YDISP 0000 /RETURN ADDRESS
    06511  7300                  15    CLA+CLL
    06512  1141                  16    TAD 141 /DOUBLE PUPIL
    06513  7004                  17    RAL /CENTER
    06514  1142                  18    TAD 142 /COMPLEMENT
    06515  7041                  19    CIA /AND
    06516  3160                  20    DCA 160 /STORE
    06517  1145                  21    TAD 145 /DOUBLE
    06520  7004                  22    RAL /CR CENTER
    06521  1146                  23    TAD 146
    06522  1160                  24    TAD 160 /SUBTRACT PUPIL CENTER
    06523  7430                  25    SZL
    06524  5304                  26    JMP ZERO
    06525  7041                  27    CIA /PUT LINK 1
    06526  3333                  28   STOR DCA TEMP /IN
    06527  7010                  29    RAR /BIT 0 AND
    06530  1333                  30    TAD TEMP /STORE IN 161
    06531  3161                  31    DCA 161
    06532  5710                  32    JMP* YDISP /RETURN
    06533  0000                  33   TEMP 0000 /BUFFER
OPERAND CROSS-REFERENCE LISTING

    STOR   000 06526             28   000 06505 000 06507
    TEMP   000 06533             33   000 06526 000 06530
    YDISP  000 06510             14   000 06532
    ZERO   000 06504             10   000 06524
```

LEGEND

CALC	*calculate*
CR	*corneal reflection*
DISP	*displacement*
L	*line (s)*
LOCA	*locate*
PUP	*pupil*
STO	*store*



PUPIL
CENTERTIME
SUBROUTINE

```
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10-09-73  (01-02-70 VERSION)     PAGE 1

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

                         * TITLE: PCTIME
                         * THIS SUBROUTINE IS CALLED WHEN THE
                         *CP TIME SUBROUTINE ENDS
                         *IT FINDS THE LEFT EDGE OF THE PUPIL
                 07200    ORG 7200
07200  0000              START 0000 /RETURN ADDRESS
07201  7300               CLA+CLL
07202  7000               NOP
07203  1140               TAD 140 /DILATION
07204  7012               RTR /TWO RIGHT
07205  7430               SZL
07206  5311               5311  /STORE LINE 1
07207  7004               RAL
07210  1151              A TAD 151 /PUPIL TIME LINE1
07211  3033               DCA 33 /TO 33
07212  1377               TAD 7377 /177=7772
07213  3045               DCA 45
07214  7300               CLA+CLL
07215  1161               TAD 161 /Y LINE DISP
07216  7004               RAL
07217  7100               CLL
07220  7010               RAR
07221  1375               TAD 7375 /7375=7761
07222  7510               SPA
07223  5715               5715 /JMP TO 7400
07224  7300               CLA+CLL
07225  1033               TAD 33
07226  1024               1024
07227  1024               1024 /SUBTRACT 2
07230  3034               DCA 34
07231  1034               TAD 34
07232  0374               AND 7374 /7374=2000
07233  7440               SZA
07234  5302               5302 /JMP B
07235  7300               CLA+CLL
07236  1034               TAD 34
07237  1374               TAD 7374
07240  3035               DCA 35
07241  7300               CLA+CLL
07242  1035               TAD 35
07243  7001               IAC
07244  7001               IAC /ADD
07245  3036               DCA 36
07246  7300               CLA+CLL
07247  1433               TAD* 33
07250  1434               TAD* 34
07251  1435               TAD* 35
07252  1436               TAD* 36
07253  3032               DCA 32
07254  5600               JMP* START /RETURN
                 07302    ORG 7302
07302  7300              B CLA+CLL
07303  1034               TAD 34
07304  1372               TAD 7372 /-5
07305  5240               5240 /RETURN
```

```
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                     07311   255      ORG 7311
    07311  7004              256      PAL
    07312  7001              257      IAC
    07313  5210              258      5210  JMP TO A
                     07372   259      ORG 7372
    07372  6000              260      6000
    07373  7716              261      7716
    07374  2000              262      2000
    07375  7761              263      7761
    07376  7772              264      7772
    07377  7772              265      7772


OPERAND CROSS-REFERENCE LISTING

  — A         000 07210   213
    B         000 07302   251
    START     000 07200   205      000 07254


ERRORS 0     CARDS 66      PRINT 73       PUNCH 5       STORAGE 2
*18:45.39 .918 RC=0
*
```
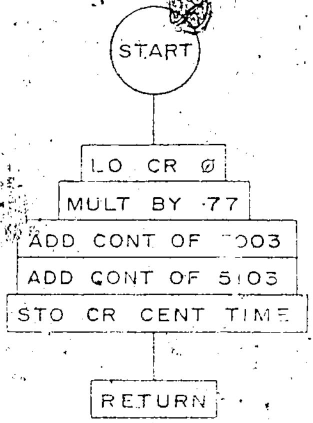

LEGEND

CENT	center
CONT	contents
CR	corneal reflection
LO	load
MULT	multiply
STO	store



CR
CENTERTIME
SUBROUTINE

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                               ◆TITLE: CRTIME
                               ◆THIS SUBROUTINE IS CALLED AFTER
                               ◆THE Y DISPLACEMENT IS FOUND
                               ◆IT LOCATES THE LEFT EDGE OF THE
                               ◆CORNEAL REFLECTION
                      06600     ORG 6600
06600  0000                    START 0000 /RETURN ADDRESS
06601  7300                     CLA+CLL
06602  1535                     TAD◆ 135 /LINE 1 ODD
06603  7041                     CIA
06604  1536                     TAD◆ 136
06605  7440                     SZA
06606  5322                     5322 /ODD FIRST
06607  7300                     CLA+CLL
06610  1135                     TAD 135 /LINE 1 ODD
06611  7001                     IAC
06612  3153                     DCA 153
06613  5216                     5216 /NEXT LINE
06614  0002                     0002 /CONSTANT
06615  3153                     DCA 153
0661   1153                     TAD 153
06617  7001                     IAC
06620  7001                     IAC /ADD 2
06621  3033                     DCA 33
06622  1153                     TAD 153 /CR TIME LINE 1
06623  0302                     AND 6702 /6702=100
06624  7440                     SZA
06625  5313                     5313
06626  7300                     CLA+CLL
06627  1153                     TAD 153
06630  1302                     TAD 6702
06631  3034                     DCA 34
06632  1034                     TAD 34 /NEXT LINE
06633  7001                     IAC
06634  7001                     IAC /ADD 2
06635  3035                     DCA 35 /NEXT LINE
06636  7000                     7000
06637  7300                     CLA+CLL
06640  1433                     TAD◆ 33
06641  1435                     TAD◆ 35
06642  1434                     TAD◆ 34
06643  3164                     DCA 164 /SUM
06644  5600                     JMP◆ START
                      06702     ORG 6702
06702  0100                     100
                      06722     ORG 6722
06722  7300                    A CLA+CLL
06723  1136                     TAD 136
06724  7001                     IAC
06725  5215                     5215
                      06713     ORG 6713
06713  7300                     CLA+CLL
06714  1153                     TAD 153
06715  1310                     TAD 6710
06716  5231                     5231 /RETURN
```

```
PDP-8 ASSEMBLER
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                 06710    155       ORG 6710
   06710  7700            156       7700

OPERAND CROSS-REFERENCE LISTING

    A          000 06722   146
    START      000 06600   106       000 06644

ERRORS 0      SCARDS 57      SPRINT 63        SPUNCH 6      STORAGE 2
#18:39.08 .82 RC=0
#
```
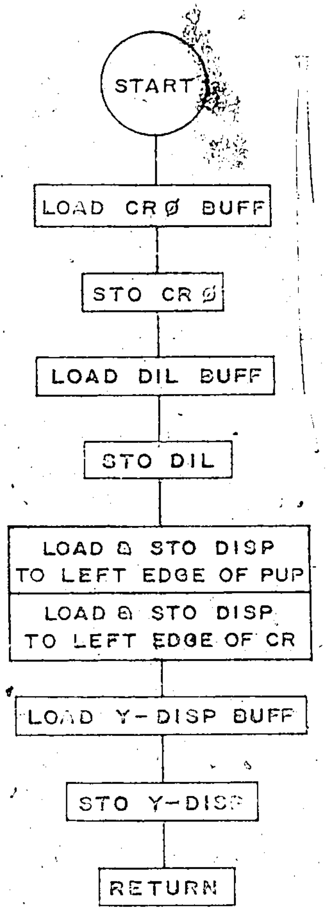
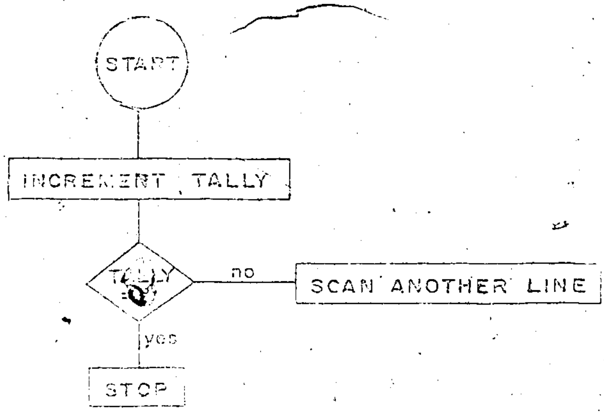

LEGEND

BUFF	buffer
DIL	dilation
DISP	displacement
CR	corneal reflection
Ø	diameter
PUP	pupil
STO	store



STORE
SUBROUTINE

```
PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

                              1    * TITLE: STORE
                              2    * THIS SUBROUTINE BEGINS WHEN THE
                              3    * Y-DISPLACEMENT SUBROUTINE ENDS.
                              4    * THIS SUBROUTINE STORES THE PUPIL
                              5    * DILATION, X-DISPLACEMENT AND
                              6    * Y-DISPLACEMENT IN CONSECUTIVE CORE
                              7    * LOCATIONS OF CORE BLOCK 0.
                     05650    8     ORG 5650
   05650  0000                9    STORE 0000 /RETURN ADDRESS
   05651  1137               10     TAD 137 /CR DIAM
   05652  4310               11     JMP 5710
   05653  1140               12     TAD 140 /PUP DIL
   05654  4310               13     JMS 5710
   05655  1164               14     TAD 164 /CR EDGE
   05656  4310               15     JMS 5710
   05657  1032               16     TAD 32 /PUP EDGE
   05660  4310               17     JMS 5710
   05661  1161               18     TAD 161 /Y-DISP
   05662  4310               19     JMS 5710
   05663  5650               20     JMP* STORE /RETURN
                     05710   21     ORG 5710
   05710  0000               22    STSR 0000 /RETURN ADDRESS
   05711  6201               23     CDF 0 /DATA FIELD 0
   05712  3415               24     DCA* 15
   05713  6211               25     6211 /DATA FIELD 1
   05714  5710               26     JMP* STSR /RETURN
                     00015   27     ORG 15
   00015  0377               28     377
OPERAND CROSS-REFERENCE LISTING

   STORE             000 05650    9   000 05663
   STSR              000 05710   22   000 05714
```



ENDCHECK SUBROUTINE

```
PDP-8 ASSEMBLER
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ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

                                       1      * THIS ROUTINE IS ENTERED WHEN THE
                                       2      * STORE SUBROUTINE ENDS.
                                       3      * THIS ROUTINE DETERMINES WHETHER THE
                                       4      * SPECIFIED NUMBER OF 1 30 SECOND
                                       5      * LOOPS HAVE BEEN STORED.
                                       6      * THE NUMBER OF LOOPS DESIRED IS
                                       7      * ENTERED IN LOCATION 6566.
                                       8      * WHEN THE SPECIFIED NUMBER OF LOOPS
                                       9      * IS COMPLETED, THE PROGRAM HALTS
                                      10      * AND WAITS TO BE UNLOADED BY MEANS
                                      11      * OF SOME OUTPUT DEVICE.
                             06560    12       ORG 6560
      06560   7300                    13      LOOPS CLA+CLL
      06561   2367                    14       ISZ 6567
      06562   5421                    15       JMP* 21
      06563   7402                    16       HLT  STOP
                             06566    17       ORG 6566
      06566   7000                    18       7000  1000 OCTAL LOOPS
                             00021    19       ORG 21
      00021   0205                    20       205  STARTING ADDRESS FOR SEARCHODD.

OPERAND CROSS-REFERENCE LISTING

      LOOPS      000,06560     13

ERRORS 0     SCARDS 20       SPRINT 24        SPUNCH 4       STORAGE 2
```

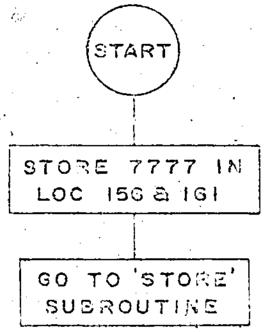

BLINK
SUBROUTINE

```
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ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

                                1      * THIS ROUTINE PLACES A 7777 IN THE
                                2      * OUTPUT OF A SEARCH THAT HAS ENCOUNTERED
                                3      * A BLINK.
                                4      * IT THEN RETURNS TO SEARCH TO LOOK FOR
                                5      * THE NEXT FRAME.
                     00321      6       ORG 321
    00321  7300                 7      BLINK CLA+CLL
    00322  1024                 8       TAD 24  /CORE 24 CONTAINS 7777
    00323  3156                 9       DCA 156  /PUT 7777 IN 156
    00324  1024                10       TAD 24
    00325  3161                11       DCA 161  /PUT 7777 IN 161
    00326  5762                12       JMP I 362  /362 STORES THE BLINK DATA
                     00362     13       ORG 362
    00362  0523                14       523  /523 POINTS TO STORE ROUTINE
                     00024     15       ORG 24
    00024  7777                16       7777 /BLINK DESIGNATION

OPERAND CROSS-REFERENCE LISTING

    BLINK     000 00321     7

[illegible]RORS 0     CARDS 16     PRINT 20     PUNCH 4     STORAGE 2
[illegible]25.17 43 RC=0
```