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BIOCYBERNETIC FACTORS IN HUMAN PERCEPTION AND MEMORY

STANFORD UNIVERSITY

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to the Advanced Research Projects Agency

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BIOCYBERNETIC FACTORS IN HUMAN PERCEPTION AND MEMORY

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PRINCIPAL INVESTIGATOR

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FOREWORD

This semi-annual technical report presents the accomplishments during the period of 1 June 1973 to 30 November 1973. The principal investigator is Dr. D. C. Lai and co-principal investigator is Dr. T. Kailath. Since the inception of this project, it has been the result of the collaborative efforts of many individuals. In particular, Dr. J. E. Anliker has spent endless hours on this project. Most of the staff members contributed in the writing of this report.

Biocybernetic Factors in Human Perception and Memory

SUMMARY

This project is concerned with the application of biocybernetic concepts to the problem of expanding human memory. In particular, the goal of this research is enhancement of visual imagery as far as possible in the direction of photographic memory. Scanpaths of the eye during inspection of visual targets are treated as indicators of the brain's strategy for the intake of visual information. This research will determine the features that differentiate scanpaths associated with superior imagery from scanpaths associated with inferior imagery. Similarly, the tachistoscopic exposure of the visual material is responsible for a number of adjustments in the brain's waking rhythm; the electroencephalographic features correlated with superior imagery will be differentiated from those correlated with inferior imagery. A computerized biocybernetic scheme will be implemented in an attempt to generate image enhancement and to train the individual to exert greater voluntary control over his own imagery. In this progress report, we give an account of our accomplishments made in this reporting period.

Work in eye-movement measurement and tracking has been extensive. New techniques for eye-movement prediction and special software for visual scanpaths study have been developed and implemented. We also describe an EEG signal model which prescribes the stimulus-response relationship. The information gained in this model will elucidate the behavior of the alpha frequency and phase, and thus lead to a more practical brain state estimator and predictor for our use in the memory studies of this project.

The implications of this project for the Department of Defense arise from the possibility of devising new and unusual techniques that will permit the development of stronger imagery in men with normal memories. Since it is definitely an asset for the military man to have the ability to absorb information rapidly and to retain it intact for long periods of time, this project will attempt to intensify the post-stimulus imagery as far as possible in the direction of photographic memory--and to search out those features of successful recall strategies so as to enhance the individual's power of redintegration.

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I. INTRODUCTION

The primary concern of this research project is the development of biocybernetic concepts and techniques required for the analysis and development of skills useful for the manipulation and control of memory functions, particularly those related to the more concrete ("eidetic") images. In particular, we are concentrating on the problem of achieving biocybernetic expansion of human visual memory through the use of real-time computerized monitoring and feedback of cues that serve as keys to memory encoding and retrieval. This approach represents a more or less logical extension of the considerable evidence that the human nervous system depends heavily upon spatial and temporal cues both in the encoding and decoding of memories, especially sensory images.

Our plan is to develop and implement techniques for real-time monitoring and prediction of central nervous activities through the electro-encephalographic signals and through eye-movement signals. We shall use this information to arrange extraordinary coincidences between various brain states, eye positions, and the delivery of visual stimulation. The visual stimuli are to be presented either on the screen of a storage scope or in complex tachistoscopic batteries for either monopic or dichopic viewing. The eye position and eye movements will be measured by a unified system so as to obtain their optical and electrophysiological estimators. Combining these techniques (in order to monitor eye pointing both when eyelids are open and when closed) and using a feedback scheme to close the control loop, we expect to obtain greater control of image persistence and image dissipation.

Our work has been progressing in the direction to achieve the following goals:

(1) Determine the temporal and spatial cues that serve as keys to memory encoding and retrieval via the tracing of brain states and eye movement.

(2) Design and implement real-time estimation and prediction algorithms for monitoring brain states and eye pointing.

(3) Use computer memory to supplement and strengthen the aspects of human memory that ordinarily result in image dissipation. We assume that a superior pattern of visual inspection (i.e., one that results in superior memory) is more consistent and also less probable of natural occurrence than a visual inspection strategy that is less consistent. Through the use of computer guidance (feedback) we will steer the subject toward improved encoding and improved decoding strategies.

In this report, we describe our accomplishments in developing and implementing those concepts and techniques which are essential in achieving our goals.

The heart for the implementation of our schemes is the PDP-15 computer system which was acquired in the last contractual year. This system has been fully utilized and expanded by the addition of 16K core memory and a cartridge disk system. This addition enhances the capabilities of the system for real-time data acquisition and processing which are prerequisites for the realization of our schemes. The updating and refinement of the system has been our continuing effort. However, we are not going to report here our accomplishments in this endeavor.

In this period, our major effort was devoted to eye-movement measurement and tracking. Progress has been made in the monitoring of eye position and predictions of fixation points. This is described in Section III. In the next section, we present new techniques in calibrating our eye-movement monitor system and in correcting the distortion due to the system. This will enable us to obtain more accurate eye-movement data. We have also completed a computer program dubbed "SEER" that was designed to open up a new avenue for the study of visual scanpaths. We anticipate using this software heavily during the next quarter and producing many interesting results in our study of eye movement and eye position. The "SEER" program is described in Section IV. In Section V, we present an EEG signal model which relates the visual stimuli and the EEG signal. The understanding of this stimulus-response relationship will help us in the determination of the temporal features that play prominent roles in the encoding and decoding of memories. We make some concluding remarks and describe future work in the last section.

II. EYE-MOVEMENT MEASUREMENT: CALIBRATION AND DISTORTION CORRECTION

The success of our project hinges on the determination of both the spatial and temporal cues that serve as keys to memory encoding and recall. For the determination of the spatial cues, it is imperative that we should have an accurate technique for the measurement of eye movement and eye position. At present, the only instrument for measuring eye movement available to us is the Eye-Movement Monitor (Type SG) manufactured by Biometrics, Inc. The Biometric Eye-Movement Monitor provides a simple and relatively easy-to-use method for measurement of horizontal and vertical movements of the eye. In the horizontal direction, the method is based on the measurement of the amount of infra-red light reflected from the junction of the iris and the sclera. In the vertical direction, the eyelid-sclera junction is used. This method of measurement, unfortunately, yields unreproducible and highly distorted results. Several sources of noise exist:

(1) Movement of the head or the spectacles on which the sensors are mounted results in translation of the X,Y coordinate space.

(2) The horizontal signal changes as the vertical position of the eye is varied. This problem is referred to as "vertical cross-talk."

(3) The vertical signal suffers from an "eyelid hysteresis" phenomenon, that is, the eyelid does not always return to the same relative position after vertical movement or blinks.

(4) Nonlinearities are introduced in both the X and Y signals due to changes in the adjustment of the apparatus and through differences in the characteristics of the eyes of the subjects.

As reported in the last annual technical report, we have made extensive modifications on this unit to suit our needs. Since then, we have improved our calibration technique and implemented new techniques for distortion correction. A subroutine "IBALL" has been written for the purpose of measuring the reproducibility of the measurement of eye fixations. In other words, it will give some reasonable bounds on the errors which might be expected and summarize certain statistical properties such as the means and variances of the measured eye fixations. This information will, in turn, aid the adjustment of the positions of the sensor-source groups which are mounted on the Biometric eye-glass frame. We intend to estimate the ranges of errors of the Biometric Eye-Movement Monitor by conducting repetitive experiments using "IBALL" program. We shall describe the operations and our results.

An operational flowchart for this program is shown in Figure II.1. The experiment can be initiated by following a dialog with "IBALL" as shown in Figure II.2. A calibration matrix as shown in Figure II.3 is used to aid in the adjustment of the sensor-source units. This matrix is presented to the subject on a storage scope point-at-a-time in random sequence and hence, the distance and direction traveled by the eyes are randomized. The subject is requested to press a button after he has fixated on the prompted point. At this time, ten pairs of the horizontal and vertical voltages from the Biometric unit are sampled and averaged. This procedure is repeated until all of the nine points in the matrix

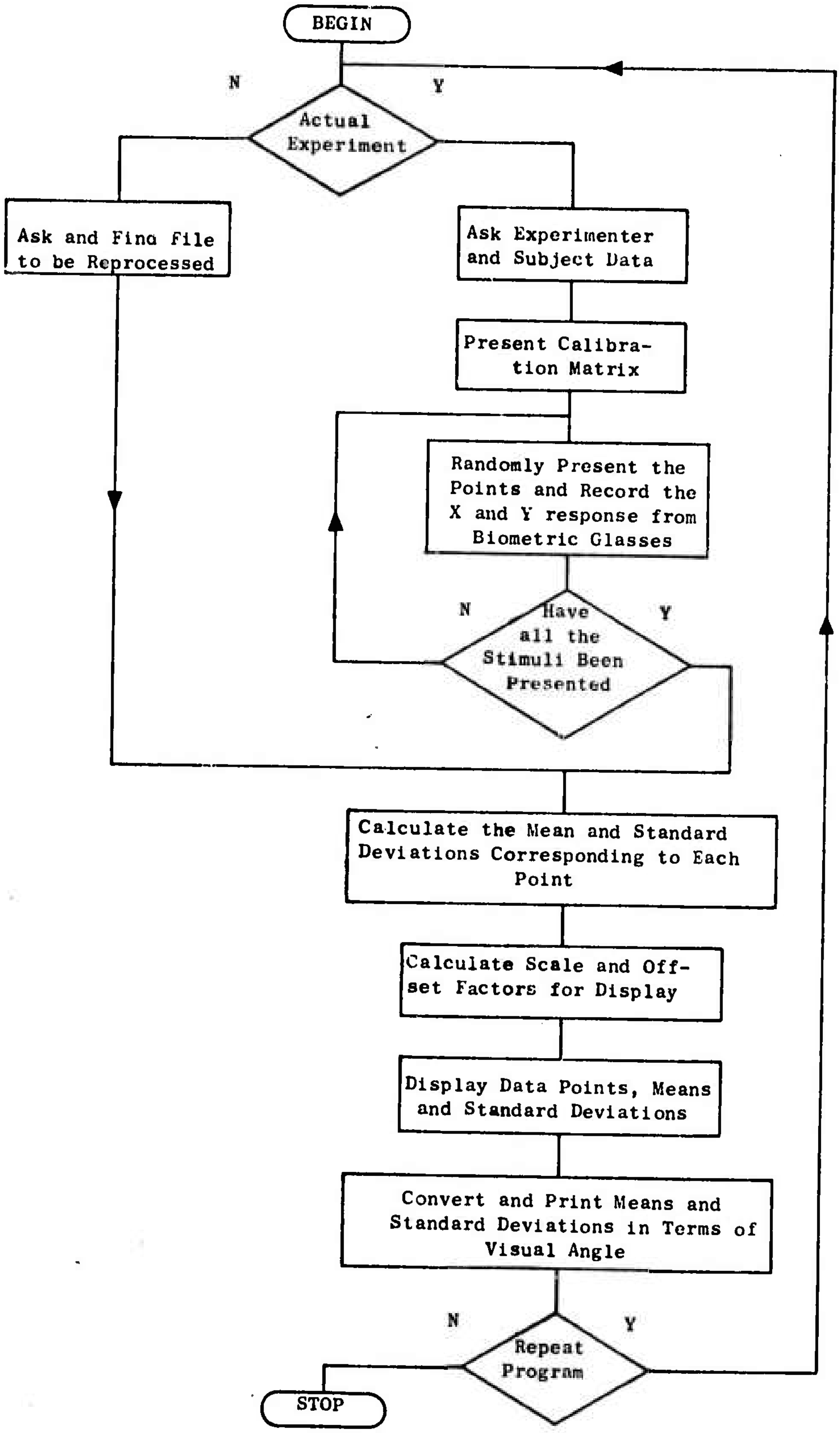


Figure II.1 Flowchart of IBALL

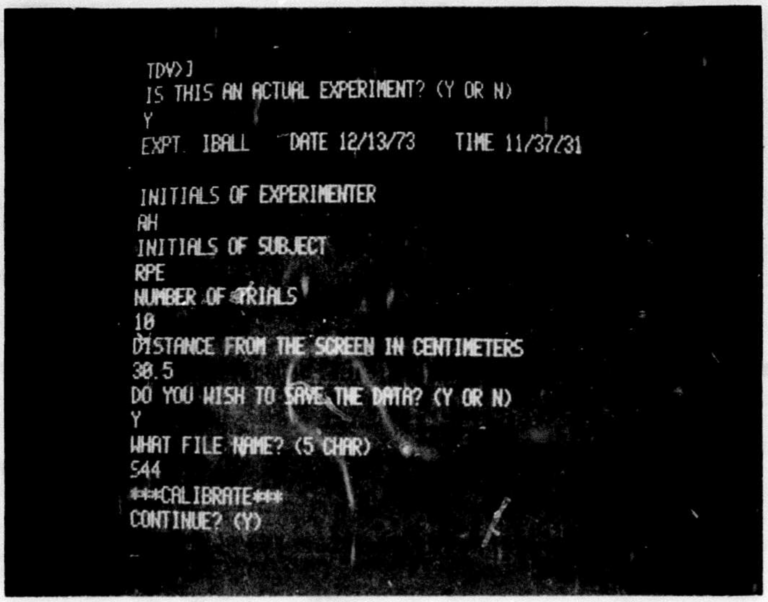


Figure II.2 Initial Dialog of IBALL

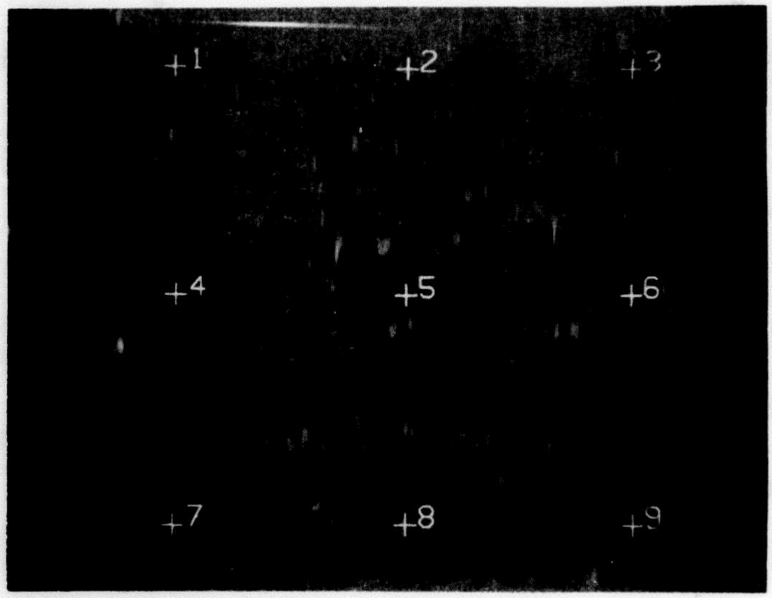


Figure II.3 Calibration Matrix for
Biometrics Eye-Movement Monitor

have been presented and thus the first trial is completed. Another trial will start automatically. We show two typical results in Figures II.4 and II.5 accompanied by summaries of statistical properties. In the figures, the circles on the pictures are the positions of the points in the calibration matrix shown and the intersection of the bars of each cross indicates the mean position where the eyes have fixated. The lengths of the upright and horizontal bars are proportional to the standard deviations in the vertical and horizontal directions, respectively, of the eye-fixation points. Ranges of horizontal and vertical errors obtained in fifteen experiments are shown in Figures II.6 and II.7. The average errors are 0.7^{o} and 1.2^{o} for horizontal and vertical values, respectively. The average error ranges are 0.4^{o} to 1.2^{o} and 0.4^{o} to 2.4^{o} for horizontal and vertical error, respectively.

As seen from Figures II.4 and II.5, the mean locations of the eye-fixations (as indicated by the crosses) have considerable skewing and distortion caused by the vertical crosstalk and nonlinearities. We now describe a technique which attempts to correct the vertical corsstalk and nonlinearities mentioned above. The technique is based on the construction of a piecewise linear mapping between the measurement or response space (the voltages at the terminals of the Biometrics unit) and the stimulus space (points in the visual field being observed by the subject).

If we let (r_1, r_2) represent the measured X,Y voltage values corresponding to some stimulus point (s_1, s_2), then the most general form of a linear mapping between r and s is of the form

$$s_1 = c_{11}r_1 + c_{12}r_2 + c_{13}$$

SUMMARY OF DATA IN EYE FIXATION REPRODUCIBILITY

ALL MEASUREMENTS GIVEN IN VISUAL ANGULAR DEGREES
FILE NAME S4 12/ 4/73 10/10/26
EXPERIMENTER AH SUBJECT JEP TRIALS 10 DISTANCE FROM SCREEN 30.

POINT	MEAN X	SD X	MIN X	MAX X	MEAN Y	SD Y	MIN Y	MAX Y
1	-7.69	1.03	6.08	9.52	9.76	0.35	9.04	10.35
2	2.73	0.64	-3.97	-1.81	10.69	0.39	10.21	11.68
3	15.65	1.04	-17.74	-14.00	10.83	0.35	9.93	11.32
4	-10.55	1.28	8.21	12.15	1.17	1.91	-3.40	3.82
5	-1.03	0.92	0.07	2.83	1.06	2.30	-1.77	4.95
6	10.17	0.85	-11.63	-9.04	1.60	1.60	-0.64	4.39
7	-13.00	1.17	11.34	14.70	-10.69	1.31	-12.09	-9.00
8	-5.27	1.24	2.94	7.79	-10.28	2.52	-14.64	-5.73
9	5.23	1.10	-7.09	-3.35	-10.10	1.52	-13.17	-7.54

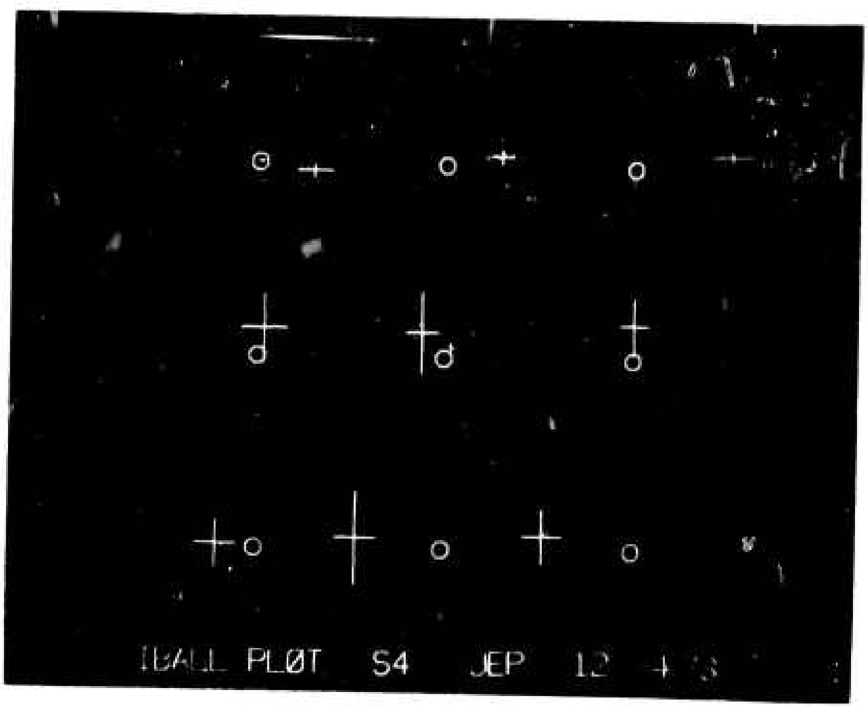


Figure II.4 Average Display of
IBALL of Subject 4

SUMMARY OF DATA IN EYE FIXATION REPRODUCIBILITY

ALL MEASUREMENTS GIVEN IN VISUAL ANGULAR DEGREES
FILE NAME S7   12/10/73   13/15/ 0
EXPERIMENTER AH   SUBJECT ME   TRIALS 10   DISTANCE FROM SCREEN 32.

POINT	MEAN X	SD X	MIN X	MAX X	MEAN Y	SD Y	MIN Y	MAX Y
1	-9.05	1.42	-11.28	-6.56	9.35	0.57	8.72	10.17
2	2.10	0.68	1.25	3.14	10.20	0.98	8.16	11.05
3	13.50	0.64	12.67	14.32	10.43	0.91	8.16	11.24
4	-10.00	1.22	-11.44	-7.93	1.76	1.28	-0.10	3.51
5	-0.10	0.84	-1.16	0.91	2.03	1.22	-0.71	3.78
6	9.67	0.47	9.25	10.89	2.60	0.81	1.32	4.39
7	-10.96	1.35	-13.08	-8.85	-10.59	1.25	-13.02	-8.69
6	-2.46	0.74	-3.51	-1.28	-9.74	1.12	-11.63	-7.79
9	6.53	0.44	6.03	7.33	-9.64	0.84	-11.47	-8.69

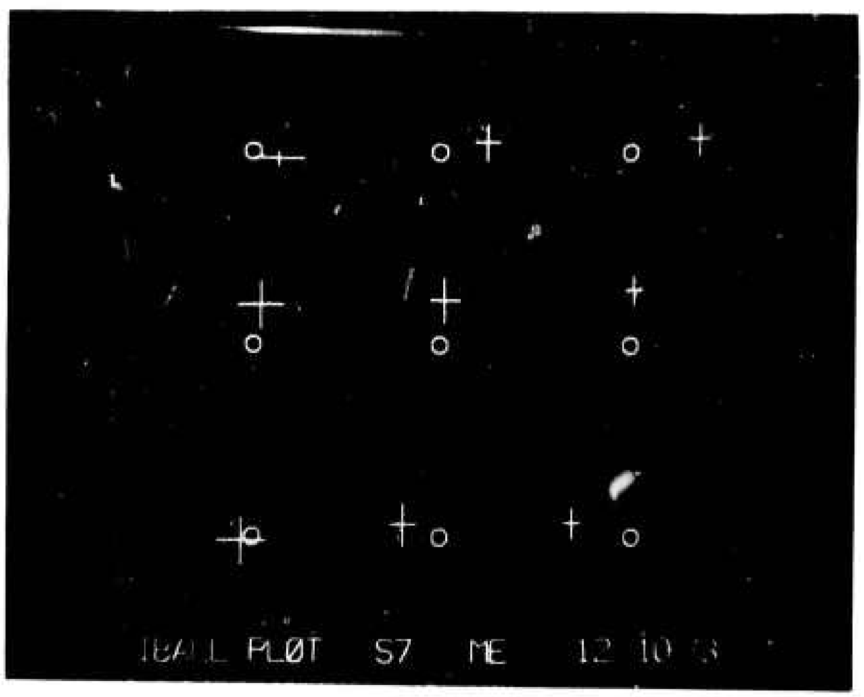


Figure II.5 Average Display of IBALL of Subject 7

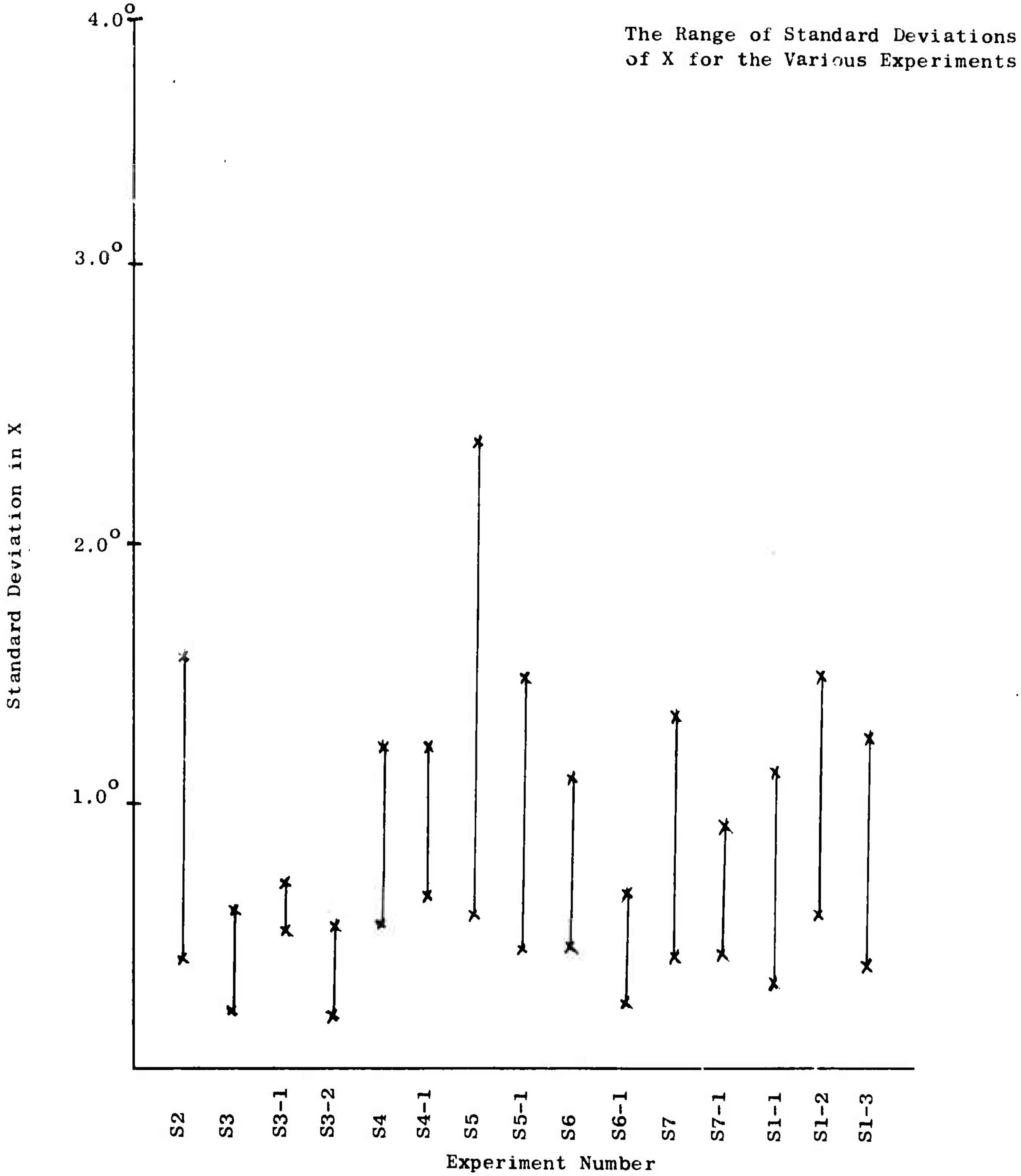


Figure II.6 Ranges of Horizontal Error

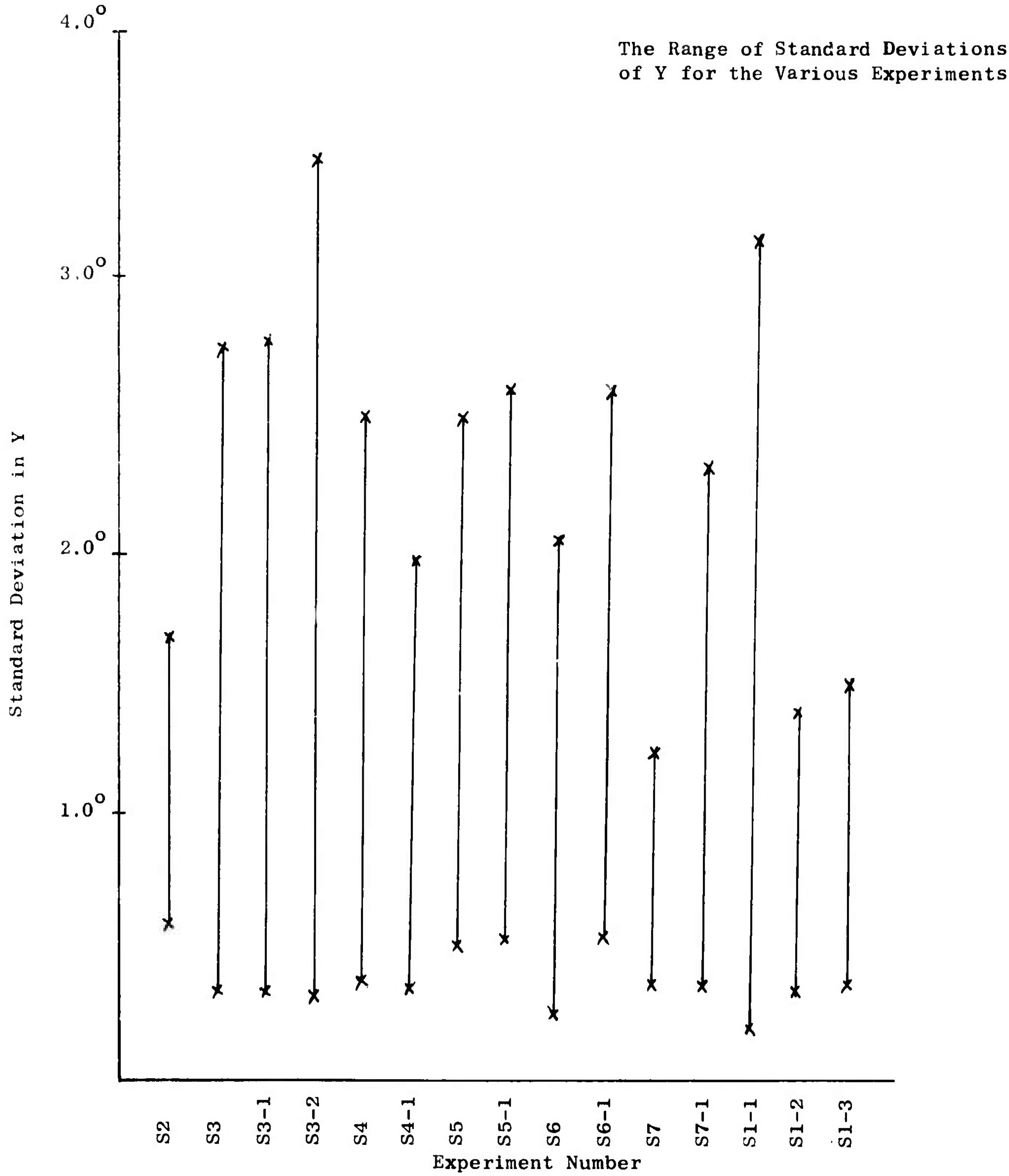


Figure II.7 Ranges of Vertical Error

$$s_2 = c_{21}r_1 + c_{22}r_2 + c_{23}$$

The coefficients c_{ij} are defined by use of a three point calibration array which empirically determines the relationship between the stimulus values (s_1, s_2) and the response values (r_1, r_2).

Measured value		Stimulus value
(r_{1a}, r_{2a})	corresponds to	(s_{1a}, s_{2a})
(r_{1b}, r_{2b})	corresponds to	(s_{1b}, s_{2b})
(r_{1c}, r_{2c})	corresponds to	(s_{1c}, s_{2c})

This correspondence allows us to set up two sets of three simultaneous linear equations, the first of which is

$$s_{1a} = c_{11}r_{1a} + c_{12}r_{2a} + c_{13}$$

$$s_{1b} = c_{11}r_{1b} + c_{12}r_{2b} + c_{13}$$

$$s_{1c} = c_{11}r_{1c} + c_{12}r_{2c} + c_{13} \quad .$$

Solution of these equations yields the required coefficients.

In practice, one such linear mapping is not sufficient to correct for distortions introduced by the Biometrics equipment. The problem, in general, is to find the minimum number of stimulus calibration points (and thus the number of mappings) needed to reduce the nonlinear distortion to a level below the other noise sources mentioned above. We have found that a calibration matrix of five to nine points (four to eight mappings) provides adequate linearization for our experiments.

A program has been written which computes the c_{ij} coefficients for the mappings. It consists of two subroutine calls named MAPSET and MAPCNV. The visual field is divided into three to eight pie-shaped sectors around a pivot point in the center of the visual field. A set of coefficients is computed for each sector by MAPSET. The second routine, MAPCNV, determines which sector applies to a given measured point (r_1, r_2) and computes the corresponding stimulus value (s_1, s_2).

As demonstration of the effectiveness of this distortion correction program, we applied this technique to the measured eye-fixations of subjects 7 and 5. The original positions of the eye fixations before correction are shown in Figures II.5 and II.9 and the corrected locations are shown in Figures II.8 and II.10. Judging by these pictures, we conclude that the correction by the use of this computer program is quite effective.

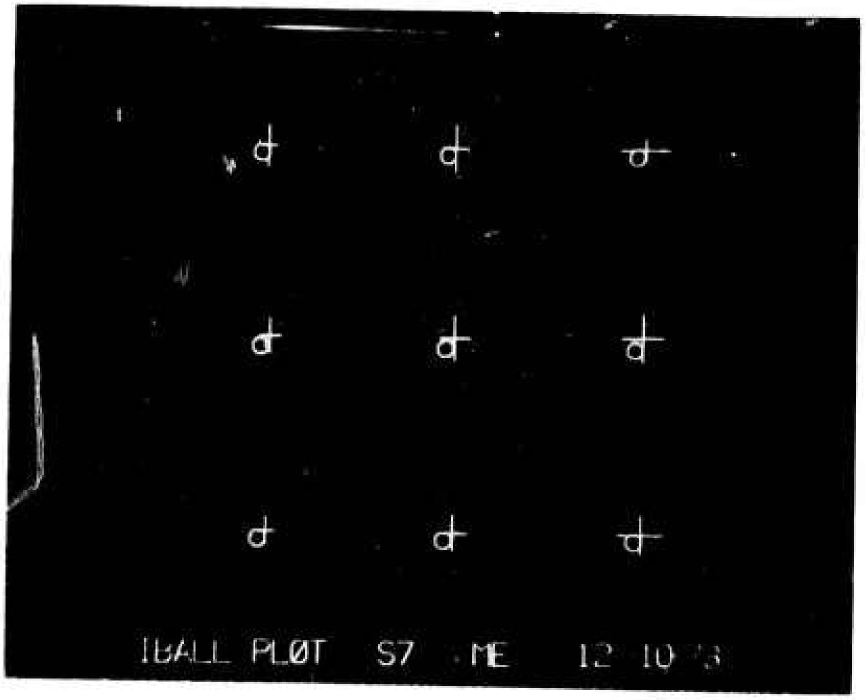


Figure II.8 Skew Removed from S7

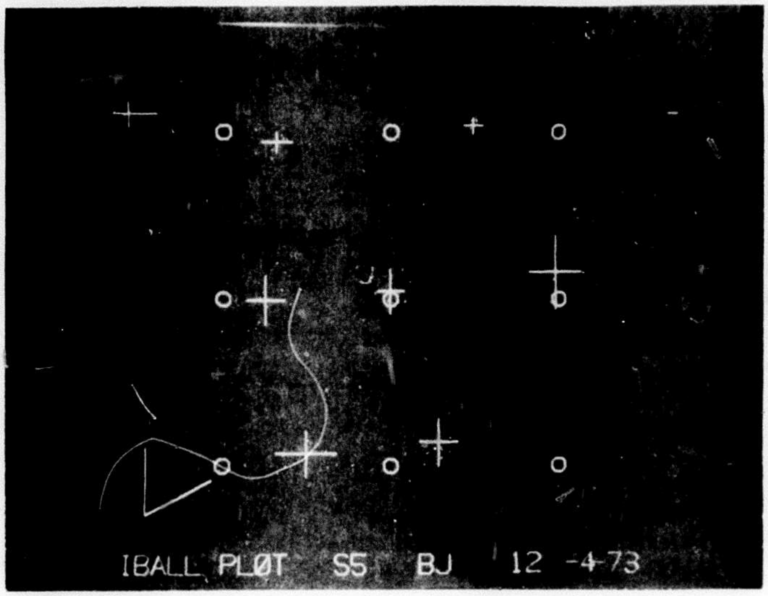


Figure II.9 Highly Distorted Before Correction

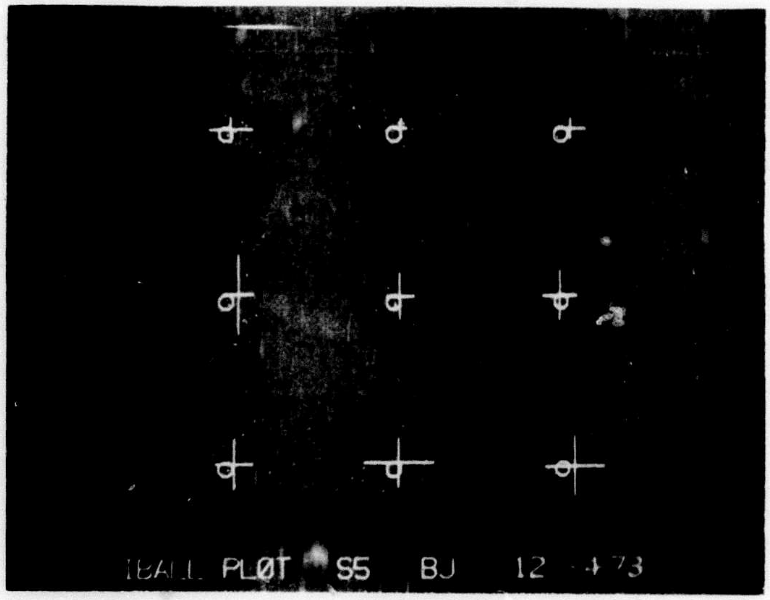


Figure II.10 Distortion Corrected

III. TRACKING OF EYE MOVEMENT

1. Introduction

The tracking of eye movement is an essential part of our research project. In order to feedback the spatial cues in encoding and decoding of memories, we have to track constantly the movement of the eyes. Basically, for the kind of eye movements we are interested in, we can classify them into two modes; viz., fixation and saccades. Thus, for the purpose of tracking we need to (a) estimate and predict the duration of a fixation when in that mode, i.e., to predict when the mode will change from a fixation to a saccade and (b) estimate and predict the duration, the direction, and the length of the saccade for the saccadic movement itself, i.e., to predict when and where the saccade will end.

The two parts are interdependent. Ultimately, we will build a model which will take care of both. However, more insight can be obtained if we deal with the two separately and then combine them into one predictive model. At present, we have looked into part (b). For the sake of simplicity, we will first develop a deterministic model which ignores the problem of the direction and the stochastic properties of the saccade (assuming it to be a straight line) and gives a prediction of the final position after looking at the onset of the saccade. The estimation of the length and duration of the saccade is the more difficult part of the problem. Some empirical observations have been made and on the basis of these, we have developed two different predictive processes; viz., the position-variance method and the velocity method. The details of these methods will be described later. The realization of various eye-movement tracking techniques requires preprocessing and manipulation of the raw eye-movement data. To this end, we have written an interactive program for eye-movement analysis (IPEMA).

2. <u>An Interactive Program for Eye-Movement Analysis (IPEMA)</u>

This program combines various packages for analysis of eye movements. It interacts with the user through the DECwriter or the VT05, and the data switches on the PDP-15 console. The eye-movement data is read off a magnetic tape. The data is stored on the tape in a particular format - files consisting of records of 63 data samples each. Through the program, the tape can be positioned at any particular point and the data can then be processed.

The program first calls an initialization subroutine which sets the data channels, determines if the plotting device is the CRT or the CalComp plotter and initializes the device and positions the tape to the beginning of the first file of the specified volume. It also reads in the calibration data (standard calibration could be used if the actual data is not available) and sets up calibration parameters.

Now the main program prompts the user with a "?." Any of a number of commands can be entered by the user. A command consists of five characters followed by an integer number. The commands essentially fall into three classes:

(i) Commands which position the tape. These commands can move the tape to the beginning of a particular file or to any record on the file. They can also cause the processing to be started from any particular sample on the record. Essentially, in the program there is a pointer to the next data sample to be processed. This pointer has three parts: the file number, the record number, and the position on this record. These commands change one or more elements of the pointer. The elements can be changed either relative to the current value or an absolute value can be given to any of them. There are thus six commands in this group.

The three commands SPFIL I, SPREC I, SPPOS I change the specified element relative to the current value. I, which is the displacement, can be positive, negative, or zero. The other three commands FILCH I, RECCH I and POSCH I specify the absolute value of the particular element of the pointer. Here I can only be positive. The SPFIL and FILCH commands position the tape to the beginning of a new file and hence alter the record number and the position also. SPREC and RECCH position the tape to the beginning of the new record within the same file. Hence, the position pointer could be altered. For the SPPOS and the POSCH commands, if the new position falls within the same record, the record number does not have to be changed. Otherwise, the tape has to be moved forward or backward, depending on the new record number.

If at any point during the positioning of the tape, either end of either the volume or the file (in case of record and position commands) is reached, the tape stops and an appropriate message is printed out.

(ii) Commands to perform the actual analysis: The analysis programs exist in the form of subroutines which are called by the main program. These subroutines are modules which are overlaid in core. Thus, a new module can easily be inserted without overrunning the core. The programs available presently are:

(a) PLOT, which simply plots the data on the plotting device.

(b) FIX I, which determines the fixation points in the data according to an algorithm described earlier and plots and numbers these points. I is a parameter for the algorithm. An example for using this program is shown in Figures III.1 and III.2.

(c) VARNC I, which determines the velocity and variance of a moving window of data and plots out the actual data, the velocity and the variance. I is the length of the window. An example is shown in Figure III.3.

For instance, in the prediction scheme to be described, we set a certain threshold and when the variance crosses this level, the predictive process starts. A certain number of points (which can be set by the program) after the onset of the saccade are read in, the variance calculated and a curve is fitted to this initial part. This gives predicted values of future variance. Direction information is obtained from this initial part of the saccade and combining the two, we get the predicted movement.

(d) WTDISP, which gives a simulated three dimensional weighted display of the eye-movement data. The X-Y plane is divided into a grid and the "weight" of each grid point is plotted along the third axis. The weight is obtained by taking a certain portion of the data and then for each sample point, assigning some weight to the corresponding grid point and to points around it. This is based on the fact that due to inaccuracies in the instrument

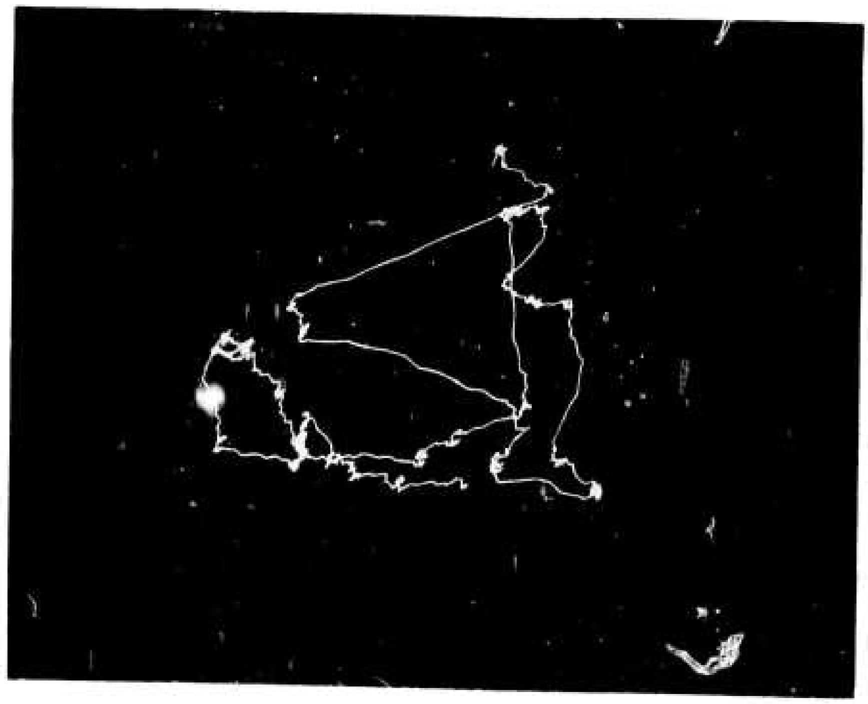


Figure III.1 A Plot of Eye-Movement Data

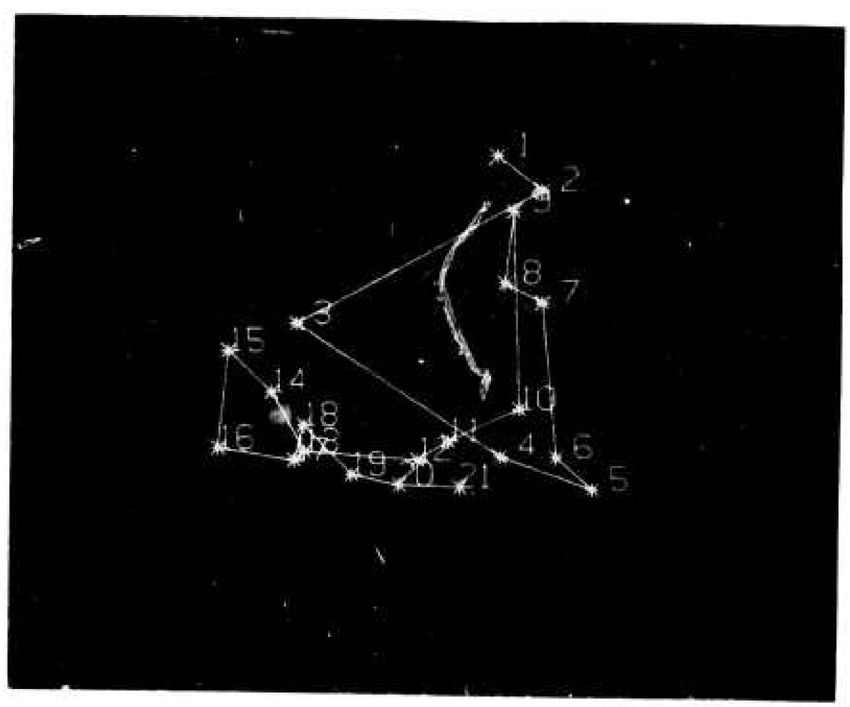


Figure III.2 Fixations in the Above Data
Determined by the FIX Program

and due to other noise sources, a given sample point actually represents a probability distribution around that point. At present, a normal distribution is used. An example is given in Figure III.4 Fixations show up as humps in the figure.

(iii) Miscellaneous commands: These commands enable us to filter the data with a three pole Butterworth low pass filter (FILTER i, $i=10f_c$), to resample the data (COMP i will use every ith point) to determine the present position of the tape (LOCATE) and to exit from the program (EXIT).

The data is acutally read off the magnetic tape by a subroutine MTREAD which is requested by other programs when data is needed. By using the switches on the console, it is possible to read in one point at a time, manually, so that the execution of the programs can be observed more easily. It is also possible to exit from any of the analysis programs by means of a switch.

3. Methods for the Prediction of Eye-Fixation Points

We have developed two predictive processes. At present, both of these methods are being tried out and showed promising results. Refinements are in progress.

(i) The Position-Variance Method

Taking n samples (X_1,Y_1), (X_2,Y_2), ... , (X_n,Y_n) of the eye-movement data, we calculate the means by

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad \text{and} \quad \overline{Y} = \frac{\sum_{i=1}^{n} Y_i}{n}$$

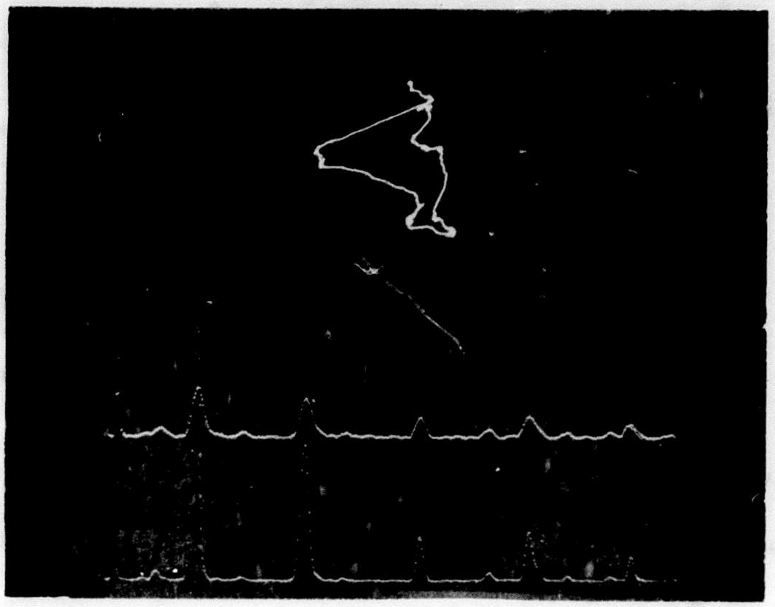


Figure III.3 A Plot of Eye Movements,
Sample Mean Velocity and Variance From
the VARNC Program. The Peaks in the Velocity
and Variance Curves Indicate Saccades.

Figure III.4 A Plot of Eye-Movement Data and
a Weighted Display by the WTDISP Program. The Peaks Indicate Fixations.

and the variance in the sample window by

$$V = \left[\sum_{i=1}^{n} (X_i - \overline{X})^2 + \sum_{i=1}^{n} (Y_i - \overline{Y})^2 \right] / n$$

It has been observed that the variance of a window entirely in the fixation mode is lower than a certain threshold value. When a saccade starts, the variance rises, reaches a peak and then settles down again when the eye fixates. Thus, by setting an empirically determined threshold, the onset of a saccade can be determined. After this point, by fitting sinusoidal curves to the variance, we can predict the future variance values which along with the straight line assumption enable us to predict the next fixation point.

(ii) The Velocity Method

In the above method, a certain time lag is present due to the width of the window. The response is slow because of the averaging process over n points. To overcome this difficulty, we used the velocity information in the data. By using the eye-movement velocity information, we developed and implemented a scheme for prediction of a new eye position at the termination of a saccadic movement about half way before that new position has been reached by the eye. The scheme is based on the observation that the eye-movement velocity is very nearly symmetrical. The velocity during a saccade increases to a maximum value, then decreases back to zero in approximately the same manner as the increase. Thus, by detecting the peak value of the velocity, the distance the eye has

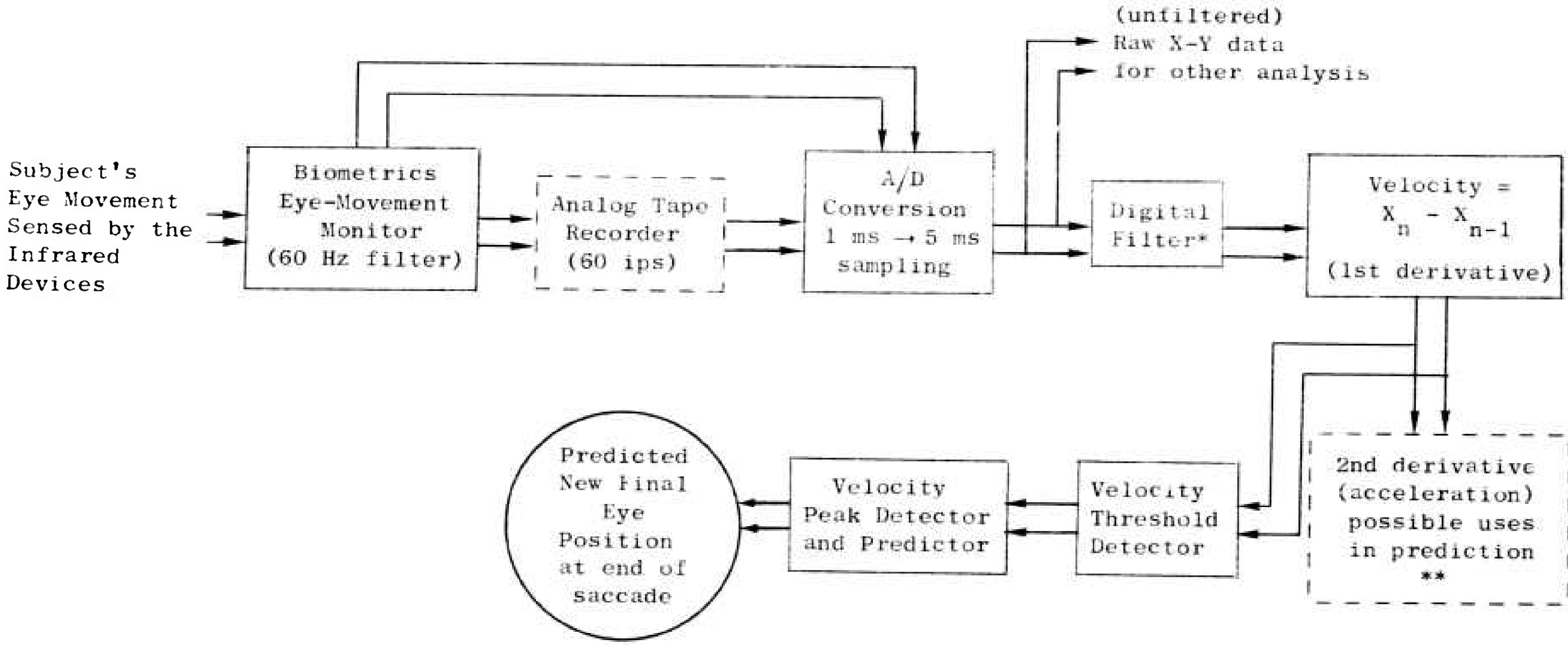


Figure III.5
Block Diagram of Prediction Scheme by Using the Velocity Information

moved since the beginning of the saccade up to the time of this peak can be doubled to get a prediction of the eye-position when the velocity will decrease to zero and the eye has arrived at a new fixation point. Therefore, when a saccade is only half completed, a prediction of where the eye will be at the end of the saccade can be made.

A block diagram of the scheme is shown in Figure III.5. X-Y eye-position data from a Biometrics Eye-Movement Monitor is sampled either on-line directly from a subject or from analog tape. Sampling rates presently used are 1 millisecond and 5 milliseconds. The data are then smoothed by using a digital filter of a bandwidth of approximately 0 to 20 Hz. This velocity calculation for one channel is performed as follows:

$$\text{"velocity"} = X(n) - X(n-1)$$

where $X(n)$, $X(n-1)$ are two successive samples. This result can be divided by the sampling period T, in order to obtain the correct magnitude for the actual velocity. However, the algorithm only requires a value proportional to the velocity, so this division is unnecessary.

During a fixation, this velocity fluctuates about zero with some variance, which is determined for each subject in each experiment. A threshold detector is used to monitor this fluctuation. When the velocity increases monotonically above the maximum fluctuation level, it is decided that a saccade has begun. At this time, the on-going means of the X-Y positions, which have been calculated throughout the fixations, are saved for later analysis. The peak detector now begins to look for peaks in the velocity curve. When a peak is detected, the X position value at the peak time is used in the equation below to predict what the final position will be at the end of the saccade:

$$X_{final\ position} = 2(X_{peak} - X_{initial}) + X_{initial}$$

$$= 2X_{peak} - X_{initial}$$

where $X_{initial}$ is the mean value of the X position which was stored at threshold detection. The same calculations are made simultaneously to predict the Y position.

As an example, we show the prediction process in Figures III.6 through III.10. In each figure, we show the eye movement on an X-Y plot, the horizontal (X) velocity vs. time, and the horizontal (X) eye position vs. time. In Figure III.6, we show the onset of the saccade. The intermediate eye-movement processes are shown in Figures III.7 and III.8. In Figure III.9, the velocity reaches its peak and the prediction of the fixation point is made. Finally, in Figure III.10, we show that the eyes arrive at the predicted fixation point.

The method just described is simple and useful; however, it restricts us to make prediction only when the eye reaches the halfway mark of its journey. We are in the process of improving this scheme. Various methods have been contemplated. Before we try any of these schemes, we think a thorough analysis of saccades is in order.

X-Y

VEL

X POS

X-Y

VEL

X POS

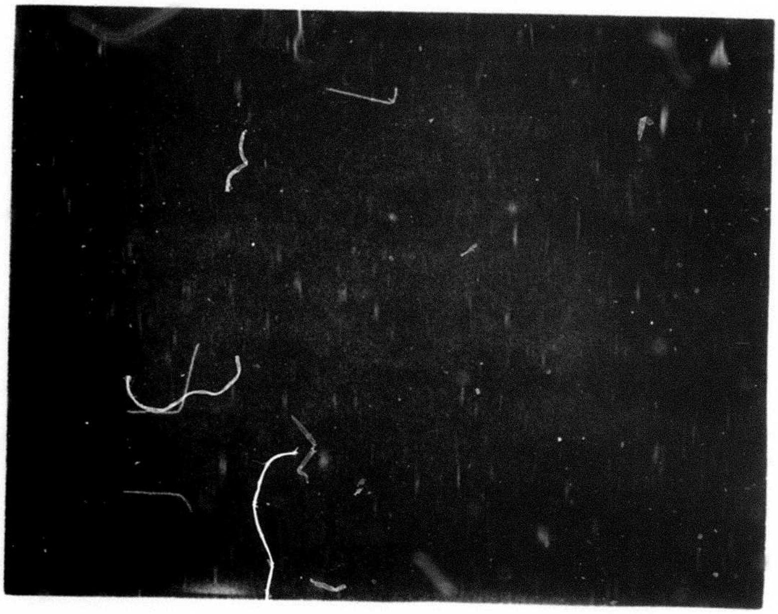


Figure III.7 Eye Movement during a Saccade

X-Y

VEL

X POS

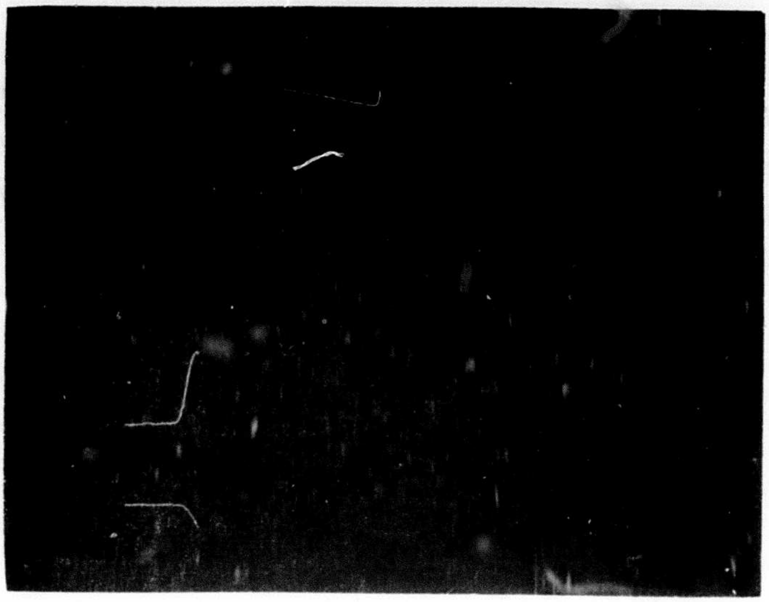


Figure III.8 Farther Movement during a Saccade

X-Y

VEL

X POS

Figure III.9 The Velocity of the Saccade having just Reached the Peak Value and the Next Fixation Point Predicted

X-Y

VEL

X POS

Figure III.10 The Saccade Terminating at the Predicted Fixation Point

It has been hypothesized that the eye does not observe anything during the saccadic movement. Thus, before the saccade is made, the decision is made about where to move the eye and with what velocity. Any information about these parameters in the eye-movement data should then be present in the data immediately preceeding the saccadic movement. Thus, by analyzing the fixation data just before the onset of a saccade, we can determine in what form this information is present and whether we can use it to predict the onset. Essentially, some velocity and direction analysis is performed on this data.

For this purpose, the onset of a saccade is determined by the velocity of filtered data. When this velocity crosses a certain threshold, we mark the end of the saccade. Then a window of data, consisting of the saccade and some samples before and after the saccade, is taken. These 'saccade samples' for a particular saccade (e.g., from point P_0 to P_1) are collected and then analyzed. In addition to this, the actual saccade data is used to obtain the characteristics of saccades such as velocity, length, duration, variance, etc. Knowledge of these characteristics is essential in building a sound predictive model.

IV. THE "SEER" PROGRAM FOR VISUAL SCANPATHS STUDY

1. Introduction

A computer program is desperately needed for the study of visual scanpaths. We believe that a superior scanpath of visual inspection, i.e., one that results in a superior memory, is more consistent and also less probable of natural occurrence than a visual scanpath resulting from an inspection strategy that is less consistent. It is important to determine the features that differentiate scanpaths associated with superior imagery from scanpaths associated with inferior imagery.

In this section we describe version 1A of SEER, a PDP-15 program that allows on-line analysis of visual methods of object recognition. SEER permits the experimenter to display previously defined images on a Tektronix 611 CRT. As a subject views these images, data may be taken and stored on magnetic tape through the use of the computer and a Biometrics Eye-Movement Monitor (Type SG).

Here we describe the first operational version of SEER. The program has been used in its present form. Further modifications and additions are in order to make SEER more versatile. At the end of this reporting period, this program has not yet been applied to the study of visual scanpaths, since it is barely finished. We plan to use this program heavily in the immediate future to study the various scanpaths in relation to visual memory.

2. Description

The most basic SEER entity is the "picture." A picture corresponds to a set of data collected together and given a symbolic name. Currently, all picture names are of the form

PCXXX

where XXX is a non-zero decimal integer less than 999 (e.g., PC174, PC011). Notice that leading zeros must be specified for integer values less than 100.

The data composing a picture consists of an ordered set of points which, when displayed by the GS-15 Graphics System, produces an image on the surface of the CRT. Pictures, i.e., groups of display data, may reside in three different locations in one of two possible formats (symbolic and binary).

Pictures in symbolic form may reside on disk or DECtape as standard RSX files. Normally, a DECtape contains the "library" of all pictures available. As part of the preparation for an experiment, the user would transfer those pictures that are needed to the disk from the DECtape library. The library could, of course, reside on the disk if sufficient space were available. The picture files on disk are collectively called the picture "album." In a later version of SEER the album will be a single random access binary file rather than a group of symbolic files. This change will allow faster manipulation of pictures since binary reads are, in general, much faster than symbolic (e.g., Fortran FORMATed READs).

Pictures may also reside in the "current picture." The current picture consists of a "point" vector (actually X and Y vectors) of 3500 points and a variable specifying how many points are in the current picture. Thus, the current picture is located in the computer's main memory as a collection of binary integers. Although the experimenter has logical access to a number of pictures, in fact he may only work with one at a time. This single picture that is of current interest is the "current picture."

As explained in detail in Section 3, there are numerous SEER commands that work with or on the current picture. For example, the CREATE sub-system allows the user to "paint" pictures by drawing simple geometric figures (points, lines, rectangles, circles, etc.) at specified locations on the CRT. As the pictures are drawn on the display, the points defining these pictures are simultaneously added to the current picture. Once the picture has been "drawn" it may be saved as a permanent file on the disk with the SAVE command. The DELETE command is also available for erasing previously drawn figures in the current picture, thus providing a simple but useful error-correcting capability.

Data acquisition is accomplished through the DRAW sub-system. In a typical experiment the FETCH command would be used to transfer a picture from the album to the current picture. Once the current picture is specified, it may be examined with the PREVIEW command. This causes the entire picture to be quickly drawn on the CRT.

When the user is convinced that the correct picture has been FETCHed (or the subject has had a chance to PREVIEW the picture), he may initiate the "taking" of eye-movement data by using the VIEW command. VIEW will cause the digitized data to be written onto 9-track magnetic tape which may later be analyzed off line.

A major reason for the creation of SEER was the need for a simple software/hardware system that could determine with a high degree of accuracy where on the CRT a subject is directing his visual attention. The proposed solution is to have a subject trace the current picture (i.e., the subject visually follows a "dot" that slowly moves over every line in the picture) while monitoring his eye movements. Thus, this traced picture, due to unavoidable noise in the system, will be a distorted version of the original undistorted picture.

Now, if the subject is asked to look freely at the original picture, the data values corresponding to his "look" will be distorted. However, since we have the entire distorted image of the current picture on magnetic tape (along with the undistorted picture), these distorted values may be mapped back into locations in the original undistorted picture (assuming the mapping is stationary over the tracing/viewing time). And since the original picture is recorded in terms of actual CRT raster addresses, we may finally determine the actual physical location that the subject was viewing.

As a by-product of implementing the above procedure, the current version of SEER allows data acquisition only when it is drawing (tracing) on the CRT. There presently is no facility to take eye-movement data with a static display. Another limitation to keep in mind is that the digitizing rate is directly proportional to the rate at which a picture is traced by VIEW (see the SPEED command in the next section).

3. Usage

A. General

The SEER system consists of a resident executive and a number of overlayed sub-systems in order to efficiently utilize core memory and allow modular programming extensions. In general, SEER will prompt the user (on LUN-12) for a command, perform the requested function, and then re-prompt. The SEER executive uses "%" as its prompt while all of the sub-systems use "%%". When SEER is initially started ("REQ SEER"), control is given to its executive which writes

SEER V1A
%

on LUN-13 and then waits for an executive (major) command to be entered by the user.

There are three valid syntatic forms of SEER commands. The first is simply a blank line. If a blank (or null) line is input, control is returned to the next higher command level. For example, if a blank line is input to a sub-system, SEER will return to the major command level ("%"). If a blank line is input as a major command, SEER will exit to the RSX system (i.e., SEER terminates its execution).

The second command form is a string of characters that start with an asterisk ("*"). This command is a "comment" and is ignored by SEER. It has been included mainly as an aid to documenting AUTOmatic files. The AUTO command (to be included in a future version) allows the experimenter to build a file of SEER commands that are input automatically to the system, thus freeing the user from having to manually input commands during a real experiment.

All other SEER commands are of the following form:

<keyword>[<parameters>] .

As a means to save command input time without forcing a cryptic command language on the user (e.g., DDT, QED, ...), SEER requires the user to type only as many characters as are necessary to uniquely specify a keyword. For example, to invoke the DRAW sub-system, only a "D" must be typed; to invoke the CREATE sub-system, both the "C" and the "R" must be input since the system has two major commands beginning with "C" (CREATE and CALIBRATE).

Once enough characters have been input to uniquely specify a command, SEER will complete the rest of the keyword by typing the remaining characters in it (unless not in VERBOSE mode; see VERBOSE command). In addition, if the command requires no parameters, SEER will automatically return the carriage. A SEER parameter list, ⟨parameters⟩, is a list of one or more integers separated by either a comma or blanks.

B. SEER Major Commands

CALIBRATE

This command causes the execution of a calibration procedure. Currently, the calibration consists of the presentation of a five point matrix on the CRT. As the subject fixates on the calibration points, SEER records the eye-movement data on magnetic tape as in the VIEW command. This calibration data may be used during later analysis to correct for "zero shift" and scaling transformations.

CREATE

DRAW

Both of these commands do nothing more than loading and passing control to their respective sub-systems. Each sub-system has numerous minor commands which are discussed below in Sections 3.C and 3.D.

SPEED N

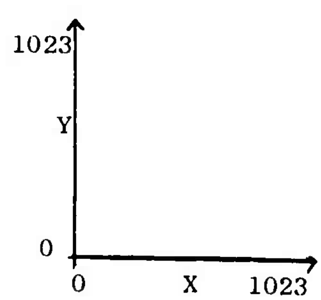
The SPEED command determines the rate at which VIEW traces the current picture (default value = 2048). Earlier in this manual, it was stated that the digitizing rate is directly proportional to SPEED. Roughly speaking, a SPEED of 1000 gives a digitizing rate of approximately 200 Hz (1 sample/5 ms). As in the GS-15 Graphics System, "SPEED 999" specifies that SPEED should be dynamically taken from the PDP-15 data switches.

VERBOSE

Keyword completion is controlled by this command. When VERBOSE is requested, it will disable (enable) keyword completion if currently enabled (disabled).

C. CREATE Minor Commands

The CREATE sub-system is used to "paint" (i.e., define) SEER pictures. In general, pictures are composed of one or more simple geometric figures such as circles, lines, etc. All CREATE commands that place figures into the current picture must specify where on the CRT screen the figure should be placed. Locations on the screen are denoted by coordinate pairs (X,Y), where by X and Y are non-negative integers less than 1024. As shown in the following diagram, (0,0), (0,1023), (1023,0), and (1023,1023) correspond to the lower left, upper left, lower right, and upper right corners of the CRT, respectively:



CIRCLE

The CIRCLE command will add a circle of radius R and center (X,Y) to the current picture. It is possible to cause an "OVERFLOW" error with this and other CREATE commands. This occurs whenever an attempt is made to CREATE a picture that requires more than 3500 points for its definition.

DELETE[N]

DELETE will remove the N most recently entered figures from the current picture. If N is not specified, N is assumed to equal one.

LINE X,Y,X',Y'

This command will connect the points (X,Y) and (X',Y') with a straight line and add the line to the current picture.

POINT X,Y,N

A user may add a point to the current picture with the POINT command. Or, if necessary, N copies of the point (X,Y) may be added by specifying N appropriately.

RECTANGLE X,Y,WIDTH,HEIGHT

A rectangle with the specified width and height is added to the current picture. The lower left corner of the rectangle will be located at (X,Y).

SAVE XXX

The SAVE command will place a copy of the current picture into the "album" (a collection of disk resident symbolic files) with the name "PCXXX." XXX must be in the range 1-999. If a picture with this name is already in the album, it will be replaced by a copy of the current picture. The user need not specify leading zeros in XXX (e.g., "SAVE 7" will save the current picture with the name "PC007").

D. DRAW Minor Commands

ERASE

The ERASE command unconditionally erases the CRT.

FETCH XXX

Pictures are transferred from the album to the current picture with this command. XXX specifies that the picture to be transferred is "PCXXX" (see the SAVE command). The image on the CRT is not modified in any way by FETCH.

PREVIEW [XXX][,N]

If this command has no parameters, SEER erases the CRT and then draws the current picture. A FETCH is first made to picture "PCXXX" whenever the first parameter is present (thus making "PCXXX" current). If N is specified, the current picture is drawn N times. Unlike VIEW, PREVIEW draws the current picture as fast as possible (i.e., independent of the current value of SPEED).

VIEW [XXX][,N]

VIEW is identical to PREVIEW except that

(1) the CRT is not erased,

(2) the rate at which the current picture is drawn <u>is</u> dependent on SPEED, and

(3) digitized data is taken and recorded on magnetic tape.

For example, the command "VIEW" (with no parameters) will draw the current picture at a rate determined by SPEED and record the corresponding eye-movement data on magnetic tape.

V. EEG SIGNAL MODELING

To better understand the relation between visual stimuli and the EEG signal, we have used a nonlinear oscillator to model the stimulus-response relationship. In particular, we are studying the entrainment of the alpha rhythm by periodic photic stimuli. This would enhance our understanding of the effect on EEG signals exerted by the repetitive photic stimulation and the various degrees of efficiency of the stimulus falling on various phases of the EEG signal. There is every reason to believe, based on the results of other researchers, that the eye takes in information only when it is fixating. One of our goals is to guide the eye to fixate only at those instances corresponding to the EEG phases while the brain is in the best state for processing information. We believe that there are relations between the effective phases for stimulation and the optimal phases for fixations. It is hoped that the development of a model for the entrainment process will elucidate the behavior of the alpha frequency and phase, and thus lead to a more practical brain state estimator and predictor for use in our memory studies. Here, we present the nonlinear oscillator model and some preliminary results.

1. Model for Photic Entrainment of EEG

A nonlinear oscillator known as the Van der Pol oscillator has been used to model the entrainment behavior of the EEG alpha rhythm. Let us denote the EEG signal by x(t). We may write the oscillator equation as

$$\ddot{x} + \mu f(x,\dot{x}) + \omega_{\alpha}^{2} x = E_{s} \sin \omega_{s} t$$

where ω_α represents the autonomous or unstimulated alpha frequency, ω_s is the stimulus frequency, E_s is the amplitude of the stimulus, and μ and $f(x,\dot{x})$ determine the nonlinear characteristic. The coefficient μ is called the coupling coefficient. We are interested in the resonance phenonmenon which occurs when $\omega_\alpha \approx \omega_s$. Letting

$$\omega_\alpha^2 = \omega_s^2 + \mu\Delta \quad \text{and } E = E_s/\mu ,$$

we obtain

$$\ddot{x} + \omega_s^2 x = -\mu f(x,\dot{x}) + \mu E \sin \omega_s t - \mu x\Delta .$$

We seek an asymptotic solution of the form

$$x = a \cos\psi + \mu v_1(a,\omega_s t, \psi) + \mu^2 v_2(a,\omega_s t,\psi) + \ldots$$

where $\psi = \omega_s t + \phi$. In the resonance case, the phase difference between the forced oscillation and the stimulus oscillation will be related to the amplitude and frequency of oscillation. We define $\underline{a}$ and ψ as solutions to differential equations of the form:

$$\frac{da}{dt} = \mu A_1(a,\phi) + \mu^2 A_2(a,\phi) + \ldots$$

$$\frac{d\psi}{dt} = \omega_s + \mu B_1(a,\phi) + \mu^2 B_2(a,\phi) + \ldots$$

where the $A_i(a,\phi)$ and $B_i(a,\phi)$ are periodic functions of ϕ with period 2π.

As a first approximation, we can write for small μ,

$$x = a \cos(\omega_s t + \phi)$$

$$\frac{da}{dt} = \mu A_1(a,\phi)$$

$$\frac{d\phi}{dt} = \mu B_1(a,\phi).$$

If we choose $f(x,\dot{x}) = (x^2 - 1)\dot{x}$, the original equation becomes

$$\ddot{x} - \mu(x^2 - 1)\dot{x} + \omega_\alpha^2 x = \mu E \sin \omega_s t .$$

Following the analysis of Bogoliubov and Mitropolsky, we obtain

$$\frac{da}{dt} = -\frac{\mu E \cos\phi}{2\omega_s}$$

$$\frac{d\phi}{dt} = \frac{\mu E \sin\phi + \mu a \omega_s^2 + \mu a \Delta}{2a\omega_s (1 - \mu/2)} .$$

Under ideal conditions of entrainment, $da/dt = d\phi/dt = 0$. This predicts a phase angle of 90 degrees, which is quite close to that usually observed in real data (see Figure V.1). Work is progressing toward a direct comparison of the frequency ranges of entrainment in the model and in human subjects. The range is a function of the coupling coefficient μ and of the stimulus amplitude E_s. In the human, the range appears to be a function of alertness and of the stimulus intensity. Current efforts are directed at quantifying the entrainment range for several subjects at various levels of alertness. This data will be used to refine the model of entrainment presented here.

2. Method of Analysis and Preliminary Results

The alpha parameters are collected in the following manner. EEG potentials are measured between the occipital region and the yoked left and right earlobes with the ground electrode over the mastoid process. Left and right occipital potentials are recorded on analog tape in addition to the analysis procedure to be described.

The subject is stimulated through closed eyelids with a stroboscope for 50 seconds on, then 50 seconds off. The frequency of stimulation is typically at the subject's mean alpha frequency. In addition, he is requested to press a key once every ten seconds.

The EEG data is bandpass filtered with a bandwidth of 5 Hz and a center frequency at the subject's mean alpha frequency. The parameters of interest are computed online and stored digitally on magnetic tape in addition to being output on a strip chart recorded with the EEG.

The mean alpha period is determined from the period of its auto-correlation function, which is obtained once every 160 milliseconds from a digital correlation analyzer. The internal integration step is exponentially weighted with a time constant of 4 seconds to provide a reasonably stationary period. The phase between the alpha rhythm and the periodic stimulus is obtained by cross correlation, again with a time constant of 4 seconds. The correlational analyses provide a simple real-time evaluation of two key parameters and minimize the computation performed by the computer running the experiment.

We show some results of this analysis in Figure V.1. Note the changes in the alpha period and phase lag as a function of the stimulus being on or off. When the stimulus is on, the alpha period becomes 100 milliseconds, the period of the stroboscopic stimulus. When the stimulus is off, the period becomes 88 milliseconds, the autonomous alpha period of the subject. In addition, the phase between the stimulus and the alpha rhythm assumes a fairly stationary value of 90 degrees when the stimulus is on and drifts at no particular value when the stimulus is off.

This data clearly exhibits the major characteristics of the non-linear oscillator model: the autonomous frequency ω_α is entrained to the stimulus frequency ω_s; the phase lag ϕ assumes a preferred value of 90 degrees; and the autonomous rhythm ω_α returns when the stimulus is removed.

Figure V.1 Entrainment of the Alpha Rhythm at High Alertness

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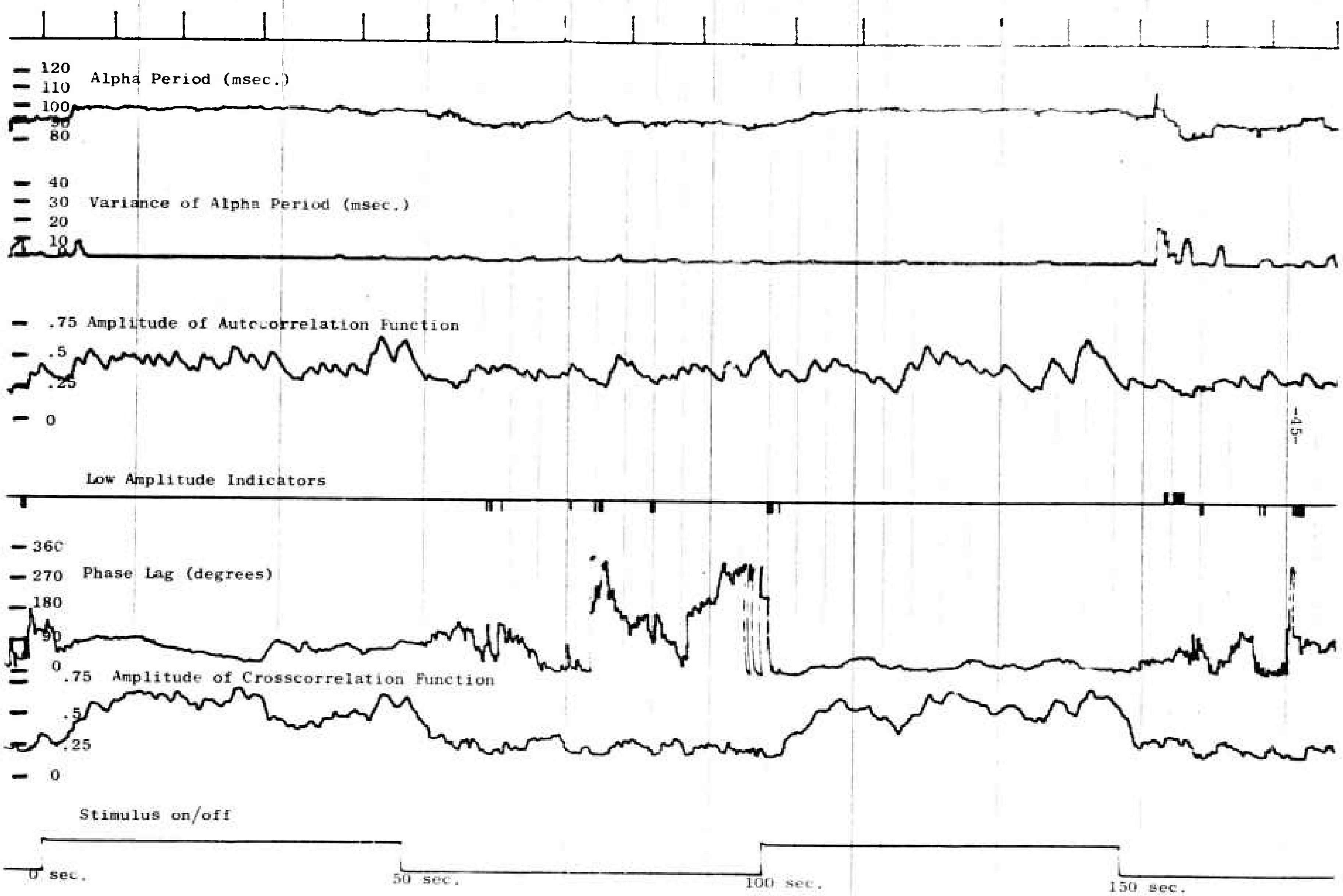
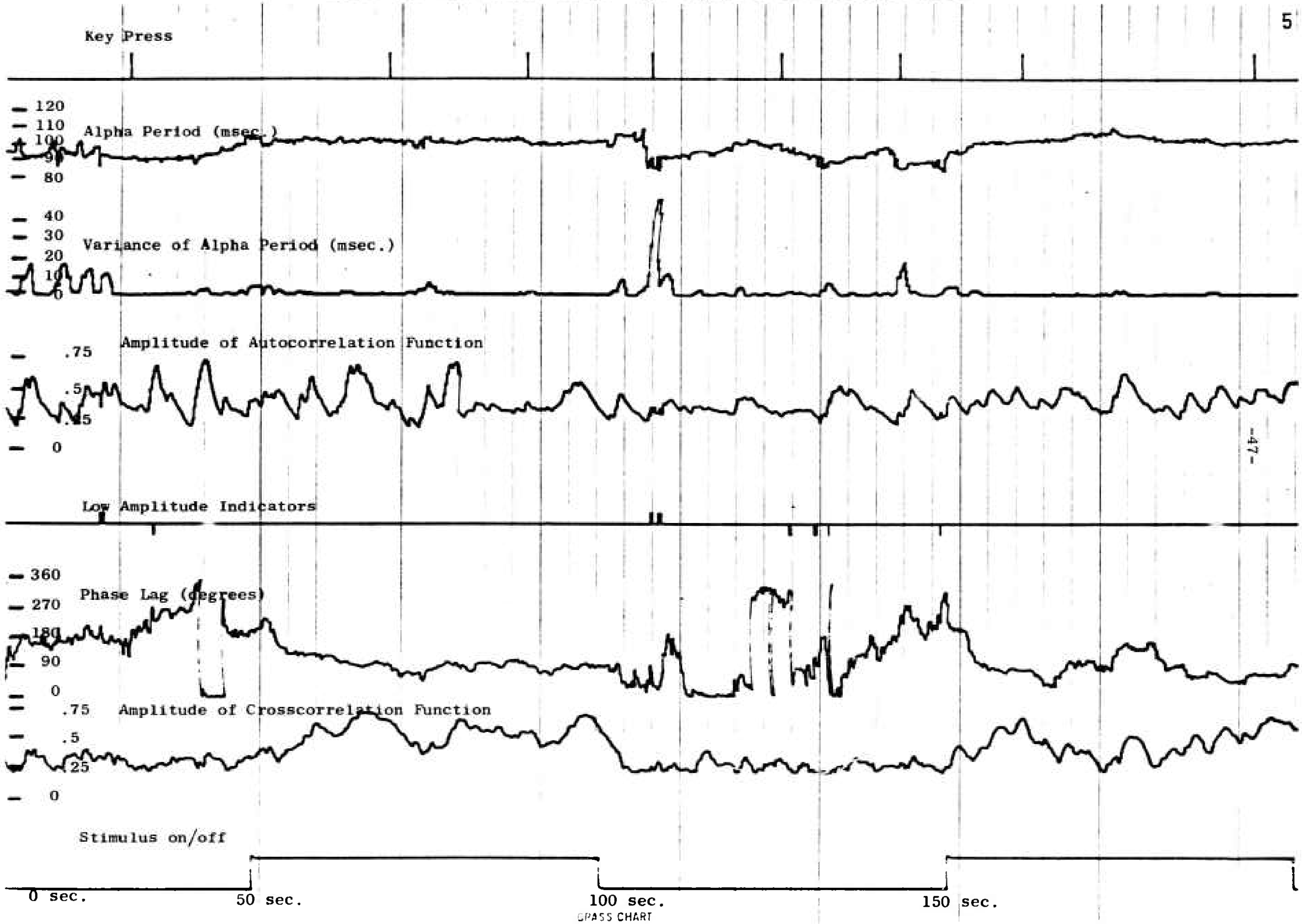


Turning to Figure V.2, we note that the mean and variance of the interresponse time for key taps is much higher than in Figure V.1. Correspondingly, the variance in the alpha period is increased, as is the nonstationarity of the phase lag during stimulus-on periods. These relationships lead us to postulate that high variance of the alpha period and the phase lag are indications of drowsiness. Similar studies have shown that these characteristics occur in the nonlinear oscillator model at the fringes of entrainment. Since the coupling coefficient μ controls the range of entrainment, we believe that μ is related to alertness. This would suggest that an internal "neuronal clock" is reduced with drowsiness. The entrainment of the alpha rhythm by an external oscillation is seen to be remarkably similar to the behavior of the nonlinear oscillator model when coupled to an external oscillation. Initial investigations indicate that the alpha rhythm will entrain to frequencies within a range of $\pm$ 2 Hz from the autonomous alpha frequency.

Figure V.2 Entrainment of the Alpha Rhythm at Low Alertness Level



VI. CONCLUSION

As described in this report, our work has been proceeding towards the goals that we proposed. We have now better techniques to deal with the errors and distortions of the eye-movement data as measured by the Biometric Eye-Movement Monitor unit. We have implemented some prediction schemes which predict the eye-fixation points. A large amount of eye-movement data has been collected and is being analyzed. The analysis will give us a better understanding of the characteristics of the saccadic movement and the fixation. It is expected to lead to better practical predictive models. We have completed computer software dubbed "SEER" which is designed for the study of visual scanpaths in a new way. In the offing, we shall see new interesting results in the scanpath study with the aim to find the scanpath which will result in superior memory. An EEG signal model has been conceived and studied with the hope that it will aid us in building better tracking models for the brain states. We have also, in this period, expanded our computer systems to better suit our needs.

With the continuously up-dated information concerning the eye position and brain state for adjusting the stimulus parameters and the tracking and prediction techniques, we should be able to guide the eyes to fixate at the optimal locations and the optimal time instants such that the vividness and persistence of the desired after-images will be enhanced. Future works are planned along the lines to get a better handle of these optimal locations and optimal time instants. Armed with this information, we shall attempt to devise real-time strategies for the control of visual target impression and visual image (memory) persistence and/or recall ability.

LIST OF PUBLICATIONS

During this reporting period, the following papers have been published:

(1) "A Model for the Photically Stimulated Electroencephalographic Signals." Proceedings of the 12th Annual San Diego Biomedical Symposium, Vol. 12, pp. 5-16, 1973.

(2) "The Graphics Software DEC Forgot to Include." Proceedings of the DECUS Spring Symposium, 1973.

(3) "Real-time EEG Analysis and Monitoring Using In-phase and Quadrature Components." Proceedings of the 26th Annual Conference on Engineering in Medicine and Biology, p. 401, 1973.

(4) "Estimating Signal and Noise in Coherent Time Averages of EEG Data." Proceedings of the 26th Annual Conference on Engineering in Medicine and Biology, p. 398, 1973.

(5) "Error-free Representation of EEG Signals." Proceedings of the 1973 IEEE International Conference on Systems, Man, and Cybernetics, p. 242-243, 1973.