WADD TECHNICAL REPORT 60-615 (I)

TRANSFER OF TRAINING WITH SIMULATED AIRCRAFT DYNAMICS:

I. Variations in Period and Damping of the Phugoid Response

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DECEMBER 1961

Contract No. AF 33(616)-2725
Project No. 7197
Task No. 71635

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AEROSPACE MEDICAL RESEARCH LABORATORIES
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

Work covered by this report was initiated under contract by the Aerospace Medical Research Laboratories, Behavioral Sciences Laboratory, Training Research Branch, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. This work was part of a general program documented under Project 7197, "Human Factors in the Design of Operator Trainers," with Dr. R. L. Morgan acting as Project Scientist. Dr. M. R. Rockway was the Air Force initiator and technical monitor for this study under Task No. 71635, "Simulation Requirements of Training Equipment." The original research upon which this report is based was completed at the Aviation Psychology Laboratory of the University of Illinois under Air Force Contract No. 33(616)-2725, entitled "Survey and Research to Determine Simulation Requirements of Synthetic (Ground) Flight and Fire Control Training Devices." During the course of this contract, Dr. A. C. Williams, Jr., and Dr. L. I. O'Kelly served as Principal Investigators.

A number of individuals contributed to the early phases of the present program, and the authors wish to extend their gratitude to Dr. A. C. Williams, Jr., Dr. M. Adelson, and Dr. J. E. Nygaard. In particular, appreciation is extended to Dr. L. I. O'Kelly for his guidance and patience throughout the program.

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ABSTRACT

This report is the first in a series dealing with transfer of training skill as a function of variations in simulated aircraft longitudinal dynamics. The research is pertinent to the question of how accurately the aerospacecraft simulator must represent the dynamic flight responses of the aerospacecraft in order to assure optimum transfer of training.

Subjects performed one-dimensional tracking of a slow, low-amplitude sine-wave input. The control dynamics of major concern were long-period oscillatory transients (the phugoid response). Independent variations were made in the period and damping of the phugoid response. Also, pilot and non-pilot performance was compared.

During the training trials, tracking performance was poorer the longer the period of the phugoid response. For the slowest period (71 seconds), tracking performance was often below that which could have been obtained with no movement of the operator's control. Wide variations in damping had no differential effect on tracking performance. Pilots and non-pilots did not differ in tracking performance during the training trials.

Performance on the transfer trials was considerably influenced by the relationship between the period of the phugoid response in the training task and the period of the phugoid response in the transfer task. When the period of the phugoid response during training was shorter or longer than that for the transfer task, performance was inferior to when it was the same. Variations in damping did not differentially influence transfer of training.

PUBLICATION REVIEW

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I. INTRODUCTION

The Air Force depends heavily upon flight simulators and trainers in its pilot training program. That these synthetic training devices have become extremely valuable for numerous phases of flight training can hardly be doubted. Their usage has continued to increase up to the point where almost every new operational aircraft has a corresponding flight simulator.

In the design of a flight simulator, it is obvious that some degree of physical similarity must exist between the simulator and the operational aircraft. A main objective of simulator design engineers for the past several years has been the achievement of increasingly accurate physical simulation. Along many dimensions of physical fidelity this goal has been realized. The assumption that optimal transfer of training is dependent upon maximal physical fidelity has been a guiding principle in the design of simulators. This assumption was perhaps inevitable. Very little human engineering information was available to aid design engineers in deciding what aspects of the flight task should be simulated and the necessary degree of simulation that had to be reached.

The lack of appropriate human factors data is particularly evident in one of the most critical simulation areas- the problem of the fidelity of physical simulation of aircraft handling characteristics. Inherent in this problem is the question of simulation of dynamic responses about the aircraft axes of motion. The degree to which such responses must be simulated for maximum transfer of training is unknown.

This report is the first in a series of exploratory studies on transfer of training in a tracking task incorporating simulated aircraft dynamic and transient responses. The present experimental program is designed to give preliminary quantitative information on transfer as a function of parametric variations of the simulated dynamic and transient effects. The objective of the program is to generate information that may be of use in making design decisions concerning the degree of physical fidelity of simulation of transient phenomena for optimum training value.

Aircraft Handling Characteristics

In the design and operation of modern, high performance, manned vehicles the precise prediction and development of optimum aircraft handling characteristics for the pilot have become critical problems. Unfortunately, what constitutes acceptable handling characteristics from the pilot's point of view has never been precisely defined. The parameters that predominantly influence pilot control efficiency are uncertain.

There is good reason to believe, however, that the transient behavior of the aircraft is a critical determinant in aircraft handling qualities (15, 17). Although the successive steady states the aircraft assumes are of prime interest to the pilot, nevertheless transition phenomena between steady states must also be examined. As any physical body in motion, the aircraft exhibits transient response behavior when passing from one steady state to another. It is these transient, or dynamic, responses which appear to determine to a great extent aircraft handling characteristics.

Since the present experimental program centers on simulation of aircraft longitudinal response, it may be clarifying to examine briefly the dynamic pitch response of the aircraft.* In the case of longitudinal (pitch) dynamics, theoretical and experimental aerodynamic investigations have shown that two oscillatory transients may occur as a result of a stick elevator input by the pilot. The first of these is an oscillation of rather rapid frequency with (usually) high damping. This mode is termed in the literature the short period response in pitch. The second of these oscillations has a very slow frequency response with little or no damping; this has been named the long period or phugoid mode. Thus, if the pilot places his aircraft in a steady-state condition and then wishes to assume a new steady state in pitch, the passage from one to the other by means of the appropriate control action by the pilot may produce and require control of these oscillatory transients.

What precisely do these modes of motion mean to the pilot in his control of the aircraft? Since the short-period mode has been, in the past, so highly damped, it has been considered by many to be of little consequence to aircraft handling characteristics. On the other hand, the phugoid mode, while often not adequately damped, was felt to be of such a slow frequency that it could be handled easily by the pilot. Although many pilots have reported difficulty with the phugoid response in the execution of instrument flight tasks, in the past no particular design requirement was specified for the phugoid mode.

However, the demands of high performance aircraft have resulted in a number of significant changes in the characteristics of the longitudinal modes of motion. From the pilot's standpoint, two major problems have been encountered. First, in many recent designs, both the phugoid and short-period modes have been inherently unstable. Thus, the response of the aircraft may be a divergent oscillation which the pilot cannot adequately damp. This has meant in some cases that the aircraft began to oscillate, generating aerodynamic loads beyond structural limits - with the obvious consequence. Second, the frequency characteristics may be such that they cannot be handled by even highly skilled pilots. This is particularly true of the short-period mode, and accounts by test pilots of flight experience with the Bell X-1 series, for example, have clearly illustrated this fact. Although vehicles outside the earth's atmosphere will probably have considerably simpler dynamics problems, nevertheless during launch and re-entry the major aerodynamic problems occur in accentuated form, for example, during the very nonlinear phugoid oscillation which is basic to the skip re-entry technique.

Simulation of Handling Characteristics for Training

Concurrent with design interest in aircraft handling characteristics flight simulator design engineers have been concerned with adequately reproducing these characteristics in synthetic flight training devices. One of the major problems of simulator design has been to reproduce handling qualities and, therefore, dynamic response characteristics. These effects are primarily a result of the operation of

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* The analytic and empirical complexity of this whole problem area is immense; a more detailed technical account is given in Appendix I. For an introduction to the topic, standard aerodynamic texts may be consulted (e.g., 15, 23).

the flight simulator computer section. Estimating the accuracy of physical simulation of dynamic responses is essentially a question of evaluating the effectiveness of the flight computer.

There is considerable evidence that simulating these dynamic responses is important. Concerning the phugoid, Howe (8, p. 8) has noted: "We believe that the phugoid performance is a critical measure of simulator resolution and performance in longitudinal motion simulation, and that many pilots' complaints of lack of trainer stability stem from poor resolution and performance in longitudinal motion."

Also applicable is the comment of Howe and Schetzer (9, p. 15) on the same problem: "Many of the pilots' complaints about the simulators...are directly traceable to poor dynamic performance, particularly with small control-stick motions. Lack of simulator stability, difficulty in holding altitude, small rates of descent, etc., are all symptoms of inadequate resolutions of small motions in the computer. However, it is with small motion perturbations that the aircraft is normally flown." Accurate simulation of these effects is a difficult and expensive engineering problem, and the success of simulator design engineers in achieving solutions has been a matter of some debate and investigation (2, 3, 6, 8, 9, 16).

The ultimate criterion for flight simulator success is not, however, the degree of physical fidelity of simulation between the synthetic device and the aircraft. It is, rather, the degree of training that results from use of the device; i.e., can the pilot transfer skills learned in the simulator to the operational flight task with the result of better inflight performance? Many recommendations have been made about the most desired degree of fidelity of dynamic response between the simulator and the aircraft. However, what these recommendations mean in terms of pilot performance and transfer of skills from the simulator to the aircraft is simply not known.

Statement of the Problem

The very large number of possible experimental variables and the sparcity of prior published data in this area preclude more than an exploratory series of investigations. Little systematic human engineering information is available on human performance in this complex man-machine system, and it is necessary initially to define some of the performance boundaries. The primary variable throughout the series is one set of dynamic problems-- the long period or phugoid longitudinal transient response, and further, on two parameters associated with that response-- period and damping values.

Within that set, a number of studies have been conducted. The present report deals with (1) training and transfer performance as a function of period and damping variations of the simulated phugoid mode and (2) training and transfer performance as affected by varying degrees of pilot experience. The second report maintains the complex system dynamics, but primary emphasis is shifted to variations in control gain settings. The third and final report concentrates on the interaction of system dynamics effects and display variables. The display forcing function parameters of course complexity and course amplitude are specifically examined. It will be shown that human behavior in this man-machine system is exceptionally complex and subject to considerable variation as a result of the changes in the physical variables inherent in the task.

As noted above, the objective of the present program is to generate transfer of training information that might be useful in making design decisions concerning physical fidelity of simulation of system dynamics in operational flight trainers. To derive meaningful data it is necessary to study not only the transfer effects associated with system dynamics effects but in addition transfer resulting from the interaction of system dynamic responses and other display and control variables that are present in any man-machine task.

II. EXPERIMENT 1: PERIOD AND DAMPING VARIATIONS

The period and damping terms associated with the simulated phugoid oscillatory transients were selected as the two primary independent variables. The purpose of the first experiment was to discover what effects, if any, changes in these parameters have on the acquisition and transfer of tracking skill.

Experimental Method

Experimental task and Apparatus.* In all cases, the subject was required to perform one-dimensional compensatory tracking. A horizontal stimulus line was displayed on a 5-inch oscilloscope. Using a conventional aircraft control stick, the subject attempted to keep the stimulus line centered at all times.

The basic forcing function to the subject was a simple sine wave of six cycles per minute. With no input from the subject, the maximum excursion of the stimulus line on the scope face was ±0.3 inches from the horizontal axis. The subject's stick output was fed into an analogue computer which generated simulated aircraft long-period (phugoid) oscillatory transients with period and damping values as designated by the experimental conditions. The signal from the computer was mixed with that of the forcing function and the algebraic sum was displayed to the subject.

Experimental Design. Nine simulated phugoid conditions were selected for this study, representing three period values (18, 35, and 71 seconds) and three damping terms (17, 33, and 66 seconds). To investigate period and damping variations and their effect on training and transfer a 3 x 3 factorial design, as shown in Table 1, was used.

TABLE 1

Experiment 1: Experimental Design and Groups**

		Period (Seconds)		
		18	35	71
Damping (Seconds)	17	1.1	1.2	1.3
	33	1.4	1.5***	1.6
	66	1.7	1.8	1.9

***Transfer Condition

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* A detailed technical discussion of the experimental apparatus may be found in Appendix II.

** Report Notation. Since a number of studies will be reported in this and following papers, and since these studies are interrelated, notation for particular experiments and experimental groups is somewhat of a problem. Arbitrarily, a decimal notation has been adopted. The number preceding the decimal indicates the experiment under consideration; the number following the decimal indicates the particular phugoid condition. For example, "1.3" indicates Experiment 1, phugoid condition 3, with damping and period conditions as noted in Table 1; "2.9" denotes Experiment 2, phugoid condition 9. An understanding of this notation is particularly important, since the data collected in Experiment 1 is used for comparison in latter studies.

The damping term is expressed in time-to-damp-to-half-amplitude. Nine independent groups were trained on the experimental conditions. For the transfer trials all groups were shifted to condition 1.5.

Subjects. Ninety male undergraduate students from the University of Illinois served as subjects in this experiment. They were assigned at random to the nine experimental conditions, with the restriction that they were equally divided between conditions, each experimental group consisting of 10 subjects.

Procedure. Each subject was given 30 training trials on one of the nine experimental conditions. After a five-minute rest each subject was then transferred to condition 1.5 for 10 additional trials. Each experimental trial was 30 seconds in length. The response measure was time-on-target (TOT). The width of the target band was 0.2 inch from the null, or center, line. The maximum possible TOT score was 30 seconds, the length of the individual training and transfer trial. Detailed instructions given to each subject may be seen in Appendix III.

Results

The major findings of this experiment are shown graphically in figures 1 through 6. Means and standard deviations by blocked trials may be seen in Appendix IV. A detailed statistical analysis of the data is given in Appendix V.

Figures 1, 2, and 3 show the mean TOT scores for all possible period variation comparisons with damping held constant. Figure 1, for example, shows a comparison of the performance of groups 1.1, 1.2, and 1.3. Damping is held constant at 17 seconds while the period is varied from 18 to 71 seconds. The comparisons presented in figures 1, 2, and 3 represent the successive row groups in Table 1.

Figures 4, 5, and 6 show all possible damping comparisons with period held constant. Figure 4, for example, shows the performance comparisons between groups 1.1, 1.4, and 1.7. The period is held constant at 18 seconds, while the values of time-to-damp-to-half-amplitude are varied from 17 to 66 seconds. The comparisons presented in figures 4, 5, and 6 are based on the successive column groups in Table 1.

It is important to note the open loop TOT score shown on each figure. That is, if the subject had done nothing, he would have achieved a 15-second TOT score. In some cases, performance levels were below this value. Thus, the TOT score obtained after tracking during a trial was less than that which could have been obtained if the subject had not touched the stick at all.

Transfer of Training. Under the procedures of this experiment, all subjects of the nine training groups performed on condition 1.5 during the ten transfer trials. A detailed statistical analysis of the data is given in Appendix V. In brief, an analysis of the blocked transfer trials (1-5 and 6-10) showed statistically significant total and column (period) chi-square values. There was no significant row (damping) or interaction effect. The 5% level of significance was selected for this, and all other studies in this series.

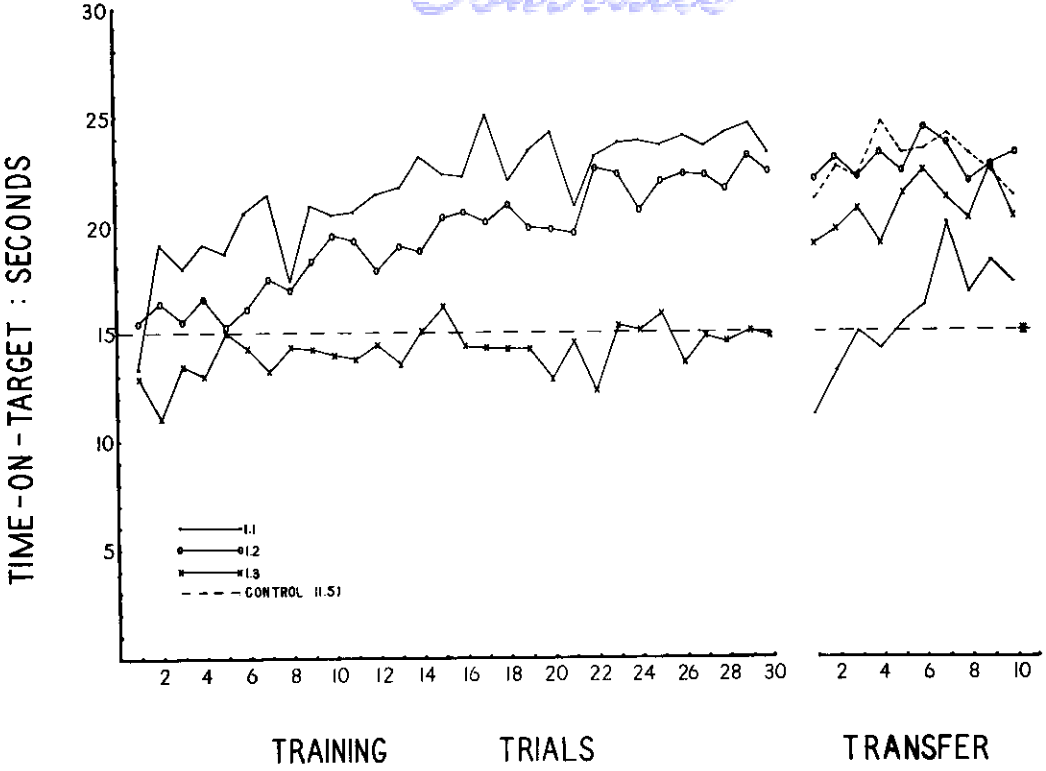

Figure 1. Experiment 1: Training and Transfer Performance for Groups 1.1, 1.2, and 1.3.

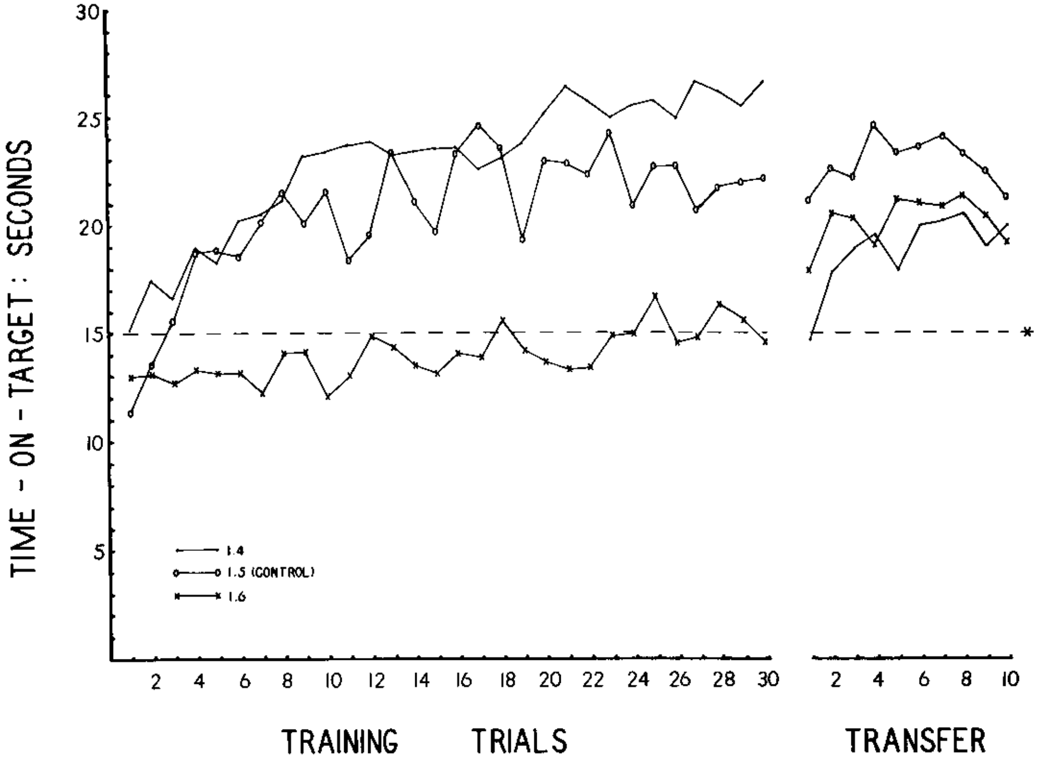

Figure 2. Experiment 1: Training and Transfer Performance for Groups 1.4, 1.5, and 1.6.

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*Theoretical "performance" with no subject response.

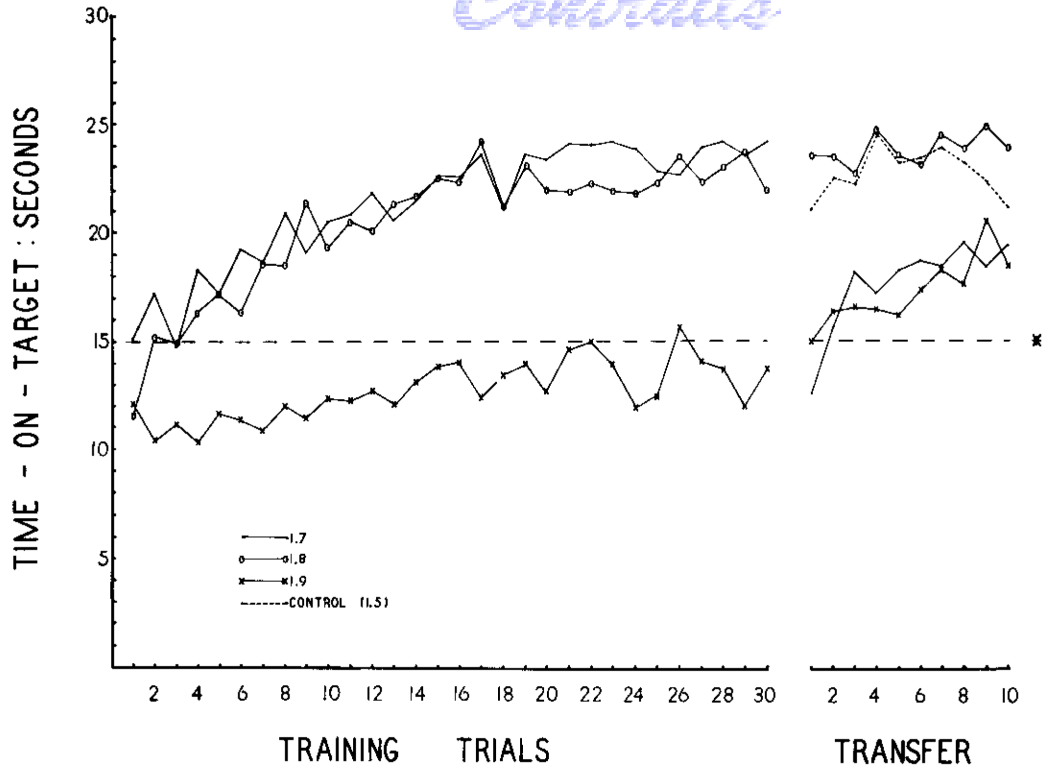

Figure 3. Experiment 1: Training and Transfer Performance for Groups 1.7, 1.8, and 1.9.

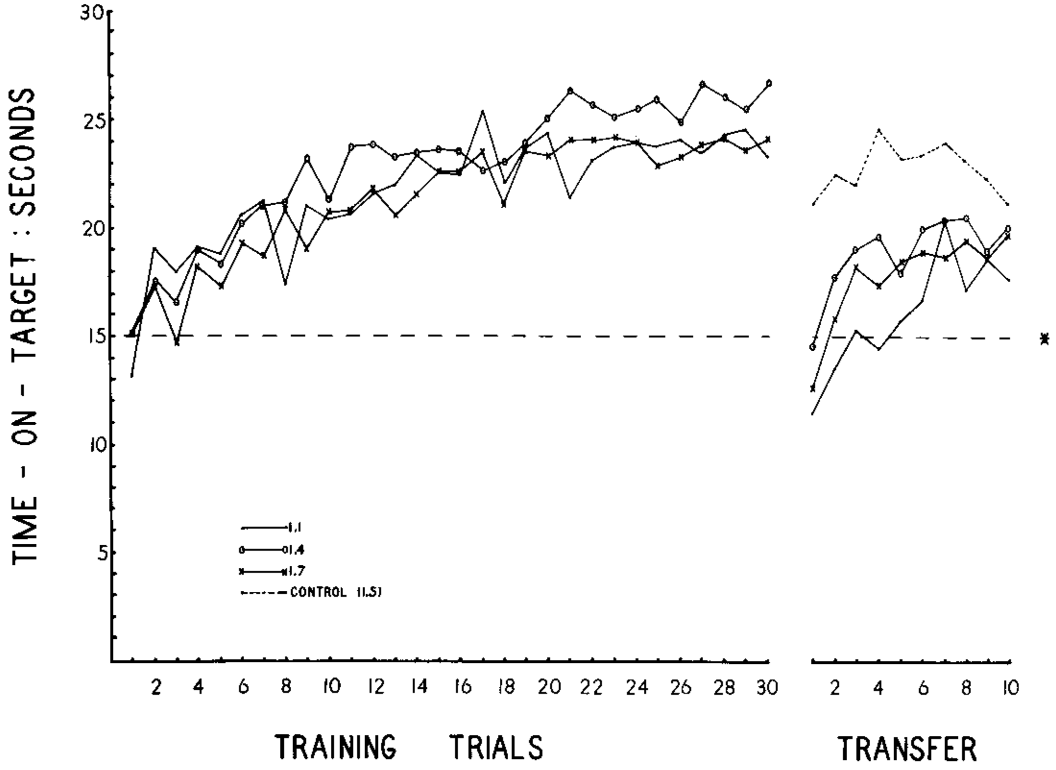

Figure 4. Experiment 1: Training and Transfer Performance for Groups 1.1, 1.4, and 1.7.

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*Theoretical "performance" with no subject response.

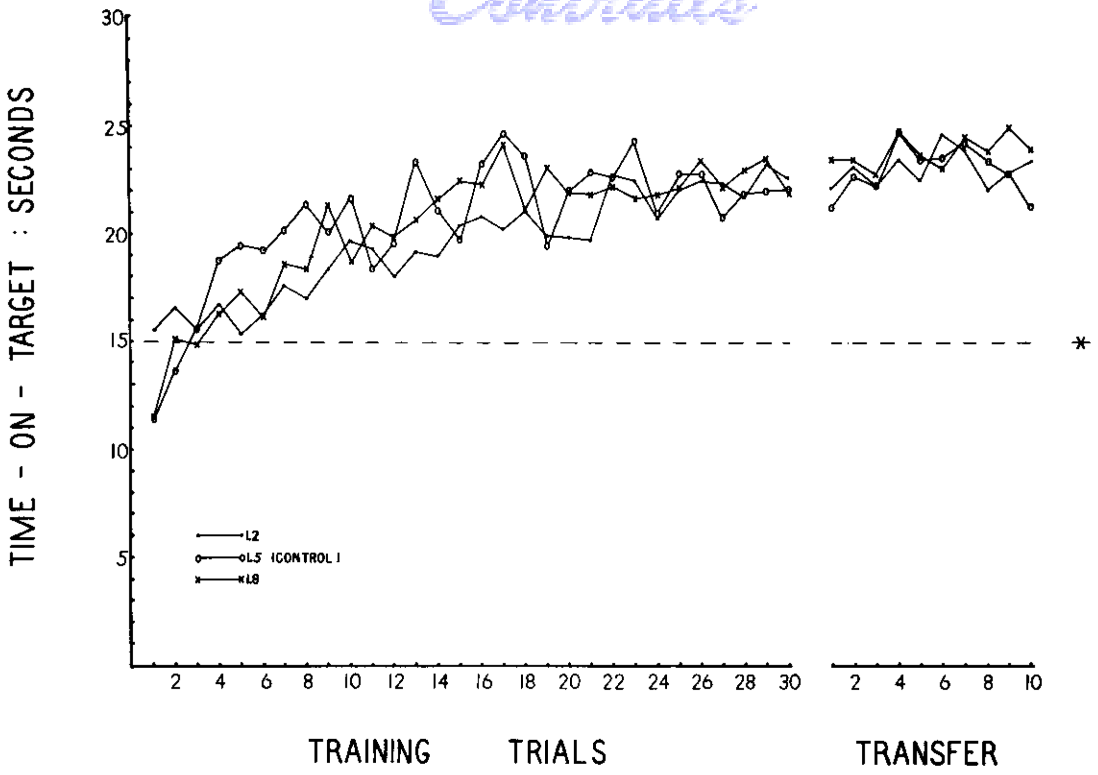

Figure 5. Experiment 1: Training and Transfer Performance for Groups 1.2, 1.5, and 1.8.

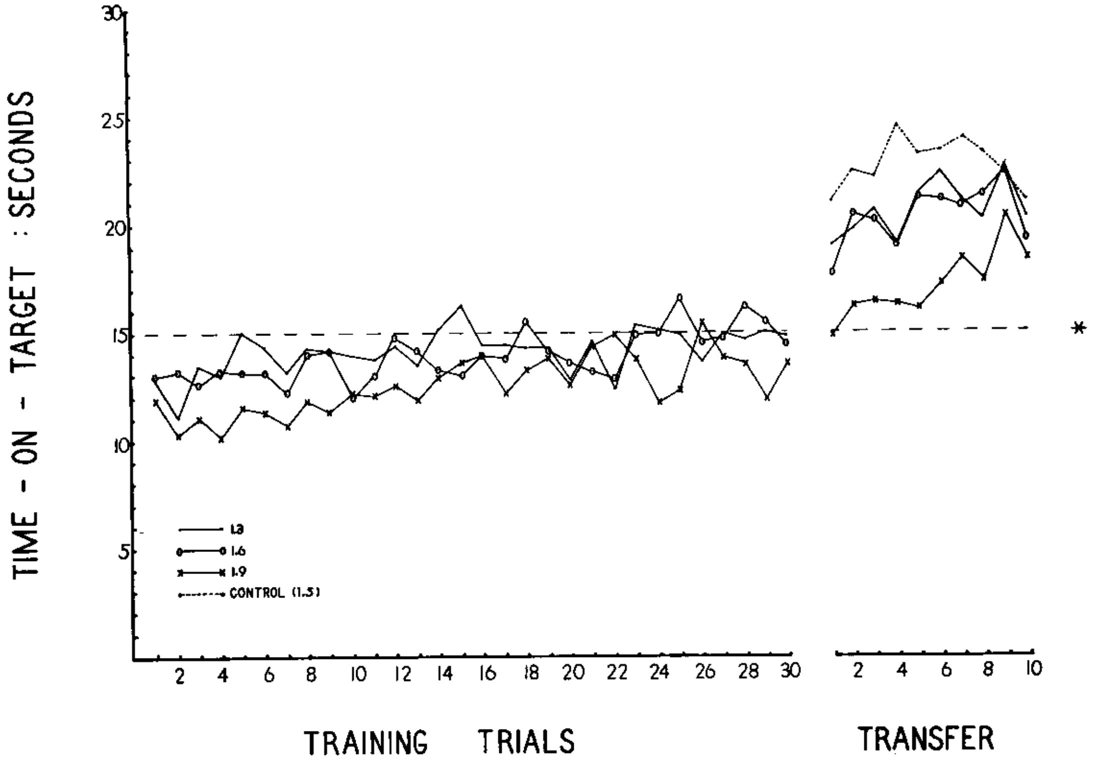

Figure 6. Experiment 1: Training and Transfer Performance for Groups 1.3, 1.6, and 1.9.

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*Theoretical "performance" with no subject response.

In all of the experiments completed in this series, the studies were specifically designed so that two different transfer comparisons could be made. Arbitrarily, these are denoted here as "absolute" and "relative" transfer effects. The distinction between these two measures should be kept clearly in mind, since quite different questions are being asked when the two kinds of transfer effects are being computed.

1. The classical question asked in the study of transfer of training is, "What is the effect of learning a preceding activity on the learning of a subsequent activity?" In the present experiment, subjects in several experimental groups trained first on one phugoid condition and then all groups were transferred to the same phugoid condition (1.5). Using the transfer paradigm designated by Woodworth and Schlosberg (<u>25</u>, p. 735) as Plan 4, per cent <u>absolute</u> transfer effect may be computed using the equation proposed by Gagne, Foster, and Crowley (<u>5</u>):*

$$\text{Per cent Absolute Transfer Effect} = \frac{\text{Transfer Group Score} - \text{Control Group Score}}{\text{Total Possible Score} - \text{Control Group Score}} \times 100$$

This computation expresses the ratio between obtained transfer and the improvement possible after a few trials under the control condition. In computing the per cent absolute transfer effect for blocked transfer trials 1-5, performance on blocked training trials 1-5 for the control group (1.5) was used as the "Control Group Score." Similarly, scores on blocked training trials 6-10 of Group 1.5 were used as the "Control Group Score" when computing the per cent absolute transfer for blocked transfer trials 6-10. The values obtained in the present study are shown in Table 2.**

TABLE 2

Experiment 1: Per cent Absolute Transfer Effect

Blocked Transfer Trials	Per cent Absolute Transfer Effect - All Groups								
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
1-5	-12	48	30	15	(50)	29	6	55	0.3
6-10	-21	29	9	-3	(25)	2	-13	36	-20

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* This transfer formula was originally proposed by Gagne, Foster, Crowley (<u>5</u>). For discussions of the advantages and limitations of this formula, this paper and the more recent one by Murdock (<u>13</u>) should be consulted.

** For some purposes, performance on blocked training trials 1-5 for the control group (1.5) would be used as the Control Group Score in all computations of absolute transfer effects. Using this method would indicate, for example, that greater rather than less absolute transfer was obtained during transfer trials 6-10 than transfer trials 1-5. Using this method of computation, the last row in Table 2 would be as follows: 18, 52, 39, 31, (50), 34, 24, 57 and 19.

Another way of presenting these same data is to show per cent absolute transfer effect as a function of the period and damping variations. For transfer trials 1-5, this has been done in Table 3. Table 3 shows that highest positive transfer resulted when the period conditions were the same between training and transfer trials. Least transfer (and in condition 1.1, negative transfer) was obtained when the period was faster than that of the transfer condition. These same relationships hold for the second group of transfer trials (6-10), but as Table 2 shows there is a complex trend for continuing transfer effect. Four of the groups (1.1, 1.4, 1.7, and 1.9) show negative transfer during transfer trials 6-10, whereas only group 1.1 produced negative transfer during the first five transfer trials. Thus, the superiority of groups 1.4, 1.7 and 1.9 during initial transfer over the control group was not sustained as transfer progressed.*

TABLE 3

Experiment 1: Per cent Absolute Transfer Effect by Period and Damping Conditions, Transfer Trials 1-5

		Period (Seconds)		
		18	35	71
Damping (Seconds)	17	-12	48	30
	33	15	(50)	29
	66	6	55	0.3

2. The second major transfer comparison asks a quite different question than that posed in the classical transfer comparison. All nine experimental groups received a total of 40 learning trials. Eight of the groups trained for the first 30 trials on conditions other than the transfer condition. For the last 10 trials, however, all groups practiced on the same phugoid condition (number 5). Thus the performance of all groups may be compared on the last 10 trials. The question asked, then, is: What is the <u>relative transfer effect</u> between the experimental and control groups after all groups have received an equivalent number of training trials?

Operationally, the comparison is between improvement due to transfer and improvement due to direct practice. Equation 3, as presented by Gagne, Foster, and Crowley (5) expresses this comparison:

$$\text{Per Cent Relative Transfer Effect} = \frac{\text{T score (trial x)} - \text{C score (initial)}}{\text{C score (trial x)} - \text{C score (initial)}} \times 100$$

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* Negative transfer during transfer trials 6-10 is indicated by a lower score on blocked transfer trials 6-10 then the score obtained by the control group on blocked learning trials 6-10. For no group was performance on blocked transfer trials 6-10 lower than performance of the control group on blocked learning trials 1-5.

Since the control group was given direct practice without change, the performance of this group is used as the base. With this equation, 100 per cent relative transfer means that the transfer gain was equal to the direct practice gain over an equivalent number of trials. Negative transfer values means that there was a transfer loss relative to the direct practice gain over the trials block. In Table 4, the percent relative transfer effect is shown for all groups for transfer trials 1-5 and 6-10. The figures shown for control group 1-5 are computed simply by comparing the control group with itself giving the score of 100 per cent.

TABLE 4

Experiment 1: Per Cent Relative Transfer Effect

Transfer Trials	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
1-5	-23	95	59	30	100	58	12	108	3
6-10	37	105	78	61	100	69	48	115	39

These data may also be shown as a function of period and damping variations; for transfer trials 1-5, this is given in Table 5.

TABLE 5

Experiment 1: Per Cent Relative Transfer Effect
by Period and Damping Conditions

		Period (Seconds)		
		18	35	71
Damping (Seconds)	17	-23	95	59
	33	30	100	58
	66	12	108	3

Table 5 indicates that performance levels equal to or higher than the direct practice group (1.5) can be obtained from groups whose original training was with the same period value but with other damping terms. If, however, the period value is less or greater than that of the control group, transfer performance will be considerably lower as compared with the direct practice group after all groups have had the same amount of learning trials. The second row of Table 4 gives some indication of the relative transfer effect to be expected as the transfer trials continue; it may be seen that all groups which were below the direct practice group are demonstrating higher performance levels.

In summary, the following inferences are drawn from these data:

1. When the transfer performance of the experimental groups is compared with the original training trials of the control group (i.e., the absolute transfer effect),

a. transfer to a slower period by groups 1.1, 1.4, and 1.7 (i.e., from 18 to 35 seconds) resulted in transfer performance reliably below that of the control group;

b. transfer to the same period by groups 1.2 and 1.8 demonstrated high positive transfer;

c. transfer to a faster period by groups 1.3, 1.6, and 1.9 (i.e., from 71 to 35 seconds) also showed transfer performance to be positive but not as high as when the period was held constant; and

d. there was, in general, no differential damping effect on absolute transfer. Variations in period values produced the major differential transfer data.

2. When the transfer performance of the experimental groups is compared with that of the control or direct practice group after all groups have had an equivalent number of practice trials (i.e., the relative transfer effect),

a. transfer to a slower period by groups 1.1, 1.4, and 1.7 resulted in transfer performance reliably below that of the direct practice group;

b. transfer to the same period by groups 1.2 and 1.8 produced transfer performance as high as that obtained by direct practice;

c. transfer to a faster period by groups 1.3, 1.6, and 1.9 showed transfer performance below that of the direct practice group; and

d. there was, in general, no differential damping effect on relative transfer. Figure 6 does suggest that the performance of group 1.9 may demonstrate a more pronounced relative transfer effect. Analysis revealed that group 1.9 was the only experimental group whose performance remained significantly less than the direct-practice group throughout the transfer trials. If this result is confirmed, it would imply a damping effect and/or a period and damping interaction. The present data are not adequate to reject or support this possibility.

Training Trials. Analysis of the blocked-training trials shows that only performance differences due to period variations are statistically significant. Figures 1, 2 and 3, which represent period variations with damping held constant, show these performance differences clearly. As the period is increased, level of tracking performance decreases. Indeed, mean performance on the longest period conditions was often less than that which could be obtained with no subject stick movement at all. As may be seen in figures 4, 5, and 6 variations in the damping term had no statistically significant differential effect on tracking performance during the training trials.

III. EXPERIMENT 2: PILOT-NONPILOT PERFORMANCE

Considering the common assumption that slow transient conditions can easily be handled in aircraft control, the finding in Experiment 1 that certain period characteristics of the simulated phugoid transient response led to poor tracking performance was somewhat surprising. An immediate problem, however, arises from the fact that none of the subjects in Experiment 1 had had any pilot training. It is reasonable to ask the question: "Can experienced pilots effectively control these simulated long-period transient effects?"

The purpose of the second experiment was to compare the training and transfer performance of two pilot groups with the performance of nonpilot subjects on the same simulated phugoid condition.

Experimental Method

Subjects. Four groups of subjects were selected for this study based on prior pilot experience. The first of two pilot groups was the private pilot group. Ten graduates of the Aviation 101 (Private Pilot) Course at the Institute of Aviation, University of Illinois, were selected as subjects. Each of them had a private pilot's license, had not flown more than 100 hours altogether, had had no instrument flight training (other than in the use of normal cockpit instruments in light aircraft), and had flown as pilot-in-command within the preceding six months. The mean number of total flight hours for the group was 66.4, with a range of from 36 to 100 hours.

The second pilot group of 10 subjects were instrument pilots. The mean number of total flight hours was 1,866, with a range of from 500 to 3700 hours. All had held at one time either a military and/or civilian instrument rating, and seven of the ten held current instrument cards. The mean total instrument time for these subjects was 114.5 hours, of which approximately half was actual flight instrument time while the remainder was Link instrument time. Only three of the subjects had had jet aircraft training, and in these three cases it was limited to brief experience in the T-33 aircraft. In all cases, the instrument pilots had flown within one month prior to the experiment.

Experimental Design. For purposes of the present experiment, one transient condition from Experiment 1 was selected, phugoid condition 9. As may be seen in Table 1, this condition was characterized by a period value of 71 seconds and by a damping value (time to damp to half amplitude) of 66 seconds. Thus, the condition was one of a long-period transient with low damping.

The experimental comparison to be made here is between experienced pilot groups and nonpilot subjects. As shown in Table 6, four groups of subjects were compared in this experiment. The data for groups 1.9 and 1.5 were derived in Experiment 1.

Procedure. The purpose of the present experiment was to compare the training and transfer of the pilot groups on conditions 1.9 and 1.5 with the training and transfer performance of nonpilot subjects on the same conditions from Experiment 1. Therefore, it was essential that all experimental techniques and procedures be the same for the pilot groups and the nonpilot groups.

TABLE 6

Experiment 2: Experimental Design and Groups

Groups	N	Training Condition	Transfer Condition
2.9: Instrument Pilots	10	Phugoid Condition 9	Phugoid Condition 5
2.9: Private Pilots	10	Phugoid Condition 9	Phugoid Condition 5
1.9: Nonpilots	10	Phugoid Condition 9	Phugoid Condition 5
1.5: Nonpilots (C)	10	Phugoid Condition 5	Phugoid Condition 5

The 10 private pilots and the 10 instrument pilots were given 30 training trials on condition 9. This was followed by 10 transfer trials on phugoid condition 5 which was the common transfer condition for all groups in Experiment 1. Care was taken that the same procedures were applied to the pilot groups as had been used with the nonpilot groups. In all cases, TOT was the response measure.

Results

Figure 7 shows the training and transfer performance for both pilot groups and nonpilot groups. In addition, the performance of the control group from Experiment 1 (Group 1.5) is shown for the 10 transfer trials. Means and standard deviations for the TOT scores for each experimental group throughout training and transfer are shown in Appendix VI.

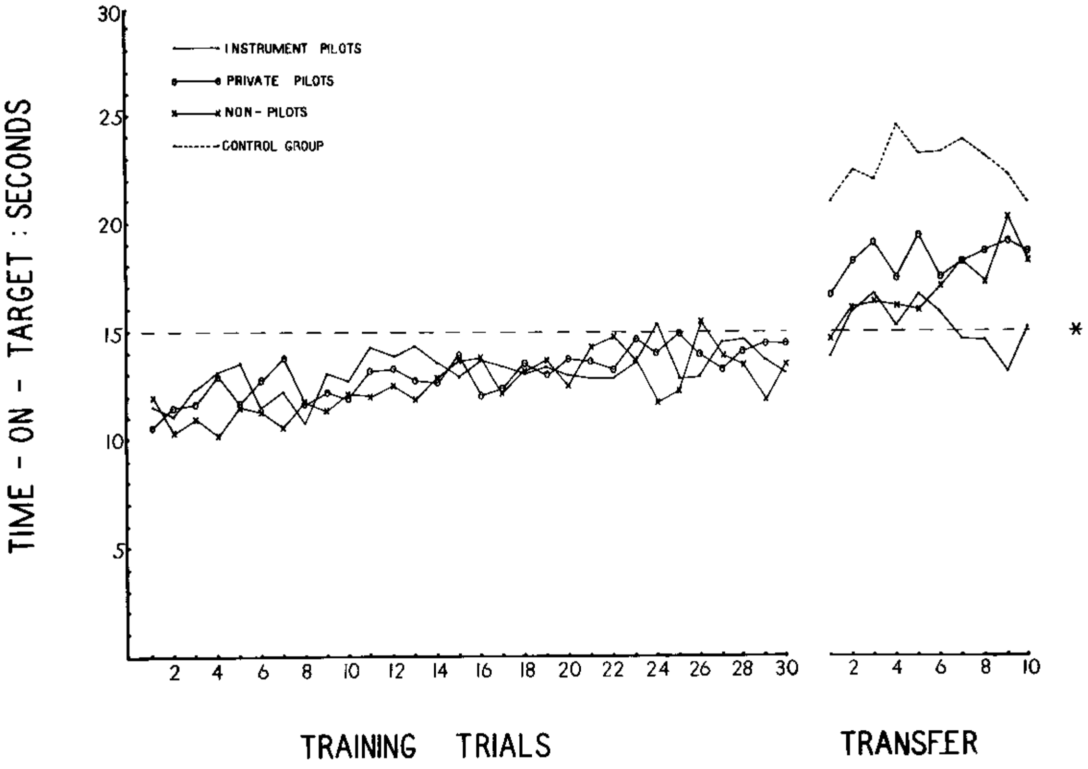


Figure 7. Experiment 2: Training and Transfer Performance for Pilot and Non-Pilot Groups.

*Theoretical "performance" with no subject response.

Statistical analysis of the data supports the rather obvious results shown in figure 7. During training, there were no statistically significant differences among the three experimental groups at any point. There were no statistically significant differences among the three experimental groups on the transfer trials.

The performances of the pilot and nonpilot groups may be compared with the control group in two ways, either for absolute or for relative transfer effect. Table 7 shows the per cent absolute and relative transfer effect obtained in this study.

TABLE 7

Experiment 2: Per Cent Absolute and Relative Transfer Effect

Groups	Percent Transfer Effect			
	Absolute Transfer		Relative Transfer	
	1-5*	6-10*	1-5*	6-10*
Instrument Pilots	1	-57	2	-12
Private Pilots	18	-18	36	41
Nonpilots	0.3	-20	3	39
Control (1.5)	(50)	(25)	100	100

* Blocked Transfer Trials

Computational formulae for absolute and relative transfer effect have been discussed in the preceding transfer comparisons in Experiment 1.

1. The course of absolute transfer shows a shift toward negative transfer. Comparing the transfer performance of the three experimental groups (transfer trials 1-5) there is no large initial difference, but during the second set of transfer trials (6-10), negative transfer is observed, as shown in Table 7.

2. Comparing the pilot and nonpilot groups with the control group after all groups had received an equivalent number of training trials (i.e., the relative transfer effect), the performance differences were statistically significant throughout the transfer trials. None of the experimental groups performed well on the transfer condition. The negative value obtained for the instrument pilot group is particularly of interest.

IV. DISCUSSION

Transfer of Training

The transfer data show clearly that transfer of training was predominantly influenced by the relationship between training and simulated period values. Where the training period condition was either faster or slower than the transfer condition, performance of the experimental groups was significantly inferior to that of the control group with equivalent training. Where the period value was identical during training and transfer, performance on the transfer trials was equivalent to control group performance.

Wide variations in the damping term did not differentially affect transfer of training. One possible exception is the transfer performance of group 1.9 which, unlike groups with other damping conditions, is inferior to that of the control group throughout the transfer trials. This might suggest that damping does become critical under more extreme conditions. Of interest would be further studies of damping values beyond the present range studied. In particular, negative damping (i.e., an unstable condition) would be an important object of inquiry.

Flight Simulator Design. If the findings of the present experiment may be extrapolated out of this particular context, it would appear that one critical variable in the simulation of aircraft longitudinal motion is a rather close correspondence between period values in the simulator and the aircraft. If deviations in the period values do become necessary, it is difficult to predict in which direction the period should be changed (i.e., either slower or faster) for the least detrimental transfer effect.

In the published literature, recent advances in simulator design have been reported in improved simulation of dynamic modes. Dehmel (3, p. 8), for example, reports achieving 98% accuracy in the simulation of period and damping values of the short period and phugoid modes. Using somewhat different computer techniques, Howe and Schetzer (9) have reported 80 to 95% accuracy in simulating the same modes. It is possible that these improvements may result in a decrease of the familiar complaint about flight simulator performance- "...the simulator doesn't fly like the aircraft".

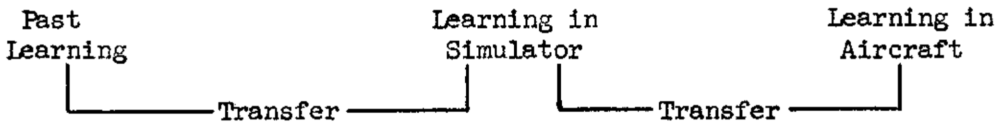
Many questions remain to be answered. What role do the parameters of simulator dynamic performance play in the pilot's judgements of handling characteristics? That is, what conditions make him say that the simulator does, or does not, fly like the airplane? Since it does not necessarily follow that complete dynamic simulation results in the most efficient transfer of training to the aircraft. What are the critical dynamic properties for transfer of training? The present results point to precise period simulation of phugoid dynamics with decreased emphasis on damping, at least for the range of periods and damping observed. Of course, it must be remembered that these data are derived from the laboratory context with considerably simplified phenomena. The present results and inferences strongly need substantiation in the simulator context itself.

Pilot-Nonpilot Performance. Transfer performance of all nonpilot and pilot groups was poor. While the differences among group performances are not statistically significant, there is some indication from visual inspection of the data that the nonpilot and private pilot groups showed improvement as the transfer trials progressed, while the instrument pilot group did not. In observing the performance of the instrument pilots, it appeared that most were attempting to apply techniques learned in the training condition, some of which were inappropriate during transfer. However, the number of transfer trials and the discriminability of the response measure were apparently not sufficient to allow any concrete data to support or reject these observations. In future work, it would be particularly interesting to extend the length of the transfer session. It is hypothesized that the instrument pilot group would continue to show absolute negative transfer effects, while the other groups would not.

The essentially inconclusive transfer findings of Experiment 2 certainly do not diminish the general importance of the study of transfer as a function of varying pilot experience levels. As has been noted elsewhere (12), transfer from the flight simulator to the aircraft is conventionally considered within the traditional transfer of training experimental paradigm:

Group	Training		Transfer
Experimental	Learn Task A	→	Learn Task B
Control	- -		Learn Task B

While this might apply to the use of flight simulators in primary flight training, it may not be applicable to the experienced pilot transitioning to a new aircraft type. In this case the process is:



A provocative experimental example of this type of complex transfer is shown by Dinsmore and DuBois (4) where the use of the B-50 flight simulator increased the flight performance efficiency of experienced B-50 pilots but not of new pilots transitioning to the B-50. In short, a great deal more evidence is needed on the effect of past pilot experience on simulator transfer effects. It may be anticipated that this factor will significantly affect transfer in the operational context.

Training Performance

For the original 30 training trials, the results indicate clearly that increasing the period of the oscillatory transients elicited a considerable decrease in the level of tracking performance. The decrease in tracking performance with increased periods does not, however, appear to be a linear function. Finally, a wide range of damping values had no differential affect on tracking performance with this system.

These data appear to give rise to a number of possible implications and interpretations, and the following four topics have been selected for discussion: (a) System "lag", (b) the operational flight task, (c) second-order control systems, and (d) pilot-nonpilot performance. In particular, the last topic is of interest in connection with the training and transfer results of Experiment 2.

System "Lag". In the instructions to the subject (see Appendix III), the point was stressed that there is a "lag" between stick movement and movement of the stimulus bar. This lag is an inherent part of the operation of the system. Because of this lag it is necessary to anticipate what the bar is going to do. The necessity for learning and using anticipatory or lead responses is critical if the subject is to perform the task correctly.

These lag effects are not unlike those associated with exponential time delays (e.g., 10, 11, 18). However, the present experimental task is additionally complicated by the presence of the oscillatory transients. If a transient is elicited, it must be damped out either within the system or by positive subject stick movement. In general, small rapid motions on the part of the subject frequently excited the oscillatory effects. The more time spent damping the transients, the less time the subject will be tracking with reference to the steady state component alone. It might be anticipated, therefore, that the higher the system damping the more easily the subject could handle any transient effects. However, in the present studies, system damping did not appear to aid differentially in the operator's suppression of the oscillatory transients. The possible reasons for this are not immediately apparent.

Training and transfer performance with the present system is directly dependent upon at least three critical subtask skills; the subject must (1) learn the system lag characteristics and appropriate anticipatory response sequences, (2) learn how to damp effectively oscillatory transients, and (3) learn the time history of the forcing function stimulus pattern. Without learning these skill components to at least some degree, it is impossible for the subject to perform on this man-machine system task at an acceptable level of proficiency.

The Operational Flight Task. The present results might be considered applicable to the pilot's operational flight task. If this is the case, it is of interest to examine any existing parallel inflight measurement data. There are a few published studies (e.g., 14, 20) that seem appropriate.

The classic study in this area was conducted by Soule (14) in 1936. Inflight period and damping measurements were taken of longitudinal transients of eight different aircraft. Although there were no consistent damping trends, it was demonstrated that period values increased with speed ranging from 11 to 23 seconds at low speeds and 23 to 64 seconds at high speeds. Of interest here is the fact that, in the opinion of the two pilots, "...the handling characteristics of the airplanes were not influenced by the stability characteristics as defined by the period and damping of the longitudinal oscillations." Partly on the basis of this finding, aerodynamicists have tended to ignore the long period pitching oscillation (except where excessively unstable) on the assumption that the pilot can easily handle slow-frequency phenomena of the phugoid type (e.g., 15, p. 410).

The apparent discrepancy between this opinion and the data of the present experiments is a matter for considerable detailed speculation. It may be pertinent, however, to examine the relationship between the aerodynamic realities of the flight situation and abstracted laboratory experimentation.

Aircraft longitudinal motion in actual flight is subject to much variability depending on the time history and interaction of many parameters: e.g., Velocity, weight, thrust, lift, drag, etc. This means that the pilot in completing the full-flight envelope will encounter a very complex set of period and damping conditions.

In the laboratory considerable abstraction and simplification is required. Here, a number of simplifying assumptions had to be made to keep the studies within reasonable equipment limits. The major assumption involved separating the full fourth-order longitudinal response into two second-order components, the short-period and phugoid modes. Only the phugoid mode was considered, with the immediate implication that angle of attack is zero. In addition, constant thrust, altitude, weight, etc., was assumed. Thus, the subject was given one simulated flight condition which is obviously a considerable abstraction from the flight situation.

In short, it would appear that inflight experimentation suffers from the disadvantages of any multivariate situation. The complexity of the inflight task, the large number of variables involved and their interactions, often render the results of inflight investigations somewhat ambiguous in so far as specific variables are concerned.* On the other hand, the laboratory experiment suffers from the fact that it is abstracted and simplified. Generalization of laboratory results to inflight situations is a risky business. Even with well established techniques, such as the use of wind tunnel data, the discrepancy between these data and inflight measurements is sometimes considerable, and on occasion disastrous. Joint ground simulation and flight experimental programs are needed, but these are costly and time-consuming.

Second Order Control Systems. The particular properties of this equipment and the task place the present experiments within the general class of investigations concerning human operation of second-order control systems (7, pp. 32-33; 20). The order of the control system is defined by the highest derivative contained in the analytic expression descriptive of the system response. Since the computer solution involves a second order differential equation where the second derivative is the highest, the system is, by definition, a second order control system.

As might be somewhat obvious, human operator tracking proficiency with higher order control system is a difficult problem. Apart from the question as to whether man should be an element in these systems at all, it is usually the case that very long training periods are required before acceptable levels of performance are attained. The professionally competent instrument pilot, for example, undergoes years of training. When man is an element in these systems it is generally of interest to see if he can be aided in any way. There appear to be at least two possible techniques: (1) Transformations of the information displayed to the operator and (2) transformations of the operator's control response.

One possible display transformation is the separation of the forcing function signal and the subject's actual error signal, that is, switching from a compensatory to a pursuit tracking task. Accumulated experience indicates that pursuit tracking is superior to compensatory tracking in most of the experimental situations so far investigated. The ability of the subject to see the desired program as distinct from his actual error program may help in establishing the proper lead program.

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* The development of variable characteristic aircraft (1) may circumvent this difficulty to a large degree.

Another possible display transformation is the application of display quickening. The operation of display quickening fundamentally transforms the display input by adding feed-forward derivative information to the displayed input. Theoretically this provides advance information concerning the future state of the system, and it should aid the subject in establishing a phase lead program. Data by Taylor and Birmingham (21) lend very strong support to this hypothesis. Using simulated helicopter dynamics they found that an unquickened conventional display resulted in unstable performance. With the quickened display, however, man-machine system performance was quite stable. The important point is that stability was achieved without changing the control system parameters in any way and by changing only the information displayed to the pilot.

Transformations of the operator's control output is a considerably more difficult problem. The proper signal to the computer in the present apparatus is seldom clearly definable. The desired signal would be one that at least reduces or eliminates the elicitation of transients; there are, however, many ways of achieving this result. Many automatic flight-control systems are designed for this objective, but equipment implementation is formidable and rather specific to the dynamic characteristics of the flight vehicle involved.

It would seem that if the pilot is to continue as an essential primary link in higher order flight-control systems, more attention should be paid to the kind of information he receives and the nature of his control input ot the vehicle; such information may be essential, in fact, to the development of control systems for orbital and space vehicles. It is recognized, of course, that, as many have maintained, the human operator may not be an element in direct control of these vehicles. At present it would appear that while the fully automatic approach greatly simplifies the task of crew station design, it appears to magnify the task of the control system design engineer.

Pilot-Nonpilot Performance. Although the data showed no significant differences between the performance of the pilot and nonpilot groups, there did appear to be an important qualitative difference between subjects in understanding task requirements. Without exception, each individual in the instrument pilot group verbalized the task quite well. They understood the necessity for compensating for the system lag, and they were able, on occasion, to lead properly. They could not, however, take consistent advantage of this knowledge. On the other hand, individuals of the nonpilot and private pilot groups tended to track from moment to moment without any consistent attempt to introduce, or experiment with, variable lead programs.

At least two possible explanations may be made for the failure of the instrument group to obtain better tracking scores. First, it might be said that the system dynamics were such as to preclude a higher level of tracking. Experience over long training periods by the writers, however, showed that this was not the case. After several hundred trials it was possible to obtain consistent tracking scores in excess of 20 seconds (out of 30) per trial. This was due primarily to considerable overlearning on the time history of the forcing function, so that the necessary lead program could be based on anticipations of the rate and direction of change of the sine wave and ignoring moment-to-moment minor fluctuations of the displayed error signal. Using this technique the transient effects could be minimized.

It might be noted that the principle involved in this technique may well be predominant in skilled pilot performance. That is, moment-to-moment minor error signal variation is given minimal attention while the skilled pilot attempts to match a planned or predicted flight profile with a smoothed average, so to speak, of the actual flight profile. If this is the case, then laboratory experiments simulating flight conditions using a random or nonpredictable forcing function may not be sampling a critical aspect of the pilot's task. Senders and Cohen (19, pp. 12-19) have made an analogous point concerning methodology of instrument evaluation, namely, that the time history of instrument performance is always one of high objective and subjective sequential dependency and that laboratory instrument investigations should take this fact into account wherever possible.

A second possible explanation lies in the experience history of the instrument pilot group. Only three of the pilots had had experience with jet aircraft, and even here the contact was brief and primarily limited to the T-33 aircraft. Thus, none of the instrument pilots had had flight experience with very high performance aircraft. Transient phenomena of the type considered here becomes most apparent in the handling of high performance vehicles. Informal reports of experience with other simulation studies on high-performance characteristics have indicated that significant performance differences can be obtained among jet qualified pilots and other pilot samples. Concrete substantiation of this remains thus far to be experimentally demonstrated.

V. SUMMARY

The fidelity of simulation between an operational flight simulator and its associated aircraft is a matter of critical concern in determining the training value of the flight training device. Of the many physical variables that must be simulated, one of the most important set of phenomena is that concerned with the physical modes of motion of the aircraft and particularly the transient dynamics responses that are an inherent part of these modes of motion.

How accurately these transient responses must be simulated for optimum transfer of training from the simulator to the aircraft is unknown. A great deal of the cost and complexity of present flight simulators is due to computer requirements for simulating aircraft dynamic response. Some simulator design engineers have felt that even much more accurate simulation is required for proper simulator performance. But the ultimate objective of any training device is not fidelity of physical simulation, but rather the amount of positive transfer that can be obtained from the device. High physical fidelity of simulation may or may not be required to achieve the desired training result.

The solution to the problem should be found in experimental data relating transfer of training to variations in physical parameters between training and transfer. In the area of simulation of aircraft modes of motion there appears to be a considerable lack of appropriate information. This series of studies, therefore, was designed to provide at least some preliminary transfer data in this context that might aid simulator design engineers in making decisions about desired simulation levels for aircraft dynamic response modes.

An exploratory series of studies was initiated in a laboratory situation investigating transfer of training as a function of simulated aircraft dynamic responses. The studies were limited to longitudinal dynamics alone (the aircraft pitch response), and, as a further restriction, only the phugoid (or long-period) oscillatory transients were simulated. The primary independent variables were the period and damping values associated with the phugoid response.

In the first of two studies, transfer of training was studied as a function of variations in period and damping values between training and transfer conditions. Highest absolute and relative positive transfer effects were found when the period conditions were unchanged. Transfer from a faster to a slower period condition resulted in negative absolute transfer effects. Despite a wide variation in damping values, changes in damping from training to transfer had no significant differential effect on transfer scores.

For the second study, level of pilot performance was chosen as the independent variable. Training and transfer performances of a private pilot group and an instrument pilot group were compared with the performance of a nonpilot group on a slow-period, lightly damped phugoid condition. There were no statistically significant performance differences among these three groups either for training or transfer. Comparing the transfer data of these groups with a control group showed negative absolute transfer effects; further, the level of transfer performance for the three groups was significantly less than that of the control group after all groups had received an equivalent number of training trials.

Considering the training data alone, as the period of the phugoid transient was increased, the level of tracking performance decreased radically. For the slowest period conditions (71 seconds), tracking performance was often below that which could be obtained with no operator control movement at all. As was the case in the transfer data, wide variations in the damping term had no differential affect on tracking performance.

In the following reports in this series, emphasis is shifted to the interaction of various operator display and control variables and the simulated phugoid transient. The second report deals with control system gain and a selected set of the period and damping conditions used in the present study. The final report shifts to a consideration of stimulus parameters and particularly the course complexity and course amplitude of the forcing function.

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APPENDIX I

SIMULATION OF AIRCRAFT LONGITUDINAL DYNAMICS

The Oscillatory Transients

Given certain reasonable assumptions, it is possible to approximate the pitching response of an aircraft with an ordinary fourth-order differential equation with constant coefficients (15, 23). In the general terminology of physical response systems, a fourth order system must be generated (7, 22). In theoretical and experimental evaluations of aircraft pitch response, it has been shown that two types of oscillatory transient responses may result from an elevator control movement. The first of these is a response of rather rapid period with relatively high damping. The second is a long period response with usually low damping. It can be shown that, under certain reasonable assumptions, each of these transients may be treated as a second order system -- the two then combining to form the complete fourth-order system.

The present experimental series was confined to the second of these transients: The long-period response, or, as it is frequently termed in the aerodynamic literature, the phugoid response. The present laboratory experiments involve attempts to simulate oscillatory transients of this type.* In the following discussion, the analytic approach to simulation of aircraft longitudinal response and the analytic treatment of the required second-order differential equation are considered. The translation of the analytic approach into actual simulated transients is considered in Appendix II under the treatment of the apparatus computer.

It should be understood that the treatment here is considerably abstracted from the complexities of the actual flight situation. Many simplifying assumptions had to be made to circumscribe the phenomena within the bounds of an exploratory research program. In general, however, every attempt was made to follow conventional aerodynamic and simulation techniques in the process of abstraction.

Longitudinal Response of a Fixed-Wing Aircraft

The primary problem was to simulate aircraft response, and in particular, longitudinal aircraft response. It is convenient, at this point, to introduce the topic of the longitudinal response of a conventional fixed-wing aircraft. Further, the equations of motion will be developed in their complete form and then will be broken down into a simpler form for which parameters may be more easily specified.

To consider aircraft longitudinal response the following notational system must be introduced:

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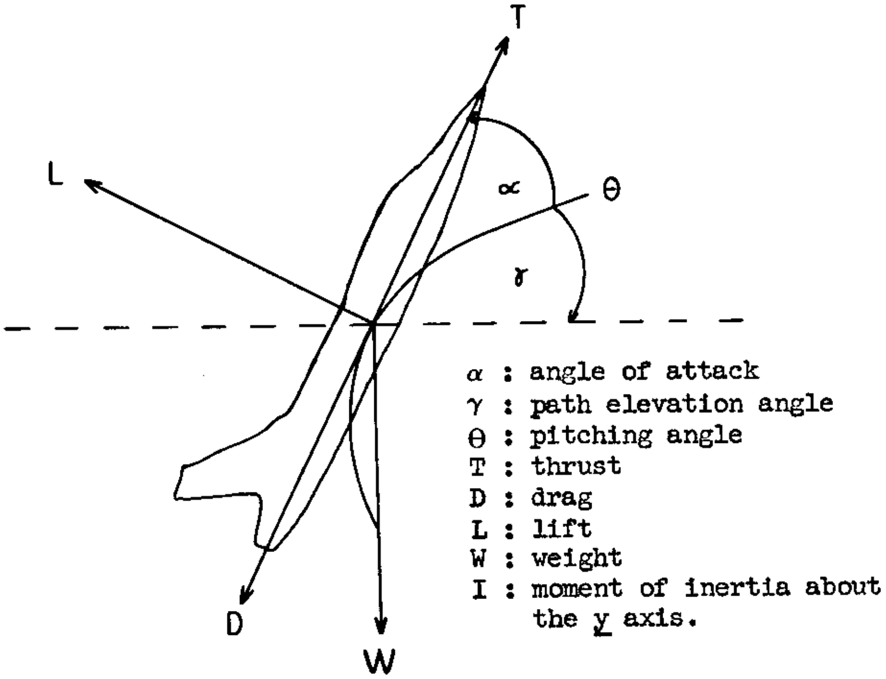
*Throughout the investigation, the reports of the University of Michigan group (6, 8, 9, 16) on evaluation of flight simulator computers were particularly valuable and illuminating.



α : angle of attack
γ : path elevation angle
θ : pitching angle
T : thrust
D : drag
L : lift
W : weight
I : moment of inertia about the y axis.

Since there are three degrees of freedom in the xz plane, three equations will suffice to describe the motion of the airplane. These are: (a) The force in the x direction which is equal to the mass of the airplane times the acceleration in the x direction:

$$\text{(a)} \quad m\dot{v} = T\cos\alpha - D - W\sin\gamma$$

(b) The force in the z direction which is equal to centrifugal force:

$$\text{(b)} \quad mv\dot{\gamma} = T\sin\alpha + L - W\cos\gamma$$

and (c) The sum of the moments about the center of gravity of the aircraft which is equal to the moment of inertia of the airplane times the angular acceleration about the center of gravity:*

$$\text{(c)} \quad I_y\ddot{\theta} = \Sigma\,\text{Pitching Moments}$$

It should be noted that the above equations are differential equations with nonconstant coefficients. In addition to the sine and cosine terms, lift and drag are proportional to the square of the airspeed.

Given a sudden elevator deflection, two sequential pitching oscillations may be noticed. The first of these is a rather rapid oscillation which usually has relatively

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* The effect of the stick on longitudinal motion appears as a change in the moments about the y-axis due to a deflection of the elevator. Commonly elevator flapping has considerable effect on the longitudinal equations but it is here ignored. An additional equation to describe elevator dynamics is usually necessary.

high damping. In the aerodynamic literature this oscillation has been commonly termed the short-period mode. The second oscillation is a very slow, lightly damped oscillation which has been called the long period or phugoid mode.

Figure 8, taken from Peterson (16, p. 11), illustrates the stimulated pitching motion of the F-86D showing the short-period response, the phugoid response, and the combined pitch response. The short-period response is shown in terms of angle of attack changes; the phugoid is shown in terms of perturbations of the aircraft velocity vector. In the combined-pitch-angle response, the short-period mode is manifested by the irregularity early in the time history. After the short period has damped out, the phugoid continues.

To simplify the longitudinal equations, it is convenient to deal with constant rather than nonconstant coefficients. Under the assumptions that altitude and velocity changes are small, it is possible to describe the aircraft longitudinal response as an ordinary fourth order differential equation with constant coefficients and with the general form:

$$A_4\theta^{IV} + A_3\theta''' + A_2\theta'' + A_1\theta' + A_0\theta = f(t)$$

Further, if one is allowed to assume that the rapid oscillation (short-period mode) is an oscillation in angle of attack (α) with path elevation angle (γ) approximately zero, and that the slow oscillation (phugoid mode) is an oscillation in path elevation angle (γ) with angle of attack (α) approximately zero, then it is possible to separate the two oscillations and to describe each with a second-order differential equation of the form:

$$A_2\ddot{\theta} + A_1\dot{\theta} + A_0\theta = f(t)$$

The separation of the two modes in this manner is frequently made in texts on aircraft dynamics (15, 23). The separation has also been made here with the purpose of concentrating on the phugoid mode alone.

The Second Order Differential Equation

The preceding paragraphs indicate that under certain simplifying assumptions the longitudinal response of a conventional aircraft can be discussed in terms of two oscillations expressible as second-order differential equations. These two second order differential equations are of exactly the same form, differing only in the constants in the equations. The present experiments deal only with equations whose constants are such as to yield the slow, lightly damped, oscillation termed the phugoid mode.

Remaining now is the task of solving the second order differential equation to indicate the necessary parameters. The equation to be simulated on the analogue computer is of the form:

$$(1) \qquad A_2\frac{d^2x}{dt^2} + A_1\frac{dx}{dt} + A_0x = \delta_e(t)$$

where $\delta_e(t)$ is the function of elevator angular displacement.

For the purposes of analyzing the differential equation, $\delta_e(t)$ will be assumed to be a step function, i.e.:

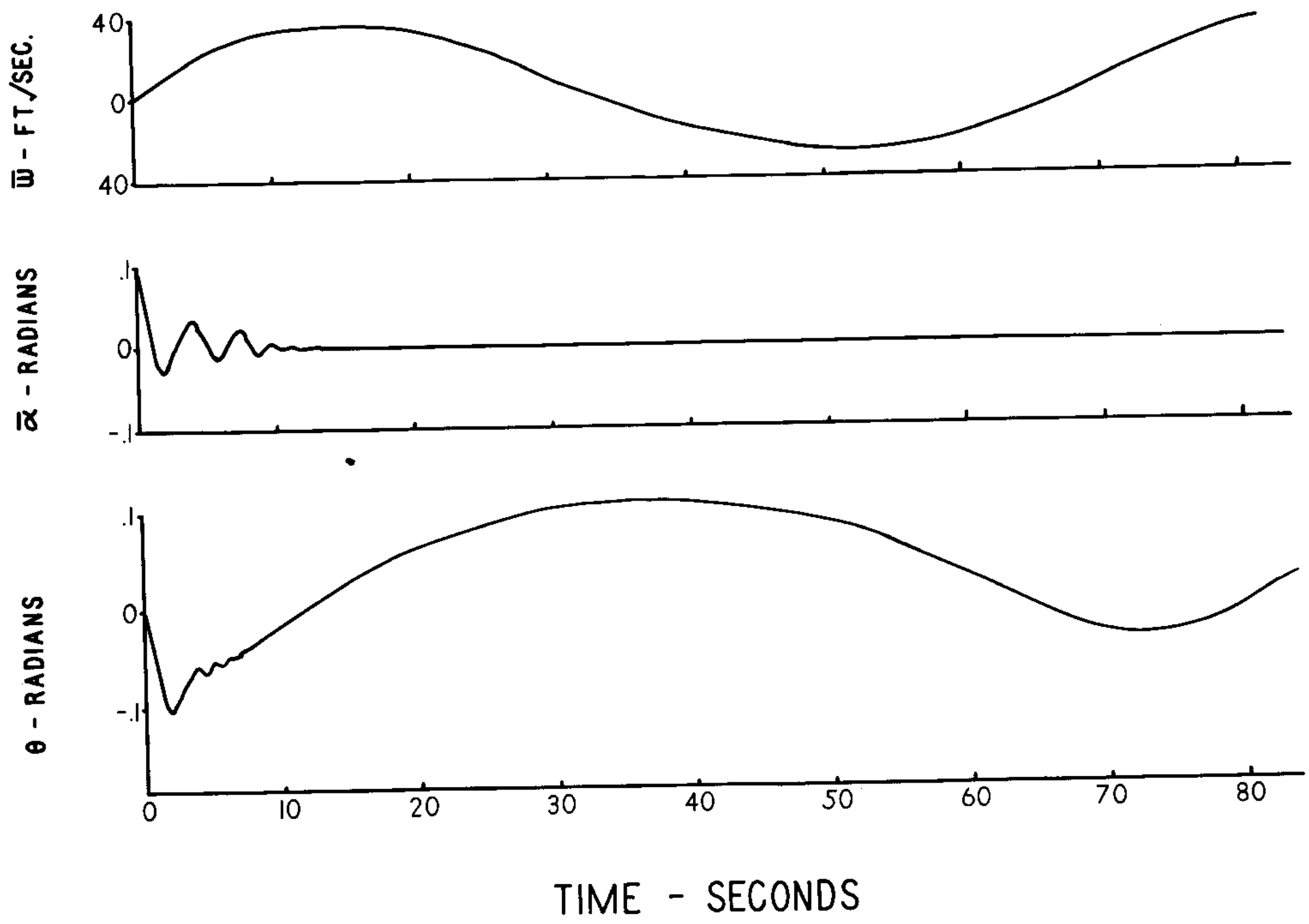


Figure 8. Simulated Pitching Motion of the F-86D Showing Short Period, Phugoid, and Combined Pitch Response.

$$\delta_0(t) = \begin{cases} \delta & t > 0 \\ 0 & t > 0 \end{cases}$$

Step functions are commonly used since they effectively bring out the effect of the transient conditions and yield a simple steady-state solution.

Writing (1) in operational form and using

$$D = \frac{d}{dt}$$

the transient response is the solution to

$$(A_2D^2 + A_1D + A_0)\,x = 0$$

or

$$[(D - m_1)(D - m_2)]\,x = 0$$

yielding

$$x = C_1e^{m_1t} + C_2e^{m_2t}$$

where m_1 and m_2 are solutions to the quadratic polynomial

$$\left\{\begin{matrix} m_1 \\ m_2 \end{matrix}\right\} = \frac{-A \pm\sqrt{A_1^2 - 4A_2A_0}}{2A}$$

and C_1 and C_2 are dependent upon the initial conditions which are usually x at t and dx/dt at t = 0.

Three possible cases for m_1 and m_2 arise: (a) m_1 and m_2 are real but not equal, (b) m_1 and m_2 are real and equal, and (c) m_1 and m_2 are complex conjugates. Cases (a) and (b) give nonoscillatory transient solutions, and only case (c) yields the oscillatory condition desired, i.e.,

$$X_1 = e^{rt}\,(K_1 \cos\omega t - K_2 \sin\omega t),\; t > 0$$

The steady state response is given by:

$$X = \frac{\delta}{A_0}$$

and

$$r = \frac{-A_1}{2A_2} \quad ; \quad \omega = \left|\frac{\sqrt{4A_2A_0 - A_1^2}}{2A_2}\right|$$

Therefore, the general solution for an equation of form (1) is:

$$x(t) = e^{-rt}[K_1 \cos\omega t + K_2 \sin\omega t \;+ J/A$$

It can be seen from this form that the oscillation is sinusoidal in nature with the amplitude of the sinusoid decreasing exponentially. Only in the case of the step function, however, is the steady state response a constant.

Experimental Conditions

In these experiments, two parameters were chosen to specify the oscillation. The first is the period of the oscillation, that is, the time between corresponding parts of the sinusoidal oscillation. The second parameter is the time to damp to half amplitude of the oscillation, that is, the time for the envelope of the sinusoid to decrease to one-half amplitude of the envelope at time t = 0. This second parameter is the damping term.

Nine oscillatory transients were selected for the experimental series. In terms of period and damping values they are:

Experimental Condition	Period (Sec.)	Damping (Sec.)
1	18	17
2	35	17
3	71	17
4	18	33
5	35	33
6	71	33
7	18	66
8	35	66
9	71	66

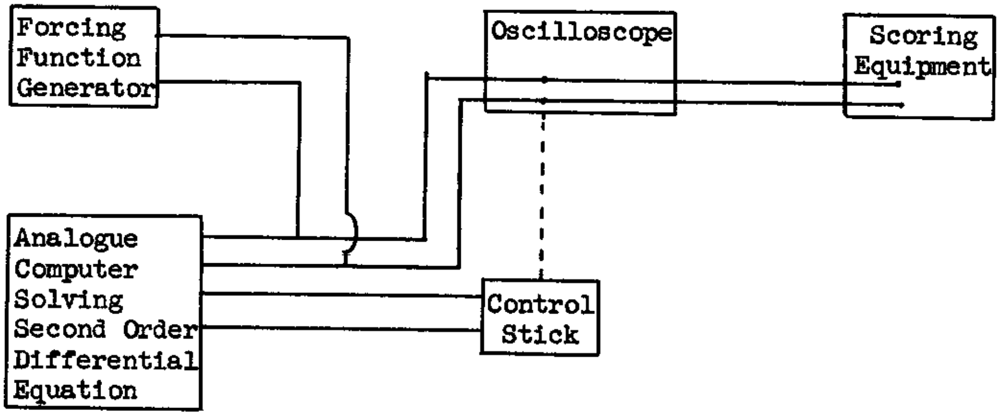
Combinations of three period values (18, 35, and 71 seconds) and three damping values (17, 33, and 66 seconds) are represented. The selection of these conditions was based on (a) an analysis of current and projected aircraft types, (b) recommendations from Air Force and industry aerodynamicists, and (c) the limitations of the experimental apparatus.

APPENDIX II

EXPERIMENTAL APPARATUS

General Apparatus Description

In block diagram form the experimental apparatus used in this series of experiments may be outlined as follows:



This system is a compensatory tracking task. The forcing function generator causes a horizontal bar on the oscilloscope to move. The human operator, in attempting to return the horizontal bar to the neutral position, moves the control stick which in turn provides a signal to the analogue computer. The output of the computer is mixed with the output of the forcing function generator prior to display on the oscilloscope face. Any vertical displacement of the horizontal bar on the scope face is sent in the form of an error signal to the scoring equipment. In the following discussion, each block of the above diagram will be described.

The Oscilloscope

The oscilloscope was a DuMont 208B 5-inch device converted to accommodate DC inputs. Conversion was made simply by applying the DC signal to the DC deflection amplifiers. The oscilloscope was inclined at an angle of 18° from the vertical, and the scope face was approximately 29 inches from the floor. It was believed that the slight inclination of the scope provided a more discriminable display for the subject. The scope face was covered with a grid divided into one inch squares. Further, each square was subdivided into smaller divisions of 0.1 inch. The stimulus target line was a horizontal line 2 inches in length and 0.025 inch wide. The stimulus line was centered horizontally, and between trials it was also centered vertically. While the subject was tracking, the stimulus line traveled only in the vertical dimension. Due to the phosphorescent coating on the scope face, the stimulus line was green. No limit was set on the amount of vertical travel for the stimulus line, and it was possible to drive the stimulus line off the scope face. The oscilloscope scale factor was 0.95 volts per inch.

Measuring from eye level, the subject was seated approximately 26-30 inches from the scope face. The visual angle subtended by a one-inch square on the scope face was 2.05°. The visual angle subtended by the scope face was 10.11°.

The Control Stick

The subject's control stick was an aircraft joystick taken from an Aeronca 7AC aircraft. The stick was approximately 22 inches long. Movement of the stick was possible in all directions; only forward and backward movements (elevator), however, were required of the subject, and side (aileron) movements were nonfunctional. The maximum deflection of the stick forward and backward was ±8.5 inches from the center. Movement of the stick described a slight arc. The angle from the center point to maximum deflection, measured from the base of the stick, was approximately 21.1°. Springs were attached to the base of the stick, and all movements of the stick were against a constant force-displacement gradient with increasing force requirements as displacement increased. A potentiometer was applied to the base of the stick mechanically. A DC voltage was applied to the potentiometer which in turn produced a DC amplified output. The stick was self-centering.

Control-display movement relationships were as follows. Forward movement of the stick caused the stimulus line to move down, while back movements of the stick caused the stimulus line to move up on the scope face.

The Forcing Function

The basic forcing function to the subject was cut into a cam which was driven by a constant speed 1-rpm motor. Further, the cam was used to time automatically the trial and rest periods and the warning lights used 10 seconds prior to every trial. The cam was a saw-tooth function very closely approximating a simple sine wave of six cycles per minute.

The displayed amplitude movement of the cam was selected arbitrarily. Given a pure cam trial without stick movement, the cam stimulus movement was ±0.3 inch on the scope at the maximum amplitudes of the sine wave pattern. This amplitude was maintained throughout the two experiments discussed in this report, although in later studies the amplitude was varied as the experimental independent variable.

The pure cam trials without control input recorded 15 ± 0.10 seconds per 30-second trial; this value is referenced in figures 1-7 and described as "theoretical 'performance' with no subject response". Variability was due to slight slippage in the cam mechanism. For the same reason, there was a slight variability in the length of each experimental trial. Over a large sample of calibration runs, trial length was found actually to be 29.95 ±0.10 seconds instead of precisely 30 seconds.

The Computer

The main purpose of the computer was to impose long-period oscillatory transients on the subject's stick output. These transients simulated aircraft longitudinal response. The general philosophy of simulation has been described in Appendix I; here specific computer techniques are described.

The Differential Equations. To produce the desired simulated aircraft transients, the computer solved a second-order differential equation. Variations of the parameters of the transients so achieved were the basic independent variables of this experimental program. For each condition a particular second-order differential equation was required; these equations for each condition were as follows:

Experimental Condition	Differential Equation * A_2	A_1	A_0	A
1	24	1.0	3.0000	30
2	24	1.0	0.7500	30
3	24	1.0	0.1875	30
4	24	.50	3.0000	30
5	24	.50	0.7500	30
6	24	.50	0.1875	30
7	24	.50	3.0000	30
8	24	.50	0.7500	30
9	24	.50	0.1875	30

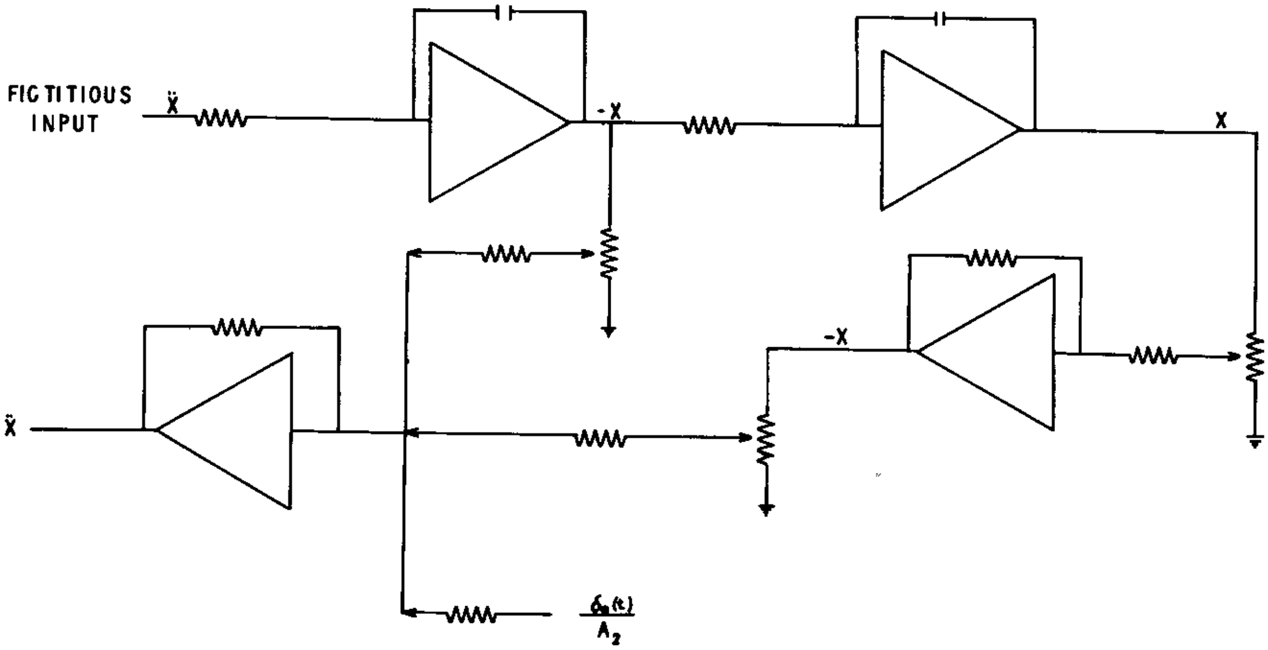
$$* \quad A_2\ddot{\gamma} + A_1\dot{\gamma} + A_0\gamma = A\delta_e(t)$$

The differential equation for each experimental condition is shown with appropriate coefficients. Solution of any given equation provided the desired period and damping values specified for the experimental condition.

Complete Simulator Simulation. A useful artifice for programming the second-order differential equation begins by solving the general equation for x:

$$\ddot{x} = \frac{\delta_e(t)}{A_2} - \frac{A_1}{A_2}\dot{x} - \frac{A_0}{A_2}x$$

If one assumes that an input representing $\ddot{x}$ is available, this input can be integrated twice:



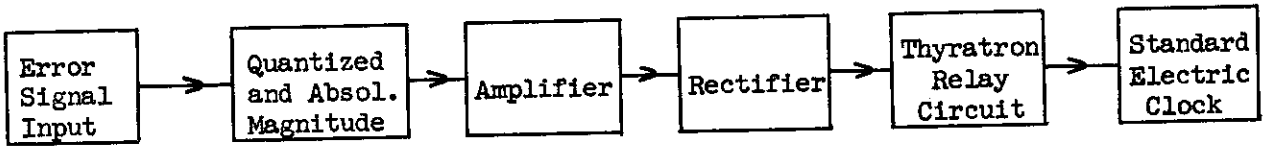
Then an output giving $\dot{x}$ and x is obtainable, and if one also provides the input δ_e then

$$\frac{\delta_e(t)}{A_2} - \frac{A_1}{A_2}\dot{x} - \frac{A_0}{A_2}x$$

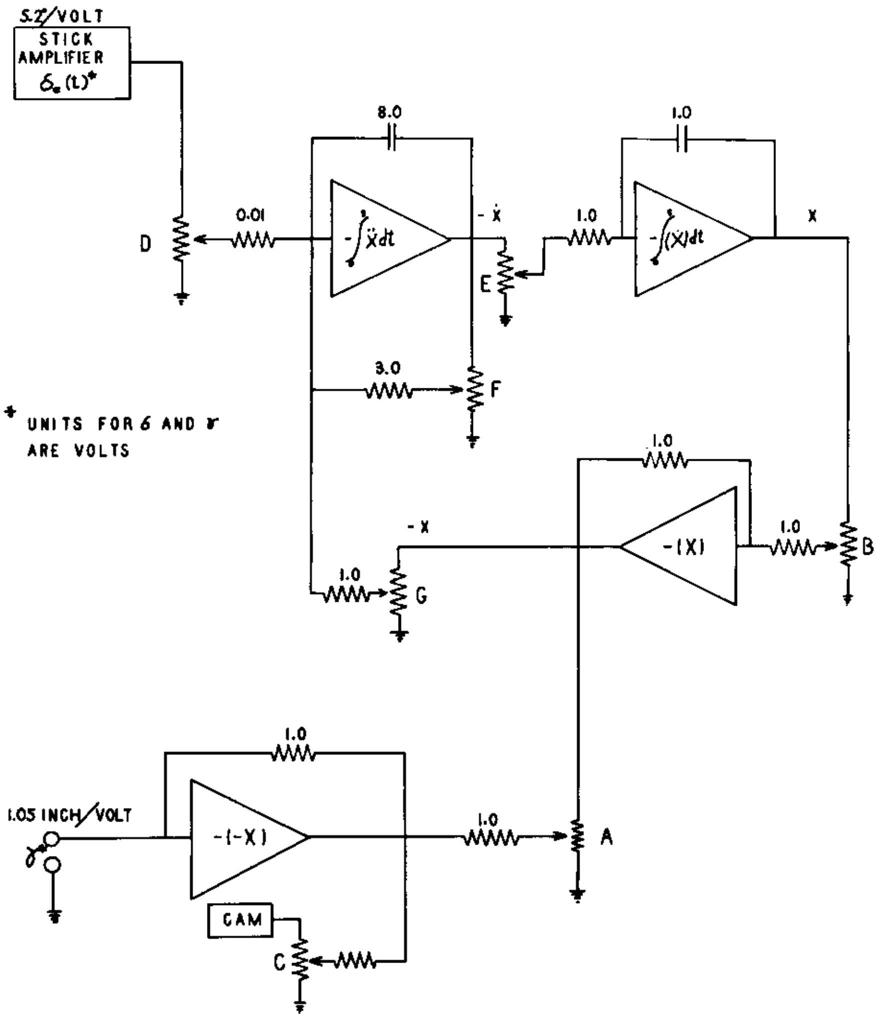
can be formed using the given operational components. However, this sum is identical to x and can be used to replace the fictitious input. The simulation is thus complete. Figure 9 shows the schematic diagram of the complete circuitry used with this experimental apparatus for the solution of the second-order differential equation.

Scoring Equipment

Time-on-target (TOT) was the response measure used. Tolerance limits were set so that the clock was running if the stimulus bar was within ±0.2 inch from the center, or null, line. A Standard electric 60-second timer recording to 0.01 second was used. Specifically, the block diagram for the time-on-target scoring device is:



The error signal was modulated on a 2kc square wave in such a way that either plus or minus polarities of the error signal produce the same modulated AC signal. This AC modulated signal was then amplified and rectified. The DC signal resulting from rectification then triggers a thyratron relay circuit, turning the clock on when the error signal has reached the predetermined magnitude.



* UNITS FOR δ AND γ ARE VOLTS

EQUATION SIMULATED

$$\ddot{\gamma} + \frac{F}{24}\dot{\gamma} + \frac{EGB}{8}\gamma = 12.5\ DA\,\delta_e(t)$$

OR: $24\ddot{\gamma} + F\dot{\gamma} + 3EGB\gamma = 300\,DA\,\delta_e(t)$

$$\left\{\begin{matrix} A = 0.2 \\ D \quad 0.5 \\ G = 1.0 \end{matrix}\right\}$$

Figure 9. The Computer Programming Board.

APPENDIX III

EXPERIMENTAL PROCEDURE

Without exception throughout these experiments, the length of the individual trial was 30 seconds. An inter-trial interval of 30 seconds was used. All subjects were required to track for 40 trials. The first 30 trials were training trials. The remaining 10 trials were performed on transfer conditions. A five-minute rest interval was inserted between the training and transfer trials.

As noted above, the trial and rest intervals were automatically programmed by microswitches placed on the cam. The subject was warned as to the onset of the trial by two red lights at the base of the oscilloscope which lighted 10 seconds prior to the start of the trial. These lights went off coincident with the start of the trial. At the end of the 30-second trial period, the stimulus line was immediately returned to center automatically, and the subject no longer had any control over the stimulus line until the initiation of the next trial.

After a subject had been seated, he was given the following instructions:

> "This is an oscilloscope. Notice this green bar (point) on the face of the scope. When the equipment is running, this bar will move up and down. Your job will be to keep the bar from moving up and down.
>
> "This is your control stick (point). Notice that it moves in all directions, but you will use only forward and backward movements. Try moving the stick forward and backward.
>
> "Movement of the stick controls the movement of the bar on the scope face. If you move the stick forward, the bar will move downward. If you pull the stick back, the bar will move upward. Now, when the task starts, the bar will begin to move independently of your stick. Your job is to use the stick correctly so that these bar movements do not occur; that is, you want to keep the bar on the center line as much of the time as you can. For example, if the bar is moving up, push the stick forward to make the bar come down. If the bar is moving down, pull back on the stick to make the bar come up. Now, the bar will be moving most of the time so you will have to keep the stick moving. If you are doing your job right, the bar will stay right on the center line and move very little.
>
> "However, this is a very difficult task. You will probably never be able to keep the bar centered all of the time, but we want you to do the best you can. There are a number of things that you should know that will help you.
>
> "First, you will find that there is a lag between the time you move the stick and the time the bar responds, so don't expect immediate action.
>
> "Second, this is a very sensitive control, so a little movement of the stick can do a lot to the bar. In the beginning, when you are just learning, we want you to move slowly with the stick and be careful not to move too far until you are sure that you can anticipate what the bar will do when you move the stick. Fast and big movements will get you into trouble, so, take it easy at first.
>
> "Third, because of the lag and the sensitivity of the control, you will find that you must anticipate what the bar is going to do if you

are going to keep it on the center line. For example, suppose that the bar is above the center line. You want to push forward to bring it down. Now, if you leave the forward stick in, the bar will keep right on going off the scope face. If you come back too soon, the bar will level off above the line. If you are late the bar will level off below the line. These are the kinds of anticipations you must make, and if you anticipate correctly the bar will neutralize itself in the center position. As I said, this is a hard task, but try to do the best you can; you should find there is plenty of room for improvement as we go along.

"While doing this task we will run for a 30-second period. When the 30 seconds are up, the bar will automatically return to center. As soon as it does return to center, bring the stick back to neutral, take your hand off and rest. Please do not move the stick during the rest period. The rest period will also last 30 seconds. The last ten seconds of the rest period these two red lights (point) will be on. Now, these are simply warning lights, and they tell you to get ready for the next trial. So, when these lights go on, put your hand on the stick and get ready. As soon as they go off, begin trying to keep the line centered. Now, we will repeat this trial-rest-trial-rest, etc., cycle 30 times, then we will take a five-minute rest, and then do ten more.

"Remember, in the beginning, move slowly and not too far until you get some control over the task.

"Now, if you will get up for a minute, I will demonstrate one cycle for you. (Experimenter demonstrates one trial, pointing out the rest and trial relationship, the warning lights, etc.)

"Do you have any questions?"

Subjects were encouraged to ask questions. An attempt was made to insure that the subjects were highly verbalized on all aspects of the task before actual tracking was initiated.

APPENDIX IV

TABLE 8

Experiment 1: Means and Standard Deviations by Blocked Trials

Blocked Trials		Experimental Groups								
		1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
Training Trials	1-5	88.16* 20.38**	78.67 21.99	67.43 9.56	86.56 24.21	77.87 10.70	65.20 4.50	82.23 14.38	74.92 17.87	55.06 13.56
	6-10	100.46 19.42	89.76 24.52	70.09 8.12	108.41 15.72	101.35 14.68	65.62 7.01	97.40 13.42	93.01 14.26	57.42 6.41
	11-15	109.69 18.21	95.46 20.24	71.67 8.31	117.74 21.04	101.72 11.97	68.70 9.10	101.83 2.95	104.82 19.93	63.01 11.31
	16-20	116.10 9.71	101.02 13.88	69.92 8.81	118.12 16.25	114.40 9.28	71.13 11.49	113.76 10.56	112.02 19.89	63.00 5.50
	21-25	115.43 10.32	105.93 17.36	72.00 9.92	127.98 12.70	112.64 14.77	73.40 11.60	118.74 14.68	109.33 21.35	66.92 9.70
	26-30	118.63 10.19	112.27 16.39	73.38 8.52	129.29 9.26	111.18 16.15	75.68 7.39	118.05 11.81	114.31 17.86	68.15 13.90
Transfer Trials	31-35	69.44 16.06	112.37 12.80	99.34 17.54	88.56 26.04	114.17 13.68	98.95 17.47	82.23 22.88	117.15 16.53	78.95 14.14
(Condition 1.5)	36-40	91.17 22.82	115.27 12.50	105.89 16.47	99.78 25.95	113.64 11.20	102.53 16.60	95.01 23.47	119.14 16.31	91.64 12.70

* Mean in seconds.
**Standard deviation in seconds.

APPENDIX V

EXPERIMENT 1: STATISTICAL ANALYSIS

From the statistical standpoint, one of the difficult problems was the extreme variability of the data. Many of these task conditions were quite difficult*, and it was possible, for example, that a single stick reversal early in the trial could result in loss of subject control of the stimulus line for 5 to 10 seconds. Accordingly, intra- and inter-subject variability was very high. Due to the data variability, analysis was, in general, conducted over blocks of five trials. (The means and standard deviations in seconds for blocks of five trials through training and transfer have been shown in Appendix IV for all experimental conditions).

<u>Training Trials</u>. Analysis of the blocked training trials showed the following probability values:

Blocked Training Trials	Chi-Square Probability Value**			
	Total	Row-Damping	Column-Period	Interaction Period x Damping
1-5	.01	.90	.01	.60
6-10	.01	.40	.01	.98
11-15	.01	.65	.01	.80
16-20	.01	.60	.01	.75
21-25	.01	.70	.01	.85
26-30	.01	.70	.01	.96

Throughout the course of training, only performance differences due to period variations are seen to be statistically significant, (accepting the 5% level of significance in all cases). Variations in the damping term had no differential effect on tracking performance during original learning. Finally, there was no statistically significant interaction effect for the training trials.

A closer examination of figures 1, 2 and 3 shows that while there were large differences in performance between the 18- and 71- and 35- and 71-second period groups, there is some question of the significance of the performance differences between the 18- and 35-second groups. To make a further analysis, advantage was taken of the fact that no statistically significant damping effects were demonstrated.

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* Although the task difficulty level varied greatly over experimental conditions, in no case could the task be termed "easy". Reflecting this is the fact that out of a total of 10,800 trials run for all experiments, only 207 or less than 2% of the total trials were recorded as perfect.

**Wilson's (<u>24</u>) distribution - free chi-square technique is used throughout.

Period Groups	Pooled Experimental Conditions
A = 18 seconds	1.1, 1.4, and 1.7
B = 35 seconds	1.2, 1.5, and 1.8
C = 71 seconds	1.3, 1.6, and 1.9

An analysis was then conducted on the training performance differences between Period Groups A, B, and C. The over-all pooled group comparison between the period groups showed the performance difference to be statistically significant ($P < .01$) throughout the course of training. The differences between Period Groups A and C were statistically significant throughout training ($P < .01$). The differences between Period Groups B and C were statistically significant throughout training with the exception of the first five trials. The critical comparison is between Period Groups A and B. The differences between these groups were not significant ($P = .10$) until the 21st trial. For the final ten training trials, the differences between these groups were statistically significant ($P < .05$). It would appear then that the performance differences between the 18- and 35-second groups, although actually small, do become reliable after several training trials.

Transfer of Training. A distribution-free chi-square analysis was made for blocked transfer trials 31-35 and 36-40. The following probability values were obtained:

Blocked Training Trials	Total	Chi-Square Probability Values Row-Damping	Column-Period	Interaction Period x Damping
1-5	<.01	.50	<.01	.07
6-10	<.01	.40	<.01	.40

As in the case of the training trials, there appears to be no over-all damping effect while period variations result in statistically significant performance differences.

Advantage was again taken of the fact that the row (damping) effect was not statistically significant. The period groups were pooled as before, and an analysis was then conducted on the transfer performance differences between Period Groups A, B, and C. The obtained probability values are as follows:

Period Group Comparisons	Probability Values: Trials 31-35	36-40
A + B + C	<.01	<.01
A + B	<.01	<.01
A + C	NS	NS
B + C	<.01	<.01

These findings are interpreted to mean that during transfer there were statistically significant performance differences between the 18 and 35-second groups and 35 and

71 second-period groups. There were, however, no significant differences between the 18 and 71 second groups.

Of particular interest in the transfer data are the differences in performance during transfer between the experimental groups and the control group 1.5. Accordingly, comparisons were made between each experimental group and the transfer control group on blocked trials 31-35 and 36-40:

Blocked Transfer Trials	Probability Values by Experimental Groups								
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
31-35	$<.01$	.99	.05	$<.01$	-	.05	$<.01$	.99	$<.01$
36-40	.07	.99	.40	.40	-	.07	.07	.99	$<.01$

The inferences drawn from these results have already been discussed in the main text. Note may be made, however, of the fact that condition 1.9 performance is still reliably worse than that of the control group throughout the transfer trials.

APPENDIX VI

TABLE 9

Experiment 2: Means and Standard Deviations by Blocked Trials for Experimental Groups

	Blocked Trials	Nonpilot Subjects	Private Pilots	Instrument Pilots	Control Group
TRAINING TRIALS (Condition 9)	1-5	55.06* 13.56**	58.34 8.03	61.57 9.06	77.87 10.70
	6-10	57.42 6.41	62.61 12.38	59.93 8.70	101.35 14.68
	11-15	63.01 11.31	65.63 10.16	68.67 7.89	101.72 11.97
	16-20	63.00 5.50	64.92 13.85	66.20 9.07	114.40 9.28
	21-25	66.92 9.70	70.67 11.84	67.43 9.12	112.64 14.77
	26-30	68.15 13.90	70.46 12.00	68.74 15.02	111.18 16.15
TRANSFER TRIALS (Condition 5)	1-5	78.95 14.14	91.03 22.29	78.51 14.98	114.17 13.68
	6-10	91.64 12.70	92.52 22.68	73.70 19.12	113.64 11.20

* Mean time-on-target in seconds
** Standard deviation in seconds