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N79-17490

A RELATIONSHIP BETWEEN EYE MOVEMENT PATTERNS AND PERFORMANCE IN A PRECOGNITIVE TRACKING TASK*

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ABSTRACT

A study of eye movements made by various subjects in the performance of a precognitive tracking task is reported. The tracking task presented by an antiaircraft artillery (AAA) simulator has an input forcing function represented by a deterministic aircraft fly-by. The performance of subjects is ranked by two metrics. Good, mediocre, and poor trackers are selected for analysis based on performance during the difficult segment of the tracking task and over replications. Using phase planes to characterize both the eye movement patterns and the displayed error signal, a simple metric is developed to study these patterns. Two characterizations of eye movement strategies are defined and quantified. Using these two types of eye strategies, two conclusions are obtained about good, mediocre and poor trackers. First, the eye tracker who used a fixed strategy will consistently perform better. Secondly, the best fixed strategy is defined as a "Crosshair Fixator".

I. Introduction

A problem of interest in the investigation of man-machine interaction is the determination of "good" and "poor" performance when the human is acting as a regulator. Virtually all modeling efforts in this area assume that the operator is acting at his "best" performance level throughout the scenario of operation. A further assumption is that the control strategy is consistent. This requires that the human operator be highly trained and highly motivated in the employment of his regulator strategy. These assumptions may or may not be met, for the human is inherently an information processor and controller. The quality and consistency of his regulator actions may depend on how he initially perceives his information and what type of information he selects for processing. These are operator specific factors contributing to individual differences seen in operator performance. Though impossible to measure the central processing functions of man, it is inviting to attempt to determine how this information processing may manifest itself in the physiological variables amendable to measurement. These would include motor control or hand movements or perhaps the eye movement behavior of the operator.

This approach has motivated the work presented here by considering the variables which could distinguish a "good" from "poor" human regulator. The hand movements certainly are a manifestation of the central processor. However, it is difficult to analyze the manipulator dependent hand response in such a way as to easily classify different types of motions and correlate these with performance. On the other hand, eye movement variables are very close to the central processor and perhaps easier to analyze. If a metric of eye movement patterns can be developed which can be shown to differ significantly with "good" and "poor" operators (in terms of total system performance), then an indication of efficiency or strategy of the human central processor may be obtained. Although this approach is by no means ideal in the sense that it is not directly measuring the central processor, it may yield an indication of the activity at the closest possible level to the brain.

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*The research reported in this paper was sponsored by the Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433. This paper has been identified by the Aerospace Medical Research Laboratory as AMRL-TR-77- . Further reproduction is authorized to satisfy needs of the U.S. Government.

The phase plane was selected as the analytic tool for the development of the eye movement metric. Clark and Stark [1] have recently used the phase plane as a tool in developing a model of saccadic eye movements in a more or less discrete paradigm. In dynamic experiments the phase plane analysis of eye movements correlated with the displayed error signal in a compensatory tracking task enables measures of eye activity to be quantified in an exact and explicit manner. The data presented here represents thoroughly trained subjects in 16 replications of an experimental task which is well known to the subjects.

II. Methods

The Experiment: The task of a gunner in an optically directed antiaircraft artillery (AAA) system provides a relevant opportunity to study the relationships mentioned above. The tracking task may be described as viewing a target aircraft through a magnifying lens system with a restricted field of view (FOV) (see Figure 1). The operator is provided with a cross hair sight reticle in the center of the FOV. The operator's manipulation of a control wheel produces an input signal which drives a plant or controller system which in turn produces the tracking movement of the optical system and gun. The AAA operator is trained to keep the tracking reticle centered on the target aircraft with as little error as the forcing function will permit. The apparent position, velocity, and range of a typical target aircraft relative to the operator are constantly changing as a function of time in a more or less predictable manner. A more thorough description of the experiment can be found in [2] with a preliminary statistical study on the sources and causes of tracking behavior reported in [3].

Subjects: Eight teams of two subjects (both male and female) each were trained on the simulator for approximately three months prior to the experiment. The subjects ranged in age for 18-20 years. The training procedure consisted of 15 replications of the forcing function flyby per day. The subjects had normal or corrected to normal vision and visual field tests showed no abnormalities or limitations.

Task: The tracking task is represented by the combined azimuth and elevation forcing function. The simulated aircraft flys at a fixed attitude of 1524 m and a constant velocity of 232 m past the gun implacement. The simulator flight lasts 50 seconds. The forcing function used in this study resembled the shape of figure (2). The effective plant dynamics in the closed loop controlled by each operator can be represented by the following lumped transfer function:

$$H(s) = \left[\frac{s+1}{s}\right] \frac{64}{s^2 + 12.5s + 64} \qquad (1)$$

Eye Movement Measurement Techniques: Summed horizontal DC electrooculographic (EOG) measurements were made on both the azimuth and elevation operators of each team. The electrodes were secured to the outer canthi of each operator with the indifferent electrode secured to the forehead. The optical system had a 2.3 mm exit pupil and a head rest was available on the binocular system to provide head stability.

III. Segmentation of The Task And Performance Results:

Crank spectrum plots and other metrics indicated that the operators tended to "give up", or regress from tracking during the mid portion (difficult part) of the task owing to the velocity or acceleration profiles of the input forcing function. This observation led to the segmentation of the task into 4 regions for analysis purposes. Figure 3 represents the segmentation of the task and a short description of the phases of tracking behavior.

The input forcing function velocity profile indicated that the azimuth task is about 4 times more difficult than the elevation task. Thus, only the azimuth task is reported here. Mean square tracking errors, ensemble mean error, spectrum analysis of error, and crank power suggested that the tracking error and eye movement patterns of 3 of the teams were representative of the entire subject complement and were selected for more extensive analysis. The tracking performance hierarchy supported by all metrics showed team 7 the best, with teams 5 and 2 following in descending order. Table 1 summarizes these results for both the e_{RMS}

performance metric and the $e_{\text{Hit Score}}$ metric. $e_{\text{Hit Score}}$ was defined as the amount of time the error signal was within a specified window width.

Table I

Performance Hierachy of Azimuth Operators

	e_{RMS}	$e_{\text{Hit Score}}$
PHASE 1	7 5 2	7 mixed
PHASE 2	7 5 2	7 5 2
PHASE 3	7 5 2	7 5 2
PHASE 4	7 5 2	mixed

IV. Time Series of Eye Movements:

Figure (4) illustrates the real time series plots of the signals e(t) and the EOG signal of team (5) (the mediocre tracker). One observes from these ensemble mean plots that the mediocre tracker has eye movements which follow the stage error position displayed to him. This is especially true during the difficult segment of the tracking task (18-35 seconds). We classify this type of eye tracking strategy as "Eye Follower". In this case the eye follows the stage position.

Figure (5) illustrates the real time series plots of the best tracker in this study. It is observed that the eye movements remain essentially around zero even under the condition of large values of the error signal. This type of eye strategy is defined as "Cross Hair Fixator". In this case when the target becomes difficult to follow (18-35 seconds), the tracker fixates on the cross hair and views the stage in the periphery of the eye.

It is noted that a cause effect question can be raised as to whether the good tracker's eye movements (near zero) may be due to the fact that his error signal is small resulting in small eye movements. Although this is a good point, it is not the case as can be seen in figures (4) and (5). During the difficult segment of the tracking task (18-35 seconds), the good tracker had an error signal which was approximately 80% to 90% that of the mediocre tracker. In other words, the difference in performance of these two trackers was not substantial. The eye movement patterns, however, differed by a factor of 5 to 1 as can be seen in figures (4) and (5).

Figure (6) illustrates the time series of eye movements and tracking error for the poorest tracker in this study. This type of eye tracking strategy is inconsistent and mixed. During the less difficult segments of the tracking task this operator uses his eyes to follow the target. During the difficult segment of tracking, the eyes change strategy and they do not follow the stage position. We define this type of eye tracking as "Inconsistent".

It is noted that all trackers achieved these eye movement patterns after an extensive training period of over 2.5 months. Of all the subjects involved in this experiment, the team 5 tracker had two and one half years experience in similar manual control tasks prior to the 2.5 months training for this study. Recall, however, that the team 5 operator was only a mediocre tracker.

V. A Phase Plane Analysis of The Error and EOG Signals:

Figure (7) illustrates the phase plane plots of the time error signal e(t) and the EOG signal of the mediocre tracker. This figure can be compared to figure (4) in real time. One observes that the "Eye Follower" has a phase plane pattern of EOG movements very similar in shape to the same phase planes of the error signal.

Figure (8) illustrates the phase plane plots of the same type as in the previous figure but for the good tracker. This plot may be compared to the real time series in figure (5). It is noted that the "Crosshair Fixator" has an eye movement phase phase plane with erratic behavior around the origin. This result is consistent with the time series analysis.

Figure (9) is the same phase planes for the poor tracker. In this case the mixed or inconsistent strategy is observed to occur. The eye movement phase plane in figure (9) appears to be a combination of eyemovements of figures (7) and (8) and demonstrates the inconsistency in eye movement patterns.

Since the results presented here so far have been based on heuristic conclusions, it is desired to quantify these patterns in some manner so that more explicit conclusions can be stated.

VI. A Methodology of Quantification of Eye Movement Strategies:

With reference to the phase plane figures (7,8,9), it is desired to quantify the similarities and differences between eye movements and the error signal. Figure (10) illustrates a vector measure in the phase plane considered here.

Taking the ratio of the vectors provides a metric of changes in the phase planes. This metric suggests that a ratio can be established to differentiate between operators who follow the error or fixate on the cross hair. The ratio suggested is:

$$\bar{R} = \frac{R_{EOG}\ \text{eye movement}}{R_{ERR}\ \text{displayed error}} \qquad (2)$$

For the case of the cross hair fixator we would expect.

$$\bar{R} \approx 0 \qquad (3)$$

for the change in eye movement which is very small compared to the change in the error signal. While in the case of the eye follower, the ratio should satisfy:

$$\bar{R} \approx 1 \qquad (4)$$

Figure (11) represents the mean and standard deviations at the 4 time periods of the phase plane vector ratios of team 5 (the mediocre tracker). From the phase plane we would expect that the condition $\bar{R} \approx 1$ should be satisfied. Using the mean value of $\bar{R}$ we see that this is the case and the eye movement and error signal are highly correlated.

For the case of team 7, we would expect $\bar{R} \approx 0$ for the crosshair fixator. From figure (11) we see this is the case from the mean values of $\bar{R}$. Also it should be noted from figure (11) the decay of the standard deviations in phases 2 and 3 which is typical of all teams. The team 7 operator who tends to fixate the cross hair and has, at the same time, the lowest RMS error, presents a further complication. There is no significant difference shown by "t" tests between the RMS error and zero in segments 1 and 4 over the 16 replications of the task. Further, "t" tests show no significant difference from zero in the eye movement signal. Thus, the vector ratio is composed of two very small numbers which merely represent noise and indeed the mean ratio in segments 1 and 4 approximate 0.5. In segments 2 and 3, $\bar{R} < 0.2$. In phases 2 and 3, however, the differences between the good and poor tracker is more sharply defined. Since this is the region where the task is most difficult, this would be the period of most interest to study the eye movements.

VII. Conclusions:

The results of this study indicate two important points. First, the trackers with the consistent strategies (Eye Followers and Crosshair Fixators) had better performance than the tracker who was inconsistent with his eye movements. The second important point is that of the two consistent strategies, the best tracker is a Crosshair Fixator.

It is also noted that the above results are independent of the extent of training. The tracker who was classified as the Eye Follower had two and one half years of experience with motor control tasks. In addition, he had almost 3 months of training on this task, tracking 16 flybys on a daily basis.

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References

[1] Clark, M. R. and L. Stark, "Sensitivity of Control Parameters in a Model of Saccadic Eye Tracking and Estimation of Resultant Nervous Activity", Bull. of Mathematical Biology, Vol. 38-1, pp. 39-57, 1976.

[2] Repperger, D.W. and E.J. Hartzell, "Performance Measures of Human Tracking Utilizing PID Modeling and a Closed Loop Error Metric", NAECON, pp. 887-893, 1976.

[3] Repperger, D.W., W.C. Summers, E.J. Hartzell, and G.D. Callin, "A Phase Plane Approach To Study The Adaptive Nature of A Human Performing a Tracking Task", 1976 IEEE Conference on Decision and Control, Clearwater, Florida, December, 1976.

AAA SIMULATOR

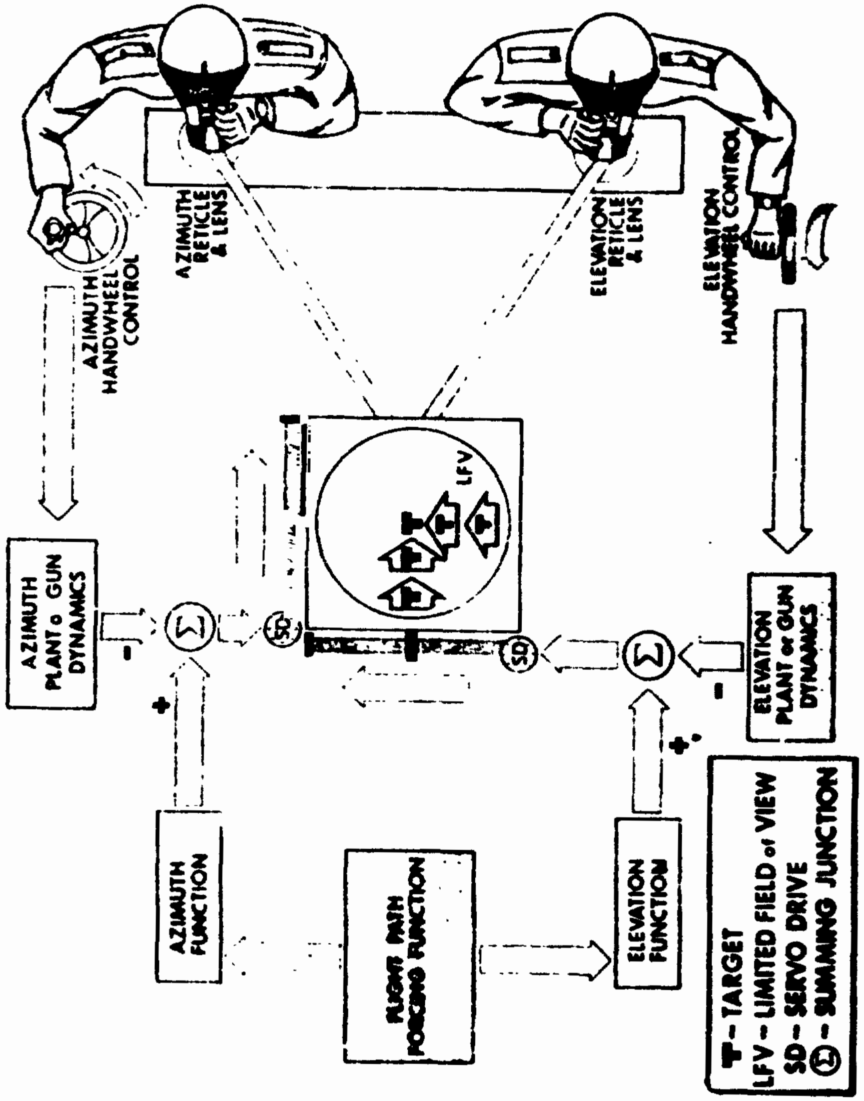

Figure (1)

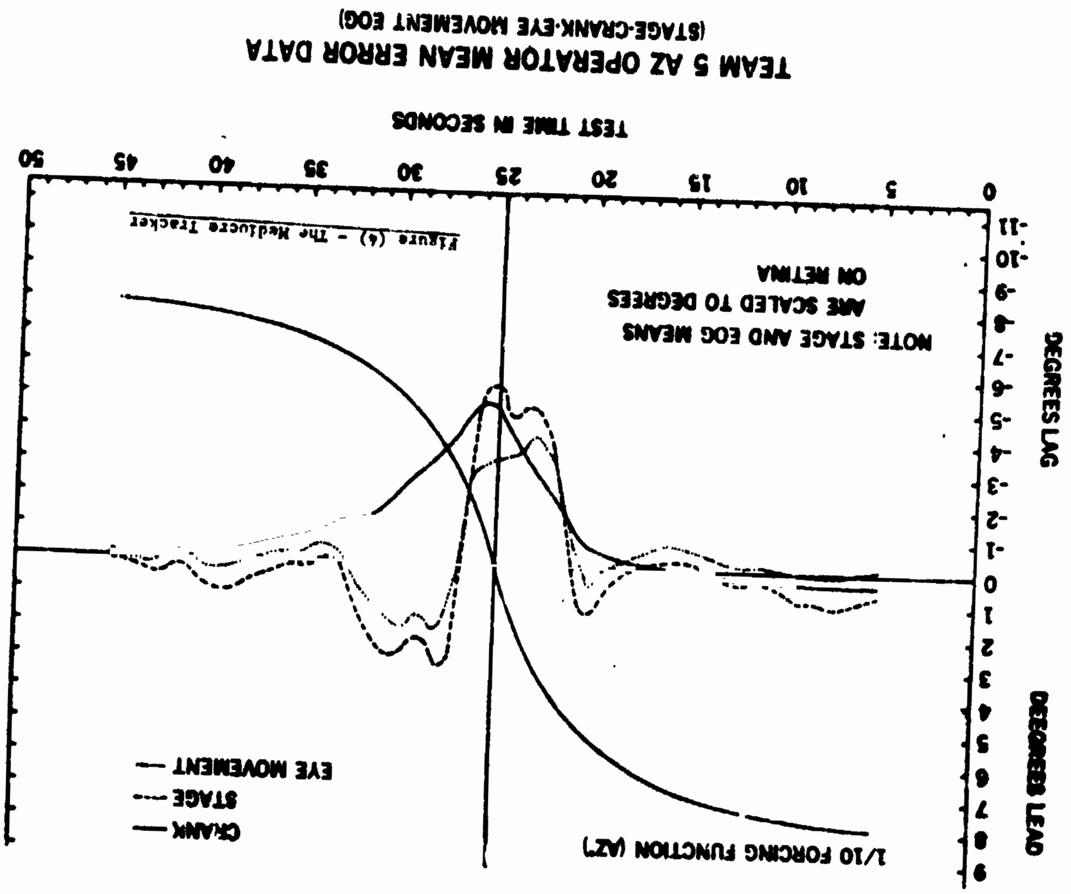

Figure (4) - The Mediocre Tracker

The Forcing Function Input

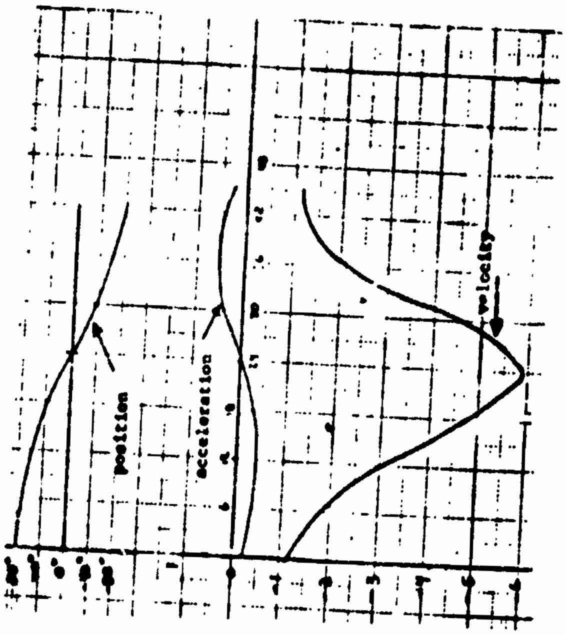

Figure (2)

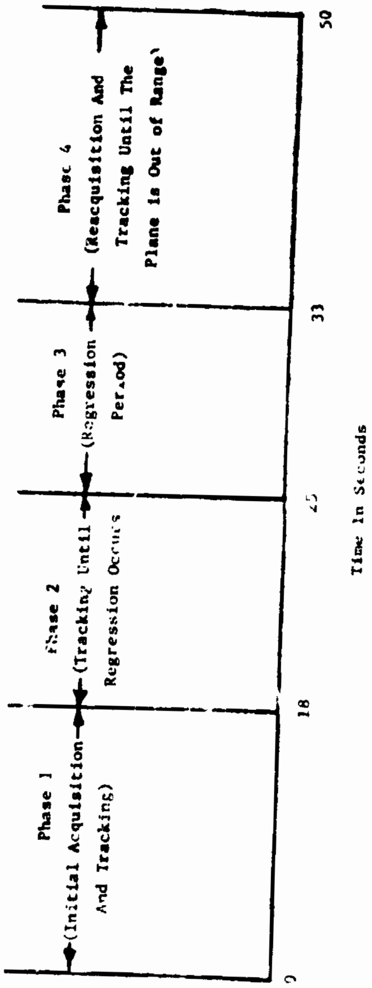

Figure (3) The 4 Phases of Tracking The Flyby Trajectory

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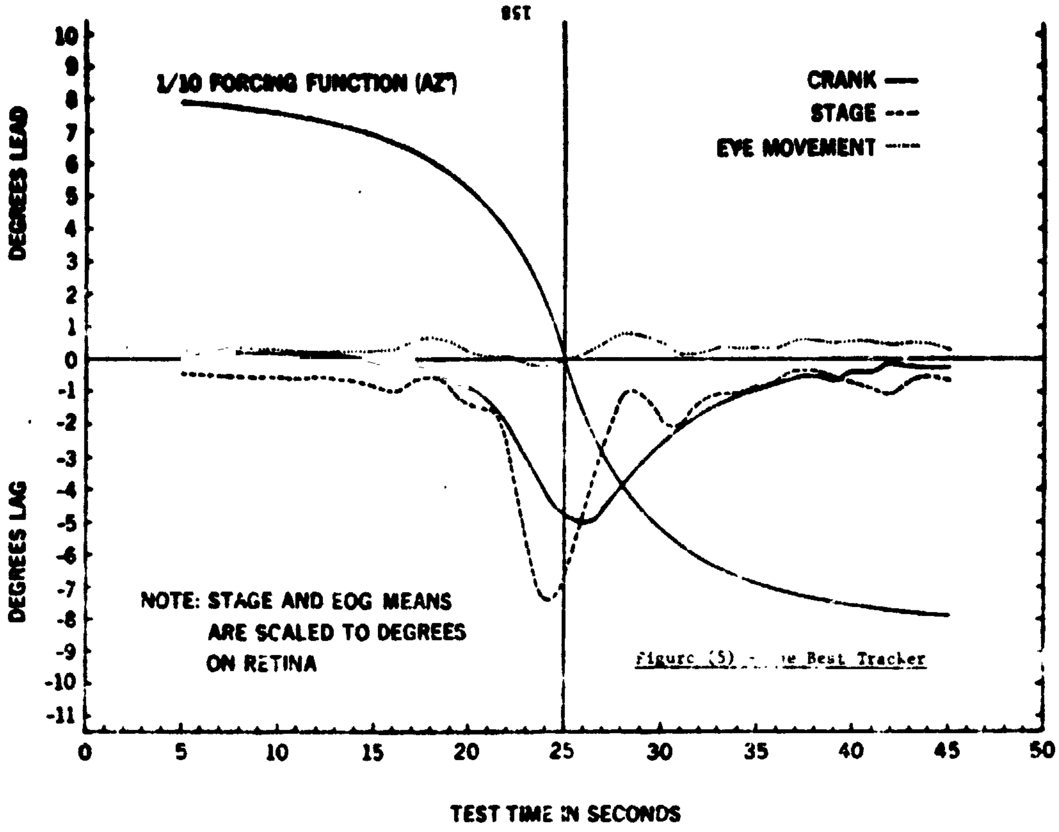
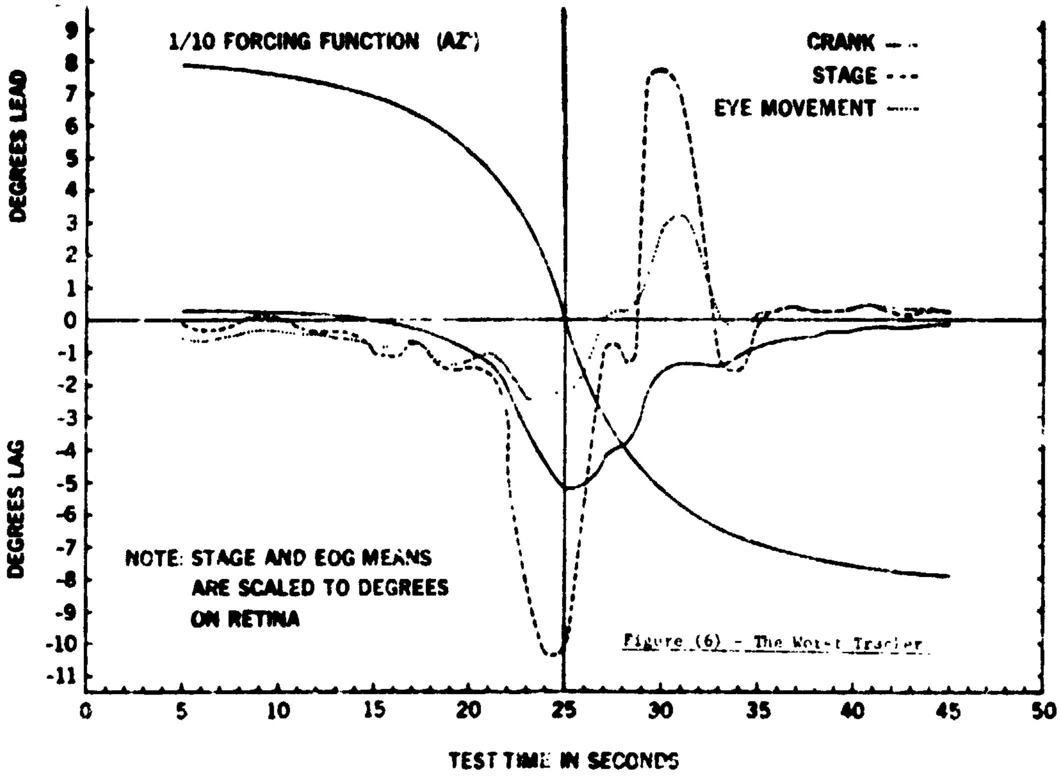


NOTE: STAGE AND EOG MEANS ARE SCALED TO DEGREES ON RETINA

Figure (5) - The Best Tracker

TEAM 7 AZ OPERATOR MEAN ERROR DATA

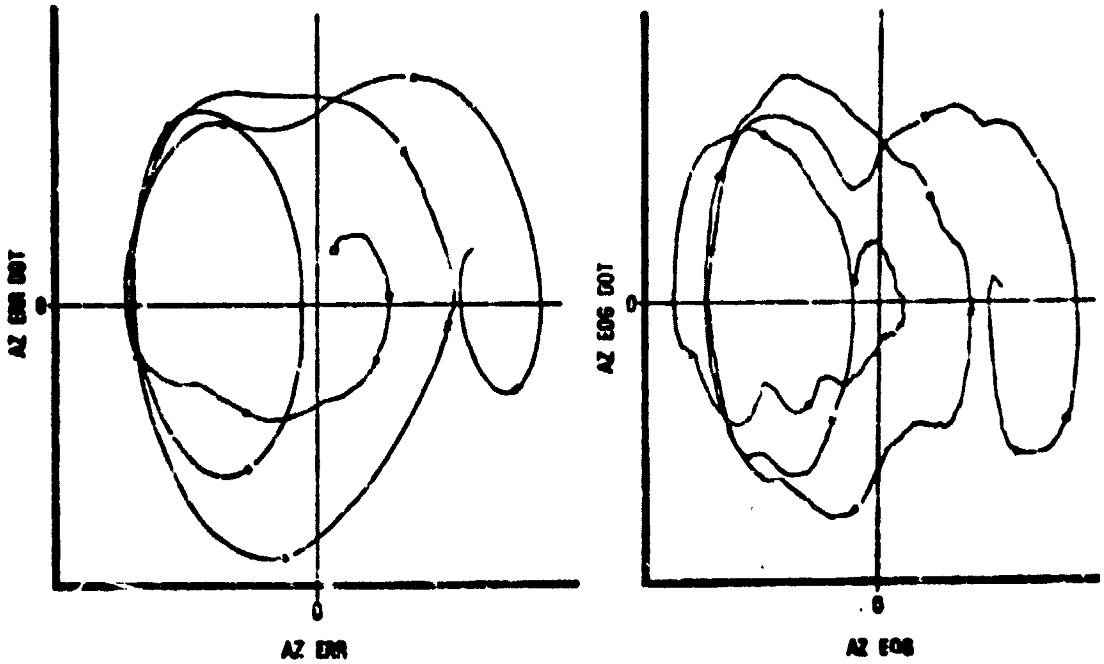


NOTE: STAGE AND EOG MEANS ARE SCALED TO DEGREES ON RETINA

Figure (6) - The Worst Tracker

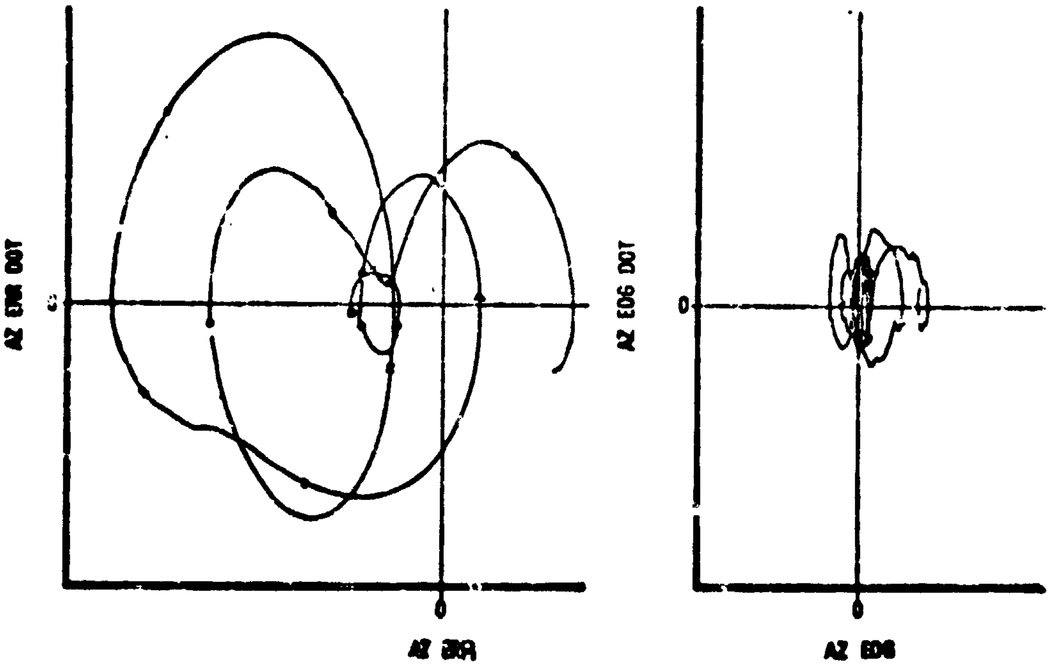
TEAM 2 AZ OPERATOR MEAN ERROR DATA

(STAGE-CRANK-EYE MOVFMENT EOG)



TROG DATA—TEAM 5
TRIAL 5—TIME 18-25

Figure (7) - The Mediocre Tracker (Eye Follower)



TROG DATA—TEAM 7
TRIAL 5—TIME 18-25

Figure (8) - The Best Tracker (Eye Fixator)

TROG DATA—TEAM 2
TRIAL 5—TIME 18-25

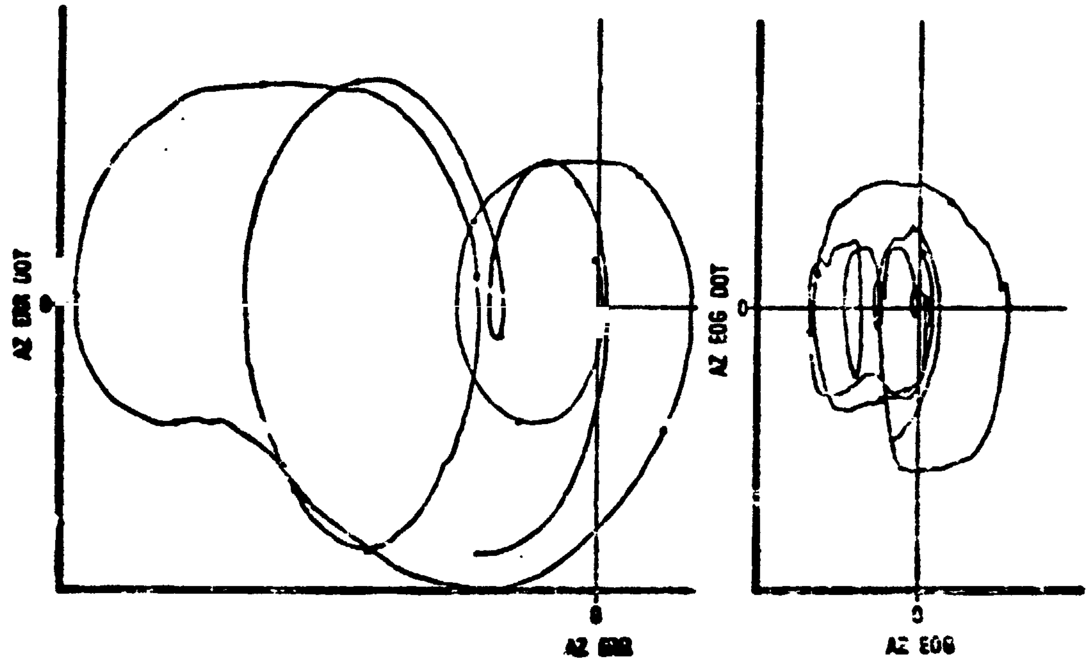
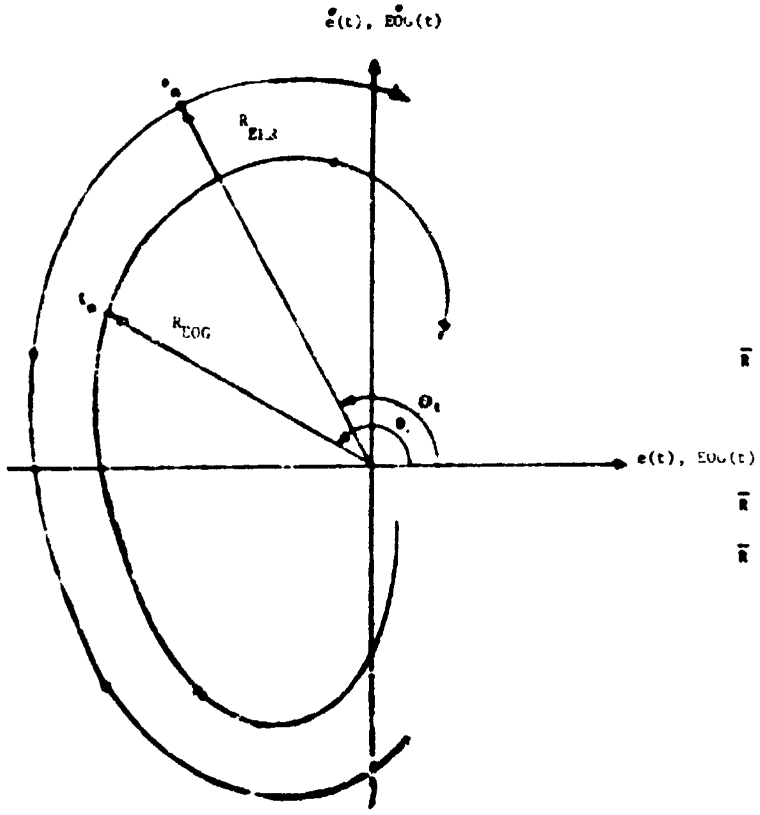


Figure (9) - The Worst Tracker (Inconsistent Eye Strategy)



$$\bar{R} = \frac{R_{EOG}}{R_{ERR}} = \frac{\Delta \text{ Eye Movement}}{\Delta \text{ Displayed Error}}$$

$\bar{R} = 0$ For [illegible] Fixator

$\bar{R} = 1$ For Eye Follower

Figure (10) - A Metric of Eye Movement Strategies

VECTOR RATIO F TEST

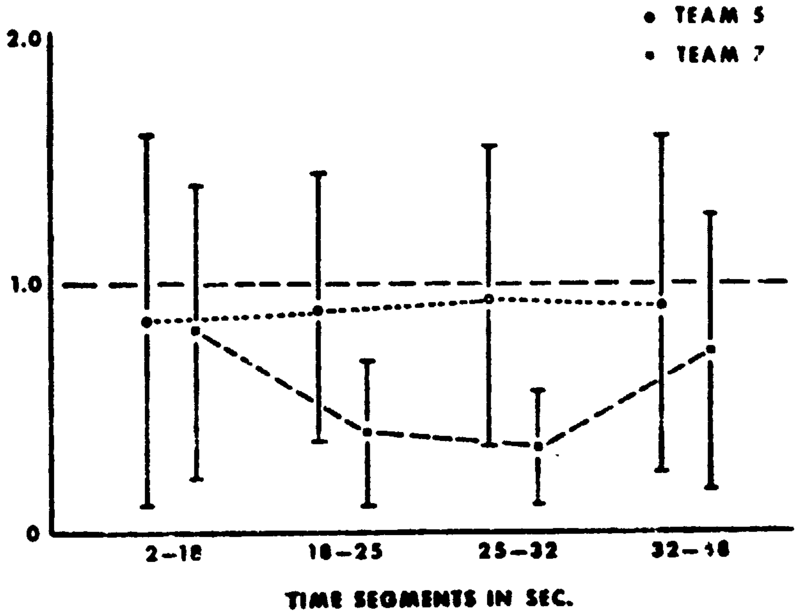


Figure (11)