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THE EFFECT OF VARIATIONS IN CONTROL-DISPLAY RATIO AND EXPONENTIAL TIME DELAY ON TRACKING PERFORMANCE

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FOREWORD

This report was prepared by the Psychology Branch of the Aero Medical Laboratory, Directorate of Research, Wright Air Development Center, for a task under Project 7197, "Human Engineering Factors in the Design of Training Equipment" with Dr. Gordon A. Eckstrand acting as Project Scientist. The task was 71635, "Simulation Requirements of Training Equipment" with Dr. Marty R. Rockway acting as Task Scientist. The experimental data were collected at the Ohio State University, Columbus, Ohio under Contract No. AF 18(600)-78 and under the direction of Dr. Delos D. Wickens. Mr. Armand N. Chambers supervised the collection and analysis of data.

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ABSTRACT

Previous investigations of the effects of control-display (C/D) time delay on the performance of continuous tracking systems have all demonstrated a decrease in system performance with increasing delay. A rational analysis of the joint effects of C/D gear ratio and exponential time delay suggests that the effects of increasing exponential delay depend upon the particular C/D ratio employed. The present study was designed to demonstrate this interaction between the effects of C/D ratio and exponential time delay on the performance of a two-dimensional tracking task.

The experimental results verified the predicted interaction. More specifically, it was demonstrated that with the "highest" C/D ratio (where a given control input produced the smallest display change) increasing delay effected a monotonic degradation in system performance. But, with the "lowest" C/D ratio (where a given control input produced the largest display change) increasing delay effected a monotonic improvement in system performance. With an intermediate ratio system performance first increased and then decreased with increasing delay.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Jack Bollerud

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Colonel, USAF (MC)
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THE EFFECT OF VARIATIONS IN CONTROL-DISPLAY RATIO AND EXPONENTIAL TIME DELAY ON TRACKING PERFORMANCE[1]

INTRODUCTION

Recently, considerable effort has been devoted to the study of man as an element in a tracking system. The procedure, quite often, has been to manipulate certain characteristics of the tracking situation and, from the effects of these variations on system performance, to infer their effects on the performance of the man.

Among the characteristics of man-machine tracking systems which have been demonstrated to effect system performance are control-display ratio and control-display time delay. Control-display ratio is defined in terms of the magnitude of display change produced by a given control input. Control-display time delay is defined in terms of the time required to produce a particular display response following a step input of the control. In subsequent paragraphs the general findings concerning the effects of experimental variations in these two parameters on the performance of man-machine tracking systems will be discussed.

<u>Control-display ratio</u>. Experimental variations of control-display (C/D) ratio have been effected in a number of ways (1). The techniques employed have included optical magnification of the display, the addition of derivatives to the control output, variation of the shape of the function relating control movement to display movement, and "mechanical" alteration of the C/D (gear) ratio. It is this latter type of variation with which we are concerned. In this situation the displayed error (problem amplitude) remains constant, but the amplitude of the control input required to eliminate it is varied.

In general, investigations of the effect of variations in C/D (gear) ratio on tracking performance have revealed that for each tracking situation there is an optimal C/D ratio. There is also some evidence (4) that the exact value of the optimal ratio depends on the nature of other system characteristics.

Helson (4), has reported a number of studies involving compensatory tracking with a handwheel control. The results of these studies indicated that tracking accuracy increased, up to a point, with an increase in the required rate of handwheel turning. However, the optimal turning rate varied as a function of the values of other system parameters (e.g., handwheel radius).

1. Previously distributed as a short laboratory note, "The effect of variations in control-display ratio and exponential time delay on the performance of a tracking task (a preliminary report)," dated 11 October 1954.

Gibbs (3) performed a study to determine the optimal C/D ratios for both isometric (pressure) and isotonic (free-moving) velocity control levers. His findings revealed that tracking efficiency first increased and then decreased with an increase in the rate of display movement resulting from a given control input.

<u>Control-display time delay</u>. Although the relationship of system output to control input might assume any shape over time, to date only three types of C/D time delays have been subjected to systematic laboratory research. These types have been classified as transmission, exponential, and sigmoid time delays. The differences in the effects of these three types of delays on system output are illustrated in Fig. 1.

In a system with transmission delay the output indicator follows the control input by a given amount of time (specified by the time constant), and the output has the same rate characteristics as the input. On the other hand, with an exponential delay a control input produces an <u>immediate</u> partial change in the output indicator, but the full effect of the input occurs as an exponential function of time. The exponential time constant is defined in terms of the time required for the output indicator to attain 63% of its final value. In a system with sigmoid delay a control input also produces an immediate partial change in the output, but the output reaches its final value as a sigmoid function of time. The definition of the sigmoid time constant is identical to that for exponential delay (2).

Several recent experiments have investigated the effect of variations in C/D time delay on tracking performance. Despite a great diversity of experimental situations, the data from all of these studies have demonstrated that increasing time delay effected a monotonic degradation of system performance.

Warrick (6), using a compensatory tracking task with a position control, varied the amount of transmission type time delay from 0 to .32 sec. He found that tracking performance, as measured by time-on-target, decreased with an increase in time delay.

Levine (5) varied the amount of exponential delay between control and display in a compensatory tracking task from 0 to 2.7 sec. His results indicated a decrease in tracking performance with an increase in delay.

Conklin (2) carried out an extensive investigation of the effects of exponential and sigmoid time delays on tracking performance. In addition to the two time delays, Conklin studied both compensatory and pursuit tracking and a variety of problem inputs. With respect to the general effect of increasing time delay, his results verified those of previous studies. That is, for both types of time delay functions, increasing delay effected a monotonic degradation of tracking performance.

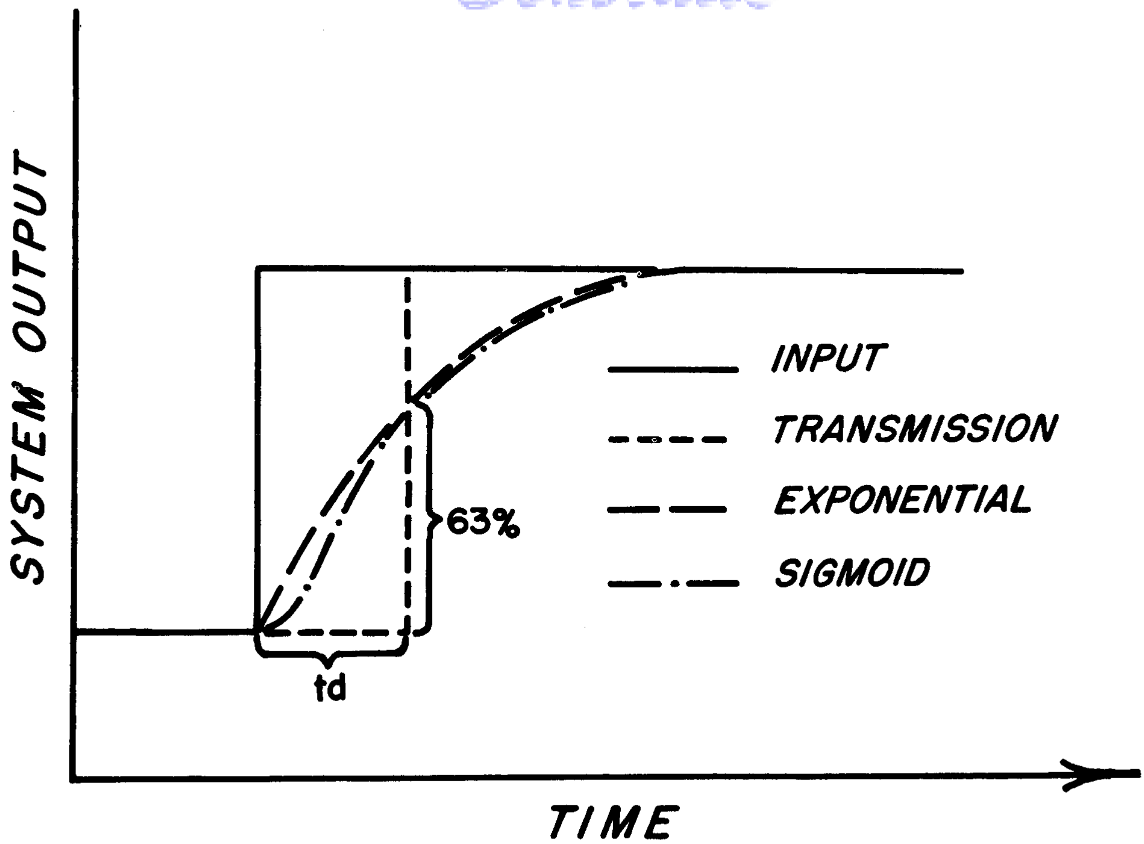

Figure 1. The system response to a step input of the control for three types of control-display time delays with the same time constants (td).

Interaction of C/D ratio and exponential delay. The author is aware of only one previous investigation specifically designed to study the interaction of C/D ratio and time delay. This experiment is described in an unpublished intra-laboratory note by Warrick (7). Using a one-dimensional compensatory tracking task, Warrick varied exponential time delay, target frequency, and C/D ratio. He found that both increasing delay and increasing target frequency produced a significant decrease in system performance. However, neither the effect of C/D ratio alone, nor the interaction of C/D ratio and time delay were significant.

Despite Warrick's failure to demonstrate a significant interaction between C/D ratio and exponential time delay, a common-sense analysis of the effects of extreme values of these two variables strongly suggests that they do interact. In fact, it would appear that the general finding of a monotonic degradation in system performance with increasing exponential time delay is merely a special instance of a more complex relationship. Since, for certain C/D ratios, it seems reasonable to assume that an increase in delay will improve the performance of a man-machine tracking system.

Prior to an explication of the analysis referred to above two observations will be made which are relevant to subsequent arguments:

1. From the operator's point of view, the most important effect of increasing exponential delay appears to be the alteration in the characteristics of the control input required to produce a given display response. One important consequence of this alteration in control properties with increasing exponential delay is an increase in the magnitude of the control input required to produce a particular display change in a given time. (Of course, the total effect of increasing exponential delay is more complex than a simple increase in the amplitude of the required control input.)

2. When the human operator refers to "control sensitivity," he seems to be making a relative judgement concerning the magnitude of display change per time in response to a given control input. Thus, control sensitivity should be variable by the manipulation of C/D ratio and/or exponential time delay. (This is not to suggest that these two methods of manipulating sensitivity are equivalent, but only that, phenomenally, they appear to be somewhat similar.)

For purposes of exposition, the analysis will be couched in terms of a typical one-dimensional compensatory tracking system with a position control. The tracking display is a spot of light on the face of a cathode-ray tube (CRT). The spot is driven from a null position at the center of the CRT by the inputs from a problem generator producing a simple sinusoid of 1/2 cycle per second. The maximum excursion of the spot when driven by the problem generator is $\pm$ 2 in. from its null position. The operator's task is to keep the display spot at the exact center of the CRT by compensating for the inputs of the problem generator. The operator's control is an isotonic (free-moving) aircraft joystick which has a range of movement of $\pm 10^{\circ}$ from its centered position. The system is provided with a means for adjusting the control gain (C/D ratio) from zero to infinity. The system is also provided with a means for varying the exponential time delay between control and display from zero to infinity.

Assuming the system described above, we shall now proceed with an intuitive analysis of the effects of variations in C/D ratio and exponential time delay on system performance. For example, imagine that the system time constant is zero and the C/D ratio is adjusted so that the smallest possible voluntary input of the operator produces a display movement more than twice as great as the maximum problem amplitude. It is clear that this control condition would be too sensitive for manual tracking, since any voluntary input of the operator would result in an overshoot which would increase, rather than decrease, system error. Therefore, it seems reasonable to assume that a reduction in control sensitivity, up to a point, would effect an improvement in system performance. As suggested previously this reduction might be achieved either by increasing[2] the C/D ratio or by increasing the exponential time delay. If a decrease in sensitivity were obtained by increasing the C/D time delay, then it should be possible to demonstrate an improvement in tracking performance resulting from an increase in time delay. Of course, if the time delay were increased indefinitely control effectiveness would eventually be reduced to the point where system performance would begin to decrease with further increases in delay.

The prediction of an improvement in man-machine system performance with increasing delay requires certain assumptions concerning the response limitations of the human operator. The prediction of an eventual decline in system performance with increasing delay, on the other hand, may be justified completely in terms of a degradation in the transmission properties of the machine, quite apart from any considerations of operator functioning.

For example, assume that the time delay of the system is again zero and the C/D ratio is such that the maximum deflection of the control stick produces a display movement which is at least equal to the maximum problem amplitude but is less than infinite. Perfect (i.e., zero error) tracking demands that the control be manipulated so as to transmit inputs which will exactly compensate for both the frequency and amplitude characteristics of the problem signal. It is obvious, for the range of C/D ratios specified, that the system time constant may be increased to a value such that the display spot can not be moved (sinusoidally) from a position 2 in. on one side of the CRT to a position 2 in. on the other side in one second. When this delay value is reached zero-error tracking of the 1/2 cycle per second problem input is no longer possible, and further increases in delay will effect a monotonic degradation in the theoretical performance ceiling of the system.

This latter observation is not intended to suggest that all of the degradation in system performance which has been demonstrated to occur as a consequence of increasing exponential time delay can be attributed to a reduction in control effectiveness. For even under control conditions which would theoretically permit perfect tracking, the presence of an exponential delay may affect the perceptual, motor, and/or ideational requirements of the task in such a way as to effect a reduction in operator efficiency.

The present study. The present study was designed to investigate the joint effects of C/D ratio and exponential time delay on the performance of a two-dimensional compensatory tracking system. Actually, it might be more appropriate to state that the present study was designed to "demonstrate" the interaction

2. Control-display ratio is conventionally expressed as a numerical fraction (C/D). Thus, the larger the ratio, the smaller the magnitude of display change produced by a given control input. And, conversely, the smaller the ratio, the larger the magnitude of display change.

of C/D ratio and exponential time delay, since the experimental conditions were selected so as to maximize the probability of verifying the interaction predicted above.

METHOD

Apparatus. The experimental apparatus consisted of a two-dimensional compensatory tracking device mounted in a rough simulation of an aircraft cockpit.

The tracking display was a flourescent spot on the face of a 5 in. cathode-ray tube (CRT). The CRT was mounted behind an aperture in a vertical instrument panel perpendicular to the subject's (S's) line of sight and at a viewing distance of about 28 in.

The tracking control was a spring-centered aircraft joystick with which the S could move the spot about the face of the CRT in two-dimensions. Fore-aft motions of the stick moved the spot vertically, and right-left motions moved it horizontally. The exponential time delay was produced by two variable R-C filters interposed in the link between the S's control and the differential (where the S's input is compared to the problem input and the difference acquired for display). Control-display ratio was varied by means of two rheostats in the control circuit. The settings of the rheostats determined the amount of spot movement which resulted from a given control deflection. The control stick protruded thru a rectangular opening in a metal plate bolted to the deck of the cockpit. The dimensions of the opening were such as to restrict the range of stick movement to $\pm$ 11° from the vertical in both dimensions. Since the length of the stick, as measured from the fulcrum, was 28½ in., the total range of movement of the top of the stick was 10.9 in.

The problem signals to the display were generated by two low torque potentiometers driven by cam followers riding on the peripheries of masonite cams which rotated at 1 rpm. The cam contours were smoothed approximations of the sum of three sine waves whose frequencies were 3, 5, and 11 cycles per min. and whose amplitudes were equal. (The addition of the sinusoids was made with the 3 cycle wave displaced 180° in phase. This produced cams with a few extremely abrupt changes in slope which were smoothed out to reduce the complexity of the problem and to allow the cam followers to ride freely.) The cams for both dimensions were identical but were mounted so that their inputs were 90 degrees of cam (i.e., 15 sec.) out of phase. The maximum excursion of the display spot when driven by the problem cams was 33/16 in. from the center of the CRT in each dimension.

During performance of the tracking task the S's job was to keep the display spot within a 3/8 in. square target area outlined in india ink at the center of the display face. Three .001-min.

TABLE 1

The Conditions of the Experiment

C/D Time Delay (sec.)

		.3	.6	1.5	3.0
	1:3				
C/D	1:6		N=8		
Ratio	1:15				
	1:30				

Standard Electric Clocks were used to record time-on-target information. One clock recorded the time the spot was within a scoring band 3/8 in. wide and symmetrical about the vertical axis of the CRT. A second clock recorded the time the spot was within a 3/8 in. scoring band about the horizontal axis. The third clock recorded the time the spot was within both scoring bands simultaneously (i.e., within the square target area).

<u>Subjects</u>. The <u>S</u>s were eight (seven right- and one left-handed) male adults. Only individuals with considerable prior tracking experience on the apparatus used in this study were selected as <u>S</u>s. Each <u>S</u> served in all of the 16 experimental conditions.

<u>Conditions</u>. The experimental schema is presented in Table 1. Four levels of each of the two experimental variables were selected, and all combinations of these resulted in a total of sixteen experimental conditions. The four time delay constants were .3, .6, 1.5, and 3.0 sec.; and the four C/D ratios were 1:3, 1:6, 1:15, and 1:30.

The notation of C/D ratio in the form 1:X should be read as "1° of control deflection produced X/16 in. of spot movement." The relationship between control deflection and spot movement was essentially linear. Therefore, in the case of a C/D ratio of 1:3, a 1° deflection of the control moved the spot 3/16 in.; a 2° deflection moved the spot 6/16 in. (i.e., 2 x 3/16 in.); a 3° deflection, 9/16 in....; and an 11° deflection, 33/16 in.

It will be recalled that the maximum displacement of the spot produced by the problem signal was 33/16 in. from the central axes of the CRT. Thus, with the highest C/D ratio (1:3) it required full stick deflection (11°) to <u>completely</u> compensate for the maximum spot displacement.[3] On the other hand, with the lowest C/D ratio (1:30) it required only 1.1° of control deflection to completely nullify the maximum problem input.

Procedure. The sixteen experimental conditions were arranged in a 16 x 16 Latin square. The square was generated so that, for the square as a whole, each experimental condition preceeded and followed every other condition once and only once. In addition, the sequences in the first eight rows of the square were the reverse of those in the second eight rows. A systematic square with the properties described was selected because it was felt that such a design afforded the best scheme for distributing any order effects equitably over all sixteen conditions.[4]

Both the assignment of conditions to Latin letters and the assignment of Ss to sequences of conditions was made randomly. In the case of the Ss, the assignment was actually to two sequences, one being the reverse of the other.

Each S served for two days. On both days the S practiced for five trials with each of the sixteen control conditions. The order of experiencing conditions on Day 2 was the reverse of that on Day 1, so that an ABBA type of counterbalancing was effected. On each day practice was distributed as follows: Four blocks of (five) trials, 15 min. rest interval, four blocks of trials, 1-hr. rest, four blocks of trials, 15-min. rest, and four blocks of trials. Trials were 1 min. in length, the inter-trial rest interval was 30 sec., and the inter-block rest interval was 2 min.

The S performed the tracking task while seated in a simulated cockpit which was housed in a sound-proof cubicle. A low level of glare-free illumination was provided by a shielded 60-watt bulb placed behind the S. A few seconds prior to start of each trial the experimenter (E) would say "Ready." This was the signal for the S to center the spot within the target area and to prepare to track. During the intervals between trials the S was permitted to manipulate the stick as much as he wished to get the "feel" of the control-display condition. The S remained seated in the cockpit during the 30-sec. and 2-min. rest intervals but left the cockpit and the cubicle during the 15-min. and 1-hr. rests.

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3. Since the scoring bands extended 3/16 in. on each side of the central axes, it actually required less than full stick deflection to activate the scoring clocks.
4. It is recognized that if precise normative data were desired a more satisfactory procedure would have been to use sixteen independent groups of Ss.

TABLE 2

Mean Percent Time-on-Target Scores for Each Combination of C/D Ratio and Time Delay

		C/D Time Delay (sec.)			
		.3	.6	1.5	3.0
	1:3	52	45	25	10
C/D	1:6	64	69	68	36
Ratio	1:15	57	67	70	70
	1:30	44	55	65	72

RESULTS

Two types of experimental data were obtained. During the course of the experiment proper, quantitative data in the form of time-on-target scores were collected for all Ss. Following completion of the regular experimental program, graphic records of tracking error and control movement were obtained from a single highly proficient S.

Time-on-target scores. Three different cumulative time scores were recorded during each 1-min. trial throughout practice. One score indicated the time that the display spot remained within the vertical scoring band, a second score indicated the time within the horizontal band, and a third indicated the time within both bands simultaneously (i.e., within the square target area). Since all three sets of scores lead to the same conclusions, only the analyses of the simultaneous time-on-target (TOT) scores will be described.

The mean percent TOT scores for all conditions are presented in Table 2. Each mean is a measure of group performance for both days of practice and is the average of 80 individual scores, 10 for each of the eight Ss. The mean scores for each day separately are tabled in the Appendix.

An analysis of variance of the TOT scores is summarized in Table 3. Using the remainder mean square as an error term, all of the F-ratios, except that for the interaction of Ss and time delays, are significant. Because of the significant interactions, the main effects of C/D ratios and time delays are not amenable to exact statistical test. However, if it is assumed that the experimental

TABLE 3

Analysis of Variance of the Mean Percent Time-on-Target Scores

Source of Variance	df	Mean Square	F	p
Ratio (R)	3	679,680	310.20	<.01
Delay (D)	3	90,577	41.34	<.01
Subject (S)	7	123,986	56.59	<.01
R x D	9	181,152	82.68	<.01
S x R	21	5,083	2.32	<.01
S x D	21	1,488	0.68	n.s.
Remainder	63	2,191		
Total	127			

Ss were a random sample from some specified population, then the mean square for the interaction of Ss and ratios may be used as an error term to test the main effect of Ss. However, the F-ratio resulting from such a comparison--although significant--probably is not of general interest, since it merely indicates the presence of individual differences. No attempt was made to analyze the data for the various levels of C/D ratios and time delays separately, since it was felt that differences of practical significance among conditions were adequately revealed in the graphical and tabular presentations of mean TOT data.

The group performance curves in Fig. 2 clearly indicate the predicted interaction between C/D ratio and time delay. The most dramatic example of this interaction is displayed by the curves for the 1:3 and 1:30 ratios. With the 1:3 ratio tracking performance decreases monotonically with increasing exponential time delay, while with the 1:30 ratio tracking performance increases monotonically with increasing time delay. The curve for the 1:6 ratio, which first rises and then falls, undoubtedly forecasts the eventual shapes of the 1:15 and 1:30 curves with further increases in delay. It will be noted that the amount of delay which is optimal for tracking increases with a decrease in C/D ratio.

It is interesting to compare the relative efficiency of

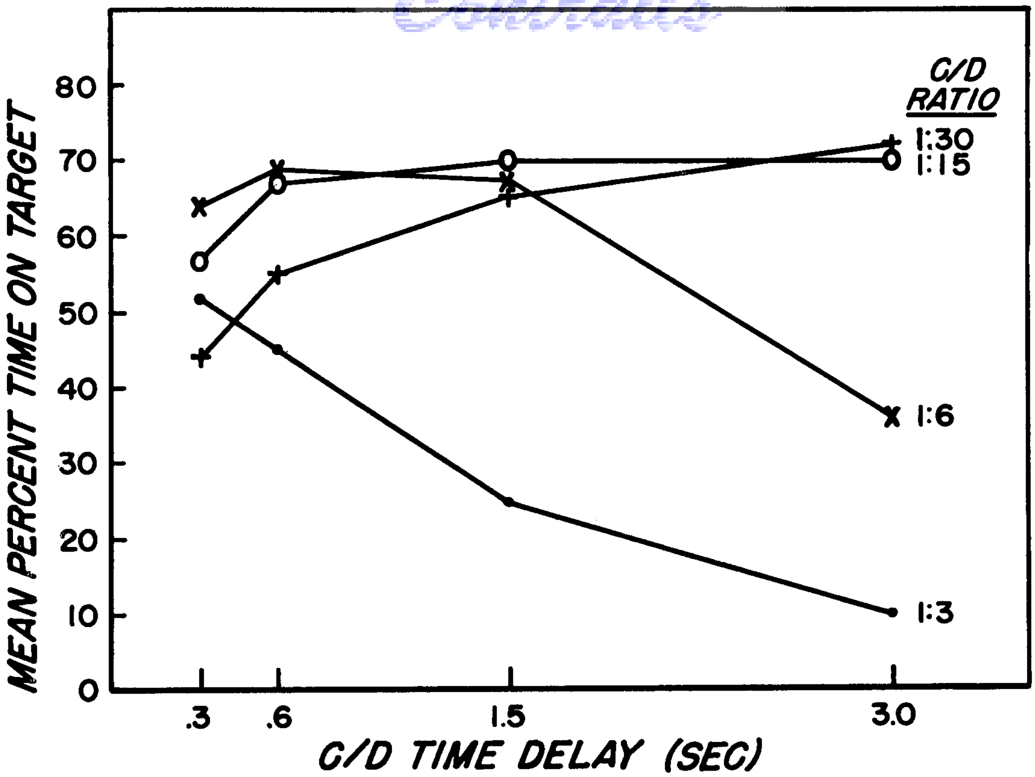

Fig. 2. Mean percent time-on-target scores for each combination of C/D ratio and time delay.

tracking with the various C/D ratios at particular values of exponential delay. For example, when the system time constant is greatest (3.0 sec.), it appears that the lower the C/D ratio the better the performance. But with a decrease in delay, the relationship systematically changes until at the minimum delay (.3 sec.) the poorest performance is obtained with the lowest C/D ratio. Unfortunately, it was not possible to reduce the time delay to zero without a deterioration in the quality of the CRT presentation. Therefore, we can only speculate that the relationship between tracking performance and C/D ratio with zero delay would be the reverse of that obtained with 3.0 sec. delay.

Graphic records. Following completion of the main experimental schedule, simultaneous pen recordings of display error and control-stick movement during tracking were obtained from a single highly proficient S. Although S tracked the regular two-dimensional problem, records were taken of movement in the horizontal (right-left) dimension only. Samples of the obtained records for the 1:3 and 1:15 ratios are reproduced in Fig. 3 and Fig. 4.

The records presented were all taken during the first 32-sec. portion of the regular 1-min. trial. The "problem input" tracing

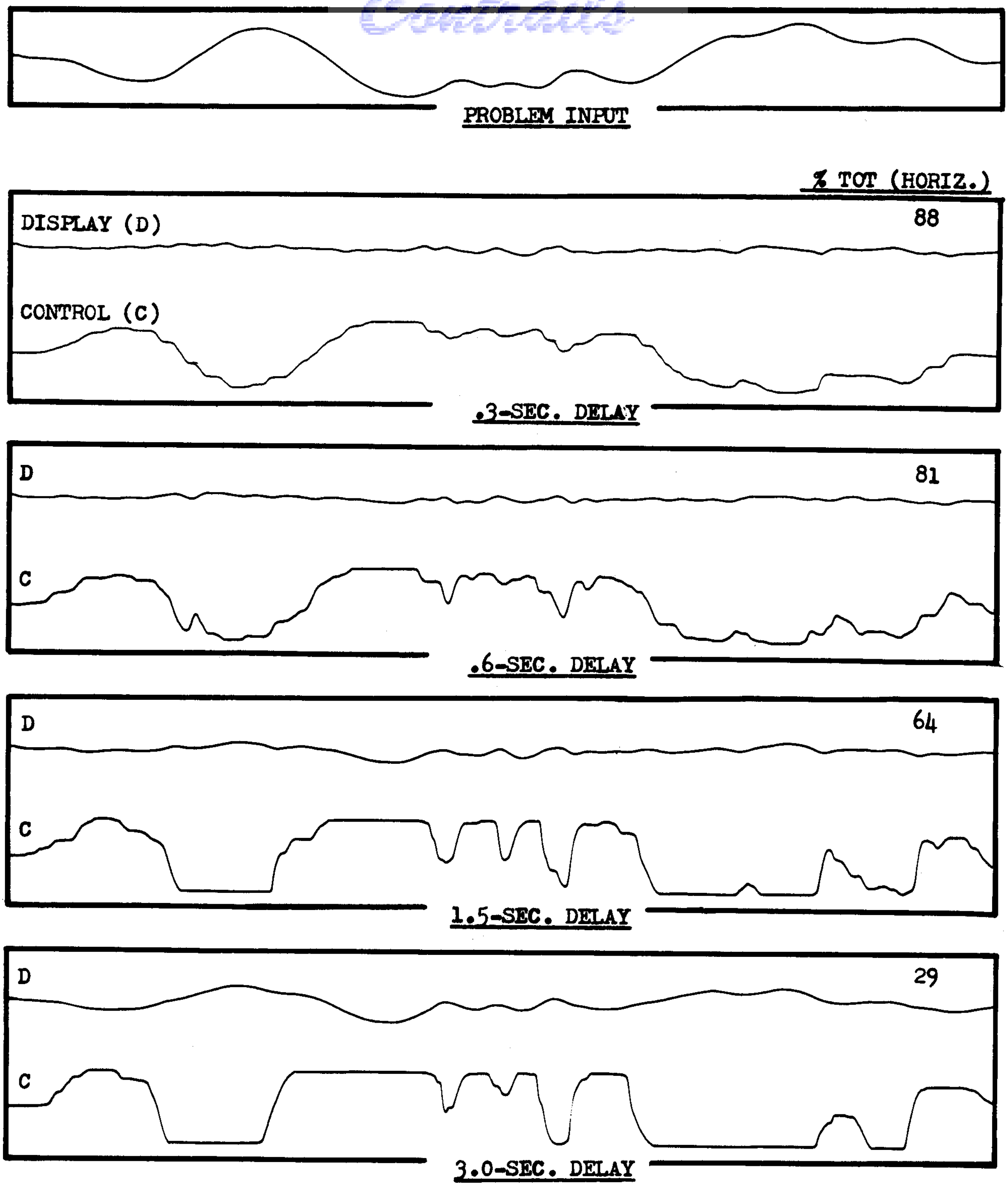

Figure 3. Pen recordings of problem input, display error, and control-stick movement during tracking with the 1:3 C/D ratio. Records are for the horizontal (right-left) dimension only.

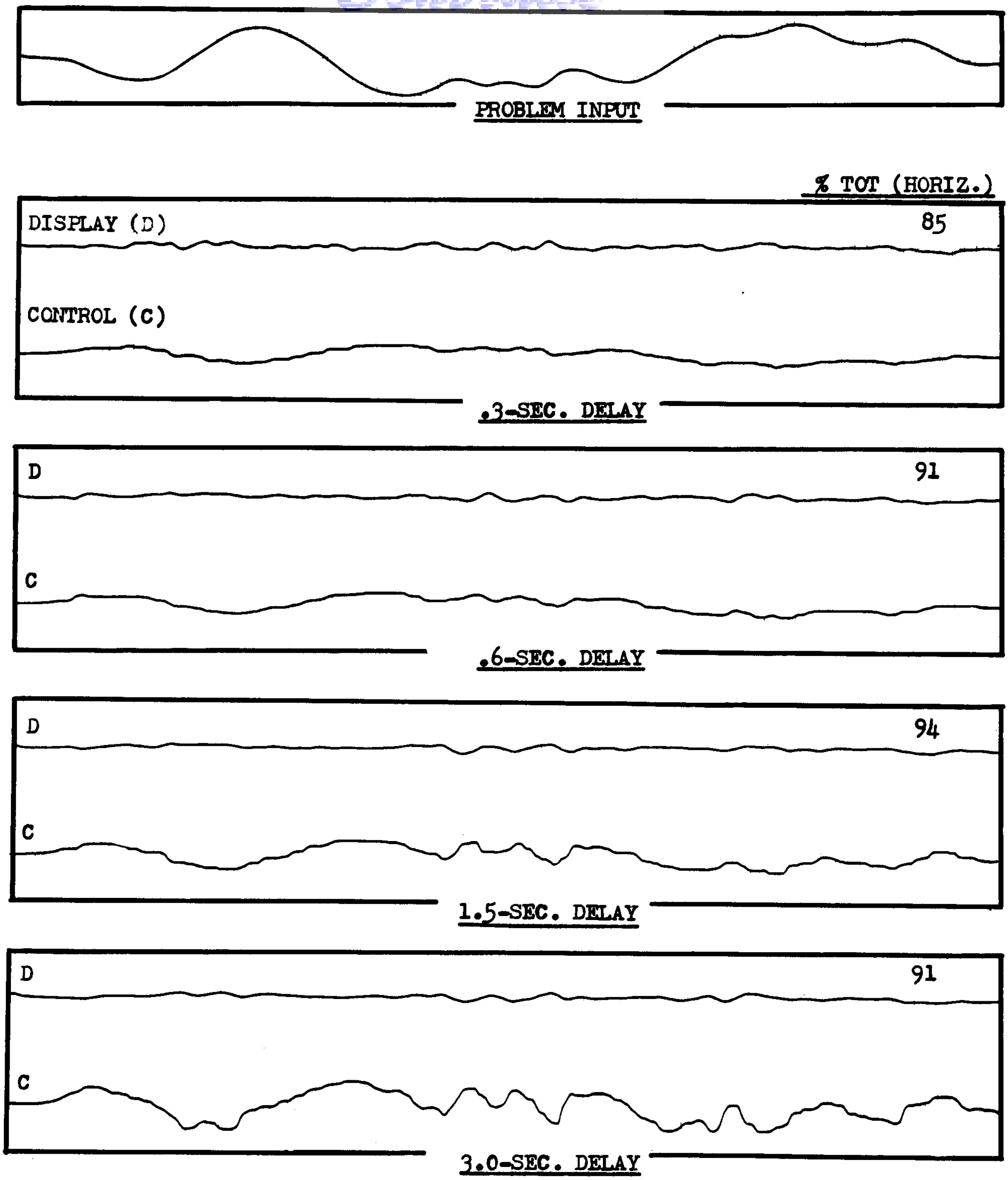

Figure 4. Pen recordings of problem input, display error, and control-stick movement during tracking with the 1:15 C/D ratio. Records are for the horizontal (right-left) dimension only.

shows the movements of the display spot to the right and left of the center of the CRT with the control-stick fixed in its centered position. The "error" tracings show the right-left movements of the display spot with the operator in the control loop. And, the "control-stick" tracings show the operator's right-left control movements when attempting to maintain the display spot within the square target area. Since the operator tracked a two-dimensional course, his right-left control movements probably were considerably different than they would have been had he tracked only the horizontal problem input. However, it is unlikely that the general characteristics of the records with which we are concerned would be differentially affected by the complexity of the input.

To facilitate cross-comparisons of the graphic data, all records of a similar type are to the same scale. That is, equal amplitudes on the error records, including the problem input, represent equal amounts of display spot displacement on the face of the CRT. Likewise, equal amplitudes on the control-stick records, represent equal amounts of control deflection. It will be recalled that the maximum spot displacement when driven by the problem signal was 33/16 in. from the center of the CRT. And, it will also be recalled that the maximum possible stick deflection was 11° from the centered position. Thus, the maximum amplitudes on the problem input curves correspond to a spot displacement of 33/16 in.; and the maximum amplitudes on the control-stick curves <u>for the 1:3 ratio</u> correspond to a control deflection of 11°.

No attempt was made to subject the graphic data to precise analyses, since the features of primary interest for the present investigation are amenable to visual inspection. For example, it was pointed out in the Introduction that one important consequence of increasing exponential delay was the increase in the magnitude of control movement required to produce a particular display change in a given time. Implicit in this observation, of course, was the assumption that the operator would tend to increase the amplitude of his control movements with an increase in exponential delay. This assumption is obviously verified for the operator whose records are shown in Fig. 3 and Fig. 4, and, undoubtedly, it could be verified for any experienced operator motivated by a desire to minimize tracking error.

It was also pointed out in the Introduction that, under some conditions, exponential delay could be increased to a value which would alter the transmission properties of a control to a degree which would preclude "perfect" tracking. Inspection of the error and control movement records in Fig. 3 suggests that such a situation obtained at the long time delays with the 1:3 ratio. It will be noted that both the magnitude of tracking error and the amount of time the control was at the limits of its range of movement increased with an increase in delay. With the 3-sec. delay, control effectiveness deteriorated to the point where almost all control movements were, of necessity, of maximum amplitude. Despite this, it can be seen that display error often continued to increase even <u>after</u> the control had been deflected maximally in the appropriate direction.

DISCUSSION

The experimental results verified the prediction of an interaction between C/D (gear) ratio and C/D (exponential) time delay. More specifically, it was demonstrated, for the conditions of this study, that with relatively high gain (low ratio) controls increasing delay effected an initial improvement in tracking performance, while with a low gain (high ratio) control increasing delay effected a monotonic degradation in tracking performance. In addition, it was found that for the longest time delay tracking performance tended to be best with the lowest (1:30) C/D ratio, while for the shortest time delay tracking performance tended to be worst with the lowest C/D ratio.

Time-on-target-scores. The quantitative data upon which the experimental results are based are the simultaneous TOT scores. These scores are measures of the performance of the total man-machine system; therefore, taken alone, they permit only a limited number of inferences concerning the effect of experimental variations on the performance of the human operator.

For example, for experimental variations which might logically be expected to reduce the efficiency of the machine (e.g., increasing delay and/or C/D ratio), it would not seem legitimate to infer that decreasing TOT scores demonstrated a reduction in operator efficiency. Likewise, for variations which might be expected to improve the efficiency of the machine (e.g., decreasing delay and/or C/D ratio), it would not seem legitimate to infer that increasing TOT scores demonstrated an improvement in operator efficiency. On the other hand, if system performance were found to increase with increasing delay and/or C/D ratio--or decrease with decreasing delay and/or C/D ratio--it would seem permissible to make some inferences concerning the functioning of the operator. However, regardless of the findings, it is apparent that some caution should be exercised in generalizing from the effects of experimental variations on the total man-machine system to their effects on the human operator.

General remarks. Perhaps the most important outcome of the present investigation was the demonstration of a significant improvement in tracking performance resulting from an increase in exponential delay. The importance of this finding lies not in its uniqueness, since even an analysis as unsophisticated as that presented in the Introduction makes it appear almost obvious. Rather, it is felt that this finding is important because it serves to emphasize the differences in the effects of transmission and exponential C/D time delays on the performance of continuous control systems. For, it is difficult to conceive under what conditions one might feel justified in postulating an improvement in tracking performance with increasing transmission delay.

There seems to be a general disposition to equate both transmission and exponential delay with a delay in the critical components of response feedback. Clearly, transmission delay may be considered to effect a delay in the feedback channel in which it operates to the extent that it delays the onset of the displayed reproduction of the operator's control manipulations. However, whether or not exponential delay is considered to effect a practical delay in feedback would appear to depend upon the task to be performed. For, exponential delay does not delay the onset of the displayed effect of the operator's control inputs but, instead, changes the pattern of inputs required to produce a particular display response.

With respect to the facilatory effect of increasing exponential delay with low C/D ratios, it appears that the delay exercises a "smoothing" or "damping" effect upon the operator's inputs. (Actually, of course, it was the R-C filters in the present system which accomplished the damping and produced the delay.) With low ratios and short time delays the control may be so sensitive that it taxes, or exceeds, the human operator's capacity to respond without overcorrecting. In addition, the very sensitive control may amplify the operators tremors and other involuntary responses to the point where they act as perceptual "noise" and further interfere with his performance of the tracking task. When such a situation obtains, the introduction of a longer time delay appears to filter out these inappropriate high frequency, low amplitude, responses and, thereby, increases tracking efficiency.

Certainly the introduction of exponential delay is only one of many techniques which might be employed to reduce control sensitivity. In the present study, for example, the 1:30 ratio with a .3-sec. delay resulted in a control which was virtually isometric relative to the course to be tracked. Because of the extremely small movements required, the forces needed to deflect the control appropriate amounts were very low and almost imperceptibly different. In this case one could undoubtedly decrease the operator's tendency to produce large transient display errors and oscillations by increasing the amount of control force required to effect a given display movement.

No attempt will be made to adduce arguments to explain the deleterious effects of increasing exponential delay on operator performance; for, as has already been noted, the TOT scores do not permit a separation of the effects of increasing delay on the operator from the effects of increasing delay on the machine. However, as far as the present study is concerned, it is felt that much of the degradation in system performance at long delays may be attributed to a reduction in control effectiveness, rather than a deterioration in operator functioning.

To reiterate, the problem signal generator can be considered to produce a series of position changes of the display spot over time. However, the rate and higher derivate characteristics of the problem cams are such that many portions of the series can not be matched, or compensated for, with a control having the properties of high C/D ratio and long time delay. Therefore, even a perfect tracking machine, using the control with the 1:3 ratio and attempting to compensate for the relatively complex problem inputs of this study would obtain considerably less than perfect TOT scores at the longer time delays.

Considering the analysis recapitulated above, it seems clear that the effect of increasing delay on system performance would also interact with problem frequency. For, other things being equal, the higher the frequencies in the problem input the lower the exponential delay at which perfect tracking is precluded.

The finding of an increase in tracking performance with decreasing C/D ratio at the longest delay suggests that range of control movement is another parameter which may interact with C/D ratio and exponential delay. It will be recalled that the range of control movement in this study was held constant for all conditions. Thus, as C/D ratio was decreased the maximum extent to which the display spot could be moved was increased--with a 1:30 ratio the display spot theoretically could be moved 10 times as far as with a 1:3 ratio. Clearly, if C/D ratio is held constant as exponential delay is increased, the extent to which the control must be deflected to produce a particular display movement in a given time is also increased. Therefore, for a combination of C/D ratio and exponential delay which does not permit efficient tracking (e.g., 1:3-3.0 sec.), it seems reasonable to assume that an increase in the maximum range of control movement, up to a point, will result in an improvement in system performance.

Final remarks. There has been a tendency to adopt as a principle of human engineering the proposition that "Any delay between control and display has a detrimental effect on the performance of a man-machine system." The findings of the present study suggest that for exponential time delay a more appropriate principle would be, "The optimum delay between control and display depends, among other things, on the magnitude of display change produced by a given control input."

SUMMARY

Eight experienced operators performed a two-dimensional compensatory tracking task using each of the sixteen combinations of four control-display (C/D) gear ratios and four C/D exponential time delays. The four C/D ratios were such that 1° of control movement produced either 3-, 6-, 15-, or 30-sixteenths inches of display movement. The four time delay constants were .3, .6, 1.5, and 3.0 seconds.

The results demonstrated an interaction between the effects of C/D ratio and exponential time delay on system performance. More specifically, it was found that:

1. For the 1:3 ratio, there was a continuous decrease in system performance with increasing delay.

2. For the 1:6 ratio, performance first increased to .6-second delay and then decreased with additional increase in delay.

3. For the 1:15 ratio, performance increased to 1.5-second delay. There was no difference between performance with 1.5- and 3.0-second delays.

4. For the 1:30 ratio, performance increased continuously with increasing delay.

5. At the 3.0-second delay, performance was best with the 1:30 ratio; while at the .3-second delay, performance was worst with the 1:30 ratio.

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APPENDIX

TABLE 4

Mean Percent Time-on-Target Scores on Day 1.

		Time Delay (sec.)			
		.3	.6	1.5	3.0
	1:3	48.6	41.2	22.0	9.0
C/D	1:6	60.8	63.2	61.9	33.2
Ratio	1:15	53.6	64.9	65.7	65.9
	1:30	41.5	50.6	62.9	69.1

TABLE 5

Mean Percent Time-on-Target Scores on Day 2.

		Time Delay (sec.)			
		.3	.6	1.5	3.0
	1:3	55.6	48.7	28.8	10.5
C/D	1:6	67.2	75.0	74.5	39.6
Ratio	1:15	60.6	69.6	74.0	73.6
	1:30	46.8	59.3	67.8	74.7