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TRACKING PERFORMANCE AS A FUNCTION OF EXPONENTIAL DELAY AND LEARNING

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FOREWORD

This report represents a portion of the program of the Training Research Division of the Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories. Preparation of the report was accomplished under Project 1710, "Training, Personnel and Psychological Stress Aspects of Bioastronautics," with Dr. Eckstrand as Project Scientist.

The data were collected several years ago at Antioch College under Contract AF 18(600)-50 by Dr. Marvin Levine with the assistance of Mrs. Louise Doxtater. In addition to his participation in the planning of the research, Mr. John Senders designed and developed the apparatus. At the time the research was conducted the authors were members of the Behavioral Sciences Laboratory.

Dr. Ross L. Morgan is primarily responsible for reviving interest in the publication of this report. Drawing heavily upon materials prepared earlier by Dr. Levine, he prepared the final manuscript and guided its publication. The authors thank Dr. Gordon A. Eckstrand for his guidance in the conduct of the research and the review of the manuscript.

This technical report has been reviewed and is approved.

WALTER F. GRETHER, PhD
Technical Director
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ABSTRACT

Eighty subjects performed a one-dimensional compensatory tracking task for 55 one-minute trials. The subjects were divided into five separate groups and each group performed the task with a different exponential delay between the control input and the display, a dot of light on a cathode ray tube. The time constants for the exponential delays were 0.015 seconds, 0.150 seconds, 0.900 seconds, 2.100 seconds and 3.000 seconds respectively. The results indicate that time-on-target scores decrease with increasing delay. For delays greater than 0.150 seconds, the decrease is linear. There is a sharper decrease in performance from 0.015 seconds delay to 0.150 seconds delay than for other portions of the function. Increased practice changes the level, but not the shape, of the total function. The effects of delay and learning were within the same range, indicating that a given level of system performance often can be achieved either by altering the delay or by training the operator. Hówever, performance is maximized if delay is reduced and the operator is trained.

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SECTION I

INTRODUCTION

One characteristic of complex man-machine systems is that there usually is some interval of time between the control manipulations by the operator and the corresponding output of the system. To the operator the delay usually appears between his manipulation of a control input and a change in some indicator which describes the state of the output. The existence of such control-displays delays has created a need for research on the effects of delay upon the performance of the operator. The research performed on this problem (refs 1, 2, 3, 4) has, in general, indicated that performance deteriorates with increases in delay. It is important to determine as exactly as possible the nature of the functional relationship and how this changes with various parameters. Such information along with cost considerations will provide the best basis for deciding when it will be most profitable to tolerate, shorten, or eliminate delays.

Of particular interest in Air Force research are the effects of exponential delay, since such delays frequently occur in the control systems of aircraft. Exponential delay may be defined as a delay having the following effect upon a system. For a given step-input the change in the output indicator begins immediately, but its final resting position is reached exponentially. The amount of delay is measured in terms of the time required for the output indicator to travel approximately 63%[1] of the total output generated. The length of time thus specified is called the time-constant. The effects of two exponential delays are illustrated in figure 1. Note that the amount of delay may be specified conveniently by the time-constant. Throughout the remainder of the report, the amount of delay will be referenced by a given number of seconds, the time-constant.

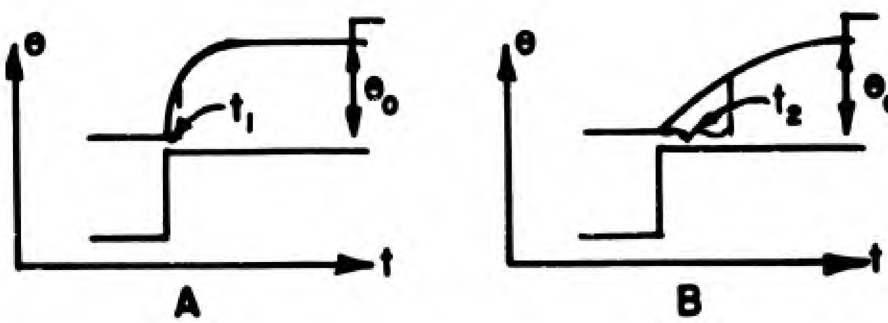

Figure 1. Two different input-output relations caused by two different exponential delays in the system. In example A, following a step input, 63% of the output displacement (θ_0) occurs in time t_1; in example B, 63% of θ_0 occurs in time t_2. These times, or time constants, define the amount of delay in the system.

1. The exact figure is 1/e, or 1/2.7182818285, or 63.4901852%.

An earlier experiment (ref 5) investigated the effects of exponential delay upon tracking performance. Because the conclusions generated by that experiment have relevance to the present research, the experiment will be described in detail.

Eleven subjects performed a one-dimensional, compensatory tracking-task. The apparatus employed was the same as that used in the present research. A more complete description of it, therefore, may be found in section II under "Apparatus." Exponential delay was inserted between the subject's control knob and his display. The delay could be varied from 0.015 seconds to 3.000 seconds. Eight delays between 0.015 and 2.700 were selected, and all eight delays were presented to all 11 subjects eight times in counterbalanced sequences. The data from all 11 subjects were combined to produce a function relating time-on-target (TOT) to amount of delay. It was concluded that tracking performance deteriorates as delay increases; that for delays greater than 0.150 seconds, the decrease in TOT is linear with increase in delay; and that for delays less than 0.150 seconds the decrease has a steeper slope than the rest of the function.

The present experiment was designed to obtain evidence relevant to two questions: (a) Will the conclusions be confirmed if the function is generated by having different groups of subjects each track with a single delay? and (b) what is the effect of learning upon the function?

SECTION II

METHOD

APPARATUS

The apparatus used in this study constituted a one-dimensional compensatory tracking task. The problem display was a pinpoint of light of less than 1-mm diameter on the face of a cathode ray oscilloscope. A rotating cam drove this blip in the horizontal diameter through a maximum of $\pm$ 2 inches from center. The cam contour was the sum of three sine-waves having frequencies of 3, 5, and 11 cycles per minute, and equal amplitudes. The cam rotated at one rpm.

The subject could exercise independent control over the blip by turning a knob, 2.25 inches in diameter, which rotated on a horizontal axis. The control-display ratio was 30° of knob-rotation per inch of spot movement. The subjects task was to keep the blip between two vertical lines which were inscribed 0.20 inch apart at the center of the display. An R-C filter which permitted the production of delays ranging from 0.015 to 3.000 seconds was inserted between the subject's control movement and the movement of the blip.

A clock recorded the amount of time that the spot was maintained between the two vertical lines. The clock operated for all but the first and last five seconds of each trial. A trial began when the experimenter started the problem cam, and ended after 1 minute, when the cam automatically stopped.

In general, the design of the apparatus was such as to yield a mean random score of 4.0 seconds TOT. The random score is the clock reading when the problem is inserted for one trial and the knob is stationary at the zero point.

DESIGN[2]

Eighty right-handed subjects were distributed into five groups in the manner described in table I. Each subject performed for 55 one-minute trials during three experimental sessions. Trials 1-25 were run during the first session, trials 26-50 during the second session, and trials 51-55 during the third session. Whenever possible, the sessions for each subject were run at the same hour on three successive days.

Prior to the training trials on day 1, each subject received five one-minute matching trials. Ten subjects in each group were matched on the 3.000 second

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2. It should be indicated that the experiment described here formed a portion of a larger study on transfer of tracking performance (ref 1). The present report represents a further analysis of data collected in the earlier study. As a result, the design is not as simple as it would have been if only the present problems had been studied.

delay; the remaining subjects were matched on the 0.015-second delay.

TABLE I

EXPERIMENTAL DESIGN*

Day	Trials	GROUP				
		1 (n=20)	2 (n=10)	3 (n=20)	4 (n=10)	5 (n=20)
1	1-25	0.015	0.150	0.900	2.100	3.000
2	26-50	0.015	0.150	0.900	2.100	3.000
3	51-55	0.015	0.150	0.900	2.100	3.000

* (cell entry is delay in seconds)

PROCEDURE

On the first day the subject was seated alone with the cathode ray oscilloscope and the control knob. The oscilloscope screen was at eye level, approximately 14 inches away from the subject. The control knob was to the right of the display. The delay was set at either 3.000 or 0.015 seconds depending on which matching delay the subject received. He was told that each trial would be 1 minute long, that during this time the spot would move continuously, and that his task was to manipulate the control knob so that the spot stayed between the inscribed target lines.

The experimenter then went to an adjacent room containing the problem generating and scoring equipment. He started the cam rotating, and simultaneously signalled the subject to begin tracking. Each subject was then given five one-minute trials on the matching delay with a 30-second rest between trials. Following these five trials the subject was given a 2-minute rest period. During this interval the experimenter assigned the subject to one of the five groups on the basis of his total TOT score for these five trials. The experimenter then inserted the training delay appropriate to the group to which the subject had just been assigned, and instructed each subject that there would be a change in some of the conditions of the experiment and that he was to continue tracking as he had been doing. Each subject was then given 25 one-minute trials on the delay appropriate to his group. These and all subsequent trials were given in blocks of five trials with a 2-minute rest between each block and a 30-second rest between trials within blocks. The experimenter recorded the scores and announced the percent of

TOT to the subject during the 30-second pauses. The first session concluded with the fifth block of training trials.

The second session began with a 1-minute warmup period. During this time the subject moved the spot from one side of the scope face to the other at the experimenter directions. The problem cam was stationary and the delay was the one at which the subject was training. Each subject was then given instructions similar to those presented at the beginning of the first session, and five more blocks of training trials were presented.

The third session began with a similar 1-minute warm-up period. The initial instructions were then repeated and one five-trial block with the training delay was presented. This concluded the training.

SECTION III

RESULTS AND DISCUSSION

Performance during the matching trials is summarized in tables II and III. Analysis of variance of the matching scores on the 3.000-second delay yielded an F of .051. A comparable analysis for the matching trials with the 0.015-second delay yielded an F of .006. In both cases the variance within the groups was homogeneous. Apparently, the groups were very well equated in terms of initial tracking ability.

The mean TOT scores per block of trials for each group are shown in figure 2. Two characteristics of the learning curves are to be especially noted. First, the means are distributed in an orderly manner with respect to both the delay variable and the blocks of trials. Second, the improvement within each session is relatively small, whereas the increments between sessions are large. This is a rather common finding in motor skills research, particularly when practice is massed. It occurred in this experiment, however, in spite of what was thought to be a relatively distributed schedule----30-second rests between 1-minute trials and 2-minute rests after every five trials.

TABLE II

MEAN TOT SCORES AND VARIANCES FOR THE MATCHING TRIALS WITH 3.000-SECOND DELAY

	GROUP				
	1(0.015)	2(0.150)	3(0.900)	4(2.100)	5(3.000)
Mean TOT	13.63	13.19	13.50	13.38	13.71
σ^2	7.34	6.51	7.50	7.92	8.00

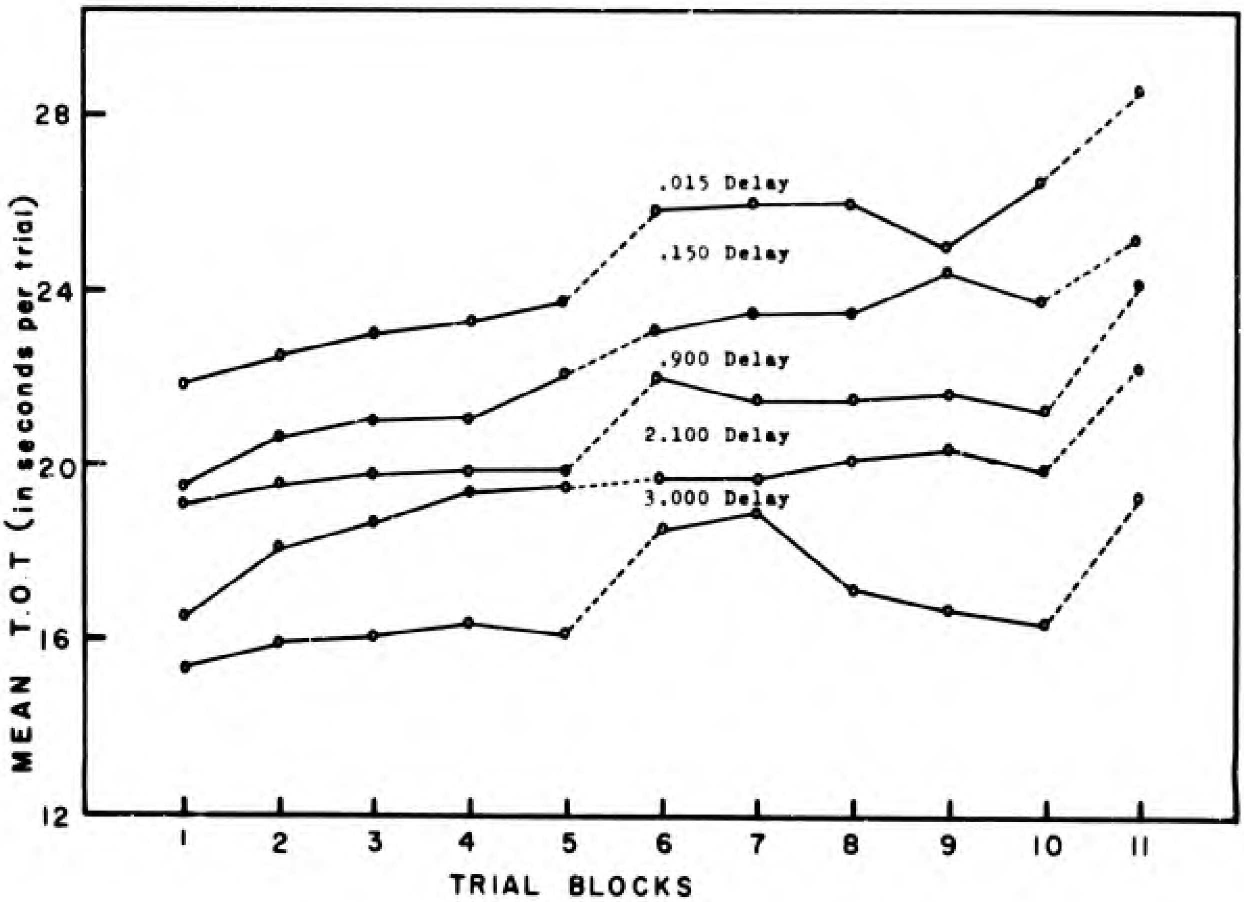

Figure 2. Learning Curves for the Five Groups of Subjects. Changes in Mean TOT per Block of Five Trials for Each Delay Time.

TABLE III

MEAN TOT SCORES AND VARIANCES FOR THE MATCHING TRIALS WITH 0.015-SECOND DELAY

	GROUP		
	1(0.015)	3(0.900)	5(3.000)
MEAN TOT	22.49	22.48	22.63
σ^2	8.06	5.92	10.00

TABLE IV

MEAN TRIAL TIME ON TARGET SCORE FOR GROUP PER DAY

	GROUP				
	1(0.015)	2(0.150)	3(0.900)	4(2.100)	5(3.000)
Day 1 (Trials 1-25)	22.90	20.84	19.57	18.21	16.02
Day 2 (Trials 26-50)	25.20	23.82	22.06	20.36	17.88
Day 3 (Trials 51-55)	28.40	24.84	24.04	22.47	18.85

The data were combined to yield mean TOT scores per group per day and are presented in this form in Table IV. In figure 3, these TOT scores are graphed as a function of delay, with days as a parameter. Included in the figure, for the sake of comparison, is the curve from the earlier experiment (ref 5). This is the lowest function on the graph. The dotted line are the lines of best fit for the last four points of each curve. Figure 3 reveals that the finding of the earlier equipment (ie, the initial sharp decrease in performance and the linear decrease with delays greater than 0.150 seconds) is also found on each day of the present experiment. There is one minor change, however. As Table V indicates, the best-fit line of the linear portion of the curve

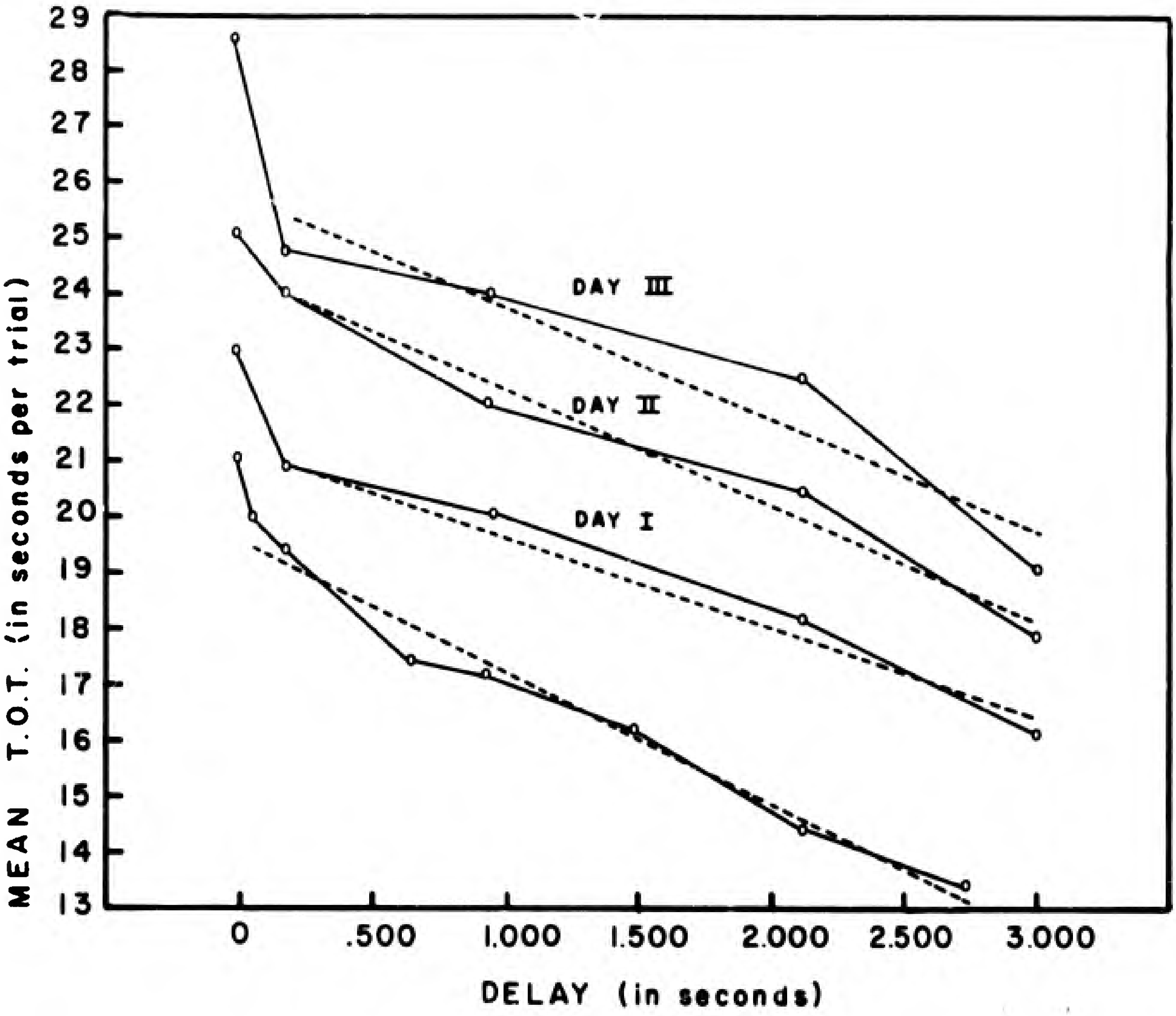

Figure 3. Tracking Performance as a Function of Delay on Each of Three Successive Days.

(dotted line in figure 3) of day 1 has a lower negative slope than that of the earlier curve. This difference may be due to differences in the experimental procedures employed, but there is reason to believe that it is at least partly caused by residual transfer effects from the matching tasks in the present experiment. Independent transfer evidence (ref 1) indicates that the subjects who trained on longer delays should have benefitted from the matching trials on the shortest delay; whereas subjects who trained on the short delays would have received no similar benefit from having been matched on the longest delay. Therefore, the scores on the longer delays would be relatively augmented, and the overall slope would be lessened. The hypothesis that the slope of the curve for day 1 is lower because of the effects of matching is borne out to some extent in the curves for days 2 and 3. The slopes for these days have increased, which is what would be expected if there had been a transfer effect and this effect tended to dissipate with successive days of practice.

TABLE V

SLOPES OF THE BEST-FIT LINES SHOWN IN FIGURE 3

	Previous Experiment	Present Experiment		
		Day 1	Day 2	Day 3
Slope	-2.26	-1.61	-1.99	-2.00

These results support a conclusion of the earlier report (ref 5). It was concluded there, in connection with the general problem of reducing delays in operational situations, that "while for most of the (delay) dimension the skill will increase linearly with a decrease in the delay, the reduction of very short delays will yield a relatively greater increase in skill. This fact suggests that, all other things being equal, it may be especially beneficial to consider the reduction of very short delays."

The present data on the effects of learning suggest another conclusion which may have value for the design engineer. From table IV it should be noted that by day 3 the group with next to the longest delay performed almost as well as the group with the shortest delay performed on day 1. Similar comparisons can be made among curves shown in figure 3. If a given level of proficiency is required two techniques can be used to obtain it. One technique is to adjust the delay, the other is to train the operator. Sometimes one technique will achieve greatest efficiency (output/cost) while other times the other technique will be more appropriate.

If the aim is to have the operator perform as accurately as possible in the task, then the effects of learning have no influence on the decision to reduce delays. The proper decision is to reduce the delay and train the operator.

SECTION IV

CONCLUSIONS

1. The results of an earlier experiment (ref 5) have been confirmed. These results are as follows:

   a. Time-on-target decreases with increasing delay.

   b. For delays greater than 0.150 seconds, the decrease in TOT is linear with increase in delay.

   c. For delays less than 0.150 seconds, the decrease has a steeper slope than the rest of the function.

2. The effect of learning is to raise the level of the total function without substantially changing its form.

3. The effects of delay and learning are within the same range of magnitude. A given level of performance often can be achieved either by altering the delay or training the operator. Which technique is more appropriate depends upon many facets of a design or operational problem. However, if the aim is to have the operator perform as well as possible, then the effects of training have no influence on the decision to reduce delays. Regardless of the level of training, the same reduction in delay will yield the same increment in system performance.

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13 ABSTRACT

Eighty subjects performed a one-dimensional compensatory tracking task for 55 one-minute trials. The subjects were divided into five separate groups and each group performed the task with a different exponential delay between the control input and the display, a dot of light on a cathode ray tube. The time constants for the exponential delays were 0.015 seconds, 0.150 seconds, 0.900 seconds, 2.100 seconds and 3.000 seconds respectively. The results indicate that time-on-target scores decrease with increasing delay. For delays greater than 0.150 seconds, the decrease is linear. There is a sharper decrease in performance from 0.015 seconds delay to 0.150 seconds delay than for other portions of the function. Increased practice changes the level, but not the shape, of the total function. The effects of delay and learning were within the same range, indicating that a given level of system performance often can be achieved either by altering the delay or by training the operator. However, performance is maximized if delay is reduced and the operator is trained.

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