NRL Report 6646

A Comparison of Three Types of Manual Controls on a Third-Order Tracking Task

December 20, 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

Three types of control levers—the spring-centered-displacement control, the on-off control, and the pressure control—were compared on a third-order compensatory tracking task. Based on an analysis of the control transfer functions, the predicted ranking of the three controls are: (1) pressure, (2) displacement, and (3) on-off. The results of a study in which five subjects tracked six trials with each control for 18 sessions were as follows: The data at the beginning of training indicated rankings of (1) pressure, (2) on-off, and (3) displacement. However, the data taken during the latter sessions ranked the controls as predicted, although the difference between displacement and on-off was not statistically significant. Differences in results between early and late training and comparisons of these results with other studies are discussed.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing on this and other phases.

AUTHORIZATION

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A Comparison of Three Types of Manual Controls on a Third-Order Tracking Task

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A COMPARISON OF THREE TYPES OF MANUAL CONTROLS ON A THIRD-ORDER TRACKING TASK

INTRODUCTION

In a typical man-machine tracking system, an operator receives information from a display and imposes a change on the system, when required, by means of a control device. The control device is frequently selected on the basis of mechanical convenience rather than any analytical or experimental determination of an optimum control. When performing a relatively simple tracking task with position or first-order dynamics, the selection and optimization of the control probably is not too important since the operator can easily compensate for the additional dynamics introduced by the control itself. However, when the vehicle dynamics become quite difficult for the operator to equalize (such as pure third- or fourth-order dynamics), the addition of a control that increases the overall tracking-system order even slightly may deteriorate task performance.

Studies comparing control levers using position (1), velocity (2), and quickened acceleration (3) have all found that the pressure type of control results in less tracking error when compared to displacement or free-moving type of controls. Third-order vehicle dynamics were used by Kilpatrick (4) in comparing displacement and "bang-bang" (on-off) controls. His results showed there was less tracking error using the latter control. These studies indicate that pressure controls are superior to displacement controls for tracking tasks requiring little equalization by the operator, whereas on-off controls are superior to displacement controls when considerable equalization is required. The literature does not reveal any studies comparing these three types of controls on the same task.

An analytical look at each type of control seems appropriate in order to make some sort of prediction as to their relative performance on higher-order vehicle dynamics. The spring-centered-displacement control is characterized by two springs with a spring constant K centering a metal rod with a mass M pivoted on a potentiometer which produces an output voltage e_o in relation to a force F applied to the rod. There is a slight damping factor C due to air resistance and friction of the potentiometer wiper arm. The Laplace transfer function for this type of control is $e_o/F = 1/Ms^2 + Cs + K$ and is of the same general form as a spring-mass-damper system (5). Information from this control is related to the operator through proprioceptive feedback from the force he applies to the rod and from the displacement of the rod. He also receives information as to the length of time the rod is displaced.

The pressure control consists of a lever connected to a strain gauge so that a force applied to the lever results directly in a control output voltage proportional to the force applied (6). There is virtually no displacement with this control. It has essentially the same transfer function as the displacement control except that the gain of K (spring tension) is so large that the mass M and damping C become negligible, and the overall gain becomes very small. Therefore, the pressure control is better approximated by 1/K and presents only a gain change to the vehicle dynamics. The operator also has information as to the length of time he is applying a force.

If a force is applied to the on-off type of control sufficient to activate it, a constant output is supplied by the control for whatever length of time the lever is held in the on position. Any information obtained from the applied force and displacement of the control

merely informs the operator whether or not the control has been activated. Therefore, the only important cue obtained from this control is the on and off time, along with the direction of the pulse.

When the on-off control is activated, its output provides a step input to the vehicle dynamics which is smoothed by the filtering action of the tracking integrators. In spite of this filtering characteristic it seems probable that difficulty will arise using this control when trying to track out a forcing function that is continuously changing, such as a sine wave. Thus, it is predicted that for sinusoidal-forcing functions the proportional output controls (both pressure and displacement) will result in less tracking error as compared to the on-off control. A second prediction is that use of the pressure control will result in less tracking error than use of the displacement control since the pressure control has an output directly proportional to the force input, whereas the displacement control has proportional output through an additional lag inherent in the dynamics of the control. The present study was designed to test these predictions by comparing system performance on a pure third-order tracking task for the three types of controls.

METHOD

Apparatus

Figure 1 is a block diagram of the third-order compensatory tracking task with a transfer function of $16/Ks^3$, where K is the particular gain used for each control. Subjects were required to center a marker dot along the x axis on a 5 inch cathode ray tube (crt) by manipulating one of the three controls. Displacement of the marker dot (tracking error) resulted from the difference between the outputs of the vehicle dynamics and the forcing function. The absolute value of tracking error was integrated for the last 50 seconds during each 1-minute trial. The forcing function consisted of three sine waves having frequencies of 2.15, 5.7, and 7.3 cpm, with amplitudes inversely proportional to frequency. This forcing function produced a maximum displacement of 2-1/2 in. on the crt. By use of a switch the experimenter selected which of the three controls the subject was to use.

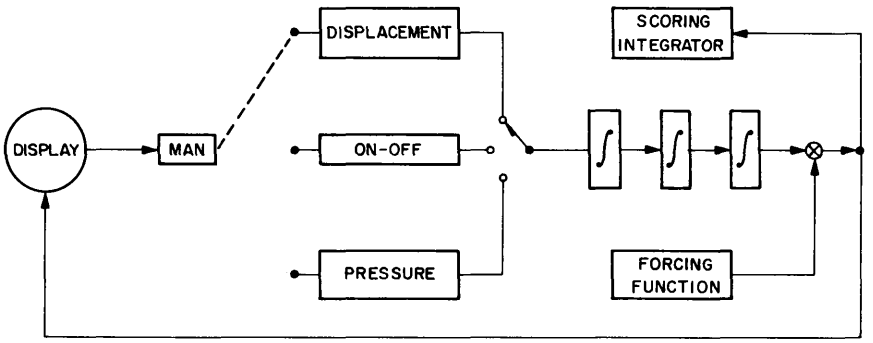

Fig. 1 - Third-order compensatory tracking system

The displacement control consisted of a spring-centered, 12-in. metal rod geared to a potentiometer and free to move 45 degrees on either side of center. A 10-degree displacement of the rod produced a 5.3-in./sec^3 change of the marker dot. The on-off control incorporated microswitches mounted on each side of the displacement control so that a 1/8-in. movement of the control in either direction activated the microswitch, resulting in a 4.5-in./sec^3 marker-dot change on the crt. The pressure control was a

commercial unit (Model 433, Measurement Systems, Inc.) whose output of 0 to 3 v dc was in linear proportion to applied pressure from 0 to 10 lb. One lb of pressure on this control produced a dot change of 3.6 in./sec^3 on the crt. These gains were established by a preliminary investigation covering a wide range of different forward gains for each control. This preliminary study used the same tracking task as described above, and the gain resulting in the lowest tracking error for each control was selected for use in the present experiment.

Procedure

Each subject was presented with 18 experimental sessions. Each session was divided into sets of three consecutive 1-minute trials on any one control. The three-trial set for each control was presented twice during each session with the order of the six sets randomized. The subjects used in this experiment were five naval enlisted men without similar tracking experience.

RESULTS AND DISCUSSION

Medians were obtained for each set of three trials. For each session the mean of the two medians was determined for each control. Each plotted point in Fig. 2 is the mean error from two consecutive sessions for five subjects. From the graph it can be seen that after initial learning, the pressure control resulted in the least amount of tracking error followed by the displacement and on-off controls.

Table 1 presents the results of an analysis of variance performed on the data taken during the last four sessions. Since the analysis revealed the main effect of controls to be significant, a Duncan Range Test was performed. The pressure control was found to be significantly superior to the displacement control ($p < .05$) and the on-off control ($p < .01$). No significant difference was found between the displacement and on-off controls.

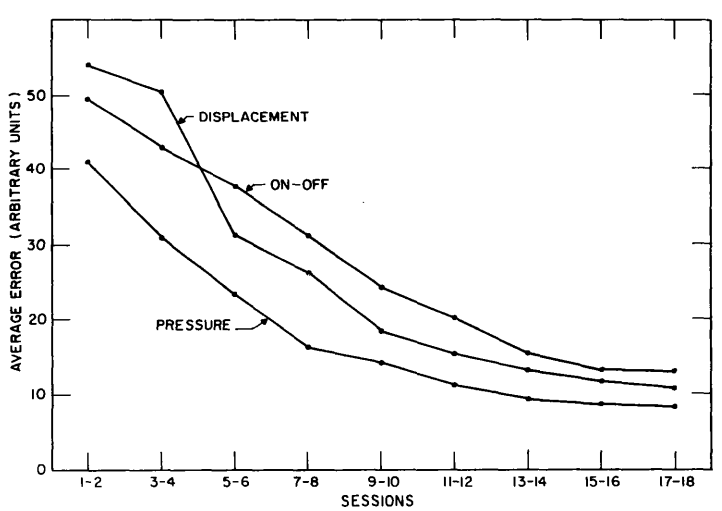

Fig. 2 - Learning curves for the three types of controls. Each point represents the mean error from two consecutive sessions for five subjects.

Table 1
Analysis of Variance for the Data of the Last Four Sessions

Source	df	MS	F
Subjects (S)	4	32.75	11.78*
Sessions (Se)	4	11.25	4.05*
Controls (C)	2	134.00	48.20*
S x Se	16	7.75	2.79*
S x C	8	10.00	3.60*
Se x C	8	7.25	2.61†
Error	32	2.78	—

*$p < .01$
†$p < .05$

From Fig. 2 it can be seen that for the first few sessions the on-off control was superior to the displacement control with a reversal occurring after the fourth session. These initial results with the on-off control may be due to the complexity of the tracking dynamics. When subjects are first introduced to a third-order system, their mode of tracking results in on-off responses, as evidenced by operating all controls in "jerky," steplike movements. This behavior was also noted by Young and Stark (7). Initial performance with the on-off control in the present experiment was better than the displacement control. This initial superiority may be explained on the basis that the operator has not learned to compensate for the vehicle dynamics, and this type of control may be more compatible with his tracking behavior. As he begins to furnish equalization, he is able to make use of the proportional output from the displacement control which results in improved performance as compared to the on-off control. As training progresses the subject makes fewer jerky movements with his displacement control. Possibly the data presented from Kilpatrick's work (4) was taken on relatively inexperienced trackers, which could explain why he found the on-off control superior to the displacement control. If the forcing function in this present study had been a series of step inputs, the early advantage shown by the on-off control may have persisted throughout training. Use of step inputs would be an interesting comparison for future research and should be informative as to the interaction among controls, vehicle dynamics, and forcing functions.

The results of this study along with the previous findings from work referenced in this report have shown the clear superiority of the pressure control over other types of controls for continuous forcing functions. This superiority found over various levels of vehicle dynamics points out the important influence of the dynamics of the control itself. From the presently available evidence it can be concluded that the control which requires the least amount of equalization on the part of the operator will provide the best overall system performance.

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