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AMRL-TDR-62-150

A COMPARISON BETWEEN TRACKING WITH "OPTIMUM" DYNAMICS AND TRACKING WITH A SIMPLE VELOCITY CONTROL

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FOREWORD

This report was prepared by the Human Engineering Branch of the Behavioral Sciences Laboratory, 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The work was performed under Project 7184, "Human Performance in Advanced Systems," Task 718405, "Weapon System Design Criteria." The author is grateful for the helpful comments of Mr. Charles Bates and the assistance of Mr. James Campbell in setting up and maintaining the apparatus. Particular thanks are due to Mr. Michael Nemeroff who ran all subjects for this experiment. This investigation was carried out at the Engineering Psychology Research Project of Antioch College under Contract AF 33(616)-6095. This study was completed in September 1962.

ABSTRACT

This study was undertaken to verify the "optimum" control dynamics reported in WADC TR 59-712 and to lend experimental validation to the method in which they were derived. A simple two group experiment was performed to compare tracking performance on a single axis tracking task using the "optimum" dynamics with tracking performance using a simple integrator (rate control). No significant difference was found in either learning rate or in tracking ability after the task was learned. A second experiment using the same experimental design requiring two-axis tracking was conducted to test the hypothesis that differences would appear only when the subjects were more heavily task-loaded. The "optimum" dynamics produced reliably better performance than the rate control in the two-axis task. This result supplied experimental validation for the predictions made using the human transfer and reported in WADC TR 59-712.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Walter F. Grether

WALTER F. GRETHER
Technical Director
Behavioral Sciences Laboratory

A COMPARISON BETWEEN TRACKING WITH "OPTIMUM" DYNAMICS AND TRACKING WITH A SIMPLE VELOCITY CONTROL

INTRODUCTION

During the past 10 years, Aeronautical Systems Division and this laboratory have had a continuing effort to determine the mathematical describing function of the pilot in a closed-loop tracking situation. The results of this work have been published in a number of WADC and ASD Technical Reports. Much of this work is summarized in the Dynamic Response of Human Operators (ref. 2). That report puts the work of previous investigators into the same format, but it does not generalize the information to a form readily usable by the design engineer. A Survey of Human Dynamics Data and a Sample Application (ref. 4) attempts to show the applications and limitations of the human describing function. In that report the "optimum"* transfer function for an aircraft was developed on a theoretical basis. This transfer function was of the form $\frac{K(T_1 S + 1)^2}{S(T_2 S + 1)}$. The time constants ($T_1$ and T_2) were such that the lead and lag terms had very little effect in the frequency region normally associated with manual tracking. The function thus approximates $\frac{K}{S}$ or a simple velocity control, as may be seen from the Bode Plots in the appendix. The purpose of the experiments described in this report was to determine whether there was any significant difference between tracking performance with the optimum dynamics and tracking performance with the simple velocity control.

EXPERIMENT NO. I

The first experiment was conducted with a simple single-axis compensatory tracking task. The subjects were instructed to maintain a horizontal line in the center of an oscilloscope face by fore-aft movement of a floor mounted aircraft-type control stick located directly in front of them.

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* The parameter values were optimum in terms of rms error criterion for the transfer function assumed for study.

Simulation Apparatus

The experimental apparatus employed in this first study consisted of an analog computer mechanization of the transfer functions, an oscilloscope to simulate the artificial horizon, and four sinewave oscillators to produce the forcing function. The apparatus was arranged as shown in figure 1. The subject was seated in the room on the left in a long-range aircraft seat. The CRT display was approximately 18 inches directly in front of the subject with the center of the display approximately 15 degrees below eyelevel. Above the display was a warning light that came on before the start of each run. Above the light was a meter on which the subject's score was displayed after the end of each run. The subject's control was an undamped aircraft-type control stick located between his legs approximately 8 inches in front of the seat. The experimenter was able to keep a constant check on the subject through the one-way glass located to the subject's right.

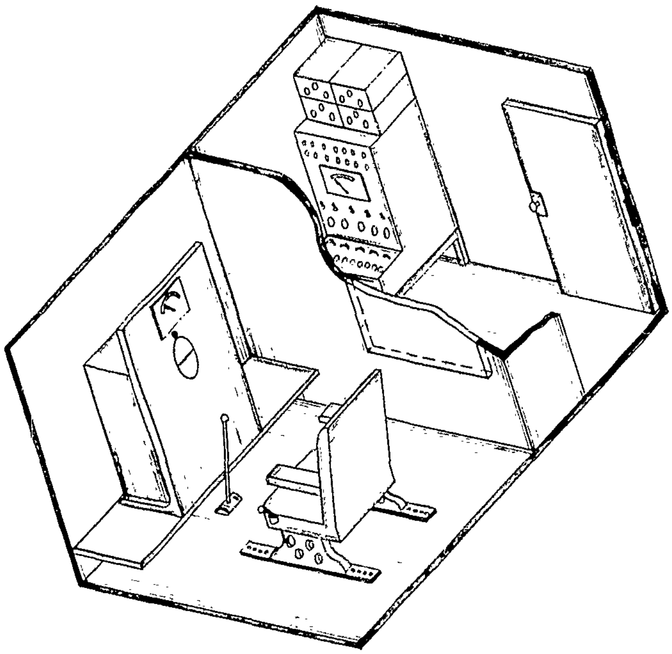

Figure 1. Experimental Situation

Measuring Apparatus

The score in this experiment was the integral of the absolute tracking error. The circuit for obtaining this score is shown in figure 2. The scoring interval was 55 seconds. Scoring started 5 seconds after the start of the tracking run to allow the subject to lock-on to the display.

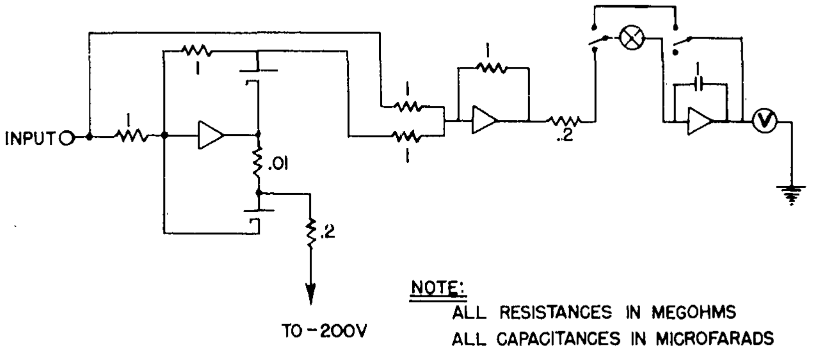

Figure 2. Scoring Circuit for $\int |E| dt$

Experimental Task

The task in this experiment was to maintain the horizon line—the scope horizontal sweep —in the center of the screen. An edge-lighted grid over the screen provided a reference frame. This was intended to correspond to maintaining an aircraft in level flight. The disturbing force was the sum of four sinewaves whose amplitudes varied inversely with their frequency (as indicated in table I). Since the frequency components were nonharmonically related, the resultant sum appeared to be random.

TABLE I

FORCING FUNCTION SPECTRUM

Frequency	Amplitude
0.11 cps	10.0 rms volts
0.23 cps	4.5 rms volts
0.48 cps	2.3 rms volts
1.00 cps	1.1 rms volts

Subjects

Two groups of subjects were tested, one group on each set of dynamics. There were 12 male college students in one group and 11 in the other. The subjects were randomly assigned to the two groups in order of appearance. None of the subjects had any prior experience. Each subject was run through 21 trials per day for 3 consecutive days. Each trial was of 1-minute duration with a 1-minute rest between trials. A 3-minute break was given after each group of three trials.

Results

The median scores for all subjects are shown in figure 3. The scores for the last 12 trials only were considered in the analysis. A mean for each subject in each group was obtained and the two groups compared with a simple t-test. No significant difference at the .05 level was found, however, as shown in figure 3, the performance over the last 12 trials was consistently better using the optimum dynamics.

The suitability of the t-test for these data can be questioned. For this reason, the median scores for each subject in both groups were determined and the median test was applied to these scores. Again, the difference was not significant at the .05 level. The exact probability by Fisher's method was 0.1504.

Figure 3 suggested a possibility of difference in the learning rate between the two groups. To determine whether there was such a difference, an analysis of variance was run on the data from the first 18 trials. To simplify the analysis each group of three trials was first averaged and these averaged scores used in the analysis. The results of this analysis are shown in the appendix. There was no significant difference in the learning rates.

Discussion of Experiment No. I

There are several possible explanations for the failure of this experiment to reveal a statistically significant superiority of the optimum dynamics as would be predicted in the Survey of Human Dynamics Data and a Sample Application (ref. 4). One possibility is the difference in methods of scoring the system performance. In the development of the optimum dynamics the criterion used was minimum rms error. In this experiment the criterion used was integrated absolute error ($\int |E| \, dt$). Fitts* states that for large samples of normal distributions the average deviation and the standard deviation are related by a constant (AD = 0.7979 SD). Since the rms error score is the standard deviation of the error signal about zero and the $\int |E| \, dt$ score is the average deviation times a constant (run length), the difference in scoring systems is probably not the cause of the difference.

Another possible source of the difference lies in the nature of the forcing function used. This is probably not a valid source since the forcing function used in this experiment contained more power at the high frequencies than did the forcing function used in the derivation of the optimum dynamics. This is shown in figure 4. The broken line represents the output of a white noise source passed through a third-order binomial filter with a break frequency at 1 radian per second. This is the forcing function used in the derivation of the optimum dynamics. The vertical bars represent the frequency components used in this experiment. Since the Bode plots (see figure 7, appendix) of the two sets of dynamics tested are nearly identical up to 1 radian per second, the spectrum used in this experiment would be more likely to show the differences in the two sets of dynamics than the one used in the original derivation.

Another possibility is that the subjects were not heavily task loaded. That is, the task may have been so easy that the subjects could easily compensate for the nonoptimum dynamics. To test this hypothesis a second experiment was conducted.

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*Fitts, P.M., et al., Skilled Performance, Final report under Wright Air Development Center Contract AF 41(657)-70, March 1959.

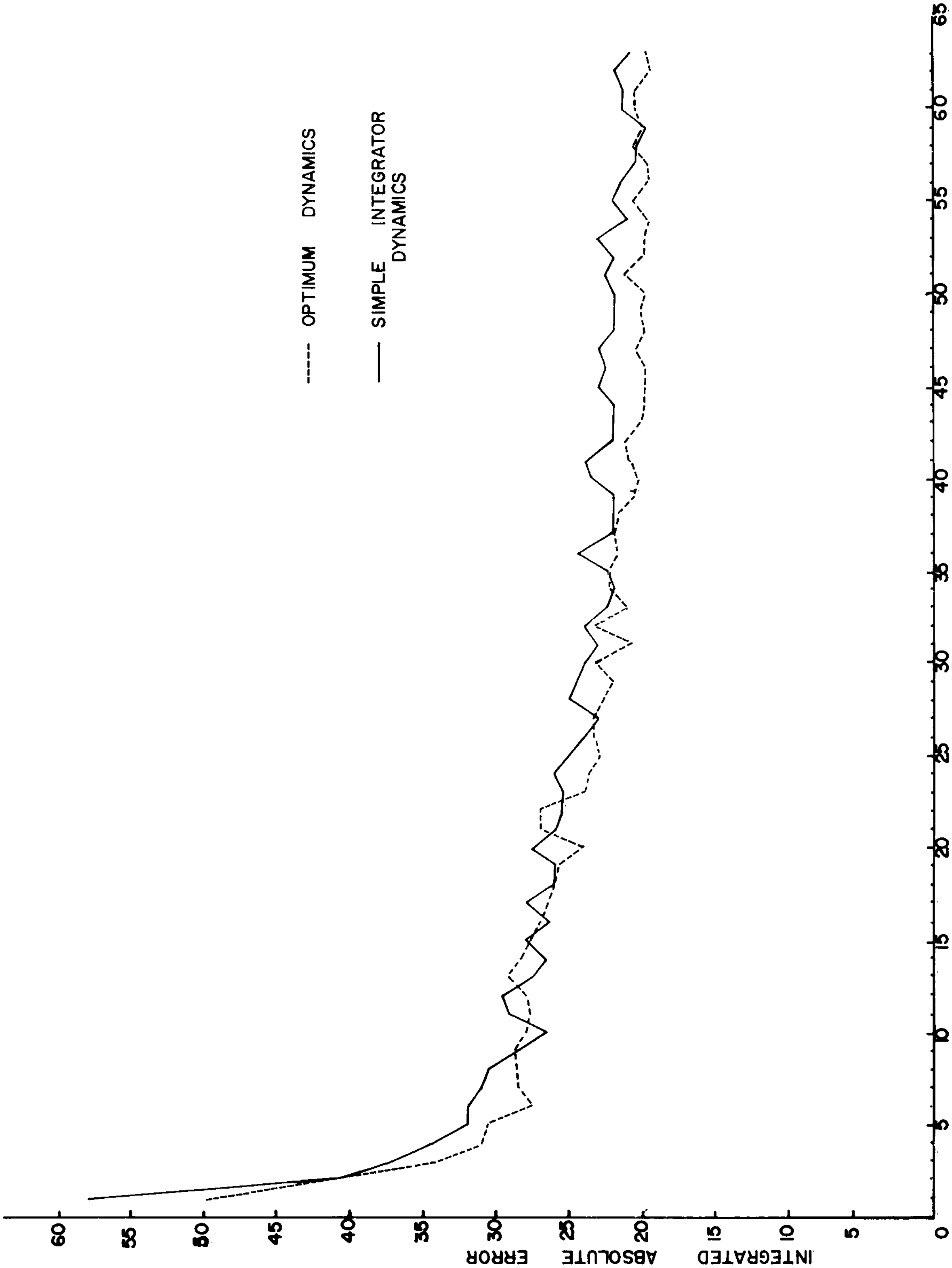

Figure 3. Median Integrated Error vs Run Number
Experiment 1

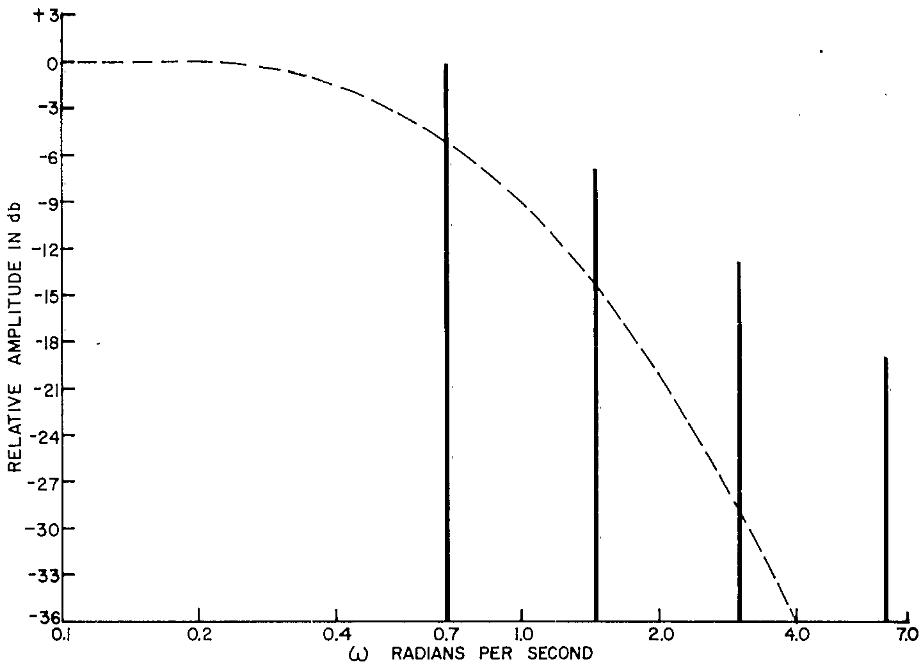

Figure 4. Forcing Function Spectra

EXPERIMENT NO. II

The second experiment was conducted using a two-axis compensatory tracking task. The subjects were instructed to maintain a spot in the center of an oscilloscope face by fore-aft and left-right manipulation of an aircraft-type control stick mounted directly in front of them.

Simulation Apparatus

The experimental apparatus used in this second experiment was identical to that used in the first experiment with the following exceptions:

1. Two white noise generators with third-order binomial filters cut-off at 1 radian per second were used to provide two independent forcing functions.

2. The display was a spot on the CRT that could translate both vertically and horizontally.

3. The control stick was free to move in two axes rather than one.

4. The computer was programmed to provide identical dynamics in two axes. Either the optimum or the simple integrator dynamics were used for both horizontal and vertical display axes. *

5. The scoring circuit was made less sensitive to accommodate the more difficult task.

6. Two meters were mounted on the subject's panel to read out his scores on each axis independently after the end of each run.

Experimental Task

The task in the second experiment was to keep a dot centered on the CRT. An edge-lighted grid was provided over the CRT face. The situation was roughly analogous to flying a tail-chase mission in an aircraft. The forcing functions in this experiment were filtered white noise with a third-order filter cut-off at 1 radian per second.

Subjects

Two groups of subjects were tested, one on each set of dynamics. There were 13 male college students in each group. The subjects were randomly assigned to the two groups in order of appearance. The subjects did not have any prior experience. Each of the subjects was run through 21 trials per day for 4-consecutive days. Each trial was of 1-minute duration with a 1-minute rest between trials. A 3-minute break was given after each group of three trials.

Results

The median integrated error scores for all subjects on each axis are shown in figures 5 and 6. The scores for the last 12 runs of the fourth day (runs 73-84) were the scores considered in the analysis. The median score for each subject in both groups was determined and the median test was applied to these scores. The results were significant at the .05 level of confidence. The exact probability by Fisher's method was 0.007864.

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* Circuit for one axis, including switching, is shown in fig 8.

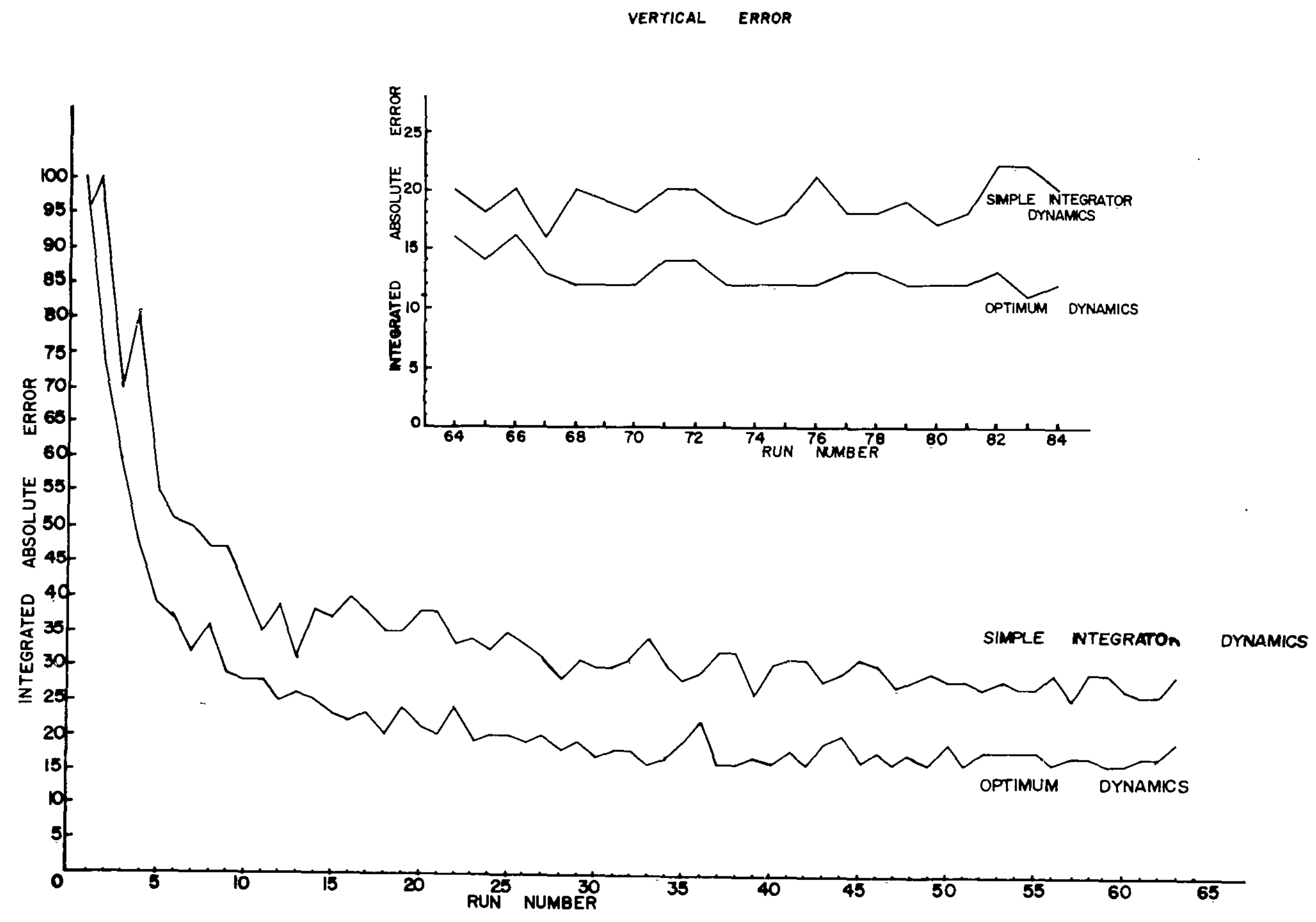

Figure 5. Median Vertical Integrated Error vs Run Number
Experiment 2

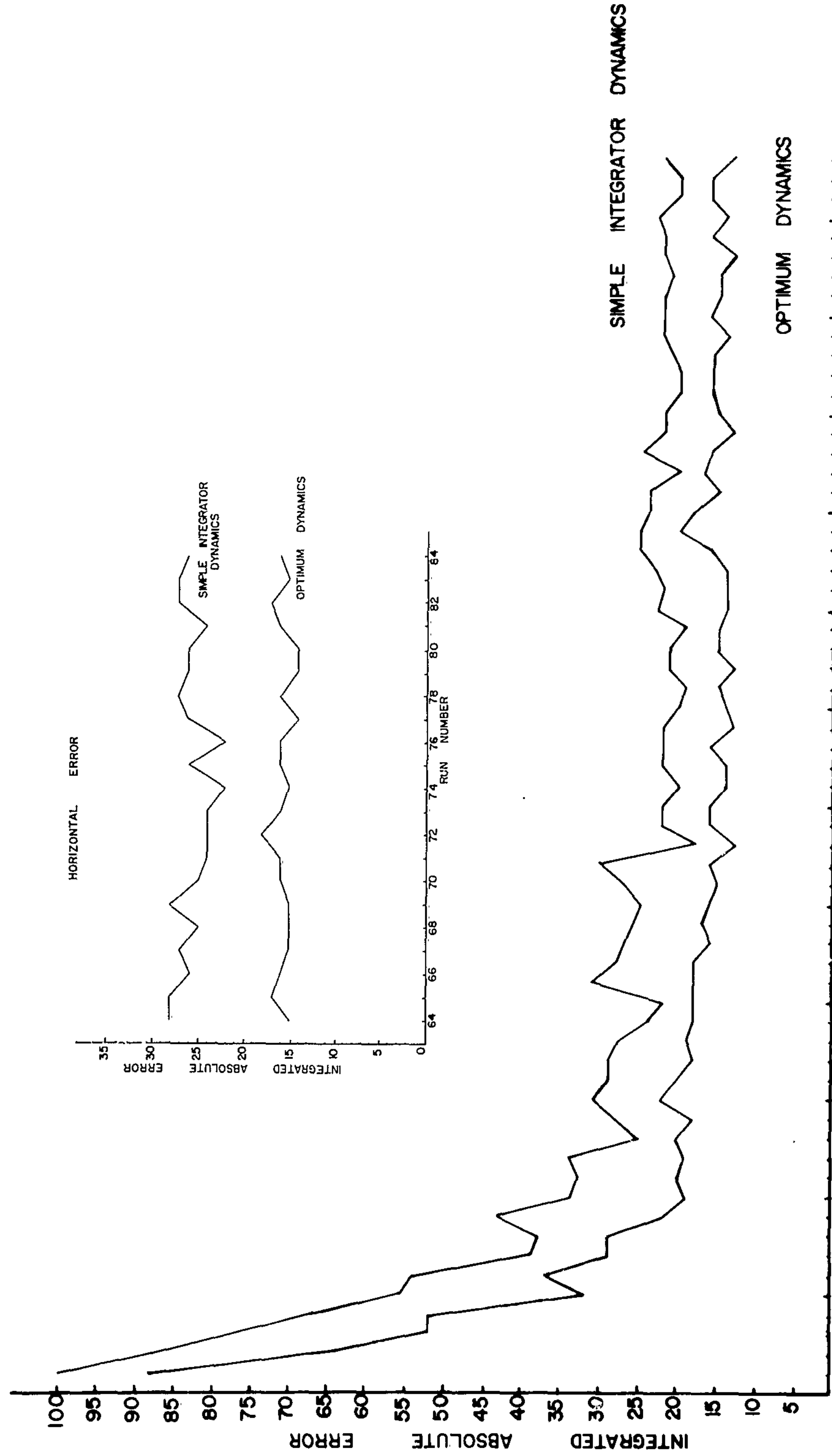

Figure 6. Median Horizontal Integrated Error vs Run Number
Experiment 2

DISCUSSION AND CONCLUSIONS

The results of this experiment agree with the results predicted by the Survey of Human Dynamics Data and a Sample Application (ref. 4). While the optimum dynamics have not been shown to be a true optimum, when the subject is moderately task loaded the optimum dynamics have been shown to be definitely superior to a nearly identical set of dynamics (figure 7). The optimum dynamics were derived using a simplified model of the human operator and a minimum rms error criterion. Basic constraints were placed on the form which the dynamics could assume and a digital computer routine was prepared to search for the parameter values which would optimize performance in terms of the given criterion (ref. 4). The fact that the results of the present study show the optimum dynamics to be clearly superior to a very similar set of dynamics makes it possible to place considerable confidence in the use of a simplified model of the operator in a tracking loop for system design. Such a method places an extremely powerful tool in the hands of the applied human engineer.

Use of the operator model rather than human subjects allows the human engineer to work directly with the structures and flight control engineers dealing with stability and control early in the design phase of a system rather than wait until a design is frozen and only the cockpit displays are amenable to change. Reference 1 gives an example of what can be done with such a model in system design utilizing an analog computer. Reference 3 gives an excellent example of what can be done analytically using the transfer function model of the pilot.

The major purpose of the experiments described in the present report was to lend experimental validation to some of the predictions that have been made using the model of the pilot. This has been done.

REFERENCES

1. Frost, G. G., An Application of a Dynamic Pilot-Model to System Design, Aeronautical Systems Division Technical Note 61-57, Wright-Patterson Air Force Base, Ohio, April 1961.

2. McRuer, D. T., and E. S. Krendel, Dynamic Response of Human Operators, Wright Air Development Center Technical Report 56-524, Wright-Patterson Air Force Base, Ohio, October 1957.

3. McRuer, D. T., I. L. Ashkenas, and C. L. Guerre, A Systems Analysis View of Longitudinal Handling Qualities, Wright Air Development Division Technical Report 60-43, Wright-Patterson Air Force Base, Ohio, January 1960.

4. Senders, J. W., Survey of Human Dynamics Data and a Sample Application, Wright Air Development Center Technical Report 59-712, Wright-Patterson Air Force Base, Ohio, November 1959.

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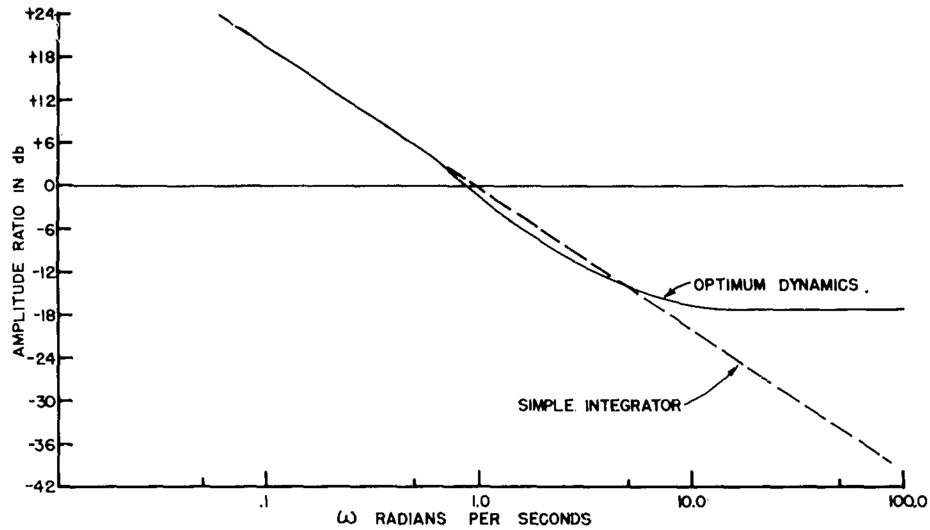
APPENDIX

BODE PLOTS, CIRCUIT DIAGRAM, AND STATISTICAL ANALYSES



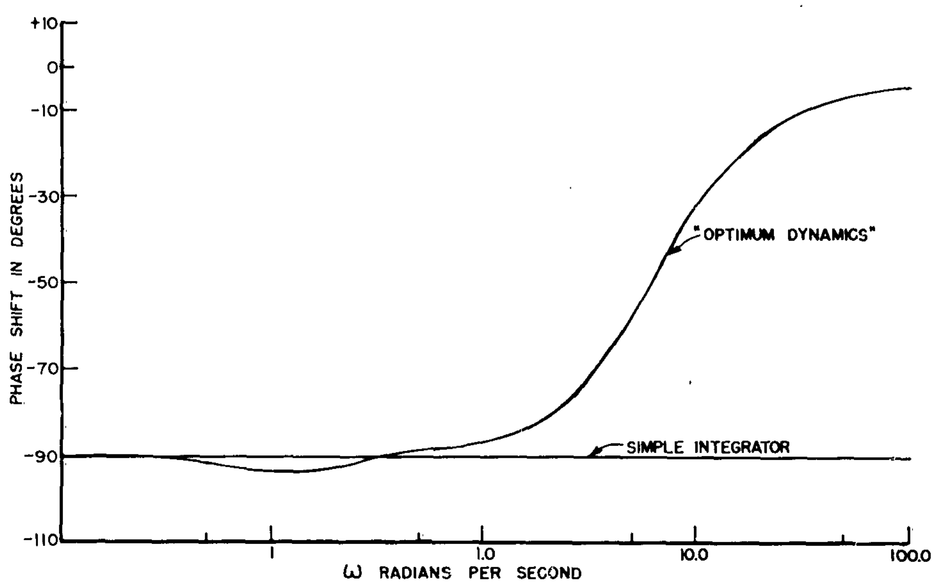


Figure 7. Bode Plots of Optimum Dynamics and Simple Integrator

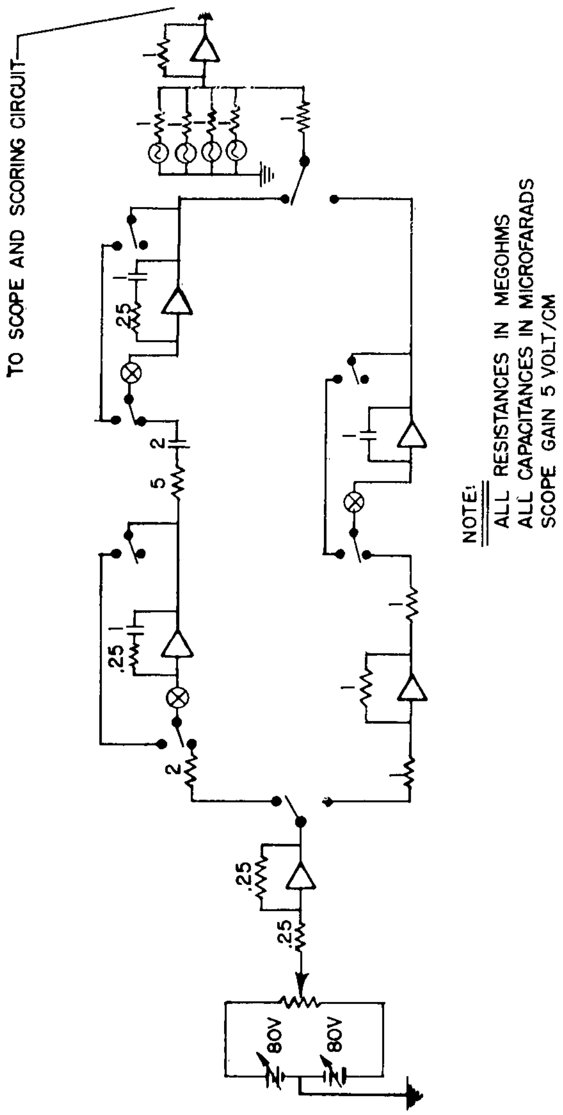


Figure 8. Analog Circuit used to Simulate Optimum Dynamics and Simple Integrator

EXPERIMENT I

ANALYSIS OF VARIANCE

Source	df		SS	MS	F	p
Between Subjects	N-1	22	4028.40	--	--	--
Dynamics (D)	D-1	1	45.54	45.54	0.240	N.S.
Error (b)	N-D	21	3982.86	189.66	--	--
Within Subjects	N(R-1)	115	2070.80	--	--	--
Runs (R)	R-1	5	817.83	163.57	14.113	$p < .001$
D x R	(D-1) (R-1)	5	36.05	7.21	0.622	N.S.
Error (w)	(R-1) (N-D)	105	1216.92	11.59	--	--
Total	RN-1	137	6099.20			

t-TEST, MEDIAN TEST AND FISHER'S P

t-Test

Optimum Dynamics	Simple Integrator	
$N_1 = 12$	$N_2 = 11$	$S^2 = 0.58$
$\overline{X} = 20.44$	$\overline{Y} = 21.28$	$S_{\overline{D}} = 0.993$
$x^2 = 82.67$	$y^2 = 70.48$	$\overline{D} = 0.84$

$$t = \frac{\overline{D}}{S_{\overline{D}}} = 0.846$$

Not Significant at .05 level

Median Test

Combined Median for Both Groups 20.0

	Above Median	Equal or Below Median	
Optimum Dynamics	4	8	12
Simple Integrator	7	4	11
	11	12	

Not significant at .05 level

$$P_{exact} = \frac{11!\times 12!\times 11!\times 12!}{23!\times 4!\times 7!\times 4!\times 8!} + \frac{11!\times 12!\times 11!\times 12!}{23!\times 3!\times 3!\times 8!\times 9!} + \frac{11!\times 12!\times 11!\times 12!}{23!\times 2!\times 2!\times 9!\times 10!}$$

$$+ \frac{11!\times 12!\times 11!\times 12!}{23!\times 1!\times 1!\times 10!\times 11!} + \frac{11!\times 12!\times 11!\times 12!}{23!\times 0!\times 0!\times 11!\times 12!} = 0.1504$$

EXPERIMENT II

MEDIAN TEST AND FISHER'S P

Median Test

Combined Median for Both Groups

Horizontal	18
Vertical	15.5

HORIZONTAL

	Above Median	Equal or Below Median	
Optimum Dynamics	3	10	13
Simple Integrator	10	3	13
	13	13	26

VERTICAL

	Above Median	Equal or Below Median	
Optimum Dynamics	3	10	13
Simple Integrator	10	3	13
	13	13	26

In Both Cases $X^2 = \dfrac{26\,(|3 \times 3 - 10 \times 10| - 13)^2}{13 \times 13 \times 13 \times 13} = 5.54$

Significant at .05

$$P_{exact} = \frac{13! \times 13! \times 13! \times 13!}{26! \times 3! \times 3! \times 10! \times 10!} + \frac{13! \times 13! \times 13! \times 13!}{26! \times 2! \times 2! \times 11! \times 11!} +$$

$$\frac{13! \times 13! \times 13! \times 13!}{26! \times 1! \times 1!\ 12! \times 12!} + \frac{13! \times 13! \times 13! \times 13!}{26! \times 0! \times 0! \times 13! \times 13!} = .007864$$

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