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A FUNDAMENTAL STUDY OF PREDICTIVE DISPLAY SYSTEMS

by John DeShon Warner

Prepared by
UNIVERSITY OF MICHIGAN
Ann Arbor, Mich.
for

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Abstract

A FUNDAMENTAL STUDY OF PREDICTIVE DISPLAY SYSTEMS

John DeShon Warner

This report presents the results of a fundamental study of the predictive display technique. It is intended to provide a basis for understanding some of the advantages and limitations of predictive displays in man-machine systems, and a starting point for both future research and eventual applications. The particular predictive technique considered in this report utilizes a repetitive, fast-time, on-line computation scheme developed by H. Ziebolz which provides a predicted response of the controlled element to the human operator based on certain assumptions about future control inputs and disturbances. It is apparent from previous studies which have been concerned with specific applications that there is a need for clarification of applicable terminology as well as a need for general investigations into the effects of certain inherent characteristics of predictive display systems.

On the basis of a review of the known literature on the subject, an in-depth discussion is provided on the various characteristics that are important in any predictive display application. In addition, the problem of performance measurement is discussed. A discussion of several potential applications is provided to point out the possible advantages of a predictive display and those characteristics which might be important.

An experimental investigation on the effects of the controlled element dynamics on performance with three display forms (exploratory prediction, on-line prediction, and no prediction) in a time vs. error format is reported. A minimum-time terminal control task for a pure inertia system driven by a fixed three-state relay controller was chosen for the study. The system is described by several independent parameters which are hypothesized as being important in a variety of manual control situations. These parameters are varied systematically to determine their effect on performance with the three display forms. Several new performance measures are developed for use in minimum-time terminal control tasks.

It is found that the human operator performs with consistent control timing accuracy using exploratory prediction, independent of the

various system parameters and the effective display gain. Performance variations in terms of the system and task-oriented criteria are found however, which are explained through an analysis of the sensitivity of the criteria to constant timing errors in the application of control changes. On-line prediction yields nearly the same level of performance as exploratory prediction. Performance with the normal display on the other hand is more variable, and generally becomes worse as the required mental prediction time spans of the operator increase.

A general conclusion from this research effort is that predictive displays are potentially useful whenever the information processing requirements are severe and required mental prediction time spans are not short, but that additional studies are needed comparing predictive displays to semi-automatic systems using command displays and fully manual systems using advanced integrated display forms. Additional specific conclusions from the experimental effort are: (1) exploratory prediction and on-line prediction result in nearly the same level of performance as long as the required decision times are not short, and (2) performance measure selection is critical to the evaluation of advanced display systems and of the effect of different system parameters.

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LIST OF SYMBOLS

IAE	Integral of the absolute value of the error, computed from the minimum time to four seconds beyond the minimum time
J	Cost function
K	Plant gain
MISS	Terminal miss performance measure
MTTG	Minimum Time-to-Go performance measure
p	Differential operator
s	Time scale factor, $= t/\tau$
T	Terminal time
T_m	True minimum time
t	Real time scale; Student's t-statistic
t_1	Time of optimal control reversal
t_1'	Actual time of first control reversal
t_p	Prediction time interval
t_r	Reset time interval
t_{sw}	Switch time, $= T_m - t_1$
u(t)	Controller output
V_a	Approach speed, $= -\dot{\epsilon}(t_1)$
VECT	Terminal state vector magnitude performance measure
x(t)	Plant output
$\bar{x}(t)$	Column vector of plant state variables
$x_F(T)$	Desired final output

$y(t)$	Control stick output
Δt_1	Error in application of first control reversal, $= t_1' - t_1$
$\epsilon(t)$	Error signal, $= x(t) - x_F(T)$
τ	Fast time scale
φ	Control stick deflection angle

Chapter 1

INTRODUCTION

Effective manual control of any system requires that the pilot be able to anticipate the response of the system. For complex systems knowledge of just the present state, including derivative information, often is insufficient to permit the human operator to predict mentally the complicated system response. The predictive display concept first envisioned by Ziebolz and Paynter in 1953 [55] and further advanced by Kelley since 1960 [20,21,22,23], can reduce this otherwise necessary mental prediction process and can place more emphasis on the decision-making capabilities of the pilot. This often can provide the overall system with a high level of flexibility and adaptability not found always in completely automatic systems.

1.1 The Fast-Time Model Method

Though other techniques are available for generating a predictive display, the fast-time model method of Ziebolz and Paynter seems to be superior in many respects for most applications. This technique utilizes fast-time repetitive computer solution of the vehicle or system equations of motion to present to the human operator a predicted response of the system based on certain assumptions about future control inputs and disturbances. Typically, a model of the controlled element (called the plant) is formed on an analog computer which is then operated repetitively on an accelerated time-scale. Information about the present status of the actual plant is used to update the model periodically through the initial condition circuitry. The model output then is displayed to the operator either as a continuous path or as one or more discrete points. The input to the model can take one of several forms, which dictates the type of predictive display that is being used.

1.2 Predictive Display Types

Predictive displays* can be separated into four categories: on-line, off-line, exploratory, and supervisory prediction. These categories are defined below and illustrated in Fig. 1.2.1.

(1) On-Line Prediction:

The input to the model is identical to the present control input into the actual vehicle or system (the plant). Thus the operator sees a prediction based on the assumption that he does not alter his input over the predicted interval.

(2) Off-Line Prediction:

The input to the model is based on the assumption that the control action by the operator will change during the predicted interval. This hypothetical input may take one of several forms, such as the present control input to the plant

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*Not to be confused with "quickened" displays [8].

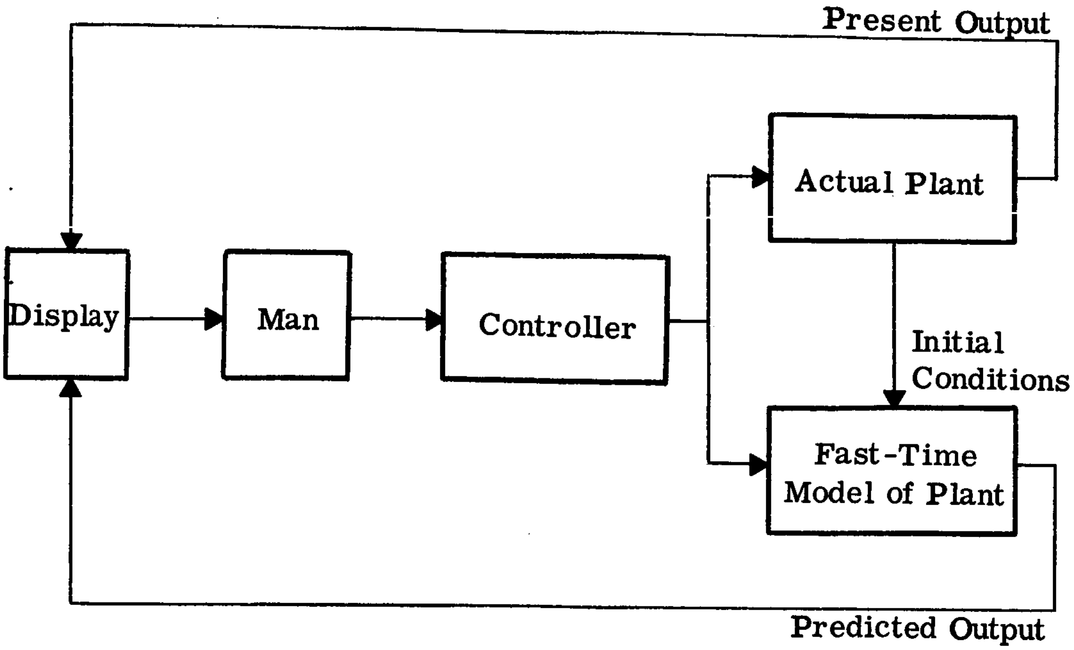
followed by a null input after a certain time lag; a complex pre-programmed control variation, in which case a command display also may be presented; or sequentially different control programs which would yield a display of several different possible responses or a display of the total maneuvering capability within the mission constraints.

(3) Exploratory Prediction:

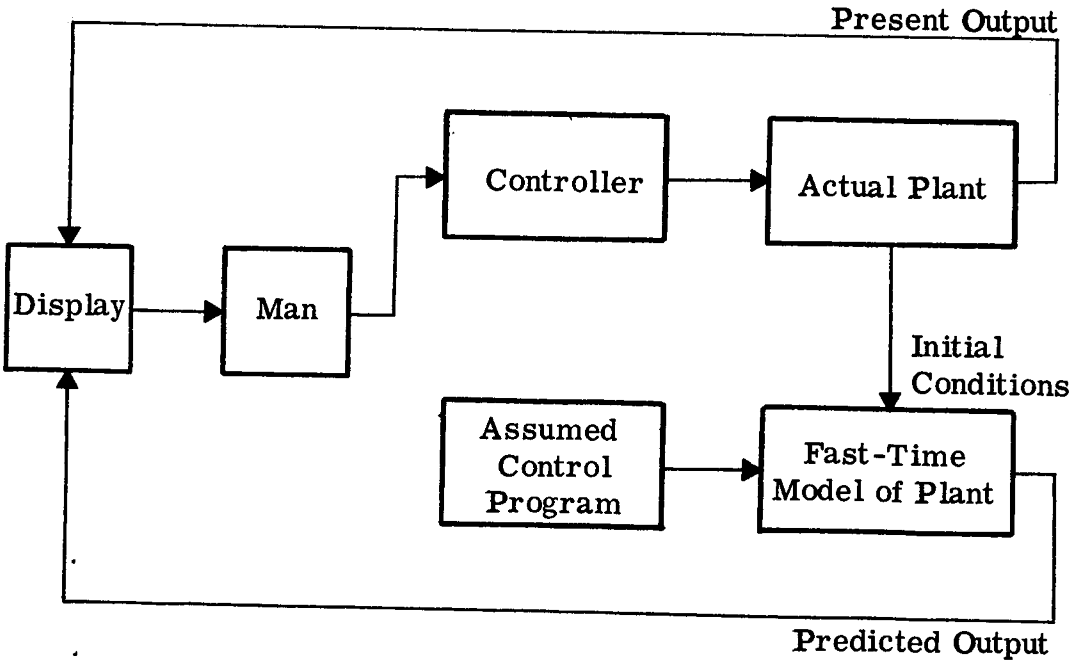
A special case of off-line prediction in which the operator selects a hypothetical input into the model and when satisfied with the predicted output, activates the corresponding input into the plant through a sample and hold circuit. A variation of this technique is the case in which the operator adjusts a hypothetical control program and then commands the actual controller to assume the form (in real-time of course) of the hypothetical program.

(4) Supervisory Prediction:

A special case of off-line prediction in which the human operator may act as a system monitor rather than as an active control element. The plant is controlled automatically so that the predictor computer also contains a fast-time model of the automatic controller. Provision may be made for the operator to adjust the controller.

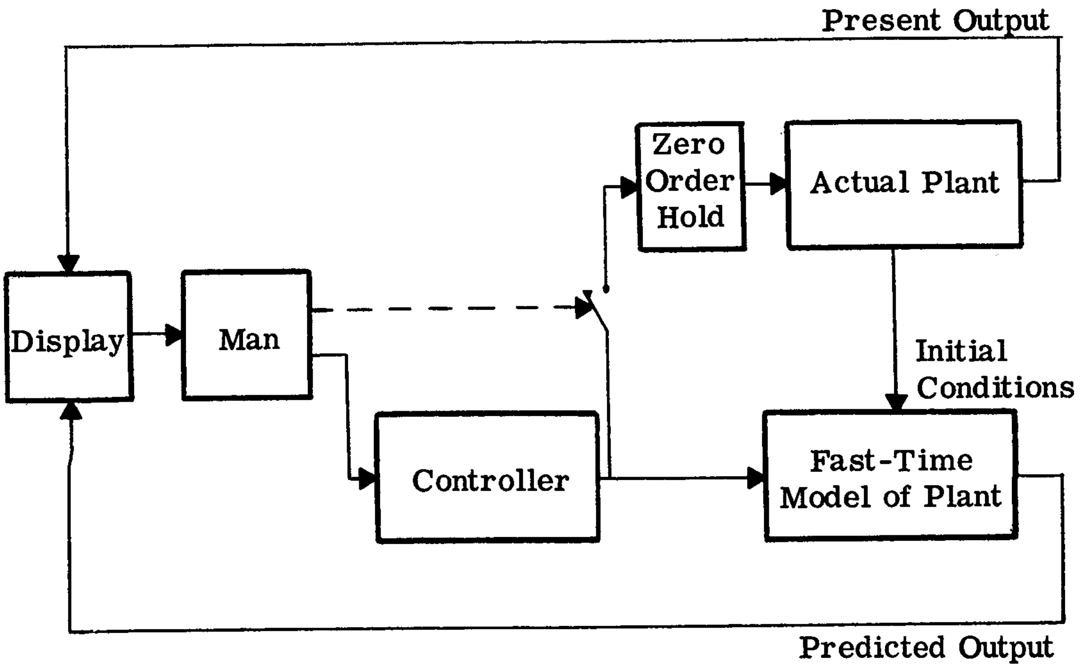


(a) On-Line Prediction.

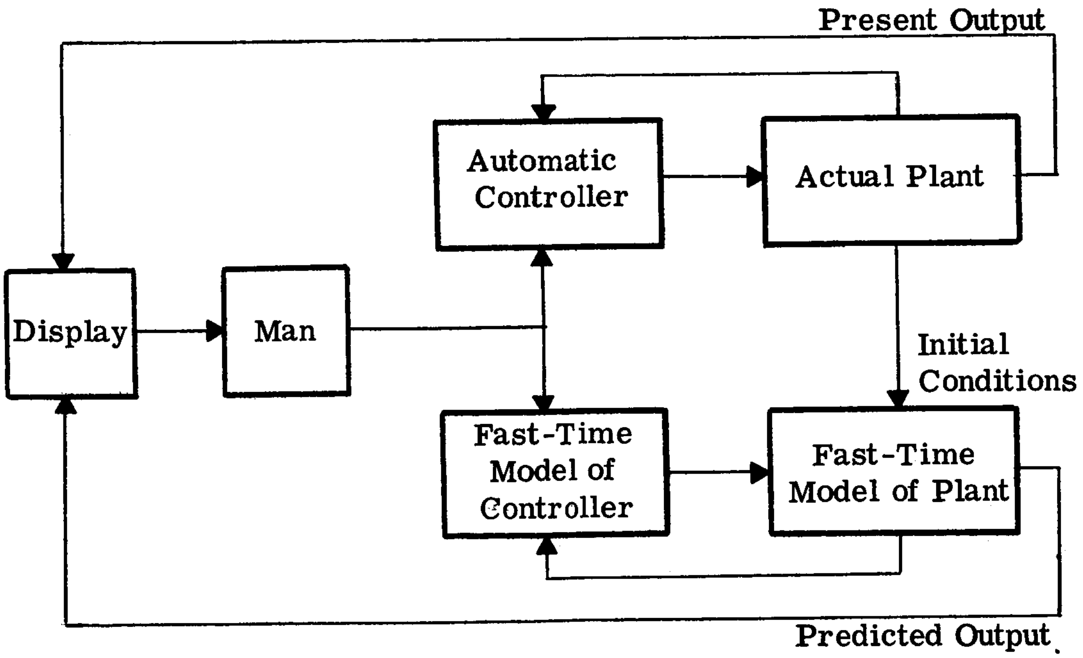


(b) Off-Line Prediction.

Figure 1.2.1 Block Diagrams of Predictive Display Types.



(c) Exploratory Prediction.



(d) Supervisory Prediction.

Figure 1.2.1 (Concluded).

1.3 Results of Previous Predictive Display Studies

Predictive displays have been receiving considerable attention since 1960 due to the advent of many complex vehicles and control situations where inclusion of the pilot in the loop is desirable. These studies which have been concerned with particular applications of predictive displays have shown several advantages to their use in manual control systems:

(1) Learning times can be decreased.

(2) Human operator effectiveness in terminal control tasks can be improved.

(3) Manual control can approach optimal control with respect to a specified performance criterion.

(4) Control of non-linear systems and of linear systems with pure time delays and other non-minimum phase characteristics can be improved.

(5) The operator can plan optional courses of action to increase the likelihood of mission success.

(6) Information processing requirements on the human operator can be reduced, especially in multi-dimensional control tasks.

Since these studies were limited to specific vehicles, few results have been obtained of a general nature that can be used in a wide variety of applications.

All the known literature on predictive display studies to date has been reviewed as a part of the research effort reported here. These studies are briefly discussed in this report, categorized according to problem area and application.

1.4 Inherent Characteristics of Predictive Display Systems

The fast-time modelling technique, regardless of the application has certain inherent characteristics which will affect the operation of the entire closed loop manual control system. These include the following:

(1) Controlled element (plant) dynamics.

(2) Controller dynamics.

(3) Accuracy of the model.

(4) Frequency at which the model is updated.

(5) Accuracy of the updating information.

(6) Repetition rate.

(7) Solution rate of the model.

(8) Prediction span of the model (related to the solution rate by the model time scale).

(9) Nature of control input to the fast-time model.

It should be noted that in an automatic predictive control system, in which the man is replaced by a logic decision element, these same characteristics will have an influence on performance. Factors peculiar to manual control systems which are not listed above include the display format and questions related to what system variables need be displayed to the pilot. Since these characteristics are common to any predictive display application, there is much that can be learned by studies of a general nature. While some of the previous predictive display efforts have discussed qualitatively several of these characteristics, no general quantitative studies have been conducted.

1.5 Performance Measurement

There is always the problem of performance measurement itself whenever an evaluation of a new display or control system concept is undertaken. In such circumstances, overall system performance (normally evaluated by measuring some specified cost function such as fuel consumed, time required to complete a maneuver, or a combination of terminal errors) is of more immediate concern than subsystem performance (measured by more specialized criteria). This is especially true in the consideration of predictive displays in which the role of the human operator may be altered over that with conventional displays. Hence the performance of the human operator in some specified task is secondary in importance to the performance of the entire man-machine system, which must be in terms of a cost function related to the overall mission objectives.

1.6 Research Objectives and Outline of the Report

This report is intended to provide some basic fundamental guidelines for a variety of predictive display applications and for research on the predictive display technique. To this end, an attempt is made to clarify the notation applicable to the technique and point out the potential problems that can arise in its use, as well as its advantages.

The inherent characteristics of predictive display systems are defined and discussed in Chapter 2. This chapter also will note results of previous studies where applicable. In Chapter 3 various potential applications of predictive displays are discussed in terms of how such a display might be useful, what problems might be encountered, and possible implementation schemes. Important results of previous studies also are mentioned for several of the applications. An experimental investigation of the plant variables that affect the man-machine system performance with predictive displays is reported in Chapter 4. The parameters associated with a relatively simple pure inertia plant were varied systematically (while keeping the control stick and controller characteristics fixed) to investigate their affect on performance with an on-line predictive display, an exploratory predictive display, and a normal display in a minimum-time control task. The results of this experiment are reported in Chapter 5. Conclusions from these results are presented in Chapter 6, along with extensions of the results to systems of more practical interest and a list of recommendations for future research into the predictive display technique.

Chapter 2

PREDICTIVE DISPLAY SYSTEM CHARACTERISTICS WHICH INFLUENCE PERFORMANCE

There are certain characteristics of the fast-time model method used for predictive displays that are common to all applications. The influence on performance of each characteristic depends both on the application considered and on the performance criteria. The following discussion of these characteristics and performance measures in general terms is intended to aid the display system designer in his consideration of predictive displays.

Since predictive display systems are relatively new, basic terminology and definitions applicable to the technique have not been standardized. The first section of this chapter is intended to clarify the notation and terminology which is used throughout this report. Subsequent sections provide a discussion of each characteristic separately, and the problem of performance measurement.

2.1 Definitions

(The types of predictive displays were defined in Chapter 1 and will not be repeated here.)

(1) Plant—the system or vehicle being controlled.

(2) Controller—the device or system which transforms the action of the operator into an input signal to the plant.

(3) Predictor Model—the computer model of the plant and possibly the controller which generates a predicted response based on the present state of the plant and assumptions about future inputs from the controller. The model operates repetitively on a fast-time scale.

(4) Updating Frequency—the frequency at which the predictor model is updated with the present state of the plant.

(5) Repetition Rate—the number of successive predictions displayed to the operator per unit of time. (See Fig. 2.1.1.)

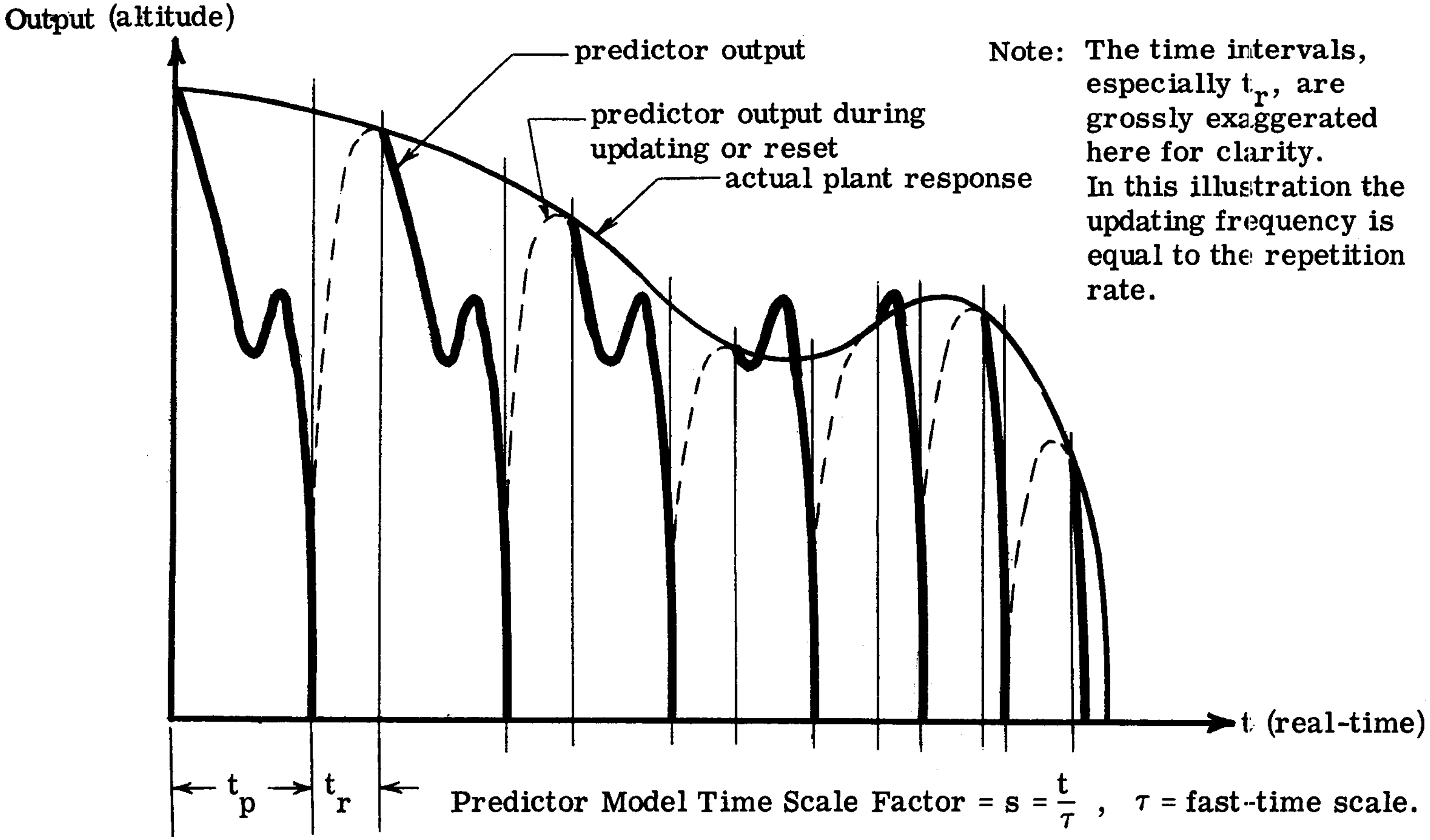
(6) Prediction Span—the real time interval over which the response of the plant is predicted. (See Fig. 2.1.1.)

(7) Predictor Control Program—the control variation that is assumed to occur during the prediction span interval and that provides the input to the predictor model.

(8) Performance Measure—a cost function which is to be minimized for optimum performance of the man-machine system. It is generally dependent upon the terminal values of the state variables, the terminal time, and some integral of the response.

2.2 Dynamics of the Plant and Controller

The human operator has shown considerable talent in predicting the response of fairly complicated systems with which he has had a great deal of training. The tossing of a ball to a target is an example



Note: The time intervals, especially t_r, are grossly exaggerated here for clarity.
In this illustration the updating frequency is equal to the repetition rate.

Predictor Model Time Scale Factor = $s = \frac{t}{\tau}$, τ = fast-time scale.

t_p = predictor computation interval

t_r = reset interval

Prediction Span = $s \times t_p$

Repetition Rate = $\frac{1}{t_p + t_r}$

Figure 2.1.1 Definition of Repetition Rate and Prediction Span—Output Time History for a Hypothetical Re-Entry Prediction System.

in which his experience has given him predictive abilities which are usually sufficient. However, we may note that as the distance or duration of the toss is increased, his accuracy worsens, in part due to the deterioration of his predictive abilities. This type of behavior is represented in the predictive model of the human operator proposed by Sheridan [42] in which, conceptually at least, a fast-time analog model of the controlled element is formed by the operator. This model is necessarily not perfect; therefore prediction accuracy will deteriorate with increases in the required prediction span. Hence, a common strategy in throwing a ball at a target is to throw it hard. This has the effect of shortening the required prediction time span, and allowing an inaccurate model to produce less error.

In the complex vehicles with which we are now concerned and will be in the future, it is not always possible for the operator to form an accurate mental model of the system. If man is then to be retained in the control loop, it is necessary to provide him with control or display aids, or both. The predictive display technique is one such aid.

It is the purpose of a predictive display system to shorten the required decision times as well as aid the operator in making the correct decisions. Thus it can be seen that the time required by the operator to make a control decision relative to the time available is critical to performance with predictive displays. The available time is not only a function of the nature of the plant and controller dynamics, but also of the particular control task objectives.

A factor pertinent to man-machine system performance in terminal control tasks is the sensitivity of the performance measure to timing errors in the application of discrete control changes. In such a case the performance measure to be minimized is usually a cost function of the form

$$J = F[\bar{x}(T), T] \tag{2.2.1}$$

where $\bar{x}(T)$ is the terminal state and T is the terminal time. The functional form of J is dependent upon the mission objectives and the nature of the plant. The terminal state can be expressed as

$$\bar{x}(T) = G[\bar{x}(0), T, u(t)] \tag{2.2.2}$$

where $\bar{x}(0)$ is the initial state and u(t) is the control function. Optimum J is denoted by J^*:

$$J^* = F[\bar{x}^*(T), T] \tag{2.2.3}$$

where

$$\bar{x}^*(T) = G[\bar{x}(0), T, u^*(t)] \tag{2.2.4}$$

and $u^*(t)$ is the optimal control function. For convenience, $u^*(t)$ is here assumed to be a simple step function in time,

$$u^*(t) = \alpha h(t - t_1) \tag{2.2.5}$$

where α is a constant. If there is some error in the timing of the step function, $\Delta t_1 = t_1' - t_1$, then the resulting control is given by

$$u(t) = \alpha h(t - t_1 - \Delta t_1) \quad . \tag{2.2.6}$$

For a given set of initial conditions and terminal time, the terminal states can be expressed as

$$\bar{x}^*(T) = g(t_1) \tag{2.2.7}$$

and

$$\bar{x}(T) = g(t_1') = g(t_1 + \Delta t_1) \quad . \tag{2.2.8}$$

Thus the timing error yields a penalty in the cost function,

$$\Delta J = J - J^* = F[g(t_1 + \Delta t_1), T] - F[g(t_1), T] \quad , \tag{2.2.9}$$

or

$$\Delta J = f(\Delta t_1) \quad . \tag{2.2.10}$$

This penalty, which can be thought of as a sensitivity of the cost function to the timing error Δt_1, is functionally dependent on the nature of the plant and the task.

Thus, two main factors of the plant and controller dynamics and task objectives are hypothesized to be influential to predictive display system performance:

(1) The time required to make control decisions relative to the time available.

(2) The sensitivity of the performance criteria to the timing of control actions.

Analytical determination of these factors for a specific system requires that a solution of the control actions required for optimal performance be available. Otherwise, an experimental investigation is necessary.

2.3 Predictor Model Accuracy

There are several reasons why we should be concerned with inaccurate predictor models. In some instances the dynamics of the vehicle may not be known accurately. Or perhaps future external disturbances operating on the real system cannot be predicted. Of course, increasing the model complexity to describe more accurately the real response may impose a penalty of increased computer weight and power requirements.

It is not always necessary however to have highly accurate models. Bernotat [6], using a Taylor series expansion* rather than the fast-time model approach, found that even inaccurate predictions gave improved performance over no prediction in the control of a third order undamped system following a step input. Kelley [23] in an early predictive display study found the same effect, but noted that the

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*The fast-time model technique can be thought of as providing the best estimate of all the terms in a Taylor series.

useful prediction span decreased with decreasing model accuracy, and learning times for effective manual control were increased. A comprehensive study of simplified models for an automatic predictive control system for aircraft landing was conducted by Chestnut, Sollecito, and Troutman [10]. Several linear controlled systems were studied, and it was found that using a predictor model with a faster response than the plant would cause overshoots in the actual response, but using a slower responding model would cause the entire closed loop to have the basic response of the model. Using a second order model for control of a third and fourth order plant, they found that by increasing the dominant time constants in the model to be proportional to the sum of the actual plant time constants, the additional time constants could be well compensated for and effective control could be established. Because of the adaptability and learning capability of the human operator, model inaccuracies are probably less of a problem in manual systems than in completely automatic predictive control systems. In fact, this adaptive characteristic of the human operator might be employed to adjust the model to fit the actual response or achieve better control.

The overall effect of an inaccurate model is of course closely related to the prediction span. The resulting prediction errors can be determined either analytically or experimentally if the real system can be simulated accurately for comparison with a less accurate fast-time model that may be proposed. When the real system is not completely known, these errors can only be estimated. There is however, one factor inherent in some control situations that tends to reduce the importance of increasing errors with increasing span: accuracy requirements on short predictions usually are greater than for long predictions. This is true whenever gross control changes are sufficient when relatively far from the target, and fine control is required only when near the target. Of course, there are circumstances in which small control adjustments near the target are impossible.

Finally it is noted that inaccurate predictor models often can be tolerated when they are updated continuously. When updating is either inaccurate or infrequent, or both, higher accuracy requirements may be placed on the model.

2.4 Repetition Rate and Updating

Repetition rate is defined as the number of successive predictions displayed to the operator per unit of time. It is controlled by three factors: the time scale of the predictor model, the prediction span, and the time spent in the updating or reset mode. (This latter time is usually very short.)

If a low repetition rate is caused by a slow computation speed (which may result from either a slow time-scale or long prediction span, or both), the overall effect on the prediction will be that of a time lag proportional to the prediction span, as it occurs in real time. In this event, the predictive display also acts as a sampled data system, so the problem becomes one of determining the tolerable time lags and sampling rates for the specific application under consideration. As pointed out by Ziebolz and Paynter [55] in very general terms, the required repetition rate will increase as system response becomes more rapid.

Low repetition rates also can cause display flicker which may be especially bothersome to the operator. Either long persistence or memory type oscilloscope displays can be used to combat this problem. However, even then there may be a stroboscopic effect present in the display if the state of the plant changes appreciably during one prediction cycle. This may cause visual fatigue problems for the operator as well as control difficulties.

The repetition rate problem is reduced when the prediction span is based on time-to-go rather than some fixed time. In this situation, with a fixed time scale for the model, the solution time will decrease, and hence the repetition rate will increase as the target is approached, resulting in more precise control when it is required the most, as noted by Chestnut, Sollecito, and Troutman [10]. They found limit cycles in some automatic predictive control applications, and noted that the limit cycle amplitudes could be decreased by employing such a variable prediction span. As pointed out in the previous section, however, some applications require exact control when far from the target.

The effects of the updating frequency on the prediction accuracy are similar to those of the repetition rate. If the updating frequency is identical to the repetition rate (being faster would be useless), there is no additional difficulty. When it is lower than the repetition rate, the first prediction after updating will be the most accurate while each successive prediction will decrease in accuracy until the model is again updated. Several solutions to this problem are available. One is to use artificial updating of the predictor model by extrapolating previous sampled outputs of the actual plant over the update period. Another is to let the predictor model update itself: Assuming that the first prediction made after the model has been updated is the most accurate, this prediction could be sampled at appropriate intervals, and then this information could be converted to real time to provide "predicted updating" at each reset interval.

As seen in this and the preceding section, both fast-time model accuracy and repetition rate requirements are dependent upon prediction span requirements, so some tradeoff will be necessary between span, repetition rate, and model fidelity when span selection is not constrained.

2.5 Prediction Span

The choice of proper prediction span is not always straightforward, e.g., if no fixed terminal state is specified. The general question then to be answered is: what system and task variables influence the choice of prediction span? As a general result, Kelley [22] found that when subjects in a submarine control task were allowed to adjust the span, they elected to decrease it as the vehicle speed was increased. He also noted that in a task such as this one, span should perhaps be in terms of distance rather than time.

From the operator's point of view more than the required span yields useless, distracting information if a continuous prediction path is displayed. If one or several discrete predicted points are displayed, too much span may omit the desired information. On the other hand, too short a span will require additional mental predictions by the operator. It should be noted that in this case continuous path prediction will be more beneficial to the operator in making such additional mental predictions than display of just a discrete predicted point, since he will have a curve to extrapolate.

In general terms the prediction span should be roughly proportional to the response time of the system, where response time as used here is a function of the plant dynamics and the control task. In some applications control decisions may be based on the occurrence of a certain relation between the predicted state variables, such as the encounter of a constraint. The span then should include this predicted state.

In terminal control tasks such as vehicle landing it is often desirable to have the terminal conditions displayed, thus fixing span length to be equal to the time-to-go. Of course this may not be desirable whenever the prediction is inaccurate due to the long time span.

Another limit on prediction span can result from the nature of the predictor control program. For example, if considerable control modulation is required over a one-minute interval then a one-minute prediction of the response for a fixed control input will be unrealistic and possibly misleading.

2.6 Predictor Control Program

The simplest predictor control program is based on the assumption that the present input to the plant will remain constant over the span interval, which yields on-line prediction. Operator strategy using on-line prediction is to explore briefly a control change by applying it momentarily to both the fast-time model and the actual system. This causes some penalty in system performance in that each trial control change is also applied to the actual vehicle. Whether or not this is significant will depend on the vehicle itself and the nature of the controller. For example, this technique obviously would be undesirable for pitch control of an aircraft, where even brief but abrupt control changes can have undesirable effects, if not on the structure, at least on the passengers and crew. If some appreciable searching is required to determine the proper control action, the on-line predictive display can result in significant degradation in performance over some forms of off-line prediction. This was the case in a minimum-fuel rendezvous task studied by McCoy and Frost, in which off-line prediction resulted in a 16% to 30% reduction in fuel consumed over on-line prediction [28].

Next in mechanization simplicity to on-line prediction is a single off-line prediction in which the model output indicates the response for a single discrete control change. An example is a prediction showing the response if the control input is returned to zero. A slight modification of this is to present a prediction based on the assumption the control input will be set to zero after some suitable time lag from the present time. This form was found to be advantageous over other simple forms of off-line prediction in the submarine control task reported by Kelley [22].

Exploratory prediction based on single, constant control inputs also is simple to mechanize, but provides somewhat more flexibility in that more than one control change may be tried out by the operator. This method can be expected to show superiority over on-line prediction when some appreciable decision time is required in selecting the proper control input.

A technique similar to the simple exploratory prediction discussed above is called multiple path prediction, in which several possible or likely responses are displayed together. It is useful in displaying the maximum maneuvering capability of the vehicle, for example. Since each prediction requires one complete prediction cycle, multiple path displays will place more stringent demands for a high repetition rate.

In terminal control tasks that require considerable control modulation between the present time and the terminal time, as when there are several mission constraints or when some sort of optimal trajectory is desired, simple control programs will not provide the operator with all the required information necessary to form the proper sequence of control actions. The predictor control program then must be quite complex. If it is a fixed, pre-stored program, then the predictive display will provide system-monitoring information, and control must be accomplished either automatically or manually with the addition of a flight director or command display. An alternate possibility is to provide a manually adjustable control program, allowing the operator to design the control sequence using the information from the predictive display. (This is referred to as automanual control by Kelley [22].) The actual controller would be made to duplicate the operation of the predictor control program (time-scaled to real time of course) upon command from the operator. Operation in such a manner requires that considerable time be available for decisions. It is however, a highly flexible technique. For example, the operator might be allowed to choose display variables such as prediction span or updating frequency, so that the display could be used for several types of prediction. When a predictive display system reaches this level of complexity, we are in essence providing the operator with an almost-general purpose high speed on-board computer to assist him in control of the vehicle through several possible modes of operation. Whether the price and weight penalties of such a system would be worth the performance improvement remains to be seen. Clearly, compromises must be considered.

2.7 Display Format

Specification of a predictive display system involves the selection of information to be displayed and the form of presentation. No definite format is suggested by the desire that a display be predictive: phase plane, contact analog, special three-dimensional, and time-shared displays—all of these can be used in a predictive display system. There is almost no limit to the possibilities (or, seemingly, the complexity) of such displays in presenting a large amount of information, predictive and otherwise. The usual criteria applied to the selection of any visual display system are still applicable to predictive displays, e.g., the criterion of control-display compatability.

Predictive information often adds an extra dimension to the display, such as a time axis or distance axis. We now have not only the present state variables to present, but the same state variables projected into the future. A possible solution is to increase the number of separate displays, though this is usually quite undesirable. Kelley [20] has proposed several representative three-dimensional displays through the use of perspective, that hold some promise for several applications.

Since a predictive system alters the nature of the control task to a large extent, the selection of the variables to be displayed becomes a new problem that must be solved in each application. In many situations either time or distance is a critical variable that naturally should be displayed. A time axis, however, is often wasteful in that it limits the number of other variables that may be represented. When time information is desired but not highly critical, two solutions are available: the predicted vehicle states can be shown at several equally spaced, discrete time increments, or a continuous path prediction may be broken by hash marks at equal time increments. Many terminal control tasks require display of only terminal point predictions rather than a continuous path or several successive predicted states, thus side stepping the problem of presenting the time dimension.

Perhaps one of the most intriguing possibilities for predictive displays is to present a predicted value of some cost function in tasks where minimization of that function is a primary goal. This would be of special value when the cost function is some complex relation among terminal conditions or a complex integral of the system response. This technique conceivably could be of value as a training device for eventual operation with more conventional displays.

2.8 Performance Measurement

Essential to the study of predictive displays (or any new display system for that matter) is the proper selection of performance measures. These problems have been discussed in general philosophical terms by Obermayer [34], who stated:

> "...what we understand through research depends upon measurement, and what we can predict in the design of systems also depends on what we have measured."
>
> "To demonstrate feasibility, it is necessary to show that some simple tasks can be accomplished and that no unsafe conditions result. Stability and safe performance are measures."
>
> "In analytic efforts with varying system parameters the primary measure is system performance, with subsystem performance and user acceptance as other measures."

In the present stage of predictive display development the system must be considered in the large, with the human operator being an internal subsystem. Though operator performance has an effect on total system performance, we are at present concerned with whether or not the technique as a whole has any merit. Thus it is appropriate to base our evaluation on overall system performance.

Whenever possible, the performance measure should be based on realistic mission objectives rather than on a more simple, less descriptive measure. This is most easily illustrated by considering a two-dimensional terminal control problem in which one possible measure is

$$J = \sqrt{\epsilon_1^2 + \epsilon_2^2} \tag{2.8.1}$$

where

ϵ_1 = terminal error in one dimension

and

ϵ_2 = terminal error in the other dimension.

But suppose that in terms of mission objectives we are more interested in a complex function of the terminal errors, $J' = f(\epsilon_1, \epsilon_2)$, which can arise when the terminal conditions are only an intermediate stage of the entire mission, as in the control of a satellite launch vehicle in which the conditions at booster engine cutoff are referred to as the terminal conditions. Superimposing several levels of these two different criteria on a plot of ϵ_1 vs. ϵ_2, we may have the situation shown in Fig. 2.8.1.

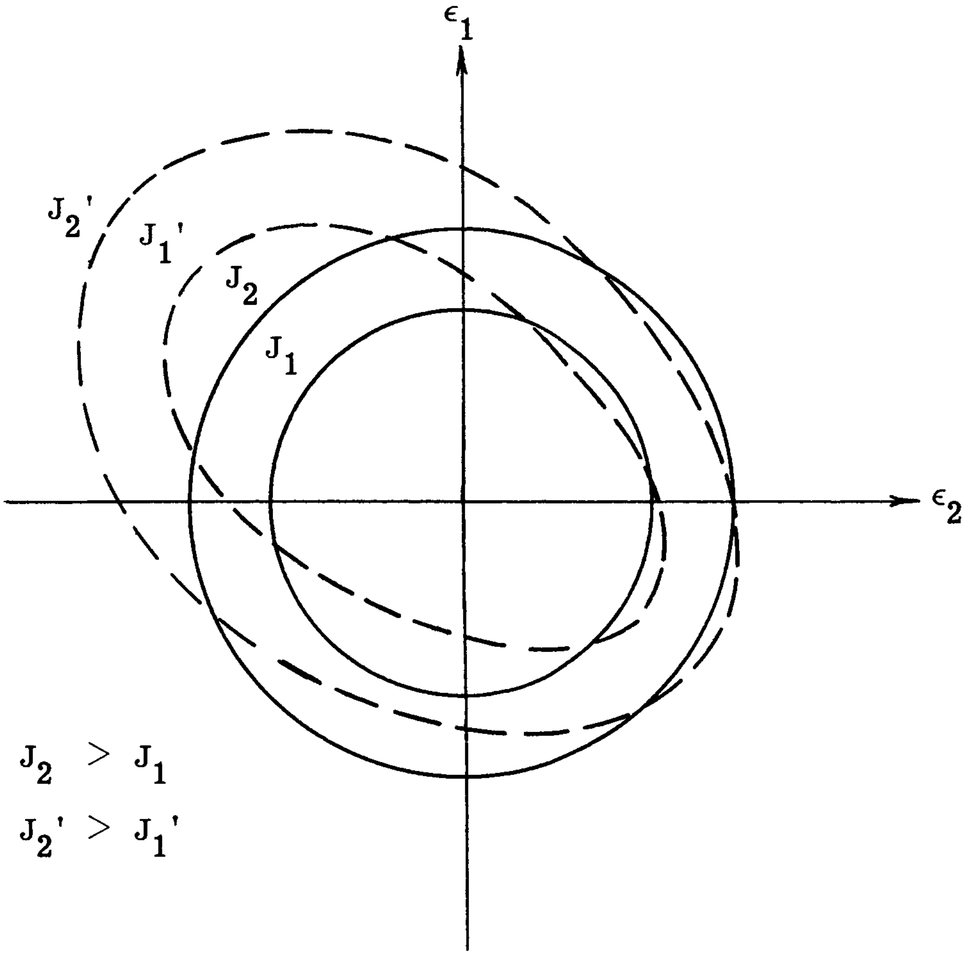


Figure 2.8.1 Constant Cost Contours for Two Different Performance Criteria in a Terminal Control Task.

Clearly, two separate trials which yield the same performance in terms of J may yield entirely different levels of performance in terms of measure J'. It should be noted at this point that the control strategy of the human operator might be the same for two different performance measures when both are minimized for identical values of the terminal state variables. This is also true in other than terminal control tasks, such as a continuous tracking task in which operator strategy might be the same whether he were told to minimize the integral of the absolute value of the error or the integral of the error squared.

2.9 Summary and General Remarks

In this chapter we have attempted to define those factors which will have an effect on performance of a man-machine system in which a predictive display is to be used. Some of these characteristics may present sufficient difficulties so as to preclude the use of a predictive display system, especially when the on-board computer requirements are excessive. The discussion here has been intended to make the display system designer and the researcher aware of the different factors that must be considered in any proposed predictive display system.

Whether or not a predictive display is superior to other control and display forms is the main question to be answered in any application. In answering this question it must be determined if predictive information is needed by the operator, and then whether or not it is worth the cost in the required computation and display equipment. In the next chapter, these questions and requirements on model accuracy, repetition rate, etc., will be discussed for a variety of potential applications.

Chapter 3

POTENTIAL APPLICATIONS OF PREDICTIVE DISPLAYS

Nearly all of the known predictive display studies that have been reported have been concerned with single specific applications, mostly in the aerospace field. These studies have been concerned primarily with demonstrating the feasibility of the concept for one vehicle, one display format, and one predictor model implementation. The general effects of the different characteristics mentioned in the preceding chapter in any single application have not been explored. This chapter does not delve into any great detail on each type of vehicle considered, but rather presents an overview of the control tasks that might be encountered, and points out the problem areas that may arise in the utilization of a predictive display system for each vehicle, drawing heavily on previous research where possible.

The discussion here is restricted primarily to control of aircraft and space vehicles. A comprehensive summary of several of the application studies for space vehicles mentioned in this chapter can be found in Ref. [20] by Kelley.

3.1 Launch Vehicles

Guidance and control of large launch vehicles is one of the most difficult tasks, either automatic or manual, that we are facing today. While there have been several studies of manual booster control, it remains an application in which the desirability of human pilot participation in other than a monitoring role is highly questionable. There have been very few simulation studies in which the human pilot has been repeatedly able to perform the specified control task within the desired constraints. If the pilot is to be included at all in the control loop, current trends would limit his participation to that of a decision maker or an emergency controller.

There are two phases to a launch vehicle flight: an atmospheric phase, in which the flexible vehicle is subjected to wind disturbances with the primary control task being the avoidance of structural failure and loss of control, and an exo-atmospheric phase in which a minimum-fuel terminal control task is normally the main objective [18].

A launch vehicle is basically an unstable system in which directional control is exerted through the gimballed main thrust engines. It has been found that the human pilot is not able to stabilize manually the vehicle without the inclusion of some automatic compensation in the control system. Several studies [24, 33] have shown that with the addition of a rate-augmentation system the human pilot can achieve stable control. However, it has been concluded from these studies that the pilot would function best in a backup role. It is doubtful that the addition of predictive information would lead to better direct manual attitude control since the time constants of typical launch vehicles are of the order of several seconds or less.

Some autopilots that have been built and that are proposed for large

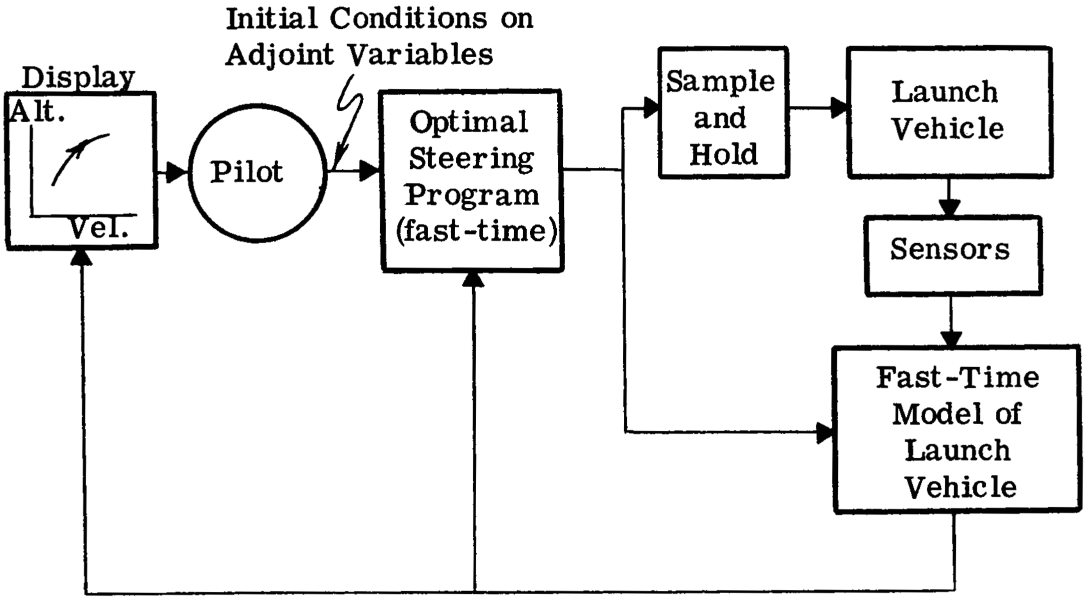


Figure 3.1.1 Predictive Model Guidance Scheme for a Launch Vehicle by Gilchrist and Soland [17].

launch vehicles employ several adaptive elements. Because of this, indirect participation of the pilot through the adjustment of the automatic control system conceivably could be of some value. A predictive display study by Gilchrist and Soland [17] was based on this concept. In their technique, called a Predictive Model Guidance Scheme (Fig. 3.1.1), an optimal steering program to yield a minimum fuel launch trajectory for the exo-atmospheric phase was generated through the use of a set of adjoint equations. With this technique, which arises from Pontryagin's Maximum Principle [38], it is necessary to select initial conditions on the adjoint variables so that the terminal constraints are satisfied. Using a fast-time model of the vehicle, a predicted trajectory was generated in an altitude vs. velocity display. The subject pilots were then given the task of adjusting the initial values of the adjoint variables. It was found that accurate terminal guidance was obtained when a digital display of the terminal errors was supplied. Though not demonstrated conclusively, the authors felt that a display of the predicted trajectory was useful in that it allowed the pilot to "shape" the trajectory. The noted however that a digital display of only the predicted terminal errors might have been sufficient.

Direct manual control has been proposed for emergency situations in which a mission abort is necessary. There is some possibility in this application for the use of predictive displays to present continuously to the pilot a predicted trajectory and landing point if an abort were executed at the present moment. This would allow a relatively rapid assessment of the abort situation.

Use of a predictive display system by a range safety officer in observing the flight of a missile has been proposed by Fogarty [15]. Though the current range safety displays provide a continuous indication of an impact point that would result from an abort, this scheme would provide nearly instantaneous information concerning many aspects of an abort that would result from a variety of subsystem malfunctions. A special real-time simulator would be used in this technique to provide updating of the parameters in the fast-time model, as illustrated in Fig. 3.1.2.

Requirements on the predictor computer for a launch vehicle vary

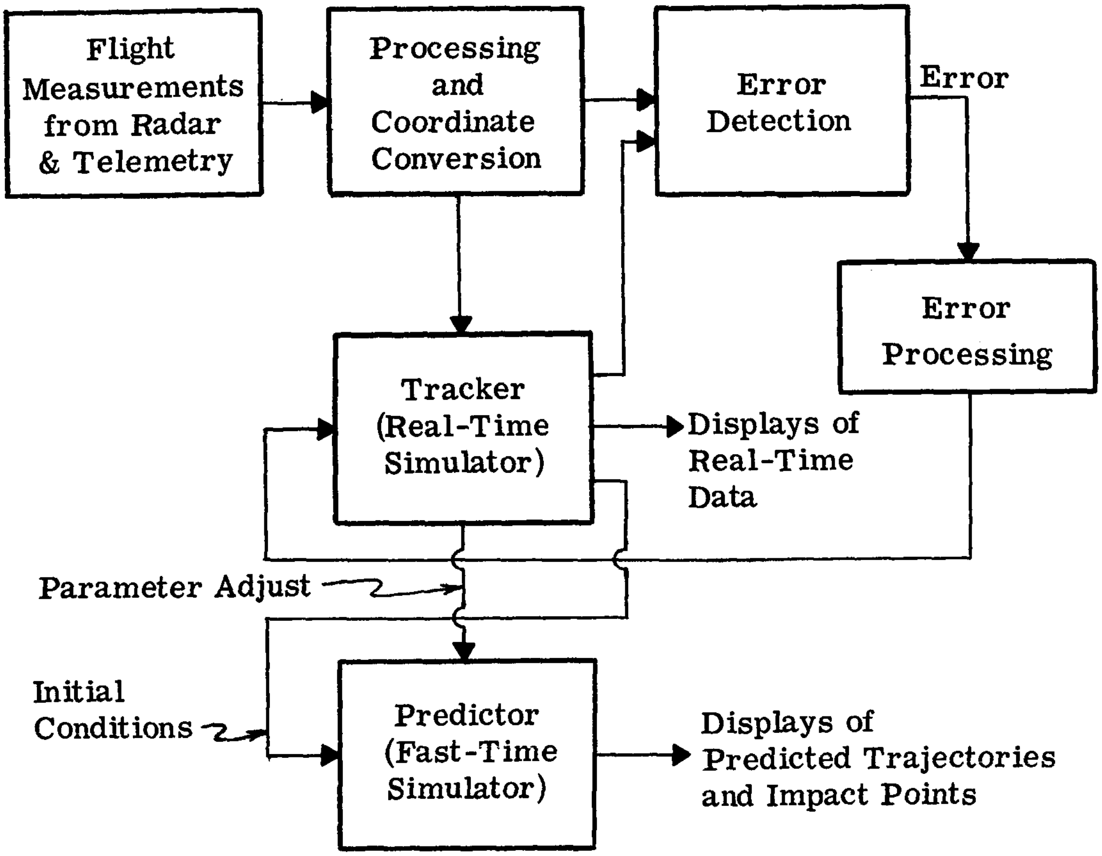


Figure 3.1.2 Trajectory Prediction Scheme for Monitoring Launch Vehicle Aborts from Ref. [15].

according to the specific use. Accurate predictions over any reasonable span for the atmospheric phase would require a modelling of the wind disturbances, which is almost impossible. In any phase of launch, there is a very rapid energy buildup which would require a high repetition rate and update rate. Thus the computer requirements are fairly stringent for most launch vehicle applications.

The prime question concerning manual control of a launch vehicle appears to be related to just where in the control loop the pilot should be placed. It is fairly probable that such a decision could be affected by whether or not the use of continuous predictive information is considered.

3.2 Rendezvous and Midcourse Maneuvers

Rendezvous between two orbiting spacecraft can be thought of as occurring in two phases: a long-distance phase and a terminal phase. The long-distance portion of the maneuver requires major orbital changes by the pursuing spacecraft, in which the relative motion of the two vehicles is characterized by a rather complicated set of dynamics with which the human pilot has relatively little intuitive feel. The terminal phase is concerned with a close range such that the relative motion between the vehicles is (for all practical purposes) fairly simple. Pilots in the Gemini program have demonstrated that this terminal portion of the maneuver, including docking with the target, can be flown successfully with visual cues through the window and radar-supplied range and range-rate data. As a result, the remaining discussion here will be concerned only with long-distance rendezvous.

In most instances rendezvous is to be completed with a minimum expenditure of fuel subject to a time constraint. The trade-offs between time and fuel lead to generally complex optimal thrust programs which are heavily dependent upon the nature of the orbital trajectories of the two vehicles. This complexity, coupled with the long transit times, is the reason for the inability of the human operator to achieve satisfactory direct manual control of long distance rendezvous without special aids.

The individual control tasks in rendezvous require that the vehicle be positioned to a proper attitude, followed by application of thrust for a specified time interval. Attitude control problems, which are discussed later, are therefore also important in rendezvous.

Computer modelling of the relative motion between two orbiting vehicles is a relatively simple problem. As a result, predictive display techniques hold a good deal of promise for rendezvous applications. McCoy and Frost at Wright-Patterson Air Force Base have investigated extensively predictive displays for coplanar rendezvous [16, 28, 29, 30]. Some discussion of their work, plus several display concepts for the terminal docking maneuver are found in an article by Kelley [20].

The initial studies by McCoy and Frost [30] compared an on-line predictive display to a time-history display for coplanar rendezvous in which the position of the interceptor relative to the target was presented. The specific task was to reach a certain region around the target within a fixed time interval using a minimum amount of fuel. The predictive display was found to be superior in terms of the amount of fuel consumed. A similar study by Mano and Ulbrich [27] also indicated a savings in total fuel consumed in rendezvous tasks with exploratory prediction. In addition, their results indicate that the technique would be useful as a training device for rendezvous using normal displays. Later studies by McCoy and Frost [28] compared on-line and off-line or exploratory prediction, in which the operator could select trial pitch attitudes and thrust durations. This yielded better performance in terms of fuel consumed than on-line prediction. They further found that when updating was reduced from continuous to once every 50 seconds, no significant performance loss resulted. Several other factors related to display size were studied by McCoy and Frost, but perhaps one of the most startling results they obtained was that naive subjects could perform successful rendezvous maneuvers with the predictive display with essentially no training.

Midcourse maneuvers in general are similar to rendezvous maneuvers except that the time spans can be considerably longer, as in the transfer from a lunar orbit to an earth orbit. Precise application of control is required since the terminal condition sensitivities are large. Minimum-fuel trajectories are usually desirable; however, under some circumstances (which may be unforeseeable for a particular mission) the time constraints may be more severe. To provide the degree of flexibility required in future manned missions, use of the pilot in decision-making functions for the midcourse maneuvers and long-distance transfers is indicated. Potentially, a form of off-line predictive display could be of value to the pilot in performing the necessarily complex decision tasks. However, analog computer models are probably insufficient because of the extreme accuracy requirements. Thus the use of a predictive display in this application is dependent upon the availability of high speed on-board digital computers.

Additional research is needed to determine the display formats and mechanizations that would be applicable to non-coplanar rendezvous. In addition, display of predicted performance criteria should be investigated for rendezvous applications. Implementation schemes for the midcourse maneuvers also need to be studied, with emphasis placed on the use of a predictive display for situations in which a great deal of flexibility is desired, such as mission aborts.

3.3 Lunar Landing

Manual control of the descent of a lunar vehicle is desirable from the standpoint of the need for flexibility in landing site selection. The pilot will be responsible for translational as well as attitude control, making this a potentially very difficult task.

Lunar landing has been envisioned to occur in three phases [9]:

(1) Minimum fuel de-orbit, with a large reduction in velocity. Main engine thrust applied opposite to direction of flight.

(2) A transition phase with the vehicle pitched up so that the landing site is observable. Less than full thrust capability will be used with the throttleable descent engine. This phase

lasts roughly two minutes, with velocity decreasing from 800 ft/sec. to 100 ft/sec.

(3) A touchdown phase with the craft in a vertical attitude. Final selection of landing site is to be made, with translational velocities over the surface controlled by pitch and roll attitude changes.

Descent and coarse translation control of a lunar landing craft involves main engine throttles and gimbal angle, while vernier translation control and attitude control involves reaction jets. There is, of course, a very definite fuel constraint in lunar landing. This makes lunar landing a time critical task since hovering is costly in terms of fuel. The complex control system, the complex performance criteria, and the time critical aspects all suggest that predictive displays might be useful here.

The terminal phase of lunar landing using a predictive display has been investigated by Fargel and Ulbrich [12]. For altitude control using a predicted trajectory in an altitude vs. altitude-rate display, they found more consistent performance with less fuel expenditures than with a display of just the current values of the state variables. For two-dimensional control with a similar display presented orthogonal to the first, improvements in performance were obtained with the predictor, although several problems with such a format were noted.

The fast-time predictor model to be used in such an application must be fairly accurate and operate at a high repetition rate due to the time-critical nature of the task and the high penalties associated with hard landings. It also appears that both on-line and exploratory prediction should be available, so that the pilot could monitor simultaneously the present predicted state and explore future control inputs without having to cycle the engine. Additional research in these areas and into desirable display formats is needed.

3.4 Spacecraft Attitude Control

The control of vehicle attitude is of concern in nearly all the missions discussed separately in this chapter; however, special techniques and problems can be found in the attitude control task independent of the overall mission.

Attitude control of a manned spacecraft is accomplished usually through the use of reaction jets. With appropriate location of these jets or special modifications to the control system, independent changes in the pitch, roll and yaw attitudes can be made, i.e., the axes can be uncoupled. When a set of reaction jets is fired, a rotation rate is built up about the corresponding axis. The lack of aerodynamic damping makes this response neutrally stable. In the past, rate command systems have been used in which a deflection of the control stick causes an angular rate about the proper axis through a pulse-modulation control law. Backup systems have employed direct reaction jet control, so that accelerations rather than rates are commanded. It should be noted that disturbances in vehicle attitude can arise through movement of internal parts, including the crew.

The requirements on attitude control vary according to the particular portion of a mission. A large amount of time in orbital flight is spent usually in a free, drifting mode, with little or no requirements on vehicle attitude. On the other hand, precise attitude control is required in several instances, e.g., when the mission calls for earth reconnaissance, or when thrusting maneuvers are necessary for orbital changes. There are also instances in which attitude control is time constrained. An example is the de-orbit maneuver in which a retrograde thrust must be applied at a specific time with a specific attitude in order to achieve a desired re-entry trajectory.

With three axes to monitor, the control task is somewhat difficult, although the addition of the rate command system simplifies it somewhat. It has been found that six variables must be displayed to the pilot: pitch, roll and yaw angles, and pitch, roll and yaw rates. The need for a display which combines this information into an easily interpretable form may be seen.

A study was made by Besco [7] comparing performance in several attitude control tasks with four different display systems:

(1) Conventional three-axis sphere with rates indicated on meters.

(2) A three-dimensional model of a spacecraft with rates indicated on meters.

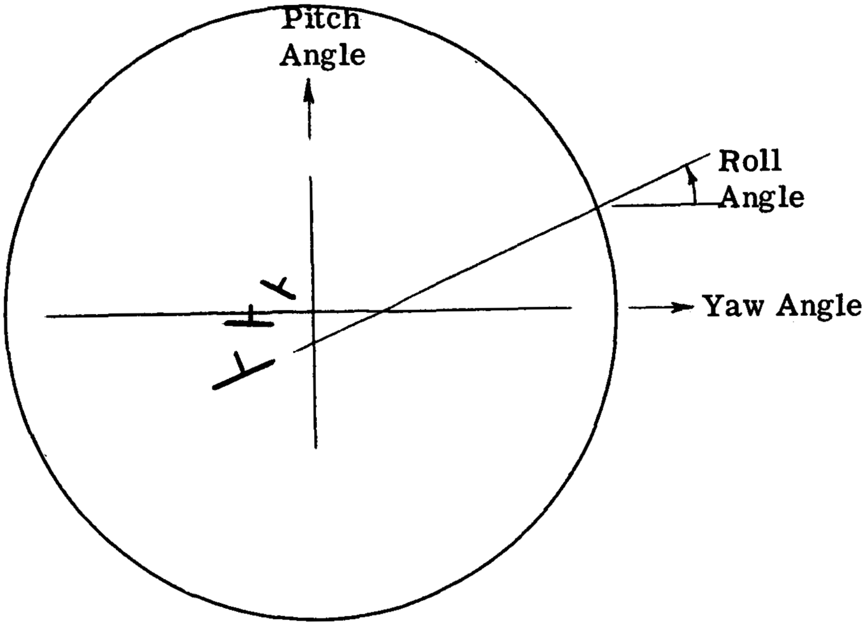


Figure 3.4.1 Attitude Predictor Display Used by Besco [7] Showing Attitude at Present and at 10 and 20 seconds into the Future.

(3) Six separate meters indicating the individual attitude angles and rates.

(4) A predictor display on a seven-inch CRT using the format indicated in Fig. 3.4.1.

Three different attitude control maneuvers were investigated:

(1) Attitude hold. Maintain a specified attitude while the vehicle is subjected to disturbance torques.

(2) Stabilization. Cancel initial attitude rates so that a specified attitude is reached and maintained.

(3) Attitude change. Change attitude from some initial orientation to a different, specified final orientation.

Three control modes were used: a single-pulse mode, a repeated-pulse mode and an on-off acceleration mode. Total fuel consumed, mean-square angular error, and elapsed time were the performance criteria.

The subjects, all experienced pilots, indicated a preference for the predictive display system. The results indicated lower fuel consumption and rms errors for the predictor than for any of the other three display forms. In his review of this effort, Kelley [20] noted that if problems with the display disappearing off the side of the CRT had been eliminated, and if off-line rather than on-line prediction had been used, additional performance improvements might have been obtained.

The simulated vehicle in this study had some coupling between the axes which was not represented in the predictor model, with the result that there were noticeable errors in the prediction. Various prediction spans from 10 seconds to 30 seconds were employed, with no significant effect on performance, probably because of the inaccuracies in the prediction due to the lack of coupling terms in the model. Kelley noted, however, that an accurate prediction span as long as one or two minutes would have been useful. Because of the requirements on prediction accuracy, repetition rates would have to be relatively high. Updating information which presumably would be available from an inertial platform or horizon sensors could be supplied almost continuously.

It should be noted that of the four attitude displays investigated by Besco, only the predictor could be classed as an integrated display form (information about all six state variables was presented in one display). It remains to be seen whether or not the predictive display would yield significant advantages over a non-predictive integrated display in attitude control tasks.

Since it is the purpose of a predictive display to reduce the information processing requirements of the operator, the advantages of the technique in attitude control tasks may be most apparent when all concurrent tasks are considered. Therefore, any complete evaluation of an attitude predictor relative to other display forms should take into account the other piloting tasks that may be present in an actual mission.

3.5 Atmosphere Re-Entry

Re-entry represents one of the most complex phases of a space vehicle mission. The usual objective is to attain a certain landing site without violating constraints on the re-entry trajectory which arise through deceleration and heating limitations. The rapid change in the environment and thus in the vehicle dynamic characteristics that is encountered during re-entry makes this a difficult control situation. Complex control modulation during re-entry is called for under many circumstances, e.g., when a trajectory for minimum heating is desired. There is always a possibility that unexpected circumstances will be encountered during or prior to re-entry which require that re-entry control not be a totally predetermined function. The inclusion of the human pilot somewhere in the control system is thus seen to be desirable.

In vehicles such as Gemini and Apollo, flight path control is effected by rolling the vehicle so that the lift force can be applied in various directions. More advanced lifting bodies will have devices which will actually change the lift and drag coefficients of the vehicle.

The information requirements for manual re-entry control are not altogether straightforward in view of the nature of the task and the trajectory constraints. For example, one proposed technique utilizes a time-history display on a drag versus velocity-squared format [46]. Several authors have investigated predictive displays for re-entry employing a landing footprint display which indicates the area on the surface of the earth that can be attained by the vehicle.

The display format for re-entry that was used in a predictive display study by Wingrove and Coate [51] is shown in Fig. 3.5.1. The display presents a non-dimensional range capability with respect to the desired destination. The contours for constant bank angle and angle of attack indicate what conditions should be held to reach a specified point. Pilot strategy with this system is to control the vehicle such that the desired destination remains near the center of the footprint. Thus a maximum amount of control is available for unexpected

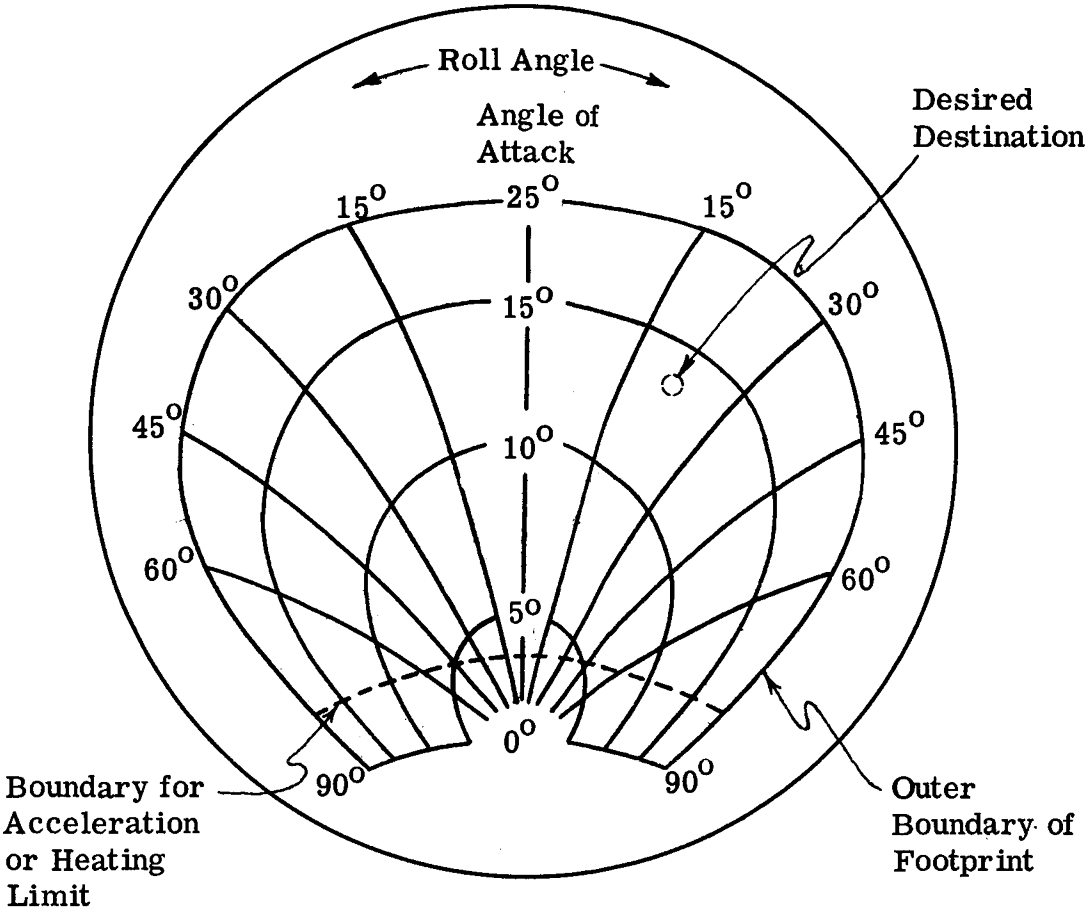


Figure 3.5.1 Re-Entry Footprint Display from Ref. [51].

changes which may result from errors in either the updating information or in the model of the atmosphere.

The fast-time model used by Wingrove and Coate computed the landing points for maximum longitudinal range, minimum longitudinal range, and maximum lateral range at the rate of one solution every six seconds. They found that this solution time was sufficient for re-entry from circular orbital speeds; however, for entry from parabolic speeds it was felt that higher solution rates would be needed because of the more rapid changes in flight conditions.

The footprint or GAA (for Ground Area Attainable) display for re-entry trajectory control has been further studied by Austin and Ryken [3]. The requirements on updating frequency and repetition rate for such a display have been explored by Anderton [1], who was concerned with re-entry predictions for launch vehicle aborts. In such a situation, according to Anderton, the total range capability of a high-lift vehicle immediately after burnout of the booster is reduced at a rate of more than 100 miles per second, placing rather stringent requirements on both updating frequency and repetition rate. He noted, however, that by using state-of-the-art computers and a special set of re-entry trajectory equations developed by Fogarty and Howe for accurate high-speed analog solution [14], footprints based on twenty individual trajectory computations could be presented in less than two seconds. Such a computer could supposedly be built weighing 40 pounds and occupying two cubic feet.

The footprint displays mentioned above function as the main source of information for re-entry trajectory control. Partial use of the predictive technique was investigated in a complete re-entry simulation study conducted at Lear Siegler, Incorporated in Grand Rapids, Michigan [25]. This study used a digital display of quantitative predictions of several specific parameters, such as nose cone temperatures. It was concluded from this effort that the predictive information allowed more precise control of the corresponding parameters, demonstrating the utility of predictive displays when the operator has several tasks which must be performed almost simultaneously.

From the studies mentioned above, it appears that predictive displays have significant application in manual control of re-entry vehicles. However, several problems remain requiring further research:

(1) Display Format: In addition to being a terminal control problem, re-entry in some circumstances must be near optimal with respect to such criteria as heating inputs and deceleration forces. Studies are needed to determine the information requirements and optimum presentation of this information for these conditions.

(2) Predictor Control Programs: The complex control modulation required during re-entry to achieve a desired optimal trajectory should be included in the predictor control program. Studies are needed on how this can be implemented while still retaining the flexibility of not being restricted to a pre-programmed control throughout re-entry.

3.6 Aircraft Takeoff

With the advent of jet-powered transport aircraft, new problems arose in the selection of criteria for safe takeoff procedures [41]. Because of the high-speed swept wings normally found on jet transports, a higher angle of attack is required to attain the lift force necessary to lift the aircraft off the runway. Associated with this high angle of attack is a large drag force. The resulting problem is one of selecting the proper combination of angle of attack and aircraft speed so that the drag force will not retard acceleration to the point of delaying lift-off or preventing a climb.

When and where lift-off can occur at a safe angle of attack and speed is dependent upon several parameters: air temperature, wind velocity, runway elevation, condition of runway, gross weight of the aircraft and acceleration profile during the takeoff roll. Prediction of the lift-off point on the runway is thus a rather complicated task. The go, no-go decision by the pilot must be based on many variables and must be made under rapidly changing conditions. The current technique used by the pilots employs an elaborate set of tables which lists the speeds at which rotation and lift-off should occur as a function of most of the above parameters. While the present safety record of the airlines in the performance of this task is impressive, increased safety and reliability is still worth some moderate cost.

A predictive display for aircraft application which presents information of physical significance will be beneficial from a pilot acceptance standpoint. A Safe Take-off Predictor (STOP) device has been proposed by Hainsworth and

Olinger [19] which indicates the aircraft position on the runway, a predicted takeoff point and a last safe stop point, all on a single vertical scale. The pilot enters runway condition, runway length, and aircraft gross weight into the instrument which then computes the predicted takeoff point on the basis of the observed airspeed and acceleration. One version of the device uses a cathode-ray tube which could be time-shared for the presentation of other information after takeoff. A fast-time analog model is not used for this device, but it is not apparent whether any increase in accuracy using the fast-time technique is necessary.

The initial climb is another phase of aircraft takeoff that is worthy of attention. The piloting task is to maintain a certain equilibrium climb which involves maintaining a certain attitude and airspeed and avoiding the natural phugoid oscillations characteristic of all aircraft. A failure of one of the engines during climb makes this a difficult task which is complicated further by the fact that the pilot has limited experience under these conditions.

In an aircraft climb study reported by Loomis [26], lead information was provided to the pilot through an acceleration-biased angle of attack indicator which used the sum of an angle of attack error signal and a signal proportional to the longitudinal acceleration. By trying to keep the indicator zeroed, pilots in a simulation study were able to fly more accurate engine-failure climbouts than with conventional instrumentation. Since a predictive display is not always a pure command device and can present more physically interpretable information, it might produce greater increases in the level of safety of this maneuver. Conceptually, such a device would show a predicted climb path on an altitude vs. range display, so that the future effect of an engine failure would be immediately apparent. The required fast-time model could probably be relatively simple since we are concerned with large rather than small changes in altitude. The repetition rate must be fairly high however, since immediate indications are necessary.

3.7 Aircraft Cruise

Present control concepts for subsonic jet transports during all phases of a flight other than takeoff and landing have proven to be quite satisfactory. Autopilots which place the crew in a monitoring role are used extensively, and current display and control systems seem to be adequate for those maneuvers that require direct pilot control. Of course, further refinements such as collision avoidance systems always are being sought.

New high performance military and civil aircraft have required a complete re-examination of flight control systems and the functional requirements of the crew. The desire for low altitude supersonic flight in military aircraft missions has fostered the development of terrain following systems, for example. The proposed Advanced

Manned Strategic Aircraft (AMSA) for the military and supersonic transport (SST) for commercial use are highly complex flight vehicles in which major advances in flight control technology are needed.

In these advanced aircraft, crew responsibilities will include the management of a variety of complex systems: the fuel system, the propulsion system, the control system, the collision avoidance system, the air data system, the clear air turbulence detection system, the navigation system, the communications system, and in military aircraft the weapons system and electronic countermeasures system. In addition to these increased responsibilities, navigation and control of the aircraft will be a very demanding task due to the large sensitivities in the flight path that result from the high speed operation of the vehicle.

In a study of supersonic transport crew responsibilities reported by Price, Honsberger, and Ereneta [39, 40], the need for anticipatory information in nearly all of the flight management and control functions was discussed. It is obvious that predictive displays are one potential source of this type of information. It appears that the capability for generating predictive information will be available in the future through a proposed centralized computer which places the crew in a supervisory role for normal flight [44]. Also, the Boeing Company is reportedly considering time-shared electronic cathode-ray tube (CRT) displays for their SST [37].

A predictive display was found to be effective in altitude control of high performance aircraft in a study by Sweeney, Todd and Heaton [45]. They also conducted a simulation study using a predictive display in monitoring an automatic flight control system in a terrain following task. They found the predictor gave an improvement over conventional displays, provided the dynamics of the automatic flight control system were included in the predictor model. They concluded that the computer requirements for generation of the predictive display were excessive (the availability of modern high speed computers was not considered) which led to a proposed synthetic predictor display. This device presents the velocity vector of the aircraft rather than a predicted path. A hash mark could be superimposed on the velocity vector to indicate some reference airspeed.

The problem of determining the proper display format for the various phases of supersonic transport control has yet to be solved. Such things as contact analog displays in which a real world presentation is made have received some attention. Incorporation of predictive information into such a display format could be of significant value.

The need for anticipatory information in this application should be apparent; whether or not this should take the form of predictive-type displays employing a fast-time model technique is a question yet to be answered. It is very possible that more simple forms of lead information such as a velocity vector display will be sufficient in several instances.

3.8 Aircraft Landing

The final approach and landing phase is perhaps the most critical and demanding of the pilot for the entire flight. Precise flight path control is required when the aircraft is the least responsive to control inputs. Several procedures are necessary for this phase of flight: (1) attainment of a desired final approach path towards a specific point on the runway, (2) initiation of a flare maneuver so that the aircraft contacts the runway without an excessive rate of descent and at a low airspeed, and (3) guidance of the aircraft after touchdown while decelerating so that the aircraft can be stopped before the end of the runway is reached. These tasks must often be accomplished under extenuating circumstances: there may be gusty crosswinds, visibility may be restricted, and in the case of a carrier landing (for which there is no flare maneuver), the runway may be quite unsteady.

All of these tasks involve the use of the primary flight controls including the engine throttles. With jet aircraft there is an inherent time lag between throttle movement and aircraft acceleration. Thus, in effect the pilot is controlling a relatively sluggish system. This sluggishness will become accentuated in the large transports aircraft being planned, e.g., the jumbo jets and supersonic transports.

Several aids are normally available to the pilot in the landing task. Ground Control Approach (GCA) facilities (discussed in more detail below) can provide the pilot with voice commands from a ground controller to follow a pre-determined glide-slope trajectory. Instrument Landing Systems (ILS) provide direct compensatory cues in the cockpit of any vertical or horizontal deviation from a specified glide path. These systems can all function down to an altitude of several hundred feet, at which point the pilot must revert to direct visual contact with the runway to complete the landing. All-weather landing systems are presently under development which would perform automatically all of the landing tasks, with the pilot functioning only in a monitoring role.

Because of the complexity and sluggishness of the aircraft system in the landing phase, manual performance depends heavily upon the anticipatory abilities of the pilot. The new larger aircraft will place additional demands on this capability of the pilot. Whether or not the present aids mentioned above will be sufficient is still open to question. It may be expected that predictive displays could provide some benefit in this application.

Following the glide path is a two-dimensional tracking task for which some sort of lead information is desirable. Presentation of simple lead information (e.g., velocity vector) is feasible using the existing format of vertical and horizontal deviations from the glide path. More complex predicted trajectory information is possible with a CRT or similar device in this format with a third dimension (future time or distance) added through the use of perspective. Prediction span would probably be on the order of 10 to 20 seconds, so that a very simple fast-time model would be sufficient.

Execution of the flare maneuver is very nearly a discrete decision process for the pilot. A continuous prediction of the flare path in relation to the runway should simplify this decision. This would be of use in all-weather landing systems, and in aircraft such as the supersonic transport for which flare must be initiated at a relatively high altitude. It is highly probable that the prediction must take into account the complicated ground effect phenomenon in order to have the desired accuracy.

Predictive information could be of considerable use to the ground controller in GCA operations. His task is to provide verbal commands to the pilot (on the basis of radar information) regarding the maneuvers which should be made to acquire the glide path and then follow it. Because of the inherent time lags in this type of operation, considerable emphasis is placed on the predictive abilities of the controller. Conceptually, a ground-based computer (with few restrictions on weight and power requirements) would provide the predictive information. The controller would enter the pertinent characteristics of the aircraft into the computer, and upon a command following radar identification of the aircraft the predicted flight path would be superimposed upon the controller's display. The controller could conceivably enter hypothetical commands into the computer so that the prediction would be exploratory in nature. A tracking computer could also be employed to generate information on the aircraft's rate of climb, rate of turn, and ground speed in addition to the position information from the radar. Alternatively, this information could be transmitted by a telemetry system on-board the aircraft. This additional rate information then could be used for updating the predictor computer in order to generate on-line predictions [13].

3.9 Remote Control

There are a wide variety of situations in which the human operator exerts indirect control on a system. The GCA operation described in the previous section is one example. Air traffic control, supervision of harbor activity, and anti-submarine warfare are some further examples of this type of activity. Control of a vehicle on the lunar surface by an operator on the earth is another type of remote control problem. A common characteristic of all these applications is that there is some pure time delay between the issue of a command by the controller and the actual implementation of the command by the pilot or remote system. For remote control of a lunar vehicle there is roughly a 1.3 second transmission delay between the earth and the moon. Thus, when an input is commanded by the earth-based operator, it is 2.6 seconds before he is able to observe any effect of his command.

The use of predictive information to compensate for pure time delays is apparent. An application to remote control of lunar vehicles has been studied by Arnold and Braisted [2]. They used a specially constructed vehicle which bore a television camera to transmit a

TV presentation of the terrain ahead of the vehicle to the remote operator. The earth-moon transmission delays were simulated, and a special predictive symbol was presented on the television receiver. This symbol was based on a prediction span exactly equal to the time delay (the fast-time model technique was not used). They found that control with the predictive symbol approximated control with no time delay and the normal display. As a result, safe lunar vehicle speeds could be increased substantially over those possible without the predictive display.

3.10 Other Applications and Summary

The specific applications discussed in this chapter by no means represent all the potential uses of predictive displays. In this section, brief mention is made of some of the applications that have been omitted.

Operations with VTOL (vertical takeoff and landing) aircraft are characterized by some very difficult control problems. Typically, a helicopter has unstable characteristics which present unusual demands on the pilot. Many VTOL missions are similar to conventional aircraft operations, with only the dynamics of the vehicles being different. As a result, implementation of a predictor computer and display may be somewhat more difficult for VTOL aircraft, but the need for predictive information may also be more pronounced. Clearly, this is an area in which much work can be done.

Many tactical and strategic aircraft missions require a high degree of anticipatory ability from the pilot. In some situations better use of the human adaptive characteristics might increase the probability of success of the mission. Thus, there is potential application of predictive displays in such operations as weapon delivery, anti-submarine warfare, etc.

Control of a chemical process is typically associated with very long effective time delays and high order plant dynamics which place severe limitations on the predictive abilities of the human controller. With the capability for extensive computer systems located in a process plant, predictive information could be available which would aid optimization of the control process without removing the man from the control loop.

The initial studies on predictive displays by Kelley [22, 23] were concerned with submarine control, with some additional work more recently by McLane and Wolf [31]. A submarine is generally a complex and slowly responding vehicle which makes it an obvious candidate for predictive displays.

It has been shown in this chapter that the number of potential uses for predictive displays is very large. In general it appears that those applications which are most likely to benefit from their use fall into one or more of the following categories:

(1) The dynamics of the controlled element are complex and slowly responding.

(2) The dimensions of the control task or number of individual tasks are relatively large.

(3) The nature of the task requires considerable anticipation by the operator.

(4) Optimization of some cost function is the primary objective of the mission.

(5) The task is time constrained, or is a terminal control task.

(6) There is a strong desire for flexibility in the mission.

Predictive displays certainly are not the only possible answer to these control problems. In any use the technique should be compared to pure command displays and displays of more simple lead information. It should be kept in mind that a predictive display need not function in a primary role. It can also be used effectively on a time-shared basis, in an integrated display, or as a system monitoring display.

Chapter 4

MINIMUM-TIME CONTROL OF A PURE INERTIA SYSTEM

The need for general studies of the predictive display technique has already been discussed. The next question that logically arises is: where do we begin? It is sufficient to say that the influence of repetition rate, prediction span, etc., are of no concern whenever the actual plant dynamics and the control task are such that any predictive display cannot provide significant improvements in performance over more conventional displays. Therefore, the experiment described in this chapter is directed towards answering the following questions:

(1) What variables associated with the controlled element (plant) dynamics are pertinent to performance with predictive displays?

(2) Under what conditions associated with the plant will performance improvements obtained with predictive over non-predictive displays be unimportant?

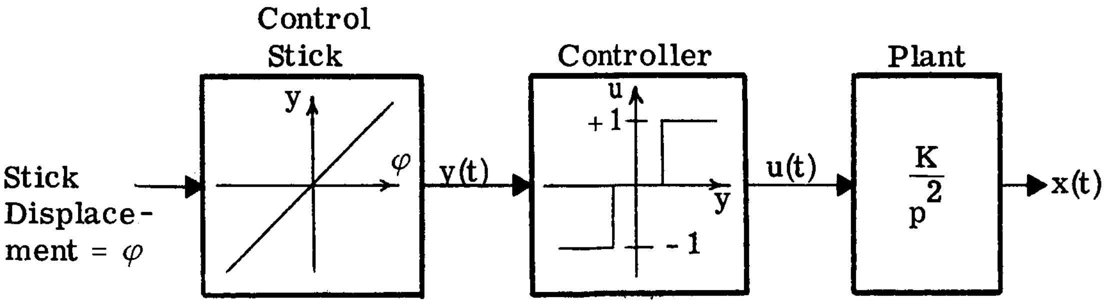
(3) What types of performance measures are appropriate for an evaluation of predictive display systems?

The answer to these questions should be obtained for a practical range of all the plant independent variables. If the plant is described by three variables, and three values of each of these variables are to be presented in an experiment, then a total of twenty seven conditions must be evaluated. Multiply this figure by the number of displays to be used, times the number of subjects, times the number of trials necessary per subject to eliminate learning effects, and we can readily see that a large experimental program is required. Increasing the order of the plant dynamics by one, thus adding one more independent variable, can easily make the experimental effort get out of hand.

Thus in the experiment reported here a relatively simple plant with fixed controller dynamics was chosen. This allows a general and thorough investigation of the independent variables of the plant without being unduly restrictive on the extension of the results to systems of practical interest.

4.1 Plant Dynamics and Control Task

Pure inertia dynamics were chosen for the plant, which was driven by a three-state relay controller. Inputs were applied to the controller by deflection of a control stick by the subjects. This system is illustrated in Fig. 4.1.1.



$$\ddot{x} = Ku \quad , \quad u = 0 \ , \ \pm 1$$

Figure 4.1.1 Control System and Plant.

Fixing the characteristics of the control stick and the controller, the entire system behavior is described by the input from the operator and three independent variables: the gain K, and initial conditions $x(0)$ and $\dot{x}(0)$ on the plant.

Since time constraints appear to be critical in discussing performance with a predictive display system, a minimum-time task was chosen for this investigation. Specifically, the task is to drive the system to a given fixed terminal state $x_F(T)$ and $\dot{x}_F(T)$ from some initial state $x(0)$ and $\dot{x}(0)$ in a minimum amount of time, and in such a manner that the terminal state can be held for a finite interval. While this objective can be described by several different cost functions, an appropriate general form of the function to be minimized might be:

$$J = T + \int_{T}^{T'} \left| x(t) - x_F(T) \right| dt \tag{4.1.1}$$

where $T' > T_m$ = absolute minimum time for the specified gain and initial conditions.

This combination of plant, controller, and task exhibits several advantages for this type of an investigation:

(1) The pure inertia plant and three-state relay controller are of some practical interest.

(2) The number of independent variables is not too large.

(3) Manual control of such a system with only a display of the

instantaneous input and output is stable though not highly accurate and efficient.

(4) In many terminal control tasks with a time constraint, typical human operator strategy probably is to attain the terminal conditions as quickly as possible so that a maximum amount of time is available for fine adjustments in the control.

(5) In minimum-time proportional control tasks with a pure inertia plant, operator strategy (as found in a preliminary experiment) is usually to apply a bang-bang control input. Thus, a three-state relay controller will not alter performance significantly over that with a proportional controller.

The terminal state which must be reached in minimum-time from some initial starting point $[x(0), \dot{x}(0)]$ was specified to be $[x_F(T) = 0, \dot{x}_F(T) = 0]$. Thus it is seen that $x(t)$ and $\dot{x}(t)$ are equivalent to error signals $\epsilon(t)$ and $\dot{\epsilon}(t)$, where $\epsilon(t) = x(t) - x_F(T)$*. The true minimum-time solution of this problem yields the well known bang-bang control law, in which the initial input is a maximum acceleration towards the target followed by a maximum deceleration such that the vehicle comes to rest just as the target is reached [(pp. 23-27), 38]. The optimum time of application of the control reversal between maximum acceleration

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*This definition of error is inverse to the usual definition, for the sake of convenience.

and maximum deceleration can be determined, and is dependent upon the system gain and the initial conditions. These concepts are best illustrated by considering a phase plane plot of the response of the system, as shown in Fig. 4.1.2.

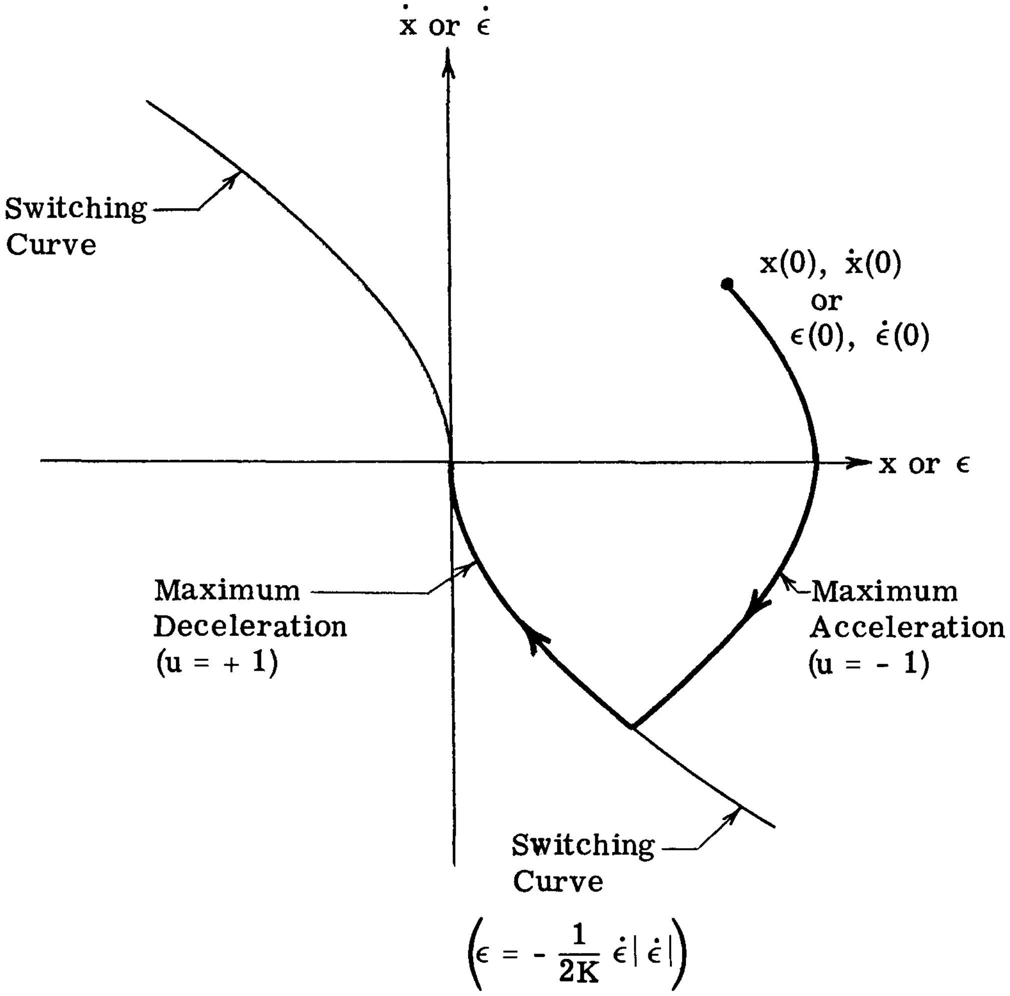


Figure 4.1.2 Phase Plane Plot of Response of Pure Inertia System to Time-Optimal Control Law.

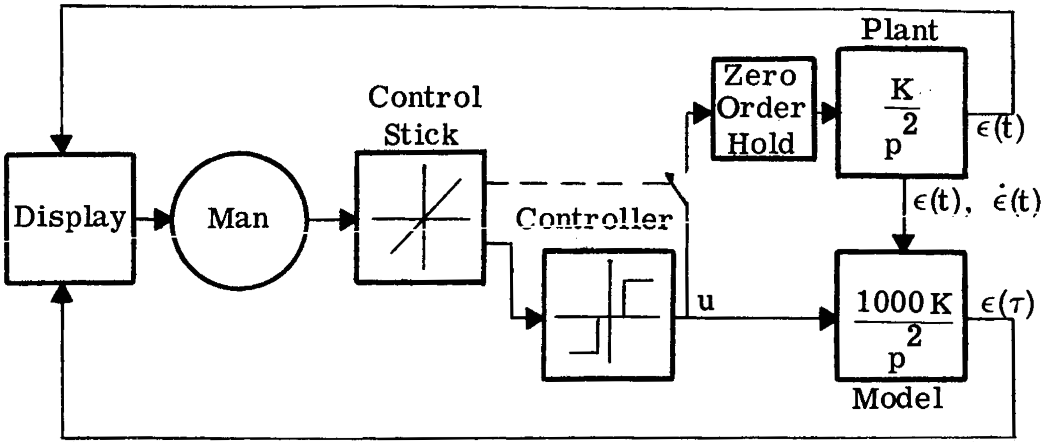
The time-optimal control law may be expressed as follows: whenever the starting point is above and to the right of the switching curve in the phase plane, a u = - 1 control input is applied until the switching curve is reached, at which time control is reversed to $u = +1$. The signs on u are reversed when the starting point is below and to the left of the switching curve.

In order to remain at the terminal state it is necessary to apply a zero control input the moment it is reached, which requires a second control change. This requirement was added to the task definition, as it was felt that simply passing through the desired final state was not indicative of completion of the transient response phase of the maneuver. It is also a realistic constraint in a practical task. (The effect on transient control strategy of this additional requirement was not determined here.)

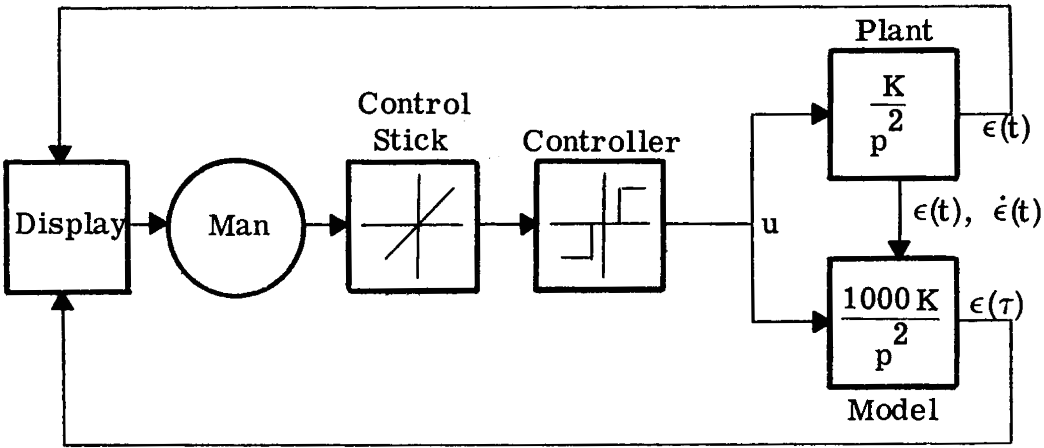
The subjects were instructed to drive the system to zero error and error-rate in minimum time and maintain that state for four seconds beyond the true minimum time. (This four second period was chosen arbitrarily.) Three maneuvers thus are required for ideal completion of the task: (1) selection of the proper initial control input, (2) appropriate control reversal at some intermediate time, and (3) nulling the input when the zero error and error-rate conditions are satisfied.

4.2 Displays

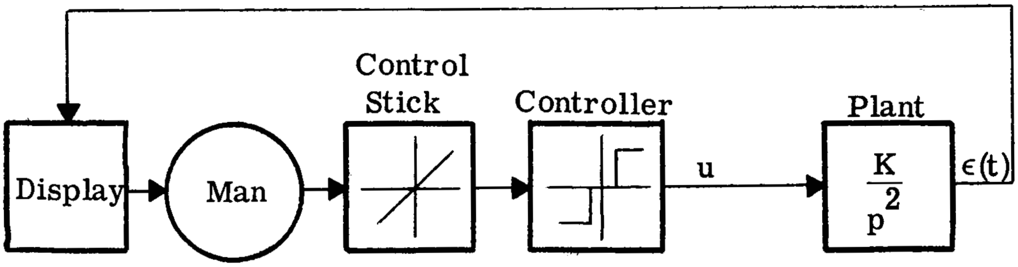
Three types of displays were chosen for evaluation: exploratory prediction, on-line prediction, and normal (no prediction). Block diagrams illustrating the implementation of these display systems for the dynamics being considered are shown in Fig. 4.2.1. The display



(a) Exploratory Prediction



(b) On-Line Prediction



(c) Normal

Figure 4.2.1 Block Diagrams of Display and Control Systems Studied.

format was time versus error with a vertical centerline representing the time axis at zero error presented on a large screen oscilloscope. For the predictive displays a 30 cps repetition rate and a span length of seven seconds were used. The model time scale was 1000 x real time. These values were chosen in order to eliminate any possibilities of performance loss due to either slow repetition rates or insufficient prediction spans for the conditions that were investigated.

Manual operation with the time vs. error display format occurs as follows:

(1) A point of light, representing the present output of the system, is shown initially at the bottom of the screen (zero time) displaced from a vertical centerline (the time axis) by the magnitude of the initial error signal.

(2) For either predictive display a trace showing a predicted path over the next seven seconds, emanating upwards from the light point, describes the future response of the system appropriate to the present control input into the fast-time model. (See Fig. 4.2.2.)

(3) Prior to the beginning of a trial, the operator selects the proper initial control input (to avoid time lags in the initial control application).

(4) Upon initiation of the trial, the light point moves upwards at

a constant rate, and horizontally according to the input into the actual system.

(5) Control reversal technique varies according to display form:

(a) No prediction: the operator reverses control when he decides it is desirable, based on his mental prediction.

(b) On-line prediction: the operator makes rapid control reversals in a sampling mode of operation, until the predicted trajectory grazes the centerline. (See Fig. 4.2.3.)

(c) Exploratory prediction: the operator reverses control well before the required time, but only into the fast-time model. When the hypothetical predicted path is tangent to the centerline, he squeezes a trigger on the control stick which commands the input into the actual system to duplicate that which is presently driving the fast-time model. (Fig. 4.2.3.)

(6) When the light point reaches the centerline, the control input is returned to zero so that the point will follow the centerline.

(7) Four seconds beyond the true minimum time for the conditions used, the trial is terminated.

Whenever any of these functions are performed improperly, additional control changes are necessary in order to reach the centerline and follow it.

An alternative display format that was not used is the error, error-rate phase plane display. Aside from the problem of poor

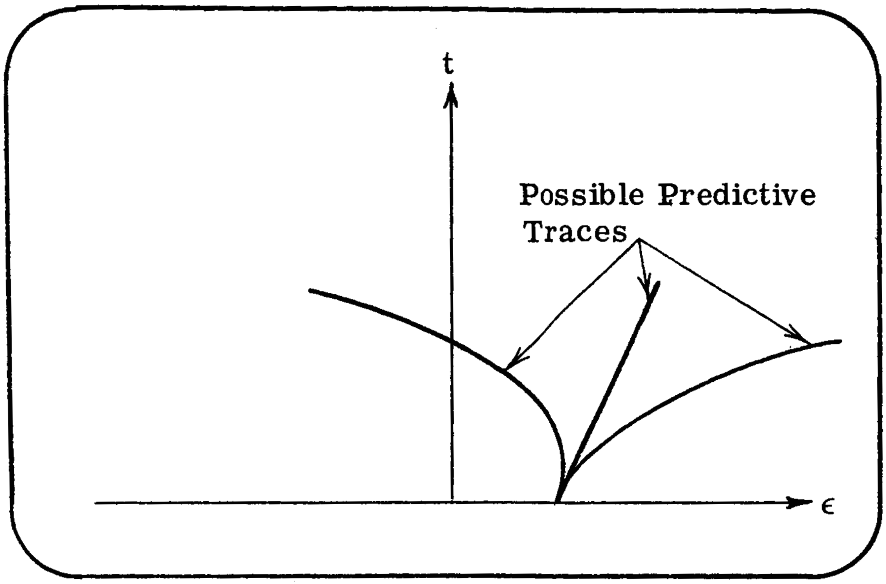


Figure 4.2.2 Display Format for Conditions at the Beginning of a Trial.

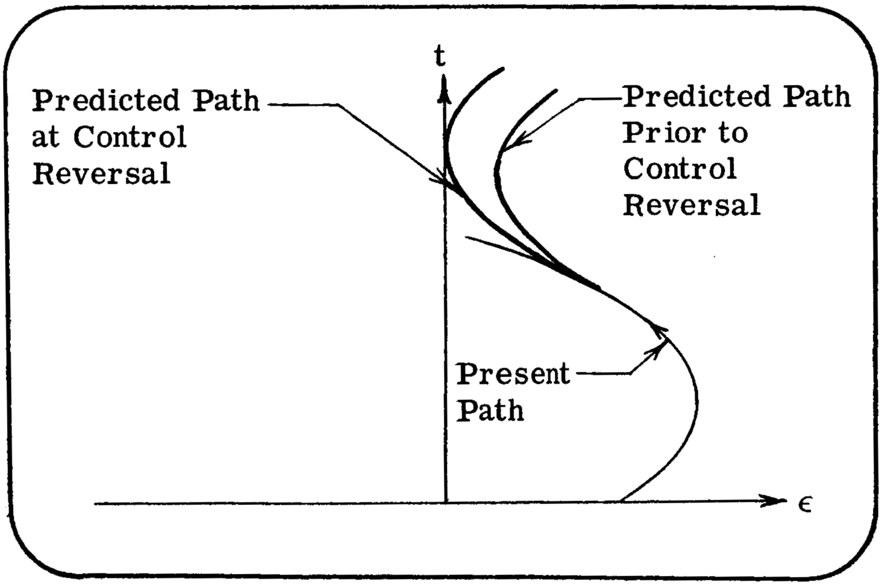
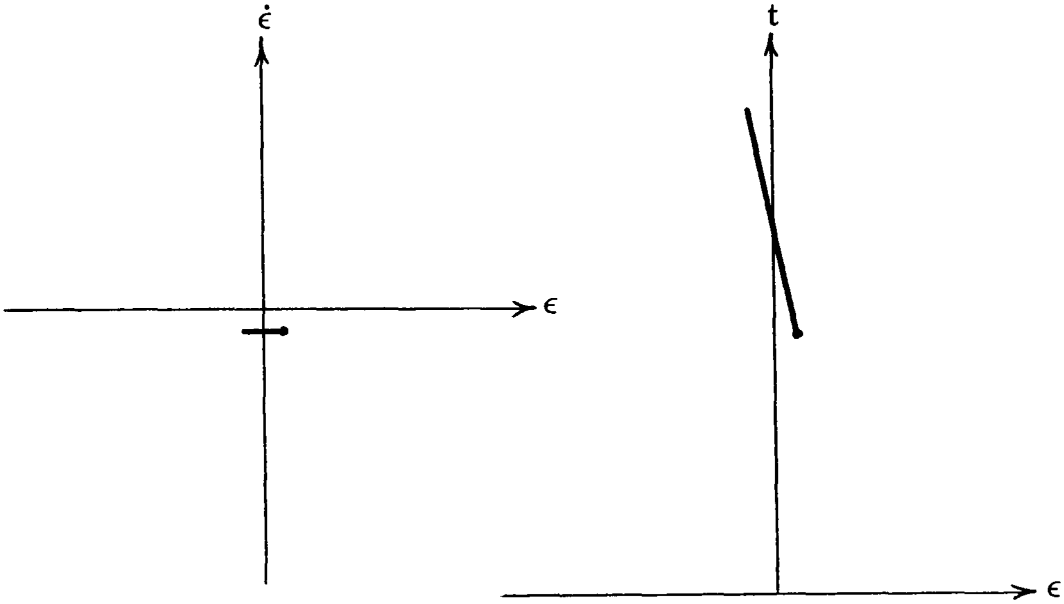


Figure 4.2.3 Predicted Paths at and Prior to Proper Application of Control Reversal.

control-display compatability that exists for such a format (the direction of motion of the light point cannot be directly related to control stick deflection), there exists a certain amount of difficulty in perceiving a predicted path for a coasting (zero input) trajectory near the origin. In Fig. 4.2.4, a predicted path for a coasting trajectory is compared between the error, error-rate format and time vs. error format.



(a) Phase Plane Format (b) Time vs. Error Format

Figure 4.2.4 Predicted Coast Trajectories with Identical Time Spans for Small Error and Error-Rate Signals.

However, there is a definite advantage to the phase plane format if the switching curves are indicated. This is simple to implement, and would probably result in as good transient control as that which exists with exploratory prediction for this task. However, a display of the switching curves is a command display (with preview of the command), not a predictive display.

It should be noted that the choice of the time vs. error display was made on the basis of the definition of the particular control task considered here, and is not intended to be the best or most efficient format in other tasks.

An off-line predictive display form applicable to this problem though not investigated is multiple path prediction, in which all three responses for the three possible control inputs are continuously and simultaneously displayed. However, the only advantage that can be seen in the transient response phase of this task is that the operator would not be required to perform the additional task of pressing a trigger, as he must with exploratory prediction. There is a possibility of some performance improvement with multiple path prediction when rapid maneuvers are required near the target, though it is felt that the differences would be quite small.

4.3 Task Variables

Since repetition rate, prediction span, and controller characteristics have been fixed in this experiment, the only remaining parameters affecting the closed loop system are the gain K, initial conditions $\epsilon(0)$ and $\dot{\epsilon}(0)$, and parameters associated with the human operator. The existing techniques for modelling the human operator such as the quasi-linear describing functions of McRuer [32], have little application in this instance. It is therefore necessary for us to treat the human as an unknown element in the control loop, and consider the effect of the three plant variables on performance of the entire system with the three different displays.

It was hypothesized that the initial conditions $\epsilon(0)$ and $\dot{\epsilon}(0)$ by themselves were not the important independent variables that affect performance. Instead, variables that are certain combinations of the initial conditions and the system gain have a more direct physical interpretation from the viewpoint of the human operator. These variables, which are hypothesized as possibly being influential to performance in tasks involving the selection of discrete control changes, are defined below and illustrated in Fig. 4.3.1.

(1) True Minimum Time, T_m:

The time required to attain the terminal state when the minimum-time control law is followed. It is a measure of the response time limitation of the system.

(2) Switch Time, t_{sw}:

The time between the occurrence of the first optimum control reversal and the encounter of the target. It is the time interval over which the operator must make a mental prediction when using the normal display.

(3) Approach Speed, V_a:

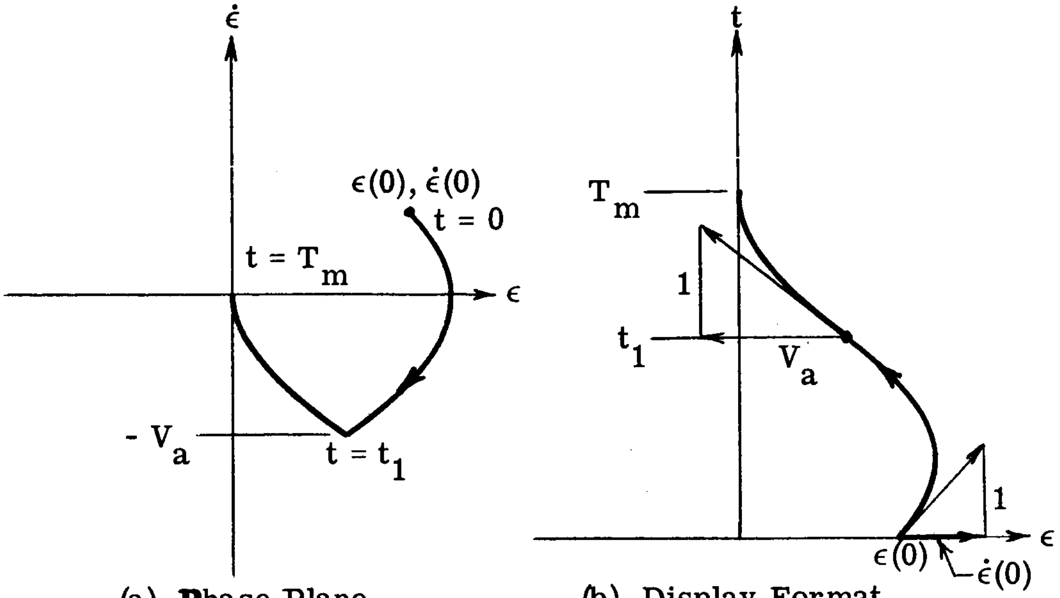
The rate at which the light point is moving towards the centerline in the time vs. error display plane at the moment of the required optimum control reversal. With the exploratory predictive display, V_a can be seen to be the horizontal component of velocity of the parabola as it approaches the centerline.

(4) System Gain, K:

The level of acceleration that is achieved through application of a control input. Note that if T_m and t_{sw} are unchanged, varying K is equivalent to varying only the display gain.

It should be noted that these parameters are nominal independent variables which describe conditions only if the optimal trajectory is followed. Deviations from the optimal trajectory will result in different values for t_{sw} and V_a to describe the actual response produced by the operator.

From the preceding development we can list four task variables that may influence performance: K, T_m, t_{sw}, and V_a. These variables are not all independent however, since $V_a = Kt_{sw}$. From the results of a preliminary series of experiments it was found that the true minimum time, which is an indicator of the overall speed of response of the system, is not sufficient to describe performance variations. For fixed display size and scale, long minimum times are associated



(a) **Phase Plane** (b) Display Format

Minimum time: $$T_m = \frac{1}{K}\left[\dot{\epsilon}(0) + 2\sqrt{\frac{1}{2}\dot{\epsilon}^2(0) + K\,\epsilon(0)}\right]$$

Switch time: $$t_{sw} = T_m - t_1 = \frac{1}{K}\sqrt{\frac{1}{2}\dot{\epsilon}^2(0) + K\,\epsilon(0)}$$

Approach speed: $$V_a = \sqrt{\frac{1}{2}\dot{\epsilon}^2(0) + K\,\epsilon(0)} = Kt_{sw}$$

Note: Definitions are for initial conditions above and to the right of the switching curve in the phase plane. For initial conditions on the other side, it is necessary to change the sign of $\dot{\epsilon}(0)$ and $\epsilon(0)$ in the above equations.

Figure 4.3.1 Definition of Task Variables.

with large values of t_{sw} and low values of V_a, so in general terms the minimum time has an influence. As a result of the preliminary experiments, the following hypotheses concerning performance with the three display types were formulated:

(1) Exploratory prediction: Performance will be dependent upon the accuracy of the control reversal at t_1 and the nulling action at zero error and error-rate. The first will be affected by the approach speed, since this operation is one of pressing a trigger when the hypothetical predicted path is tangent to the centerline* (see Fig. 4.3.2). The second operation requires the pressing of the trigger when the predicted coast trajectory lies along the centerline. The angular rate of movement of the predicted path in this case is given by the gain K (see Fig. 4.3.3). Using performance measures concerned with the transient phase of response only, the effect of inaccuracies in the application of the coasting input will not be great.

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*The task of reacting to the coincidence of a moving point and a fixed point was first discussed by several astronomers who were concerned with noting the passage of a star across the center of the field of view of a telescope. This led to some of the early reaction time studies, as discussed by Woodworth [52].

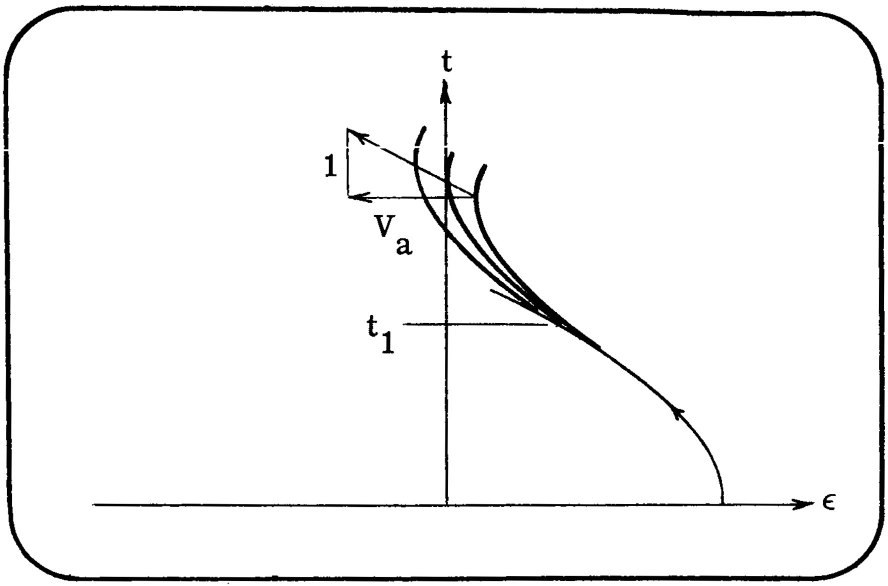


Figure 4.3.2 Successive Predictive Traces as Seen in Operation with Exploratory Prediction, Illustrating the Influence of Approach Speed on Application of Control Reversal at t_1.

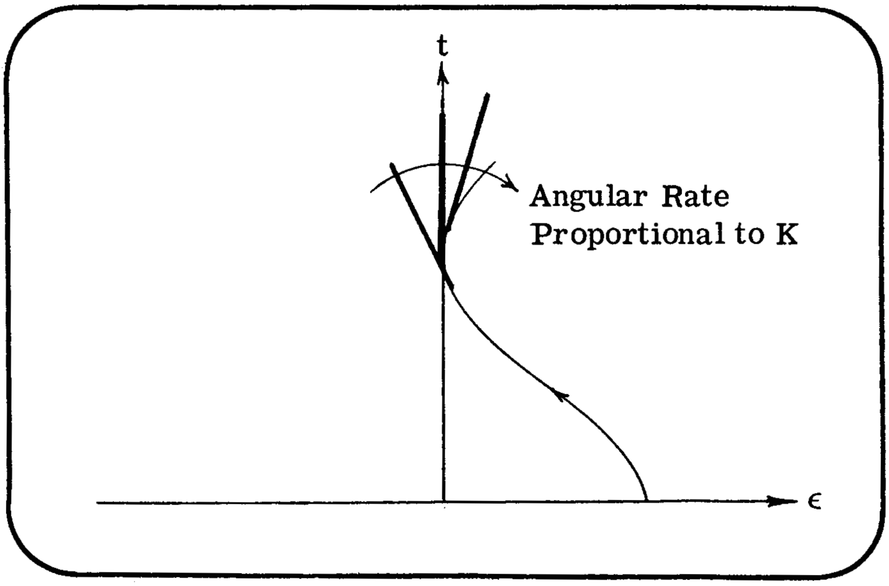


Figure 4.3.3 Successive Predictive Traces with Exploratory Prediction Showing the Influence of Gain on Selection of the Coast Trajectory when the Centerline is Reached.

(2) On-line prediction: As noted earlier, operator strategy using on-line prediction is to explore briefly the effect of a control change by rapidly reversing the control through a complete cycle. This sampling behavior by the human operator is subject to an upper bound on the sampling frequency. For a given sampling frequency, the probability of accurate control reversal at t_1 will decrease as the approach speed increases. The same is true for increasing gain effects on application of the zero control input at the terminal point. Thus, on-line prediction is assumed to be affected by the same task variables that influence exploratory prediction, although to a greater extent since the sampling frequency limitation with on-line prediction is not of concern in exploratory prediction.

(3) No prediction: The ability of the human operator to predict accurately the point at which the first control reversal should occur depends on several factors. The necessary mental prediction time is an obvious and important factor, for as that time increases the operator makes less accurate predictions. Thus, t_{sw} is expected to be a significant variable in describing performance with the normal display. Because of this, complications arise in the determination of the effect of approach speed and gain, due to the relation $t_{sw} = V_a/K$. For fixed t_{sw}, it is not possible to determine whether increasing

V_a or increasing K is the cause of performance changes. Manual control of pure inertia systems using two-state and three-state relay controllers has been investigated by several researchers, though the range of independent variables and study objectives are not the same as those reported here. Pew [36] noted that velocity information was used implicitly by the human operator in judging the proper time for the first control reversal. This brings up the question on how the operator makes this prediction. Several explanations are feasible:

(a) The operator forms a mental image of the phase plane switching curve, and bases his decision on the proper combination of error and error-rate.

(b) The operator forms an internal fast-time model of the system, and repetitively predicts the response to a control reversal from the present perceived error and error-rate signals.

(c) The operator mentally stores an image of the decelerating parabola on the time vs. error display plane, and notes when the present output lies on that parabola.

(d) A combination of these.

All of these techniques involve the accurate perception of error and error-rate signals. For high levels of acceleration, the error-rate is changing rapidly, and for high error-rates the error is changing rapidly. Conversely, when these levels are low, accurate estimation of the error-rate requires a long observation time. Thus we can expect both gain and approach speed to have some influence on performance.

Two complicating factors arise in an analysis of this sort. The first is the control strategy of the human operator, which is adopted through his awareness of his own limitations. For example, Pew [36] found that subjects using a high gain system would command an intermediate coasting phase prior to the optimum switching point, apparently in order to prevent an excessively large rate build-up. Another problem is concerned with the strategy of using a half-way position criterion for switching decisions: if the initial error-rate is either zero or away from the centerline, the proper switching point occurs halfway between the maximum error signal and the centerline (see Fig. 4.3.4). However, if the initial error-rate is towards the centerline, this cue will be absent.

Thus, several considerations arise in investigating the cause and effect relationships for performance with the normal display: the task variables, operator strategy, and presence or absence of certain visual cues.

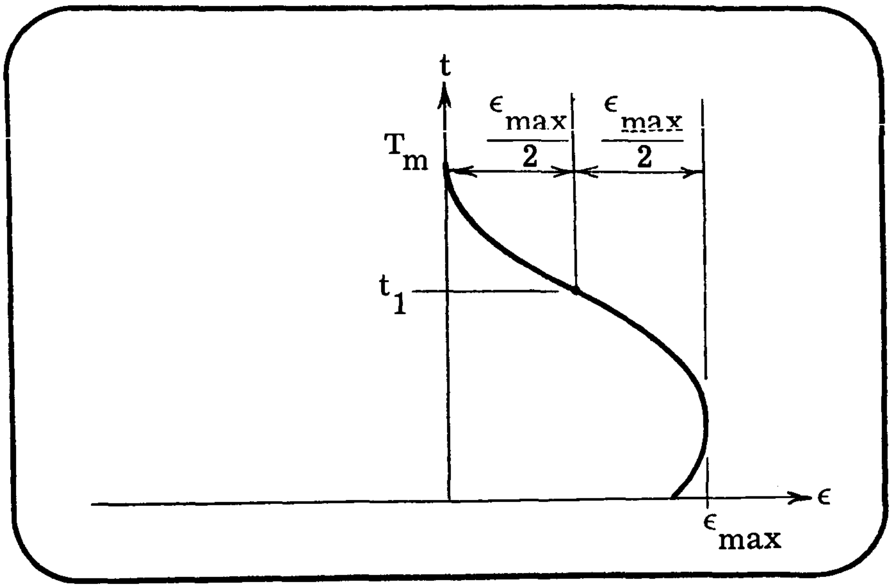


Figure 4.3.4 Half-way Position Switching Criterion.

4.4 Performance Measures

The problem of performance measure selection has been discussed in general terms in Chapter 2, where it was pointed out that comparisons made between different types of display and control systems can vary with the type of performance measure that is used. It was further noted that the proper performance measure for evaluation studies in a specific application should be related to the overall objectives of that application. Since the minimum-time control task presented here is not concerned with any single application, a variety of measures are possible.

The task under consideration is to reach the specified terminal state in minimum time. A criterion that is immediately suggested is the time required to reach a tolerance zone around the desired terminal state, since for all practical purposes the exact terminal conditions may never be satisfied. There are several problems however with using a tolerance zone, or terminal gate, in calculation of a performance measure:

(1) The terminal gate must be carefully defined, so that the true minimum-time trajectory to reach the exact terminal conditions will also yield a minimum possible time to attain the gate.

(2) To indicate successful completion of the transient phase of the response, the terminal gate must be maintained for some reasonable time interval. This complicates the performance measure definition considerably.

(3) A terminal gate necessarily limits the sensitivity of the performance measure.

Though these limitations may not be too restrictive in some applications, the terminal gate technique was found unsatisfactory for the study reported here. Instead, performance measures which are based on the conditions that exist at the true minimum time were used.

They are discussed below.

(1) Integral Absolute Error (IAE):

The integral of the absolute error signal was computed from the true minimum time, T_m, to four seconds beyond the minimum time, $T_m + 4$, to provide an index of learning. IAE is illustrated as the shaded area in Fig. 4.4.1.

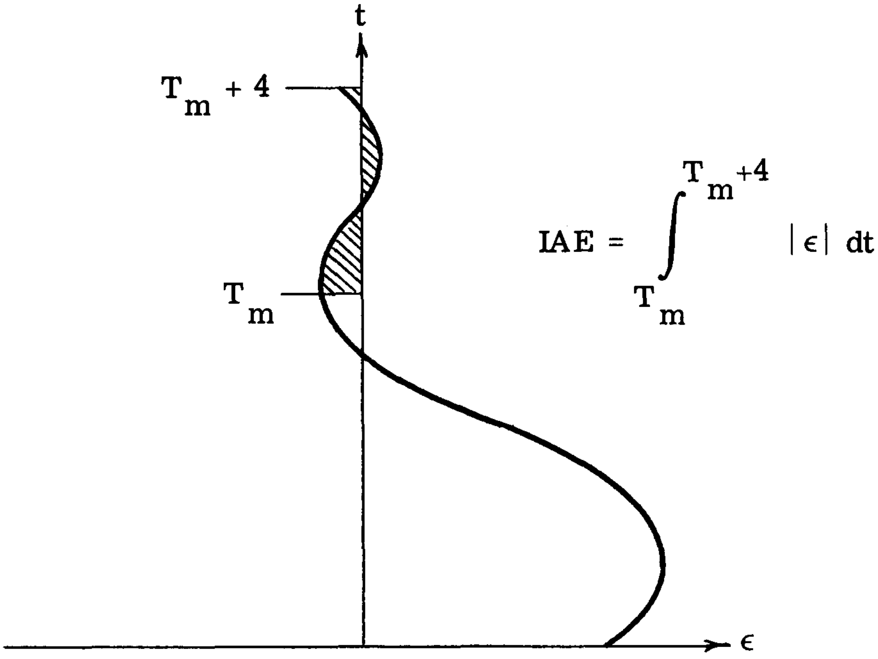
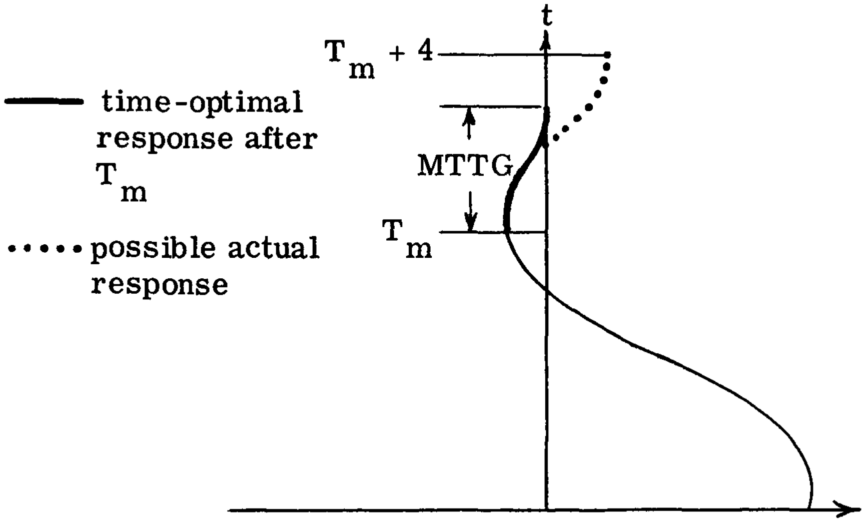


Figure 4.4.1 Integral Absolute Error (IAE) Measure for Study of Learning.

Note that if the error signal is driven to the centerline in minimum time and remains there until termination of the trial, the IAE will be zero. While IAE does not provide a direct measure of transient response,a low value necessarily implies relatively good transient behavior. Thus, when the experimental values of IAE stabilize as a function of the days of testing, we can conclude learning effects are no longer significant. This measure was used for an analysis of learning rather than the other measures because of the additional requirement of tracking the centerline.

(2) Minimum Time-to-Go (MTTG):

If the actual error and error-rate that exist at the minimum time, T_m, are known, the remaining time required to reach the terminal state assuming a time-optimal control law is followed can be calculated. This remaining time is called the Minimum Time-to -Go and is defined in Fig. 4.4.2.



$$MTTG = \frac{1}{K}\left[\dot{\epsilon}(T_m) + 2\sqrt{\frac{1}{2}\dot{\epsilon}^2(T_m) + K\epsilon(T_m)}\right] \quad \text{for}$$

$$\epsilon(T_m) + \frac{1}{2K}\dot{\epsilon}(T_m)\left|\dot{\epsilon}(T_m)\right| > 0$$

Figure 4.4.2 Definition of Minimum Time-to-Go Performance Measure.

Contours of constant MTTG performance measure in the phase plane for two levels of gain are shown in Fig. 4.4.3. The location of the contours for identical performance levels varies with the gain. However, if plotted in a $\dot{\epsilon}/K$ vs. ϵ/K phase plane, this gain dependency is eliminated (see Fig. 4.4.4). Because the operator does not necessarily follow a time-optimal control law after the true minimum time, MTTG is only a measure of the transient response, as are all of the remaining performance measures which are discussed.

(3) Miss Distance (MISS):

The MISS is equal to the error when the error-rate is zero, assuming a trajectory towards zero error-rate in the phase plane is followed after the terminal time. This performance measure is illustrated in Fig. 4.4.5, and contours of constant MISS in the $\dot{\epsilon}$ vs. ϵ phase plane are shown in Fig. 4.4.6. If plotted in the $\dot{\epsilon}/K$ vs. ϵ/K phase plane, the gain dependency is eliminated as for the Minimum Time-to-Go performance measure.

It can be seen that MISS is minimized whenever the terminal state lies on the time-optimal switching curve. It should be pointed out that operator strategy, if told to minimize the MISS, might be somewhat different than used here. Since it would be necessary only to attain the switching curve, a more

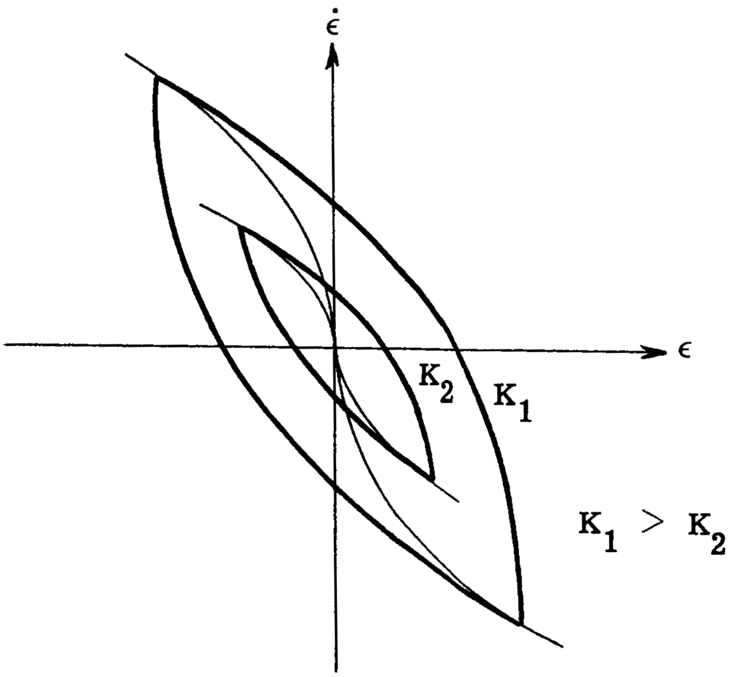


Figure 4.4.3 One Level of Constant MTTG Contours in the ϵ, $\dot{\epsilon}$ Phase Plane for Two Different Gains.

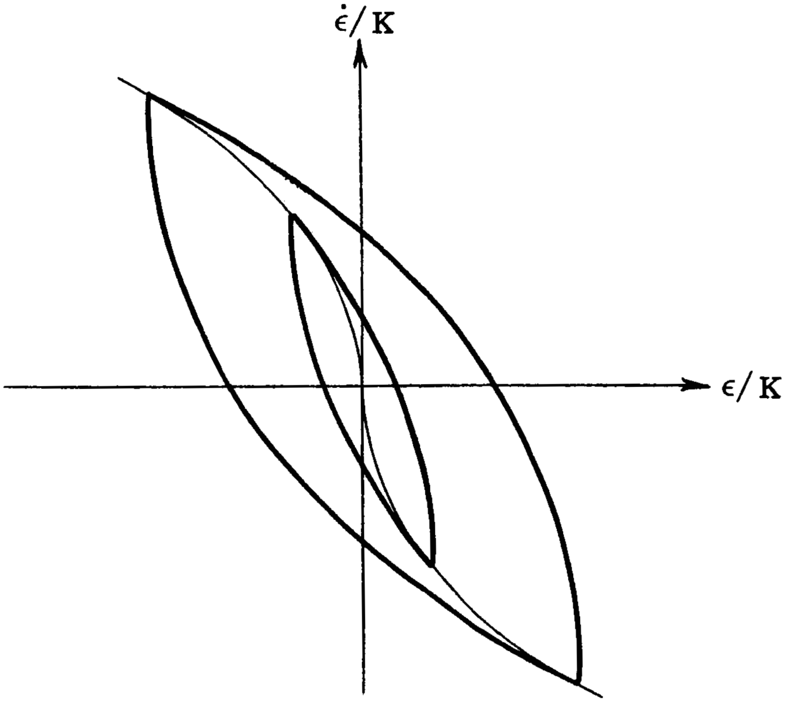
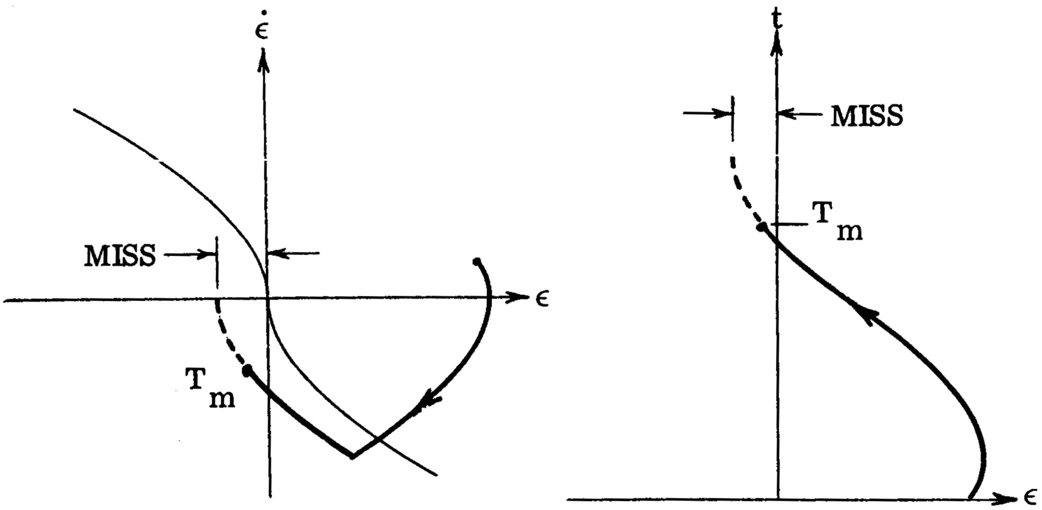


Figure 4.4.4 Two Levels of Constant MTTG Contours in the ϵ/K, $\dot{\epsilon}/K$ Phase Plane.



(a) Phase Plane (b) Display Format

$$\text{MISS} = \frac{1}{2K}\,\dot{\epsilon}(T_m)\left|\dot{\epsilon}(T_m)\right| + \epsilon(T_m)$$

(for a terminal state anywhere in phase plane.)

Figure 4.4.5 Definition of MISS Performance Measure.

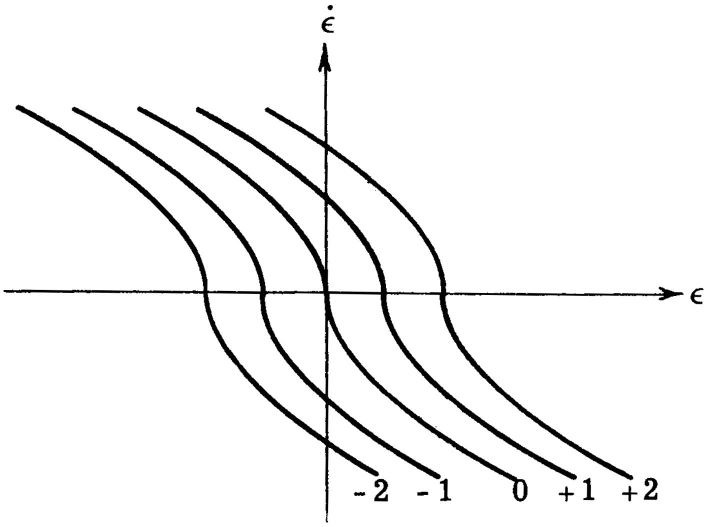


Figure 4.4.6 Contours of Constant MISS for a Single Gain.

cautious response would be desirable in which the first control reversal would be made early, followed by possibly a coast phase or several control reversals. The important thing here is to avoid an overshoot, because the switching line cannot be attained within the time allocated if an overshoot occurs.

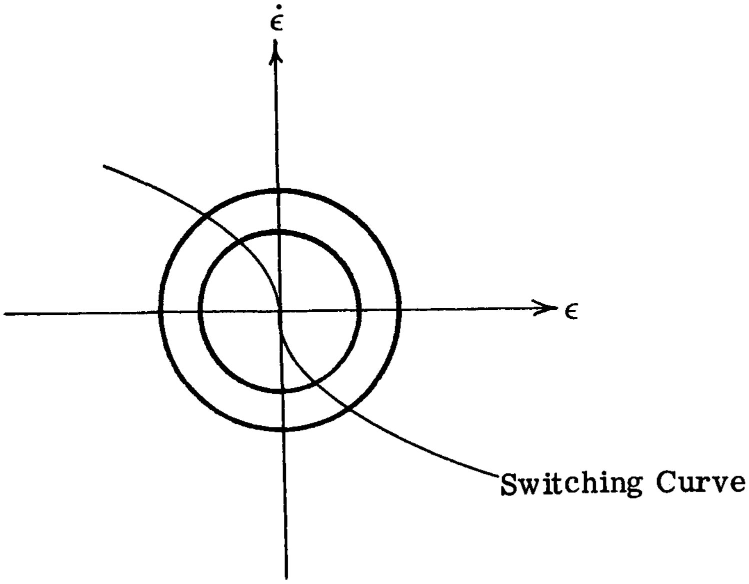
Overshoots and undershoots are indicated by the MISS performance measure, but since the subjects were not specifically told to avoid overshoots, it becomes desirable to apply the same performance penalty to equal magnitude overshoots and undershoots. This can be accomplished by looking at the absolute value of the miss distance, $|\mathrm{MISS}|$.

(4) Terminal Vector (VECT):

The terminal vector, defined and illustrated in Fig. 4.4.7, is a form often used in the analysis of terminal control problems. Though not of any particular physical significance in this task, it is included for the sake of making comparisons with the other performance measures.

(5) Timing Error of First Control Reversal (Δt_1):

For each condition there is a definite time at which the first control reversal must occur in order to obtain a minimum-time trajectory. The difference between this optimal time (t_1) and the actual time (t_1') of the first control reversal is $\Delta t_1 = t_1' - t_1$. It is a measure of operator performance rather than system performance, and is intended to provide some insight into the reasons for performance variations rather than be a measure for system evaluation.



$$\text{VECT} = \sqrt{\epsilon^2(T_m) + \dot{\epsilon}^2(T_m)}$$

Figure 4.4.7 Contours of Constant VECT Performance Measure.

4.5 Experimental Procedure

A preliminary series of experiments was conducted with the following purposes in mind:

(1) Determine the ranges of the independent variables that are of interest.

(2) Develop a more refined procedure for the final experiments.

(3) Test various performance measures.

From the results of these initial studies, the performance measures discussed in Section 4.4 were devised, and the following constraints and goals for the final experiments were specified:

(1) All treatments will be presented in each experimental session to avoid confounding the results with learning effects.

(2) No more than three system gains will be used, in order to insure familiarity of the operator with the system.

(3) Each experimental session will be divided into three blocks according to the system gain, so all treatment combinations (including displays) for one gain are presented before the gain is changed.

(4) Within each block for a single system gain all conditions will be presented for exploratory prediction first, followed by the same conditions with on-line prediction, and finally the normal display. This will provide the maximum benefit from learning to accrue to the non-predictive display so as to yield the most conservative results.

(5) The ordering of conditions and blocks of gain will be changed in a random manner between each experimental session, though display ordering will remain the same. Signs on initial conditions will be changed randomly.

(6) Display scaling will be the same throughout, and control stick dynamics will be fixed. Thus, changes in the independent variables will be implemented by adjustments only in the

gain and initial conditions.

(7) The values of the independent variables will be selected in a manner such that the following constraints are satisfied:

(a) The trajectory shall remain on the screen.

(b) Initial conditions shall not be used in which the resulting trajectory has an unavoidable overshoot. If this should occur, then the initial reaction of the operator with the normal display to an initial error to the left of the centerline would be to apply an input accelerating the system to the right. This would increase the overshoot and result in perhaps unfair comparisons between the non-predictive and predictive displays. This is a result of the choice of time vs. error as the display format, since no initial velocity information is available for the normal display.

(c) The optimum control reversal point shall occur at least one-half inch from the centerline; this avoids confounding the results with limitations on visual perception of the error signal.

(d) The time between initiation of a trial and the first required control reversal shall not be less than 0.5 seconds; this avoids reaction time problems.

(8) The subjects will be allowed to apply the proper initial input before a trial is initiated; again, this eliminates the reaction time problem.

Five volunteer undergraduate male subjects performed for thirteen days for the formal experiment, each subject receiving all test conditions in one hour each day. (Instructions to the subjects are given in Appendix A.) The subjects were all right handed, had no known physical limitations, and no prior experience with this type of control task.

The subjects were seated in a straight-backed chair with their right arm resting on the arm of the chair, and their right hand on a spring centered control stick* with a noticeable center detent. The control stick was pivoted about an axis parallel to the arm of the chair through an angle of ± 20 degrees. The controller dead zone corresponded to ± 3 degrees of stick displacement. The pivot point was approximately five inches below the bottom of the subject's hand. A trigger on the control stick could be easily depressed by the index finger for operation with the exploratory predictive display.

A large screen oscilloscope with a P-4 phosphor was located approximately twenty-six inches from the subject's eyes, with the center of the screen at roughly the same height as the subject's eye

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*The control stick was a surplus U.S. Army Air Force Type C-1 Autopilot Formation stick, with velocity limiters removed and a spring constant of 2.7 ft-lbs/rad.

level. The oscilloscope was calibrated such that the vertical centerline was 10 inches in length, corresponding to 14 seconds in time. Horizontal calibration was 8 inches = 100 volts.

The subjects were seated in an isolated test booth and wore earphones through which they could hear only a low volume white noise. The experiment monitor could interrupt this noise at anytime to converse with the subject.

The ambient light level in the booth was adjusted to provide some background light, but such that the subject could not see his own reflection on the face of the oscilloscope. An illustration of the test equipment is presented in Fig. 4.5.1.

A total of thirty-six test conditions, twelve for each of the three gains, were used such that a different combination of the values of the independent variables was provided by each condition. These conditions with their corresponding values are presented in Table 4.5.1, where each cell entry is a number assigned to that particular condition. The initial values of error and error-rate for each condition are given in Appendix B.

For every experimental session, a subject was given several practice runs with exploratory prediction prior to each change in the system gain. Before the beginning of a trial the subject was given sufficient time to observe the initial error and displace the control stick accordingly. After each individual trial, which was terminated

Figure 4.5.1 Subject's Station.

TABLE 4.5.1

VALUES OF TASK VARIABLES USED IN THE FORMAL EXPERIMENT

Note: Table entries are condition numbers assigned to each combination of values that was investigated.

K	V_a	t_{sw}	T_m (sec)				
(volts/sec^2)*	(volts/sec)*	(sec)	2.5	4.0	6.0	8.0	10.0
4.0	6.0	1.5	# 1	# 3			
	8.0	2.0	# 2	# 4	# 6		
	12.0	3.0		# 5	# 7	# 9	# 11
	16.0	4.0			# 8	# 10	# 12
8.0	8.0	1.0	# 13				
	12.0	1.5	# 14	# 16			
	16.0	2.0	# 15	# 17	# 19		
	20.0	2.5				# 22	
	24.0	3.0		# 18	# 20	# 21	# 23
	28.0	3.5					# 24
16.0	16.0	1.0	# 29				
	24.0	1.5	# 27	# 31			
	32.0	2.0	# 28	# 32	# 33		
	40.0	2.5			# 35	# 36	

In addition:

	K	V_a	t_{sw}	T_m
# 25:	16.0	11.1	0.69	1.64
# 26:	16.0	22.1	1.38	2.5
# 30:	16.0	48.0	3.0	3.5
# 34:	16.0	36.0	2.24	6.0

---

*Display scaling and other pertinent data describing the experimental configuration are given in Appendix B.

at T_m + 4 seconds, the subject was informed of the IAE score (see Fig. 4.4.1) for that trial. Approximately fifteen seconds elapsed between successive trials.

A general purpose 90-amplifier analog computer was used for the experiment. The analog computer circuit and a summary of all pertinent physical data are given in Appendix B.

The results of this experimental effort are reported in the following chapter.

Chapter 5

EXPERIMENTAL RESULTS

Since this investigation is concerned with performance assuming fully trained subjects, the first procedure in an analysis of the results is a determination of learning effects. As previously mentioned, this was accomplished through the IAE performance measure which was recorded on-line at the end of each trial. The decision concerning when learning effects could be disregarded was based on statistical tests of the IAE data. These tests are reported in Section 5.1.

The various performance measures that were used are functions of the terminal error, $\epsilon(T_m)$, the terminal error-rate, $\dot{\epsilon}(T_m)$, and the system gain, K. These values, along with the initial conditions, were recorded on-line at the end of each trial. After the days for which learning effects were insignificant were determined, the error and error-rate data were reduced to the performance measure data via a digital computer program. The signs on the terminal conditions were changed whenever necessary so that the results appear as if the initial values of the error were always positive, though this was not the case in the experiment.

Because of occasional random equipment malfunctions, several individual trials had to be discarded prior to an analysis of the results. In addition, all the data for condition number 25 (see Table 4.5.1) was omitted due to an error in the timing of the measurement of the terminal error and error-rate. All valid error and error-rate data for each subject, display, condition, and day for which practice could be disregarded are presented in Appendix C.

To determine the effects of the independent variables on the different performance measures for each display type, the performance data were averaged across subjects and days and plotted against the different variables. From Table 4.5.1 it can be seen that it is possible to look at the effect of one variable while holding the other variables constant. This was done for all combinations that are possible. In addition, other possibly pertinent independent variables not previously mentioned, as well as several dimensionless parameters consisting of combinations of these variables, were examined but found to be unimportant. The plots presented in this chapter, in which each point represents an average across the subjects and days for which learning was insignificant, summarize the important results of this graphical analysis. These results for each display form are presented in Sections 5.2, 5.3, and 5.4. Results for effects of display type are given in Section 5.5.

Statistical testing of the independent variables for each display form was conducted using an analysis of variance for a repeated-measures design (Chapter 7, Winer [49]). Referring to Table 4.5.1, it can be seen that it is impossible to use all conditions in a statistical test since many cells are missing. However, several separate tests are possible, in which the range of values of the independent variables is limited. It should be noted that these tests are not totally independent since there is some overlap of conditions. To satisfy the requirements for homogeniety of variance, a log transformation was applied to the Minimum Time-to-Go (MTTG) and absolute Miss (|MISS|) performance measures. The results of these tests are presented in summarized form where appropriate.

5.1 Learning

As mentioned in Chapter 4, learning was studied through the IAE performance measure (see Fig. 4.4.1). To simplify the procedure the IAE results were averaged across subjects and conditions for a given system gain. These results are presented in Fig. 5.1.1. With twelve conditions for each gain and five subjects, each point plotted in Fig. 5.1.1 represents an average across as many as 60 observations. (Due to the previously mentioned occasional malfunctions, less than 60 observations were sometimes available.)

Performance in terms of the average IAE for the last three days of testing was compared with that for earlier days of practice. To determine when learning effects were no longer significant, the average IAE for each gain and display was statistically compared to the average across the last three days through the use of the Student's t-statistic

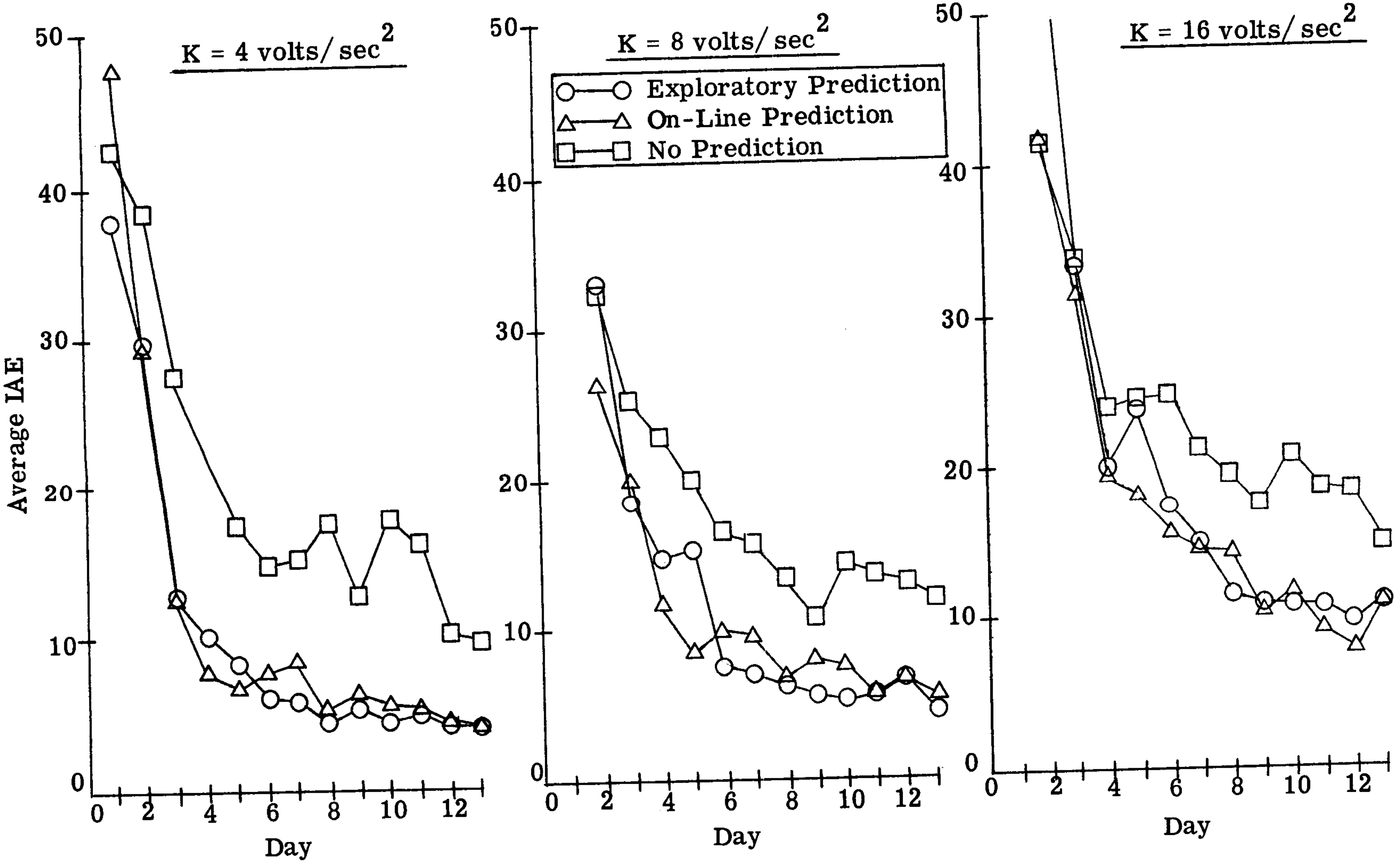


Figure 5. 1. 1 Learning Effects on IAE Performance Measure, Averaged Across Subjects and Conditions.

for testing hypotheses about the difference between two means with unequal sample sizes (pp. 24-33, Winer [49]). The results of this test are summarized in Table 5.1.1 and Fig. 5.1.2. Using a 0.05 significance level, there are no significant differences between the average IAE measures over the last six days, or days 8 through 13. Using a more liberal 0.10 significance level, only one of the nine tests indicates a significant difference for the last six days, which is nearly at the chance level. Thus it was concluded that the data for days 8 through 13 could be used to represent performance with insignificant learning effects. Though the plots in Fig. 5.1.1 show some improvement over the last six days, these variations appear quite insignificant compared to variations between subjects that can be seen in more complete plots that are not presented here.

TABLE 5.1.1

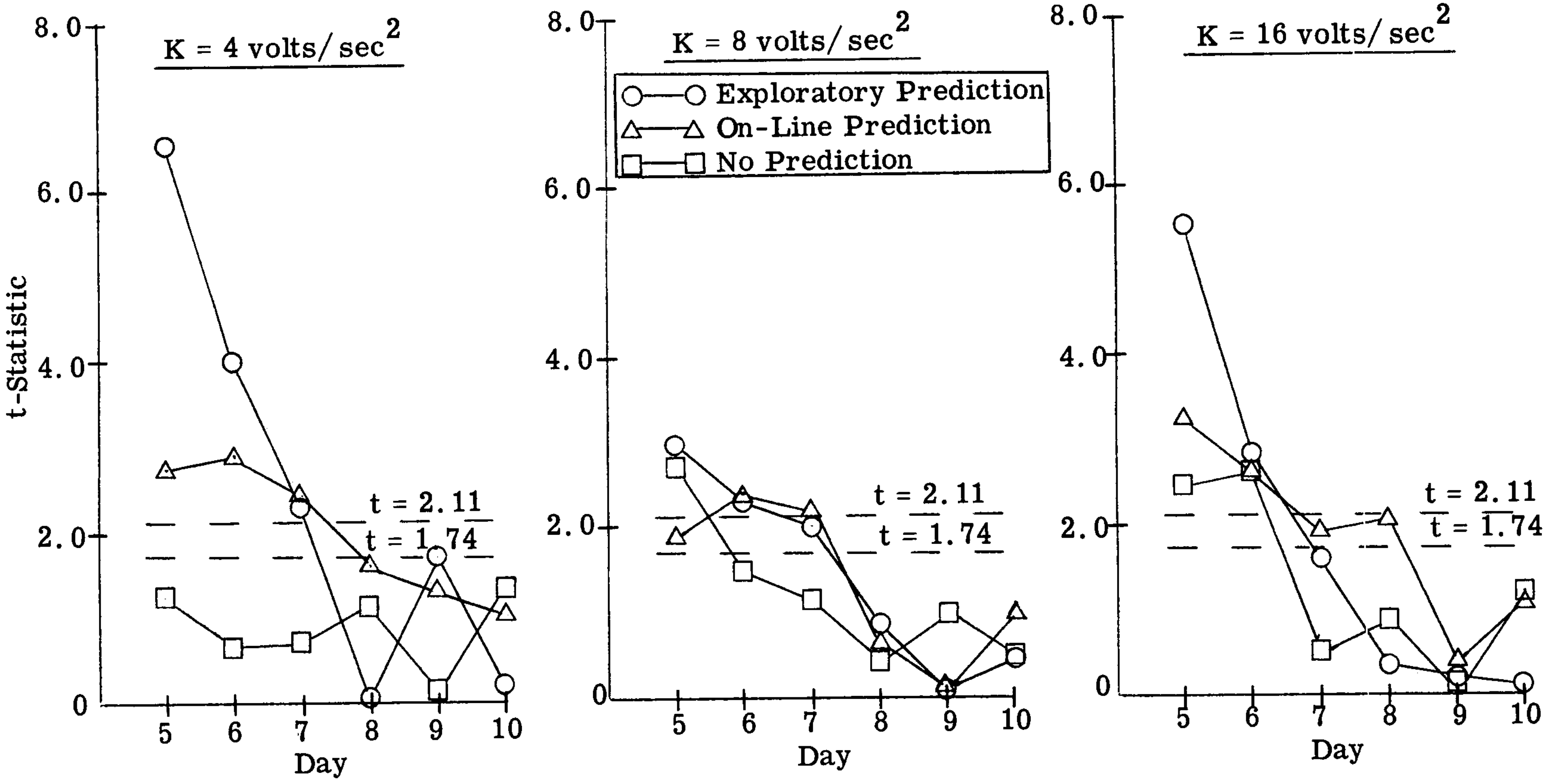
SUMMARY OF t-TESTS FOR LEARNING

degrees of freedom = 17

K (volts/ sec^2)	Day	t-Statistic		
		Expl. Prediction	On-Line Prediction	No Prediction
4.0	10	0.19	1.00	1.37
	9	1.70	1.35	0.14
	8	0.04	1.60	1.13
	7	2.29**	2.41**	0.72
	6	3.98**	2.88**	0.62
	5	6.56**	2.76**	1.26
8.0	10	0.44	0.98	0.48
	9	0.06	0.11	0.98
	8	0.67	0.64	0.42
	7	2.02*	2.18**	1.16
	6	2.32**	2.37**	1.52
	5	2.98**	1.87*	2.74**
16.0	10	0.09	1.05	1.19
	9	0.19	0.40	0.08
	8	0.35	2.04*	0.87
	7	1.60	1.92*	0.47
	6	2.83**	2.58**	2.58**
	5	5.55**	3.22**	2.45**

** Learning is significant at the 0.05 level.

* Learning is signficant at the 0.10 level.



Note: If t > 2.11, learning is significant at the 0.05 level.
If t > 1.74, learning is significant at the 0.10 level.

Figure 5.1.2 Results of t-Tests for Learning.

5.2 Exploratory Prediction

The generally high level of performance attained with exploratory prediction for all the conditions can be seen in Fig. 5.2.1, which presents the average terminal states in the phase plane (with each point adjusted in sign so that the initial condition would be above and to the right of the switching curve). Nearly all the terminal errors lie between - 1.0 volt and + 1.0 volt, which represents ± 0.08 inch on the display. The general influence of the plant gain on performance also can be seen in Fig. 5.2.1, in that the terminal errors and error-rates increase in magnitude with increasing gain. This effect is further illustrated in Fig. 5.2.2 which presents the average terminal states in a gain-normalized phase plane. Investigation of the timing errors of the first control reversal (Δt_1) showed no effect of gain on either the average error or the variance of these errors. Thus, the apparent effect of gain on the terminal states may be thought of as an artifact of the gain.

Results for the average VECT performance measure (see Fig. 4.4.7), which is not gain dependent, are presented as a function of approach speed in Fig. 5.2.3. It can be seen that there is an apparent increase in VECT with increasing approach speed which is partially due to the fact that higher approach speeds are generally associated with higher levels of gain. It should be noted however that the worst average VECT

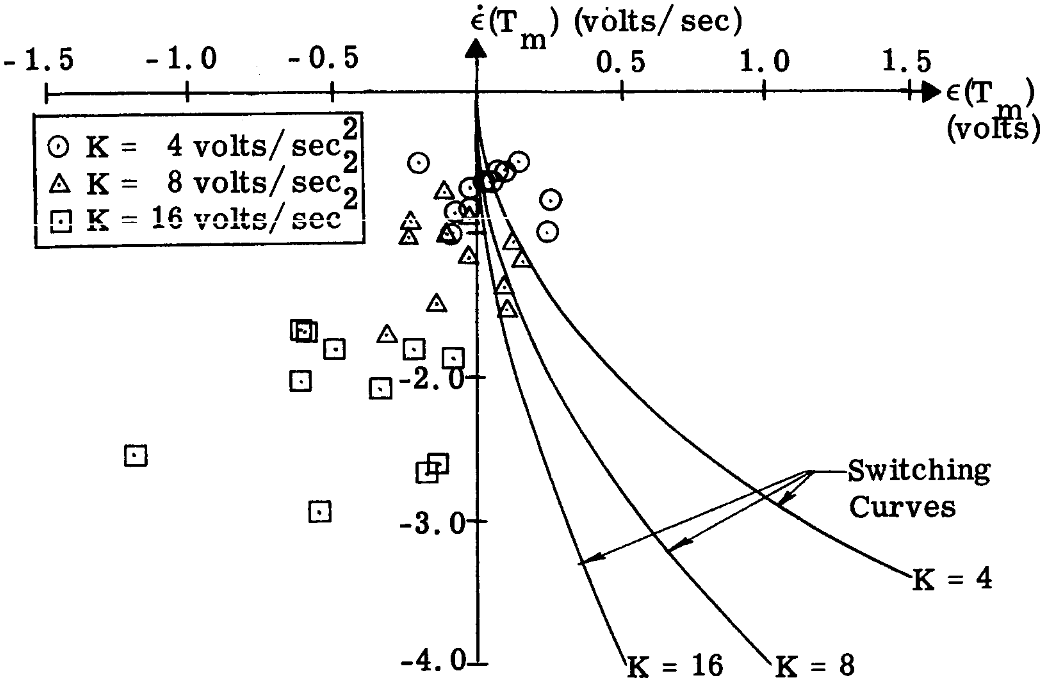


Figure 5.2.1 Average Terminal States in the Phase Plane for Exploratory Prediction.

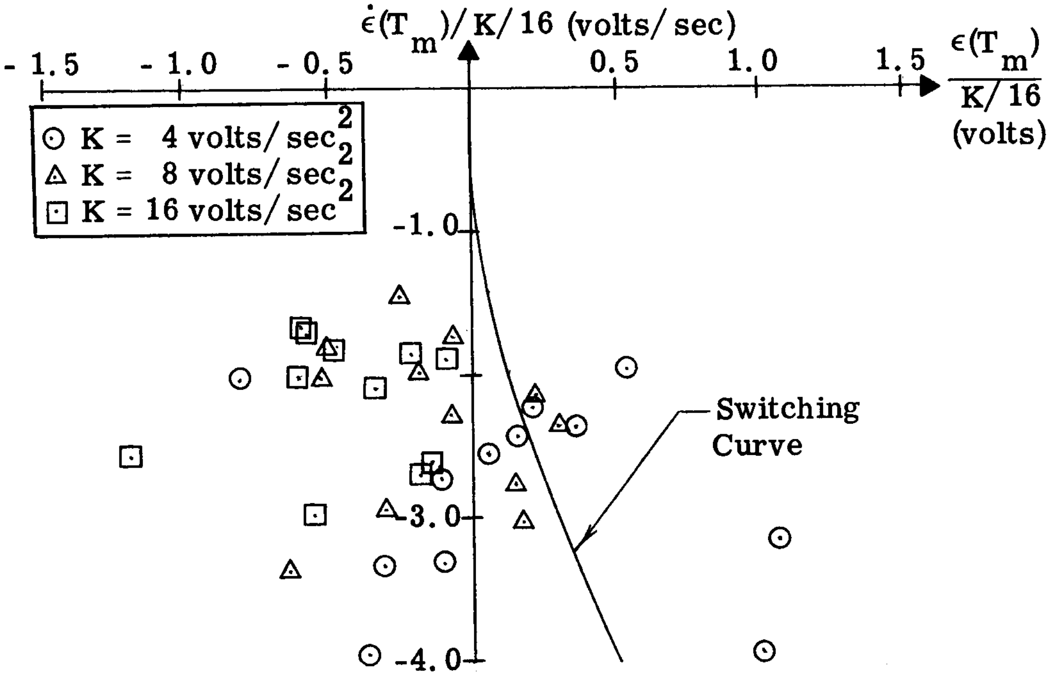


Figure 5.2.2 Average Terminal States in the Gain-Normalized Phase Plane for Exploratory Prediction.

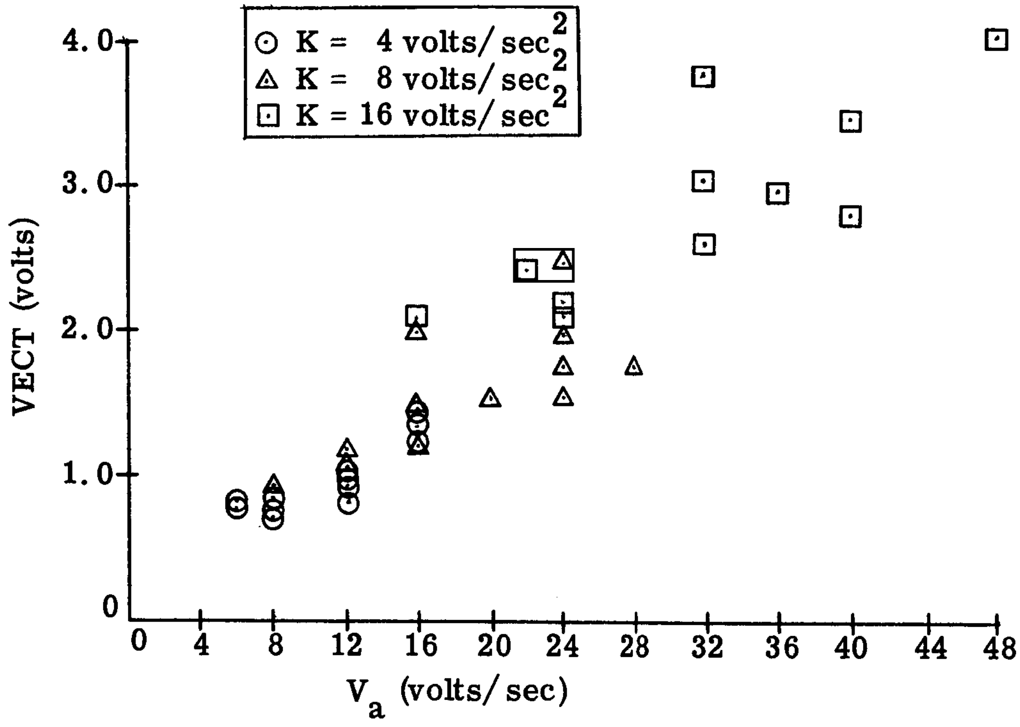


Figure 5.2.3 Average VECT Performance Measure vs. Approach Speed for Exploratory Prediction.

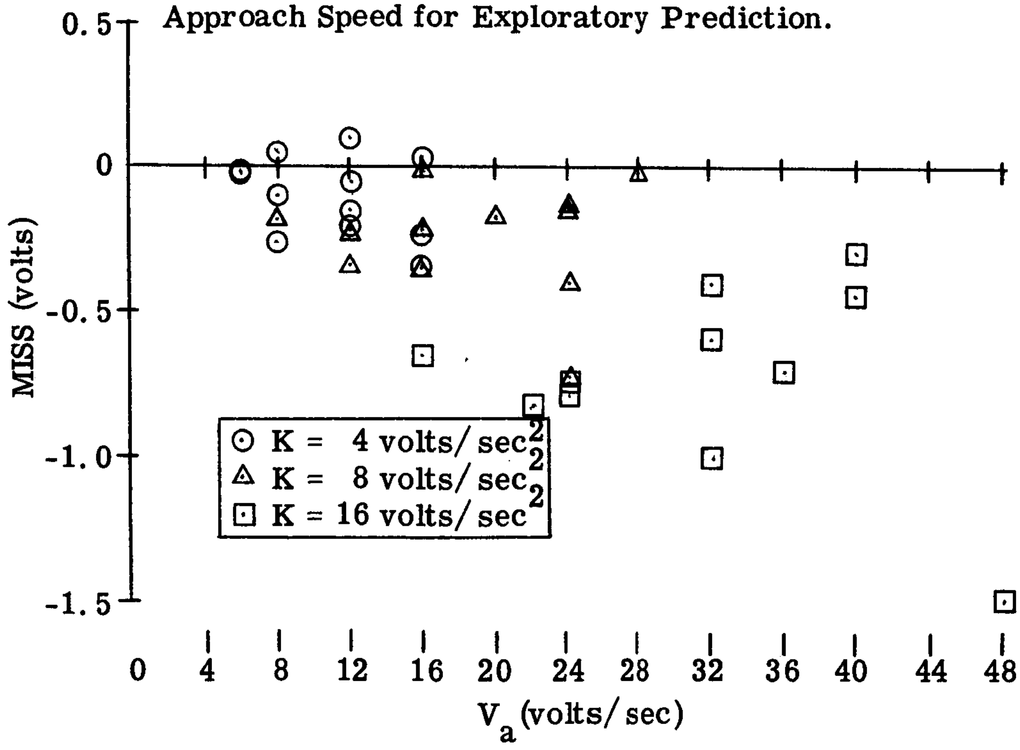


Figure 5.2.4 Average MISS Performance Measure vs. Approach Speed for Exploratory Prediction.

performance measure occurred at the highest approach speed, and a small effect of approach speed seems noticeable within each gain.

In the phase plane plot of Fig. 5.2.1, most of the terminal states indicate an overshoot rather than an undershoot. The averaged MISS performance measure (see Fig. 4.4.5), presented in Fig. 5.2.4, demonstrates this effect to a greater degree. (Note that the average MISS is not calculated from the average terminal error and error-rate, but is the average of the individual MISS measures. This explains the apparent discrepancy between Figs. 5.2.1 and 5.2.4 in indicating the number of overshoot conditions.) Approach speed is seen to be a likely cause for this tendency towards an overshoot. However, this appears to be an artifact of the performance measure since the errors in timing of the control reversal with exploratory prediction were relatively constant regardless of the approach speed. This effect is best illustrated by considering the MISS that results from an assumed constant lag Δt_1 in application of the first control reversal (see Fig. 5.2.5). For a negative terminal error-rate, the MISS is given by

$$\text{MISS} = -\frac{1}{2K}\dot{\epsilon}^2(T_m) + \epsilon(T_m) \qquad (5.2.1)$$

where a negative MISS implies an overshoot. The trajectory in the phase plane is described by

$$\epsilon(t) = \frac{1}{2Ku}\dot{\epsilon}^2(t) - \frac{1}{2Ku}\dot{\epsilon}^2(t_o) + \epsilon(t_o) \qquad (5.2.2)$$

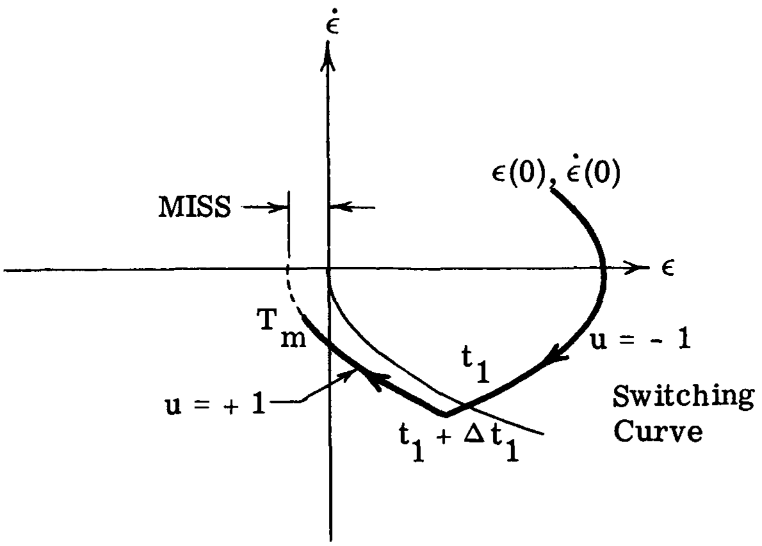


Figure 5.2.5 MISS for a Δt_1 Lag in Application of the First Control Reversal.

where u = + 1 denotes parabolas opening to the right and u = - 1 denotes parabolas opening to the left. Thus the MISS can also be written as

$$\text{MISS} = -\frac{1}{2K}\dot{\epsilon}^2(t_1 + \Delta t_1) + \epsilon(t_1 + \Delta t_1) \quad . \qquad (5.2.3)$$

Also,

$$\epsilon(t_1 + \Delta t_1) = -\frac{1}{2K}\dot{\epsilon}^2(t_1 + \Delta t_1) + \frac{1}{2K}\dot{\epsilon}^2(0) + \epsilon(0) \quad . \qquad (5.2.4)$$

Therefore,

$$\text{MISS} = -\frac{1}{K}\dot{\epsilon}^2(t_1 + \Delta t_1) + \frac{1}{2K}\dot{\epsilon}^2(0) + \epsilon(0) \quad . \qquad (5.2.5)$$

A property of a pure inertia system with a constant applied force is that an increment in time is given by the absolute change in error-rate, divided by the appropriate gain constant. Therefore,

$$\Delta t_1 = \frac{1}{K}[\dot{\epsilon}(t_1) - \dot{\epsilon}(t_1 + \Delta t_1)] \quad , \tag{5.2.6}$$

which can be re-written as

$$\dot{\epsilon}(t_1 + \Delta t_1) = - K\Delta t_1 + \dot{\epsilon}(t_1) \quad . \tag{5.2.7}$$

Therefore,

$$\dot{\epsilon}^2(t_1 + \Delta t_1) = K^2 \Delta t_1^2 - 2K\Delta t_1 \dot{\epsilon}(t_1) + \dot{\epsilon}^2(t_1) \quad . \tag{5.2.8}$$

Note that $\dot{\epsilon}(t_1) = - V_a$ and $\dot{\epsilon}^2(t_1) = V_a^2$. The latter is given by $\frac{1}{2}\dot{\epsilon}^2(0) + K\epsilon(0)$. Hence,

$$\dot{\epsilon}^2(t_1 + \Delta t_1) = K^2 \Delta t_1^2 + 2KV_a\Delta t_1 + \frac{1}{2}\dot{\epsilon}^2(0) + K\epsilon(0) \quad . \tag{5.2.9}$$

Dividing Eq. (5.2.9) by K and substituting into Eq. (5.2.5), we see that

$$\text{MISS} = - K\Delta t_1^2 - 2V_a\Delta t_1 \quad . \tag{5.2.10}$$

Therefore, for a given Δt_1 lag in application of the first control reversal, MISS will tend towards an increasing overshoot condition with increasing approach speed, V_a, as indicated in Fig. 5.2.4. The influence of gain is not nearly as significant when Δt_1 is small, due to the fact that it is only a second order effect. It should be pointed out that the relative lack of undershoot conditions is due to the ability of the operator to correct a predicted undershoot before the terminal time. An overshoot condition on the other hand cannot be corrected until after the minimum time.

Figure 5.2.6 presents the average absolute MISS performance measure (not be be confused with absolute values of the average MISS in Fig. 5.2.4) as a function of the approach speed. Here again the influence of K and V_a can be seen. These results can be approximated by Eq. (5.2.10) when a value for Δt_1 of 0.02 second is used. (The average experimental Δt_1 varied from - 0.03 sec to + 0.04 sec for exploratory prediction.) Statistical testing of the absolute MISS (summarized in Table 5.2.1) shows the main effect of gain to be significant. This can be attributed to approach speed however, since the two effects cannot be separated in the statistical treatments given here. For the few conditions for which comparisons between different gains are possible with fixed approach speed, no effect of gain was noticed.

Results for the Minimum Time-to-Go performance measure (see Fig. 4.4.2) are presented in Figs. 5.2.7 and 5.2.8. Plotted against approach speed, a slight increase in MTTG with increasing approach speed can be noticed, which is heavily dependent in slope on the system gain. This can also be described as a general increase in MTTG with increasing switch time (Fig. 5.2.8).

The dependence of MTTG on V_a, K, and t_{sw} can be shown analytically if a time lag Δt_1 is assumed in the application of the first control reversal (see Fig. 5.2.5). For a terminal point below and to the left of the switching curve, MTTG is given by

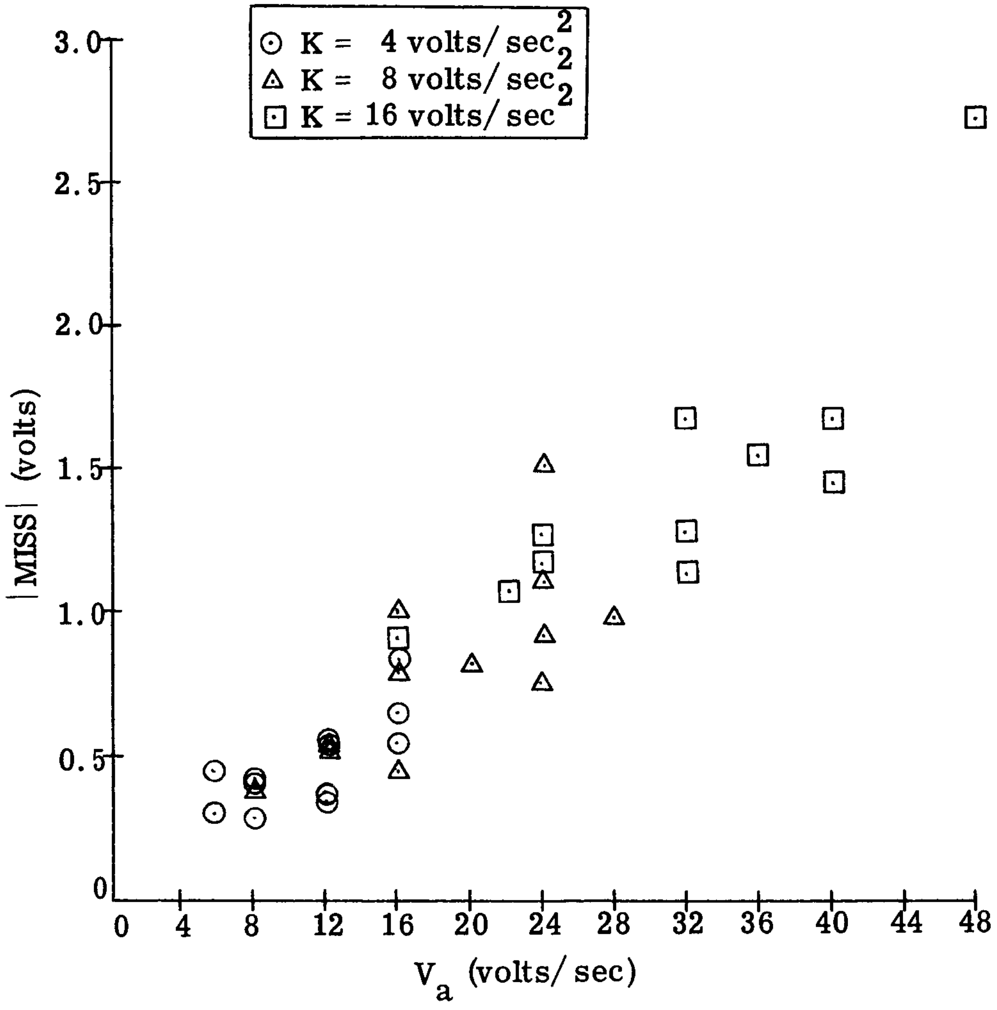


Figure 5. 2. 6 Average Absolute MISS Performance Measure vs. Approach Speed for Exploratory Prediction.

TABLE 5.2.1 ANALYSIS OF VARIANCE: LOG |MISS| FOR EXPLORATORY PREDICTION.

Min. Time = 4.0, 6.0, 8.0, and 10.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Switch Time = 3.0 secs.

Source of Variation	SS	df	MS	F
Gain	.139949	1	.139949	52.14**
Gain x Subjects	.010737	4	.002684	
Min. Time	.018392	3	.006131	1.64
Min. Time x Subjects	.044911	12	.003743	
Gain x Min. Time	.025393	3	.008464	2.23
Gain x Min. Time x Subjects	.045589	12	.003799	

Min. Time = 2.5, 4.0, and 6.0 secs,
Gain = 4.0, 8.0, 16.0 v/sec^2, Switch Time = 2.0 secs.

Source of Variation	SS	df	MS	F
Gain	.290412	2	.145206	5.67*
Gain x Subjects	.204772	8	.025597	
Min. Time	.009743	2	.004872	< 1
Min. Time x Subjects	.040999	8	.005125	
Gain x Min. Time	.042234	4	.010559	< 1
Gain x Min. Time x Subjects	.205047	16	.012815	

Switch Time = 1.0, 1.5 and 2.0 secs,
Gain = 8.0 and 16.0 v/sec^2, Min. Time = 2.5 secs.

Source of Variation	SS	df	MS	F
Gain	.109445	1	.109445	54.33**
Gain x Subjects	.008029	4	.002007	
Switch Time	.052790	2	.026395	4.17
Switch Time x Subjects	.050609	8	.006326	
Gain x Switch Time	.000052	2	.000026	< 1
Gain x Switch Time x Subjects	.051784	8	.006473	

Switch Time = 1.5, 2.0, and 3.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Min. Time = 4.0 secs.

Source of Variation	SS	df	MS	F
Gain	.094641	1	.094641	20.30*
Gain x Subjects	.018651	4	.004663	
Switch Time	.064220	2	.032110	6.56*
Switch Time x Subjects	.039151	8	.004894	
Gain x Switch Time	.011336	2	.005668	1.69
Gain x Switch Time x Subjects	.026904	8	.003363	

**Significant at 0.01 Level.

* Significant at 0.05 Level.

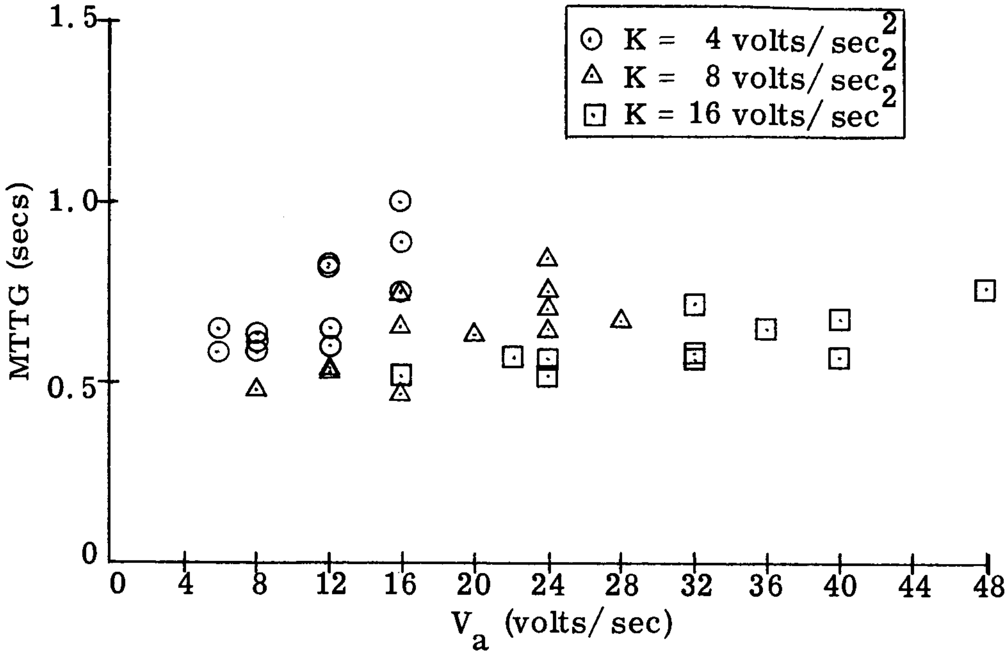


Figure 5.2.7 Average MTTG Performance Measure vs. Approach Speed for Exploratory Prediction.

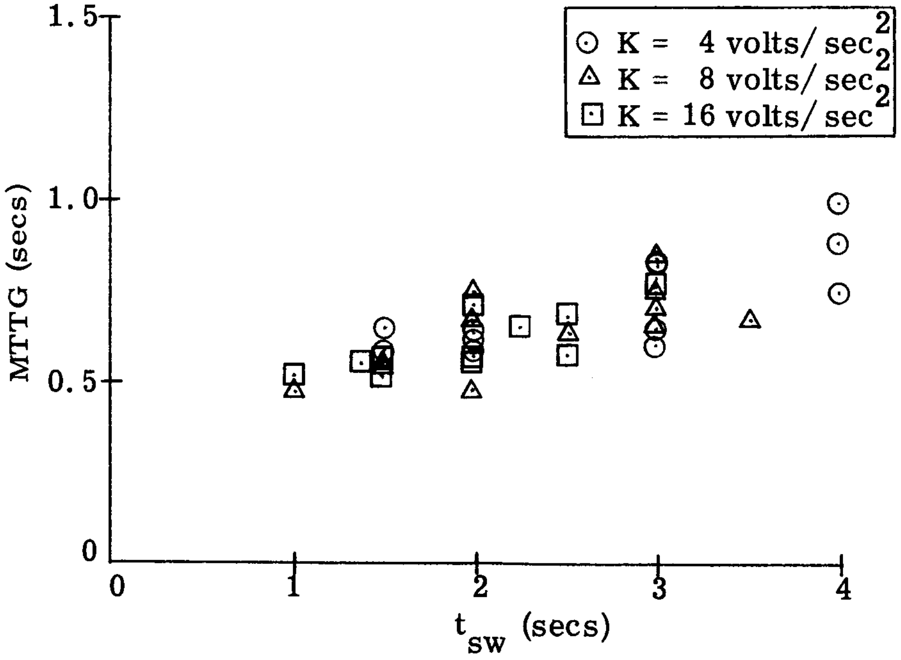


Figure 5.2.8 Average MTTG Performance Measure vs. Switch Time for Exploratory Prediction.

$$\mathrm{MTTG} = - \frac{\dot{\epsilon}(T_m)}{K} + \frac{2}{K}\sqrt{\frac{1}{2}\,\dot{\epsilon}^2(T_m) - K\,\epsilon(T_m)} \quad , \qquad (5.2.11)$$

where

$$\epsilon(T_m) = \frac{1}{2K}\,\dot{\epsilon}^2(T_m) - \frac{1}{2K}\,\dot{\epsilon}^2(t_1 + \Delta t_1) + \epsilon(t_1 + \Delta t_1) \quad . \qquad (5.2.12)$$

Note that

$$t_{sw} = \left[\frac{\dot{\epsilon}(T_m)}{K} - \frac{\dot{\epsilon}(t_1 + \Delta t_1)}{K}\right] + \left[\frac{\dot{\epsilon}(t_1)}{K} - \frac{\dot{\epsilon}(t_1 + \Delta t_1)}{K}\right] \quad , \qquad (5.2.13)$$

or

$$\begin{aligned} \frac{\dot{\epsilon}(T_m)}{K} &= t_{sw} + \frac{2\dot{\epsilon}(t_1 + \Delta t_1)}{K} - \frac{\dot{\epsilon}(t_1)}{K} \\ &= \frac{2\dot{\epsilon}(t_1 + \Delta t_1)}{K} - \frac{2\dot{\epsilon}(t_1)}{K} \qquad (5.2.14) \quad . \\ &= -\,2\Delta t_1 \quad . \end{aligned}$$

Thus Eq. (5.2.11) becomes

$$\mathrm{MTTG} = 2\Delta t_1 + \frac{2}{K}\sqrt{\frac{1}{2}\,\dot{\epsilon}^2(t_1 + \Delta t_1) - K\,\epsilon(t_1 + \Delta t_1)} \quad . \qquad (5.2.15)$$

Substituting Eq. (5.2.4) into Eq. (5.2.15),

$$\mathrm{MTTG} = 2\Delta t_1 + \frac{2}{K}\sqrt{\dot{\epsilon}^2(t_1 + \Delta t_1) - \frac{1}{2}\,\dot{\epsilon}^2(0) - K\,\epsilon(0)} \quad . \qquad (5.2.16)$$

Upon substituting Eq. (5.2.9), MTTG becomes

$$\mathrm{MTTG} = 2\Delta t_1 + \frac{2}{K}\sqrt{K^2\,\Delta t_1^{\,2} + 2KV_a\,\Delta t_1} \quad . \qquad (5.2.17)$$

Therefore,

$$\mathrm{MTTG} = 2\Delta t_1 \left[1 + \sqrt{1 + \frac{2V_a}{K\Delta t_1}}\right] \quad , \qquad (5.2.18)$$

or

$$\mathrm{MTTG} = 2\Delta t_1 \left[1 + \sqrt{1 + \frac{2t_{sw}}{\Delta t_1}}\right] \quad . \qquad (5.2.19)$$

Equation (5.2.18) or (5.2.19) thus can be used to explain the variation of MTTG under the assumption of a constant Δt_1 lag in control reversal. Using a value of Δt_1 of 0.02 second , the results in Figs. 5.2.7 and 5.2.8 can be approximated by these relations.

Statistical testing of the MTTG performance measure yielded no significant effects for exploratory prediction.

To summarize these results, it should be noted that manual performance with exploratory prediction remains at a relatively high level regardless of the independent variables. Overall closed loop system performance variations appear to be a result of the performance measure sensitivity to Δt_1. While these variations are essentially artifacts of the measures and of the independent system parameters, they are nevertheless very real.

5.3 On-Line Prediction

Performance variations with the on-line predictive display were found to exhibit generally the same characteristics as those for exploratory prediction. Figure 5.3.1 illustrates the average terminal states in the phase plane, which shows a more pronounced gain effect than found in Fig. 5.2.1 for exploratory prediction. The normalized phase plane of Fig. 5.3.2 yields a similar distribution as obtained in Fig. 5.2.2.

It was not possible to obtain a measure of timing errors in application of the first control reversal for on-line prediction due to the sampling nature of control actions. As a result, performance variations cannot be related to the timing errors as was done for exploratory prediction.

Figure 5.3.3, which presents the average VECT performance measure (see Fig. 4.4.7) for on-line prediction, shows the increase with increasing approach speed to be purely a gain effect. On the other hand, the MISS (see Fig. 4.4.5) and absolute MISS, presented in Figs. 5.3.4 and 5.3.5, indicate more of an effect due to approach speed. (As with exploratory prediction, no effect of gain was noticed for the absolute MISS for those conditions in which approach speed is held constant.) The significance of gain (or approach speed) as shown by the statistical analysis is summarized in Table 5.3.1.

The average Minimum Time-to-Go (see Fig. 4.4.2) exhibits the same characteristics with on-line prediction as for exploratory

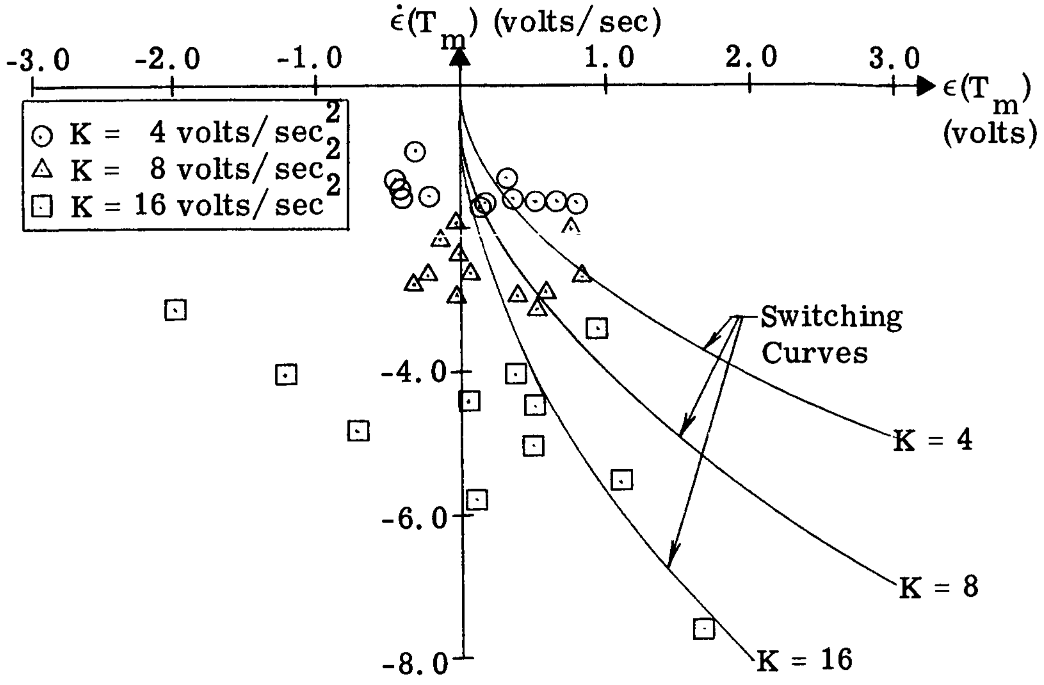


Figure 5.3.1 Average Terminal States in the Phase Plane for On-Line Prediction.

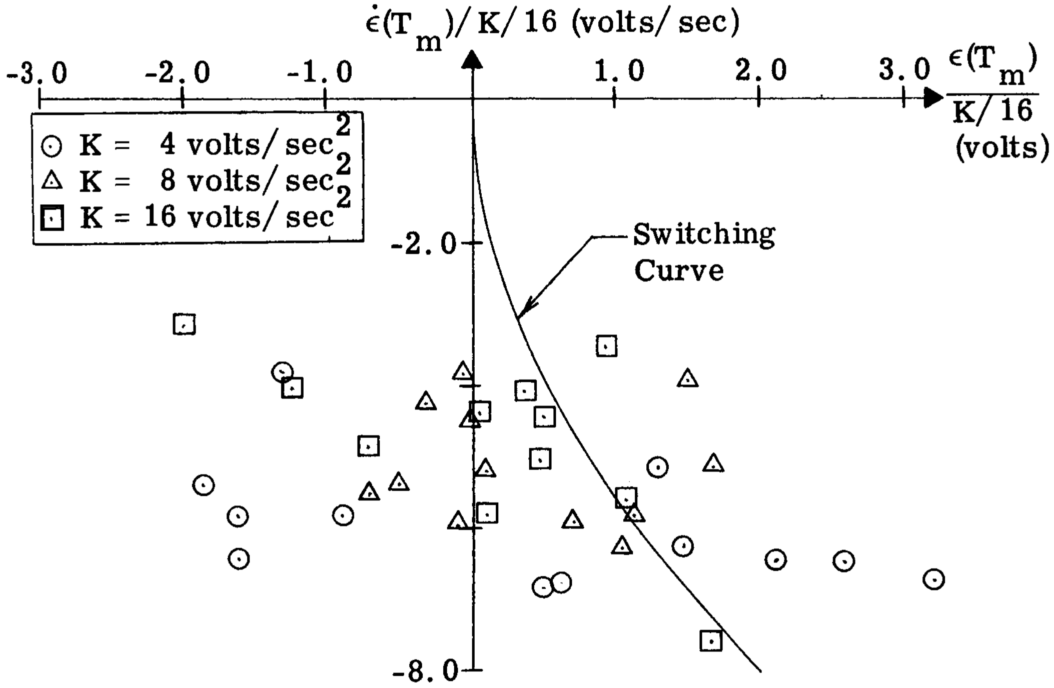


Figure 5.3.2 Average Terminal States in the Gain-Normalized Phase Plane for On-Line Prediction.

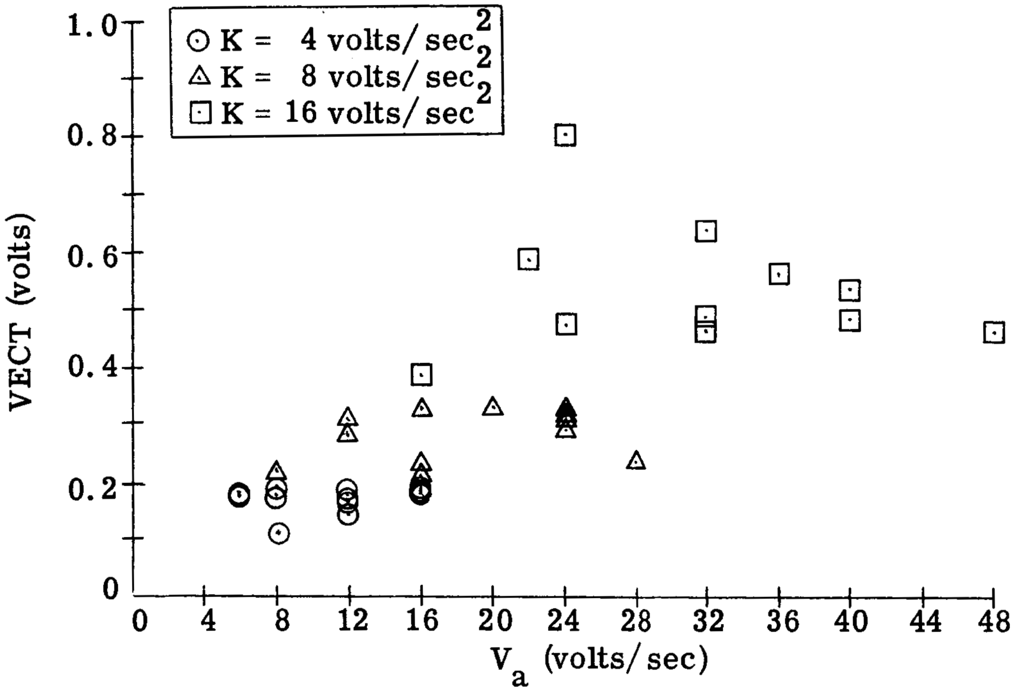


Figure 5.3.3 Average VECT Performance Measure vs. Approach Speed for On-Line Prediction.

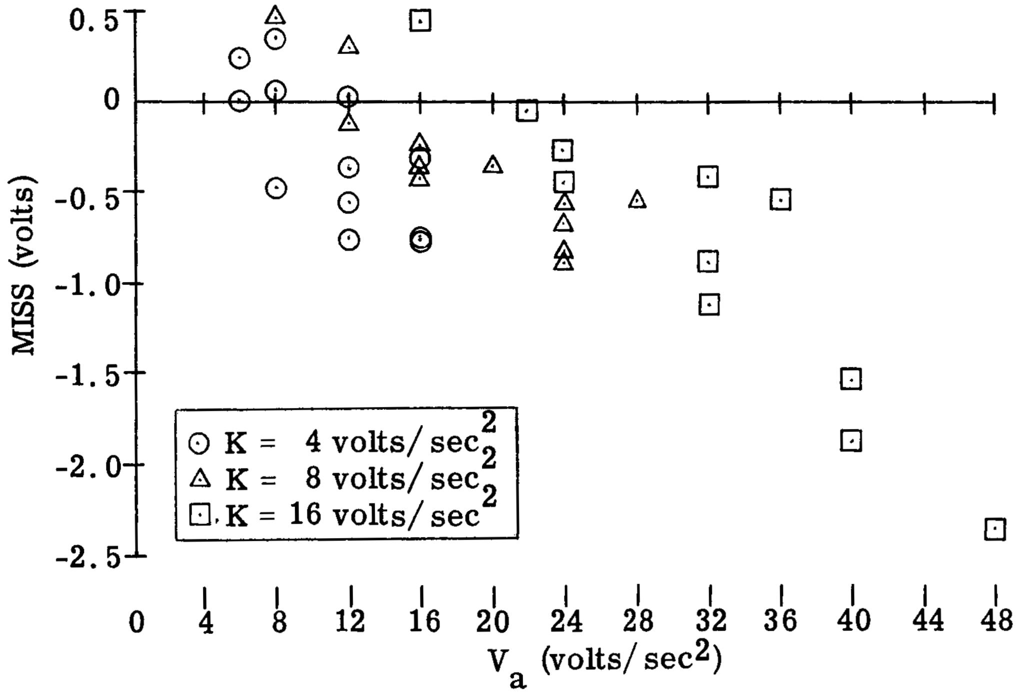


Figure 5.3.4 Average MISS Performance Measure vs. Approach Speed for On-Line Prediction.

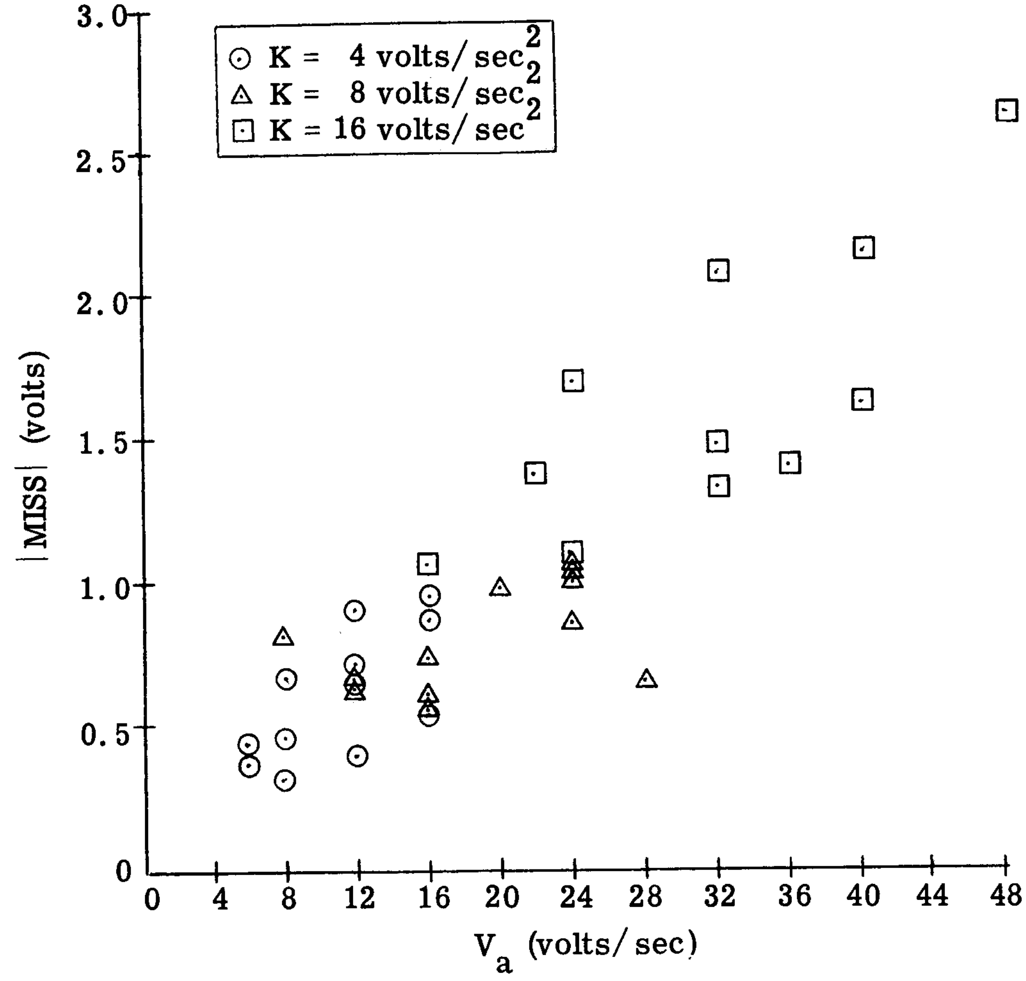


Figure 5.3.5 Average Absolute MISS Performance Measure vs. Approach Speed for On-Line Prediction.

TABLE 5.3.1 ANALYSIS OF VARIANCE: LOG |MISS| FOR ON-LINE PREDICTION.

Min. Time = 4.0, 6.0, 8.0, and 10.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Switch Time = 3.0 secs.

Source of Variation	SS	df	MS	F
Gain	.026729	1	.026729	2.37
Gain x Subjects	.045150	4	.011287	
Min. Time	.021432	3	.007144	1.17
Min. Time x Subjects	.073528	12	.006127	
Gain x Min. Time	.006186	3	.002062	< 1
Gain x Min. Time x Subjects	.080868	12	.006739	

Min. Time = 2.5, 4.0, and 6.0 secs,
Gain = 4.0, 8.0, and 16.0 v/sec^2, Switch Time = 2.0 secs.

Source of Variation	SS	df	MS	F
Gain	.290412	2	.145206	5.67*
Gain x Subjects	.204772	8	.025597	
Min. Time	.009743	2	.004872	< 1
Min. Time x Subjects	.041000	8	.005125	
Gain x Min. Time	.042234	4	.010559	< 1
Gain x Min. Time x Subjects	.205047	16	.012815	

Switch Time = 1.0, 1.5, and 2.0 secs,
Gain = 8.0 and 16.0 v/sec^2, Min. Time = 2.5 secs.

Source of Variation	SS	df	MS	F
Gain	.086082	1	.086082	17.18*
Gain x Subjects	.020037	4	.005009	
Switch Time	.001775	2	.000887	< 1
Switch Time x Subjects	.036914	8	.004614	
Gain x Switch Time	.030458	2	.015229	3.48
Gain x Switch Time x Subjects	.035022	8	.004378	

Switch Time = 1.5, 2.0, and 3.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Min. Time = 4.0 secs.

Source of Variation	SS	df	MS	F
Gain	.011021	1	.011021	1.38
Gain x Subjects	.032034	4	.008008	
Switch Time	.054252	2	.027126	7.17*
Switch Time x Subjects	.030250	8	.003781	
Gain x Switch Time	.002193	2	.001096	< 1
Gain x Switch Time x Subjects	.036796	8	.004600	

**Significant at the 0.01 Level.

* Significant at the 0.05 Level.

prediction, as can be seen by comparing Figs. 5.3.6 and 5.3.7 to Figs. 5.2.7 and 5.2.8. Again, no statistical significance for MTTG was noted.

In general terms, on-line prediction yielded the same performance variations as exploratory prediction but at somewhat higher levels. Though no measure of the timing errors for the first control reversal was available, the relations developed in the preceding section may be theorized to be applicable here also. The increased magnitudes and slopes of the performance measures for on-line prediction can be hypothesized to result from either larger, constant values of Δt_1 than for exploratory prediction, or from a Δt_1 which is a function of the independent variables.

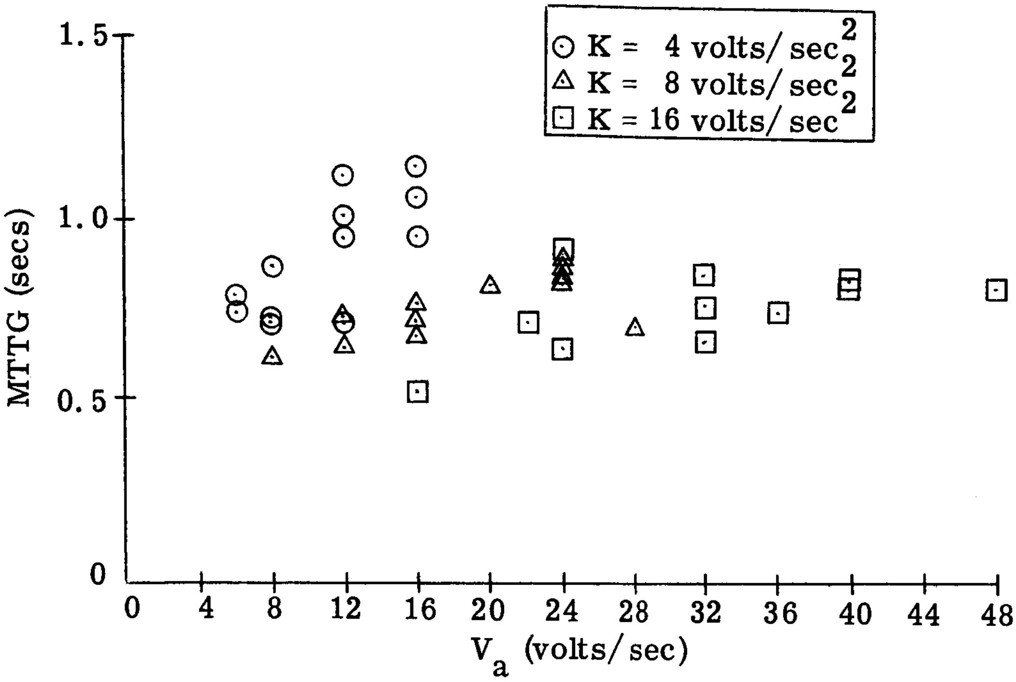


Figure 5.3.6 Average MTTG Performance Measure vs. Approach Speed for On-Line Prediction.

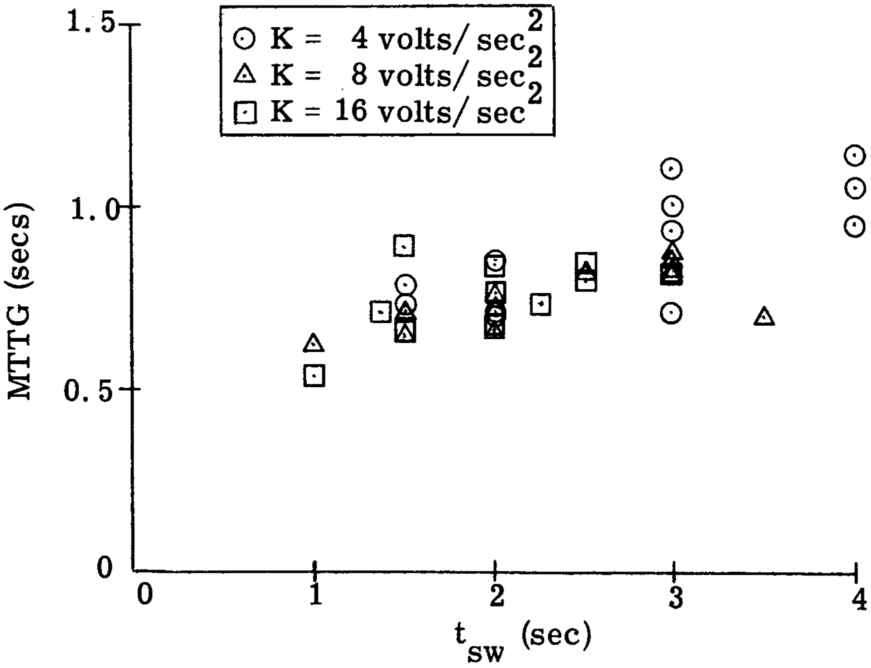


Figure 5.3.7 Average MTTG Performance Measure vs. Switch Time for On-Line Prediction.

5.4 No Prediction (Normal Display)

Performance variations with the normal display were noticeably different than those for the predictive displays. This can be seen in Figs. 5.4.1 and 5.4.2, which present the average terminal states for each condition in the phase plane and normalized phase plane respectively. The most apparent differences between these plots and those for the predictive displays is the large number of undershoot conditions.

An examination of the timing errors of the first control reversal shows a definite tendency towards early switching, the only exceptions being those conditions for which the time available between the start of a trial and the time at which optimum control reversal (t_1) must occur was 0.5 sec. This can be attributed to reaction time limitations of the operator, and his requirements on observing the response for some finite time interval in order to perceive the rate of movement. The Δt_1 data for no prediction showed a high variability, with the result that trends of the average Δt_1 as a function of the different independent variables were largely inconsistent. However, a rough increase in the standard deviation of Δt_1 with increasing switch time was noticed, as shown in Fig. 5.4.3.

The influence of approach speed and switch time on performance in terms of the VECT criterion (see Fig. 4.4.7) is illustrated in Figs. 5.4.4 and 5.4.5. The latter is essentially a gain-normalized plot of the former.

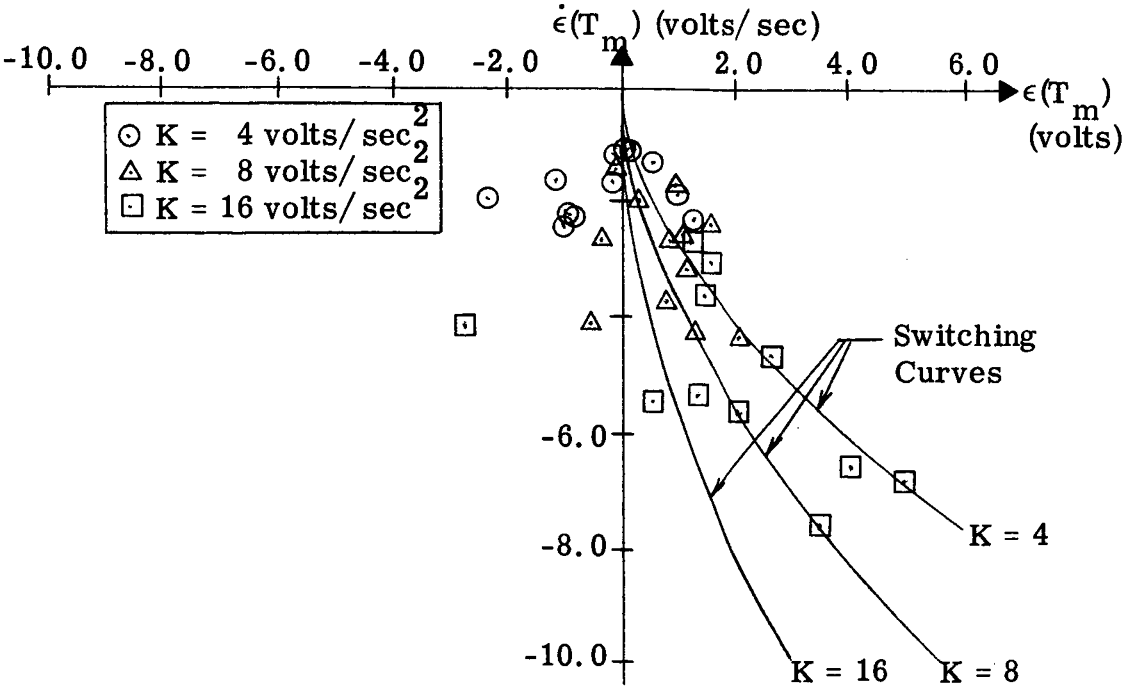


Figure 5.4.1 Average Terminal States in the Phase Plane for the Normal Display.

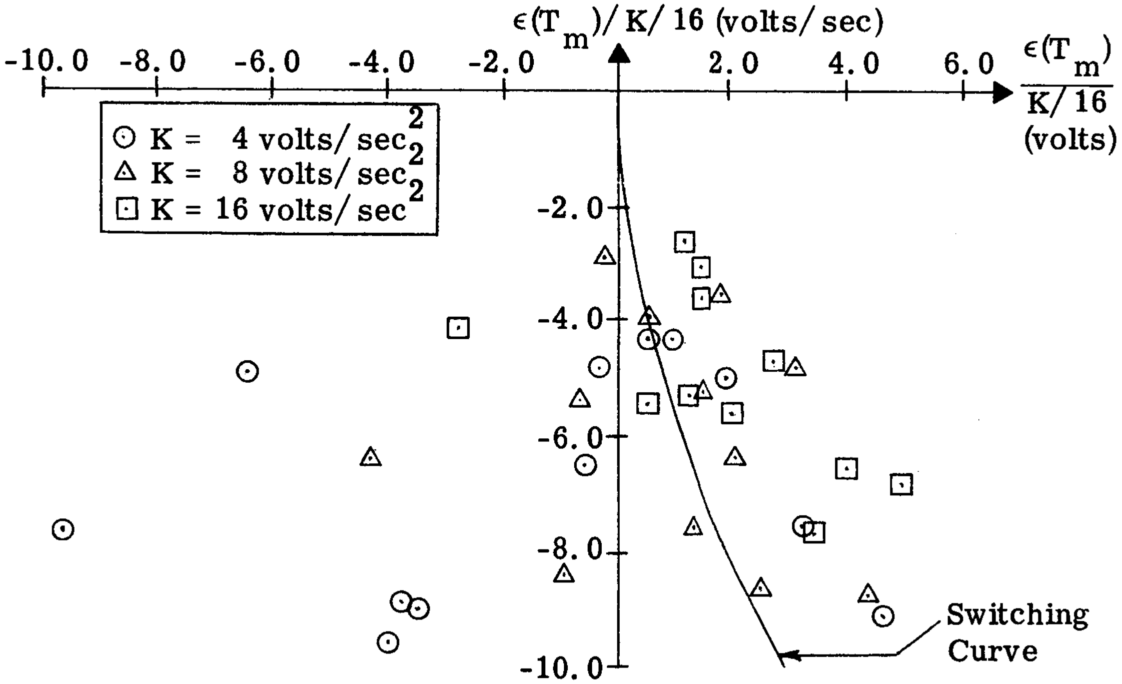


Figure 5.4.2 Average Terminal States in the Gain-Normalized Phase Plane for the Normal Display.

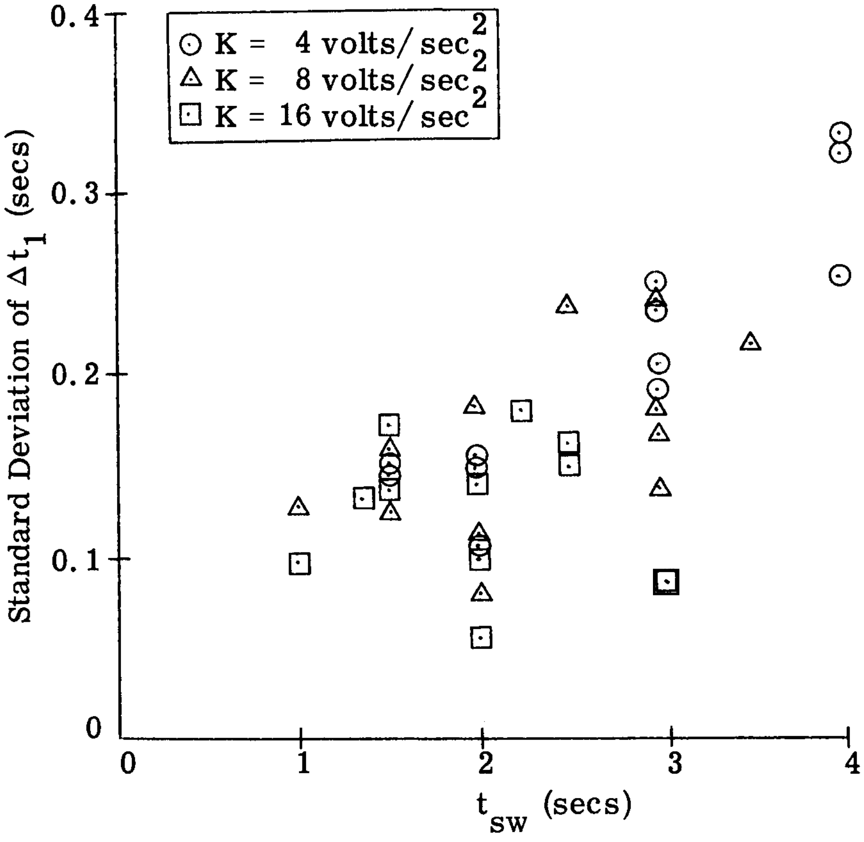


Figure 5. 4. 3 Standard Deviation of Timing Errors for the First Control Reversal vs. Switch Time for the Normal Display.

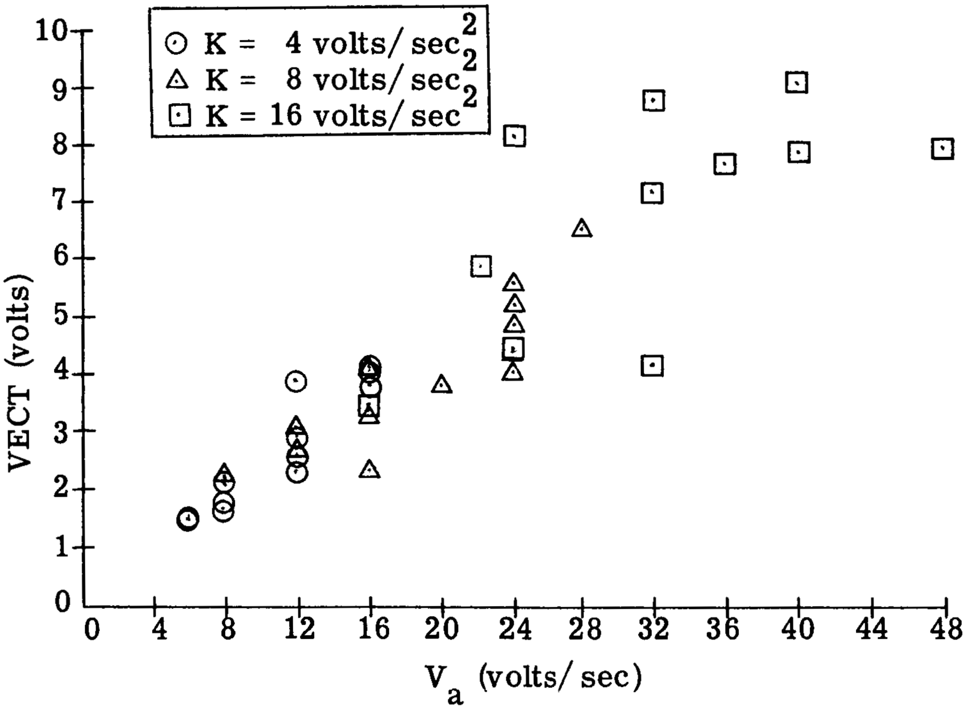


Figure 5. 4. 4 Average VECT Performance Measure vs. Approach Speed for the Normal Display.

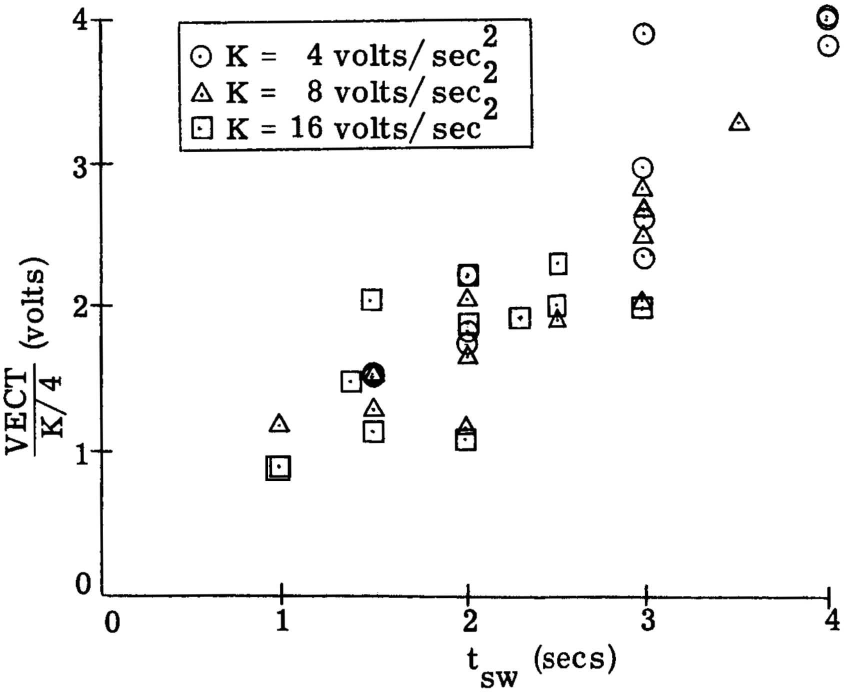


Figure 5. 4. 5 Average Gain-Normalized VECT Performance Measure vs. Switch Time for the Normal Display.

This behavior is also true of the absolute MISS performance measure (see Fig. 4.4.5), plotted against approach speed in Fig. 5.4.6, and in gain-normalized form against switch time in Fig. 5.4.7. (The MISS criterion by itself did not exhibit consistent trends because of the frequent undershoot tendencies which could not be related to the independent variables.) Results of the analysis of variance for absolute MISS are presented in Table 5.4.1. It should be noted that the significance of the minimum time, T_m, in the first test can be attributed to the fact that the $T_m = 4.0$ secs conditions had initial error-rates towards the centerline while the other six conditions had either zero or positive initial error-rates. (Recall from Chapter 4 that the half-way position cue is absent for negative initial error-rates.) However, the general influence of the sign of the initial error-rate was not consistent in terms of the absolute MISS; about half of all the negative initial error-rate conditions yielded average absolute MISS levels which were noticeably higher than the rest of the results.

Performance with the MTTG criterion (see Fig. 4.4.2) shows a more definite effect of the independent variables for the normal display than for the predictive displays. Since the first control reversals were usually early with this display form, it is not possible to explain performance on the basis of an assumed switching lag, as was done for exploratory prediction. However, it is possible to illustrate analytically

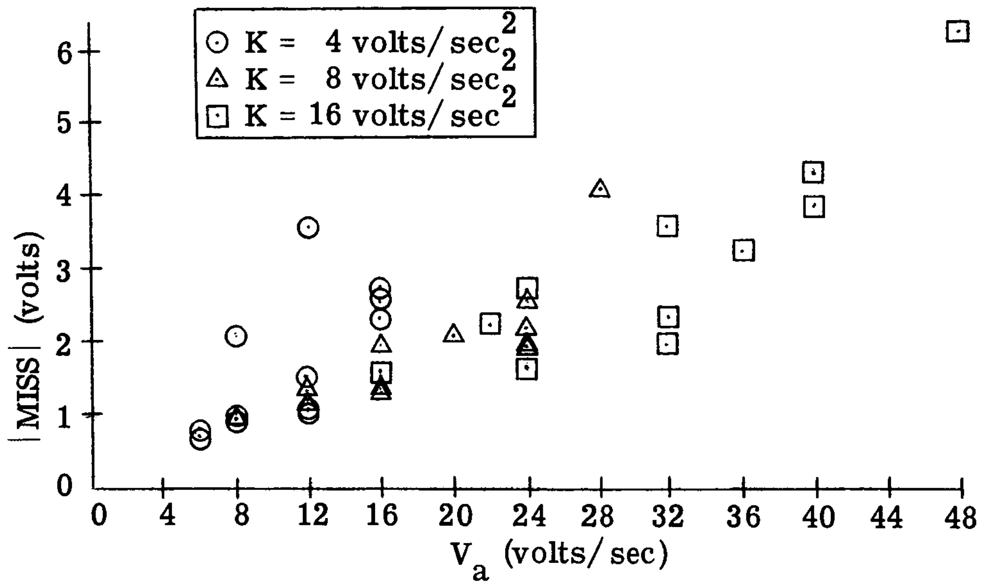


Figure 5.4.6 Average Absolute MISS Performance Measure vs. Approach Speed for the Normal Display.

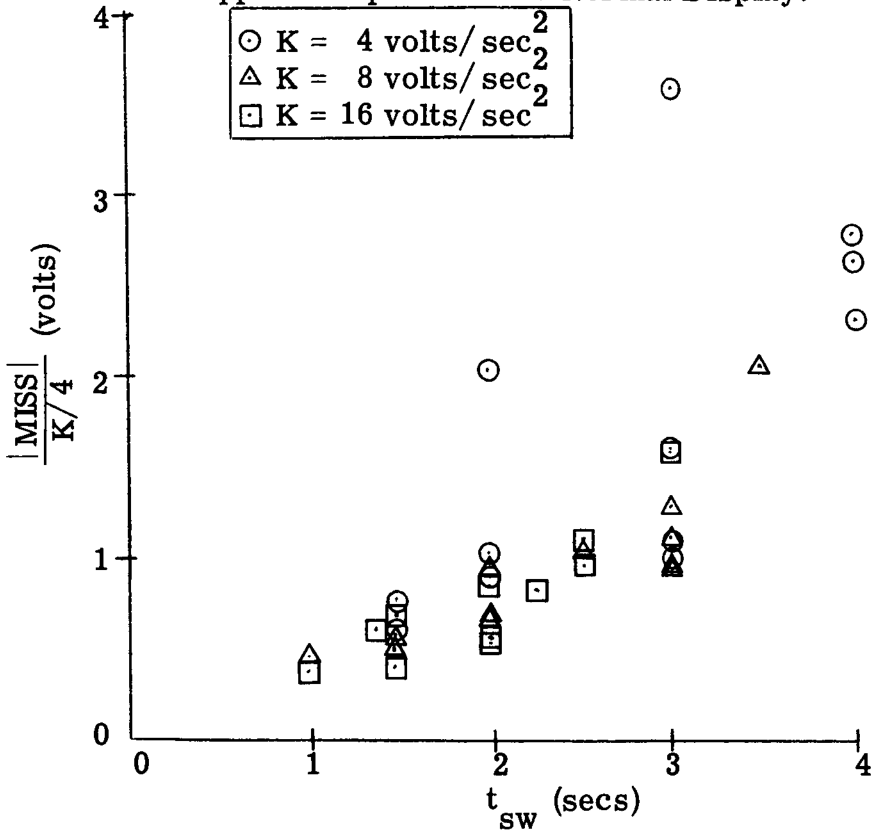


Figure 5.4.7 Average Gain-Normalized Absolute MISS Performance Measure vs. Switch Time for the Normal Display.

TABLE 5.4.1 ANALYSIS OF VARIANCE: LOG |MISS| FOR NORMAL DISPLAY.

Min. Time = 4.0, 6.0, 8.0 and 10.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Switch Time = 3.0 secs.

Source of Variation	SS	df	MS	F
Gain	.033063	1	.033063	3.86
Gain x Subjects	.034276	4	.008569	
Min. Time	.166706	3	.055569	4.12*
Min. Time x Subjects	.161788	12	.013482	
Gain x Min. Time	.086463	3	.028821	2.08
Gain x Min. Time x Subjects	.165856	12	.013821	

Min. Time = 2.5, 4.0, and 6.0 secs,
Gain = 4.0, 8.0, and 16.0 v/sec^2, Switch Time = 2.0 sec^2.

Source of Variation	SS	df	MS	F
Gain	.258779	2	.129389	14.85**
Gain x Subjects	.069684	8	.008711	
Min. Time	.002689	2	.001344	< 1
Min. Time x Subjects	.160875	8	.020109	
Gain x Min. Time	.199300	4	.049825	6.04**
Gain x Min. Time x Subjects	.131938	16	.008246	

Switch Time = 1.0, 1.5, and 2.0 secs,
Gain = 8.0 and 16.0 v/sec^2, Min. Time = 2.5 secs.

Source of Variation	SS	df	MS	F
Gain	.142692	1	.142692	8.13*
Gain x Subjects	.006476	4	.001619	
Switch Time	.078474	2	.039237	2.02
Switch Time x Subjects	.155764	8	.019471	
Gain x Switch Time	.011662	2	.005831	1.03
Gain x Switch Time x Subjects	.045109	8	.005639	

Switch Time = 1.5, 2.0, and 3.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Min. Time = 4.0 secs.

Source of Variation	SS	df	MS	F
Gain	.025288	1	.025288	3.27
Gain x Subjects	.030918	4	.007729	
Switch Time	.295848	2	.147924	9.79**
Switch Time x Subjects	.120847	8	.015106	
Gain x Switch Time	.089064	2	.044532	4.52*
Gain x Switch Time x Subjects	.078810	8	.009851	

**Significant at the 0.01 Level.
* Significant at the 0.05 Level.

the advantage of this early switching strategy in terms of MTTG whenever there is an uncertainty in when switching should take place.

A four segment trajectory illustrated in Fig. 5.4.8 is hypothesized as representing the response with early switching. The following development illustrates the penalties obtained due to early switching of ($-\Delta t_1$) seconds followed by a second reversal Δt_2 seconds later which drives the system to the switching curve. It is assumed that the terminal point will lie on the switching curve. These penalties are then compared to the penalties that are obtained with a control reversal lag of Δt_1 seconds, following the development presented in Section 5.2.

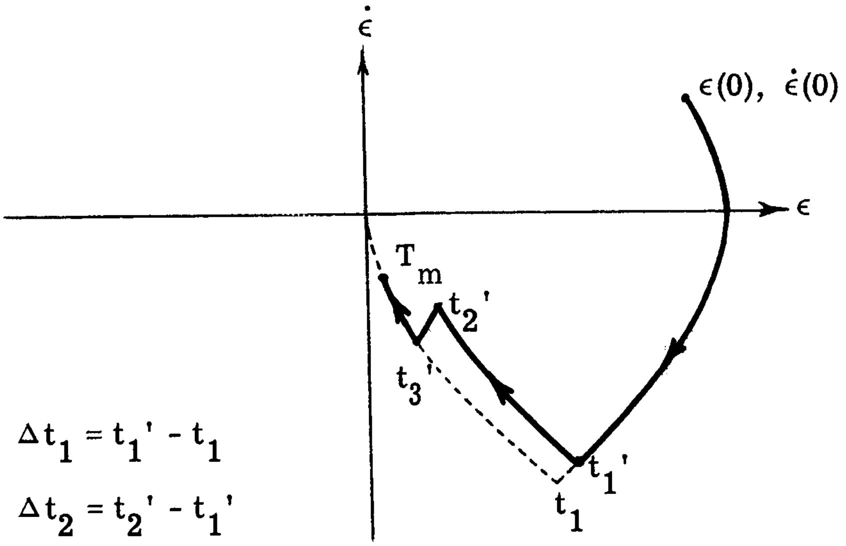


Figure 5.4.8 Hypothesized Phase Plane Trajectory for Response with Early Control Reversal.

Since the terminal state is assumed to lie on the switching curve, MTTG is given by

$$\text{MTTG} = -\frac{\dot{\epsilon}(T_m)}{K} \quad . \tag{5.4.1}$$

It can be seen that

$$t_{sw} - \Delta t_1 = \Delta t_2 + (t_3' - t_2') + (T_m - t_3')$$

$$= \Delta t_2 + \left(\frac{\dot{\epsilon}(t_2') - \dot{\epsilon}(t_3')}{K}\right) + \left(\frac{\dot{\epsilon}(T_m) - \dot{\epsilon}(t_3')}{K}\right) \quad . \tag{5.4.2}$$

Rearranging Eq. (5.4.2),

$$-\frac{\dot{\epsilon}(T_m)}{K} = -t_{sw} + \Delta t_1 + \Delta t_2 + \frac{\dot{\epsilon}(t_2')}{K} - \frac{2\dot{\epsilon}(t_3')}{K} \quad . \tag{5.4.3}$$

Δt_1 and Δt_2 are given by

$$-\Delta t_1 = \frac{\dot{\epsilon}(t_1') - \dot{\epsilon}(t_1)}{K} = \frac{\dot{\epsilon}(t_1')}{K} + t_{sw} \tag{5.4.4}$$

$$\Delta t_2 = \frac{\dot{\epsilon}(t_2') - \dot{\epsilon}(t_1')}{K} \tag{5.4.5}$$

which yields

$$\frac{\dot{\epsilon}(t_2')}{K} = \Delta t_2 + \frac{\dot{\epsilon}(t_1')}{K}$$

$$= \Delta t_2 - \Delta t_1 - t_{sw} \quad . \tag{5.4.6}$$

From the equations for the parabolas in the phase plane, we can write:

$$\epsilon(t_3') = \frac{1}{2K}\dot{\epsilon}^2(t_3') - \frac{1}{2K}\dot{\epsilon}^2(t_1) + \epsilon(t_1)$$

$$\epsilon(t_3') = -\frac{1}{2K}\dot{\epsilon}^2(t_3') + \frac{1}{2K}\dot{\epsilon}^2(t_2') + \epsilon(t_2')$$

$$\epsilon(t_2') = \frac{1}{2K}\dot{\epsilon}^2(t_2') - \frac{1}{2K}\dot{\epsilon}^2(t_1') + \epsilon(t_1') \qquad (5.4.7)$$

$$\epsilon(t_1') = -\frac{1}{2K}\dot{\epsilon}^2(t_1') + \frac{1}{2K}\dot{\epsilon}^2(0) + \epsilon(0)$$

$$\epsilon(t_1) = -\frac{1}{2K}\dot{\epsilon}^2(t_1) + \frac{1}{2K}\dot{\epsilon}^2(0) + \epsilon(0)$$

These five relations can be combined to yield

$$\frac{1}{K}\dot{\epsilon}^2(t_3') = \frac{1}{K}\dot{\epsilon}^2(t_2') - \frac{1}{K}\dot{\epsilon}^2(t_1') + \frac{1}{K}\dot{\epsilon}^2(t_1) \quad . \qquad (5.4.8)$$

Substituting expressions for $\frac{1}{K}\dot{\epsilon}^2(t_1')$ and $\frac{1}{K}\dot{\epsilon}^2(t_2')$ from Eqs. (5.4.4) and (5.4.6),

$$\frac{1}{K}\dot{\epsilon}^2(t_3') = K(\Delta t_2 - \Delta t_1 - t_{sw})^2 - K(-\Delta t_1 - t_{sw})^2 + Kt_{sw}{}^2$$

$$= K\left[(\Delta t_2 - t_{sw})^2 - 2\Delta t_2\,\Delta t_1\right] \quad . \qquad (5.4.9)$$

Dividing by K and taking the square root (noting that the error-rate is negative),

$$\frac{\dot{\epsilon}(t_3')}{K} = -\sqrt{(\Delta t_2 - t_{sw})^2 - 2\Delta t_2\,\Delta t_1} \quad . \qquad (5.4.10)$$

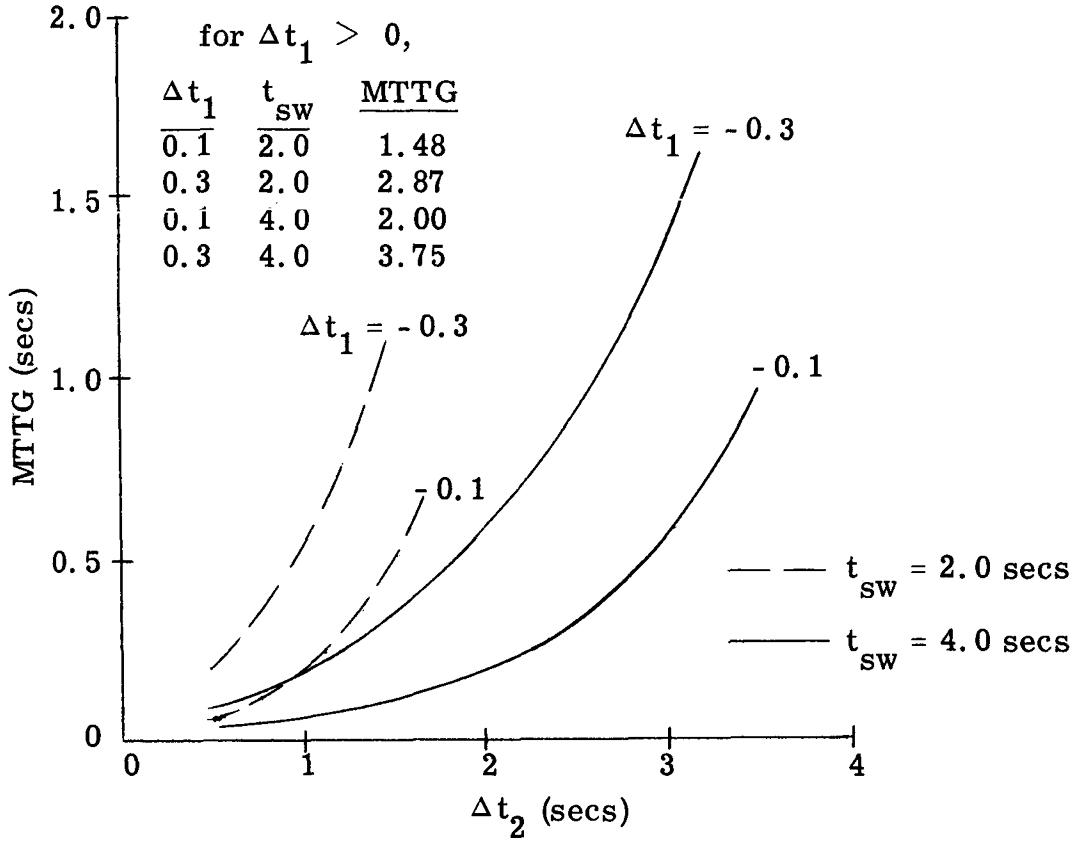


Figure 5.4.9 MTTG Performance Penalties for Early Control Reversal of $(-\Delta t_1)$ secs, Followed by a Second Control Reversal Δt_2 secs Later. Terminal Point Assumed to Lie on the Switching Curve.

Substituting Eqs. (5.4.6) and (5.4.10) into Eq. (5.4.3) it follows that

$$MTTG = -2t_{sw} + 2\Delta t_2 + 2\sqrt{(\Delta t_2 - t_{sw})^2 - 2\Delta t_2 \Delta t_1} \,. \quad (5.4.11)$$

The MTTG penalty for early switching is plotted against Δt_2 with Δt_1 and t_{sw} as parameters in Fig. 5.4.9. Note that for all cases shown, a lag in control reversal causes worse performance than an early control reversal.

Performance in terms of the MTTG criteria is illustrated in Figs. 5.4.10 and 5.4.11. The influence of switch time is fairly obvious, which of course could also be interpreted as an effect of approach speed. The analysis of variance tests with the MTTG performance measure indicate a main effect due to gain and a less consistent main effect due to switch time. (Note again that either may be attributable to approach speed.) These statistical results are summarized in Table 5.4.2. (Note that a fifth test with fixed gain was added here.)

In summary, system performance with the normal display shows a definite dependency upon the system parameters. Since manual operations are not highly constrained, a high level of variability was observed in both the application of the first control reversal and the overall system performance measures. The subjects used a cautious switching strategy, indicating their awareness that large penalties are associated with overshoot conditions. This behavior seemed more pronounced at the higher values of switch time and approach speed, though no consistent variation was noticed.

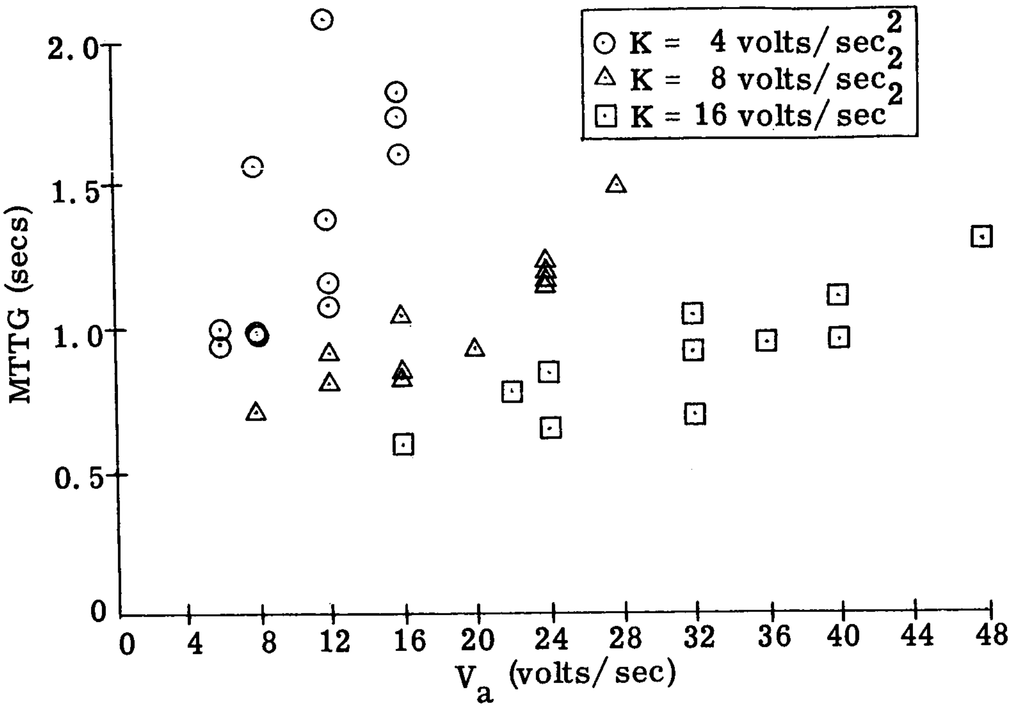


Figure 5.4.10 Average MTTG Performance Measure vs. Approach Speed for the Normal Display.

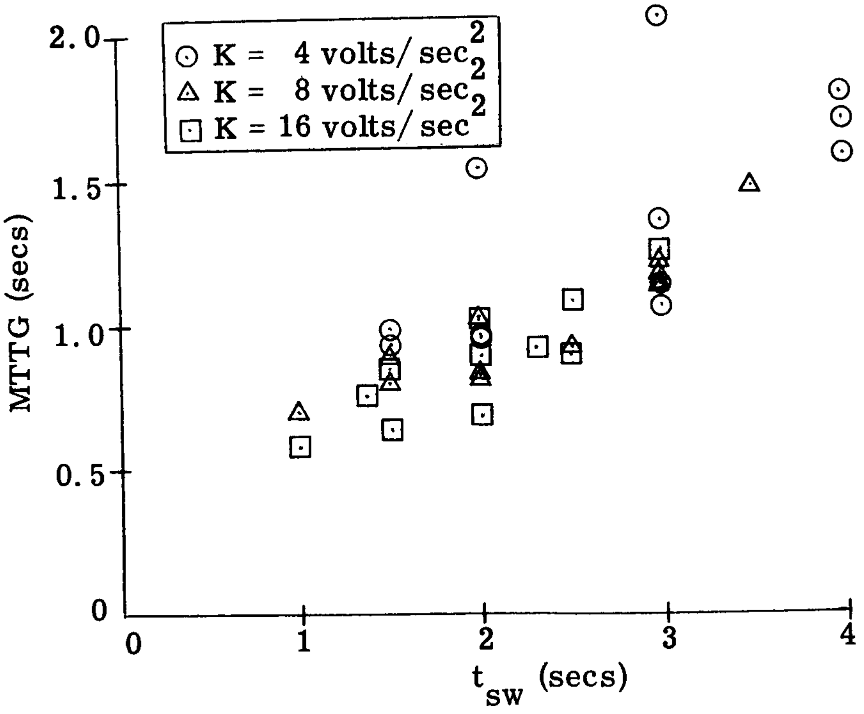


Figure 5.4.11 Average MTTG Performance Measure vs. Switch Time for the Normal Display.

TABLE 5.4.2 ANALYSIS OF VARIANCE: LOG (MTTG) FOR NORMAL DISPLAY.

Min. Time = 4.0, 6.0, 8.0, and 10.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Switch Time = 3.0 secs.

Source of Variation	SS	df	MS	F
Gain	.012960	1	.012960	3.84
Gain x Subjects	.013508	4	.003377	
Min. Time	.041790	3	.013930	4.53*
Min. Time x Subjects	.036876	12	.003073	
Gain x Min. Time	.030888	3	.010296	3.41
Gain x Min. Time x Subjects	.036261	12	.003022	

Min. Time = 2.5, 4.0 and 6.0 secs,
Gain = 4.0, 8.0, and 16.0 v/sec^2, Switch Time = 2.0 secs.

Source of Variation	SS	df	MS	F
Gain	.027424	2	.013712	4.94*
Gain x Subjects	.022200	8	.002775	
Min. Time	.000179	2	.000090	< 1
Min. Time x Subjects	.036026	8	.004503	
Gain x Min. Time	.050894	4	.012723	5.85**
Gain x Min. Time x Subjects	.034825	16	.002177	

Switch Time = 1.0, 1.5, and 2.0 secs,
Gain = 8.0 and 16.0 v/sec^2, Min. Time = 2.5 secs.

Source of Variation	SS	df	MS	F
Gain	.002017	1	.002017	6.45
Gain x Subjects	.001251	4	.000313	
Switch Time	.014094	2	.007047	1.59
Switch Time x Subjects	.035470	8	.004434	
Gain x Switch Time	.001600	2	.000800	< 1
Gain x Switch Time x Subjects	.013470	8	.001684	

**Significant at 0.01 Level.

* Significant at 0.05 Level.

TABLE 5.4.2 (concluded)

Switch Time = 1.5, 2.0, and 3.0 secs,
Gain = 4.0 and 8.0 v/sec^2, Min.Time = 4.0 secs.

Source of Variation	SS	df	MS	F
Gain	.018155	1	.018155	12.31*
Gain x Subjects	.005899	4	.001475	
Switch Time	.095236	2	.047618	19.70**
Switch Time x Subjects	.019342	8	.002418	
Gain x Switch Time	.024834	2	.012417	3.58
Gain x Switch Time x Subjects	.027717	8	.003465	

Min.Time = 6.0, 8.0, and 10.0 secs,
Switch Time = 3.0 and 4.0 secs, Gain = 4.0 v/sec^2.

Source of Variation	SS	df	MS	F
Min.Time	.004755	2	.002377	1.82
Min.Time x Subjects	.010449	8	.001306	
Switch Time	.049613	1	.049613	15.94*
Switch Time x Subjects	.012451	4	.003113	
Min.Time x Switch Time	.003201	2	.001600	< 1
Min.Time x Switch Time x Subjects	.025242	8	.003155	

**Significant at 0.01 Level.

* Significant at 0.05 Level.

5.5 Relative Effects of Display Type

Conclusions regarding the effect of display type must necessarily rely somewhat upon statistical results. It was found that in nearly all of the previously mentioned analysis of variance tests which were conducted to determine the effect of the different independent variables, the display factor was significant at the 0.01 level when it was added to the test. To determine which conditions yield significant differences between displays, it is possible to consider each condition separately in a single-factor (display type) design with repeated measures. These tests (pp. 105-116, Winer [49]), which were conducted for each of the thirty-six conditions, yield not only a measure of the significance of the display factor, but also a critical value for the individual differences between displays. The results of these tests for absolute MISS and Minimum Time-to-Go measures (with appropriate log transformations) are summarized in Tables 5.5.1 and 5.5.2. The thirty-six separate single factor tests show that differences between on-line prediction and exploratory prediction are of little statistical significance. It is apparent however from the results for each display presented in the preceding sections that exploratory prediction does yield some small improvements over on-line prediction.

It has been noted previously that performance variations with the predictive displays are small relative to performance variations with the normal display. Thus, differences between the normal and

TABLE 5.5.1

RESULTS OF ANALYSIS OF VARIANCE TESTS ON INDIVIDUAL DISPLAY DIFFERENCES: LOG |MISS|

CONDITION NUMBER	F RATIO	$\Delta \|\text{MISS}\|_{\text{P-EP}}$[†]	$\Delta \|\text{MISS}\|_{\text{N-EP}}$	$\Delta \|\text{MISS}\|_{\text{N-P}}$
1	1.25	- 0.047	0.211	0.257
2	12.43**	0.389	1.730**	1.341**
3	4.58*	0.147	0.442*	0.295
4	16.60**	- 0.085	0.503**	0.588**
5	12.39**	0.352	3.005**	2.653**
6	4.11	0.055	0.573	0.518
7	30.34**	0.332	1.121*	0.789**
8	5.04*	0.043	1.947*	1.904
9	3.47	0.090	0.512	0.421
10	5.70*	0.403	1.752*	1.349*
11	48.43**	0.045	0.698**	0.653**
12	10.14**	- 0.126	1.933*	2.059**
13	3.38	0.392	0.523	0.131
14	9.35**	0.092	0.737**	0.645*
15	1.02	- 0.085	0.543	0.628
16	5.80*	0.123	0.688*	0.565*
17	7.54*	- 0.431	0.955*	1.386*
18	4.35	- 0.541	1.011	1.525
19	16.85**	0.143	0.885**	0.742**
20	5.27*	0.111	1.013*	0.902*
21	4.00	0.288	1.180	0.892
22	8.67**	0.172	1.241**	1.069**
23	16.97**	- 0.224	1.092**	1.361**
24	10.17**	- 0.308	3.111**	3.419**
25	(Condition No. 25 Eliminated.)			
26	3.48	0.303	1.153	0.850
27	7.37*	0.414	1.393*	0.979*
28	3.00	- 0.277	0.358	0.635
29	2.16	0.152	0.558	0.405
30	16.52**	- 0.096	3.516**	3.612**
31	3.57	- 0.038	0.443	0.481
32	4.10	0.951	1.196	0.245
33	30.53**	0.209	2.239**	2.030**
34	10.77**	- 0.142	1.689**	1.830**
35	5.95*	- 0.046	2.200*	2.246*
36	6.90*	0.704	2.839*	2.135*

**Significant at 0.01 Level.

* Significant at 0.05 Level.

[†] Average difference in volts (statistics based on log transformation); EP - Exploratory Prediction, P - On-Line Prediction, N - Normal Display.

TABLE 5.5.2

RESULTS OF ANALYSIS OF VARIANCE TESTS ON INDIVIDUAL DISPLAY DIFFERENCES: LOG (MTTG).

CONDITION NUMBER	F RATIO	Δ MTTG$_{P-EP}$†	Δ MTTG$_{N-EP}$	Δ MTTG$_{N-P}$
1	3.06	0.144	0.350	0.206
2	11.24**	0.275	0.964**	0.690*
3	15.17**	0.152*	0.361**	0.209*
4	9.60**	0.067	0.352**	0.285*
5	10.08**	0.289	1.263**	0.973*
6	3.37	0.092	0.374	0.283
7	20.06**	0.293*	0.725**	0.432**
8	6.89*	0.163	0.806*	0.643*
9	4.54*	0.190	0.322*	0.133
10	20.16**	0.318*	0.853**	0.535**
11	13.52**	0.103	0.489**	0.387**
12	28.43**	0.063	0.855**	0.791**
13	3.24	0.135	0.243	0.108
14	5.21*	0.110	0.375*	0.265
15	< 1	0.038	0.173	0.135
16	6.60*	0.172	0.257*	0.085
17	4.29	- 0.072	0.276	0.348
18	2.67	0.036	0.399	0.363
19	21.67**	0.296**	0.385**	0.089
20	6.40*	0.080	0.442	0.362
21	8.72**	0.207	0.508**	0.301*
22	3.41	0.179	0.311	0.132
23	15.04**	0.107	0.439**	0.332**
24	8.95**	0.022	0.821*	0.799**
25	(Condition No. 25 Eliminated.)			
26	2.42	0.142	0.206	0.064
27	6.87*	0.333*	0.306*	- 0.027
28	< 1	- 0.039	- 0.004	0.034
29	< 1	0.017	0.093	0.076
30	10.08**	0.025	0.499**	0.474**
31	3.98	0.146	0.136	- 0.010
32	9.72**	0.271**	0.324**	0.053
33	12.58**	0.197*	0.454**	0.257*
34	7.06*	0.090	0.283*	0.193*
35	2.77	0.156	0.254	0.098
36	7.89*	0.227	0.534*	0.307*

**Significant at 0.01 Level.

* Significant at 0.05 Level.

†Average difference in seconds (statistics based on log transformation); EP - Exploratory Prediction, P - On-Line Prediction, N - Normal Display.

predictive displays are largely a function of those parameters which have a significant effect on operation with the normal display. This effect is summarized in Figs. 5.5.1 through 5.5.4, in which the trends for the differences in performance are similar to the trends for the normal display alone. The statistical significance of each point is indicated by either a solid symbol (0.01 level of significance), a dashed symbol (0.05 level of significance), or a dotted symbol (insignificant).

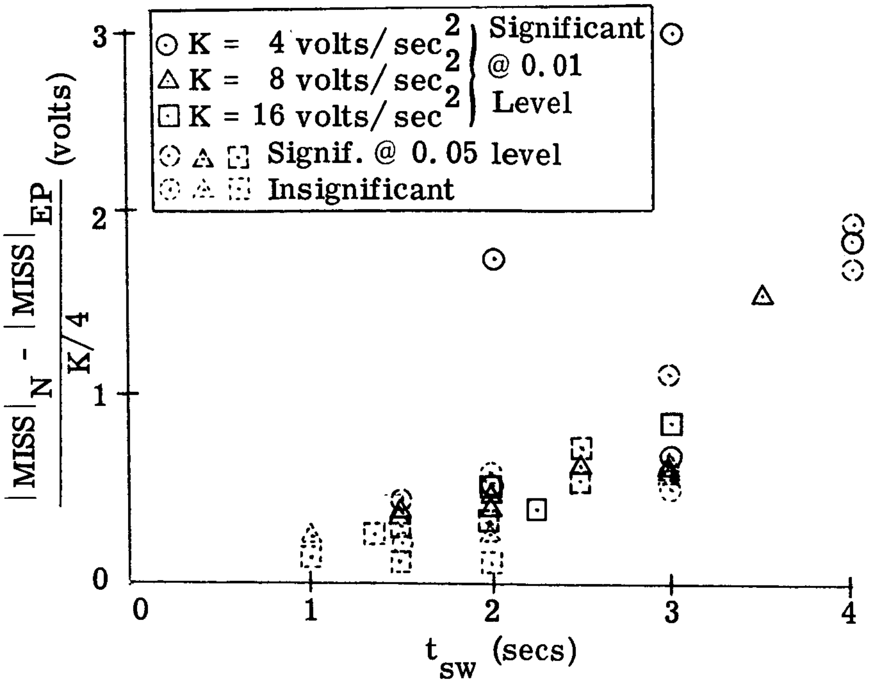


Figure 5.5.1 Difference in Gain-Normalized Absolute MISS Between Normal Display (N) and Exploratory Prediction (EP) vs. Switch Time.

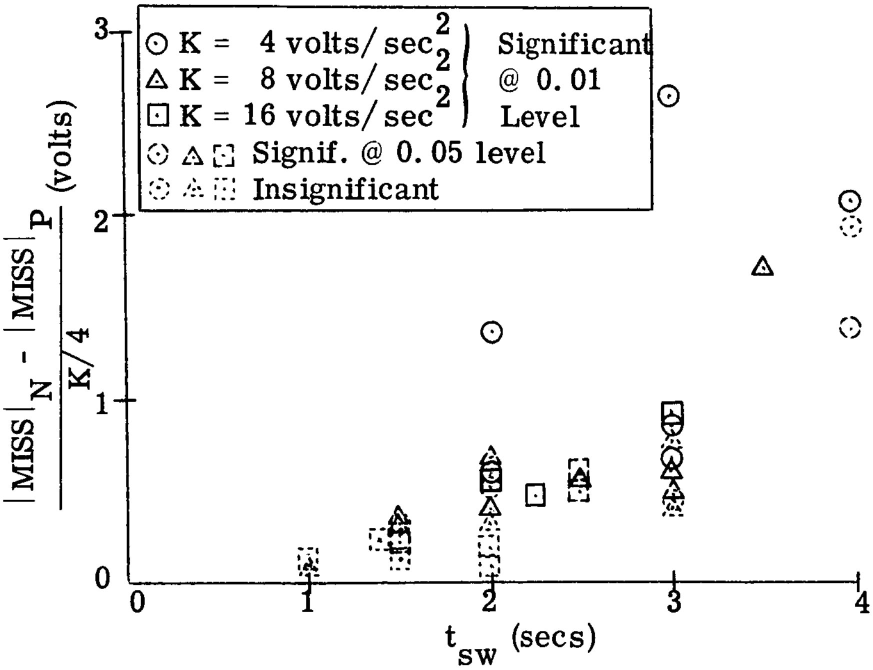


Figure 5.5.2 Difference in Gain-Normalized Absolute MISS Between Normal Display (N) and On-Line Prediction (P) vs. Switch Time.

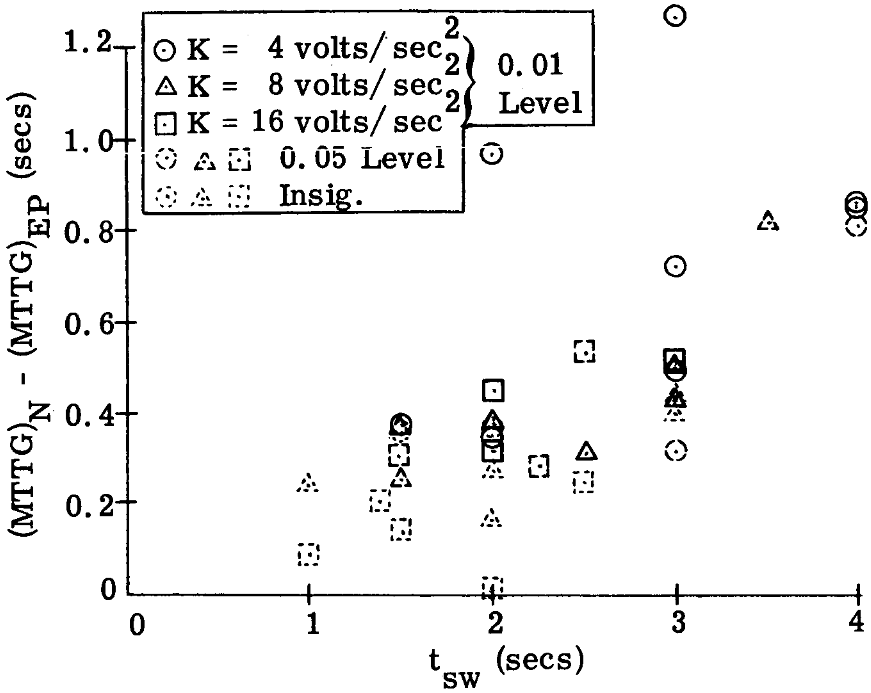


Figure 5.5.3 Difference in MTTG Between Normal Display (N) and Exploratory Prediction (EP) vs. Switch Time.

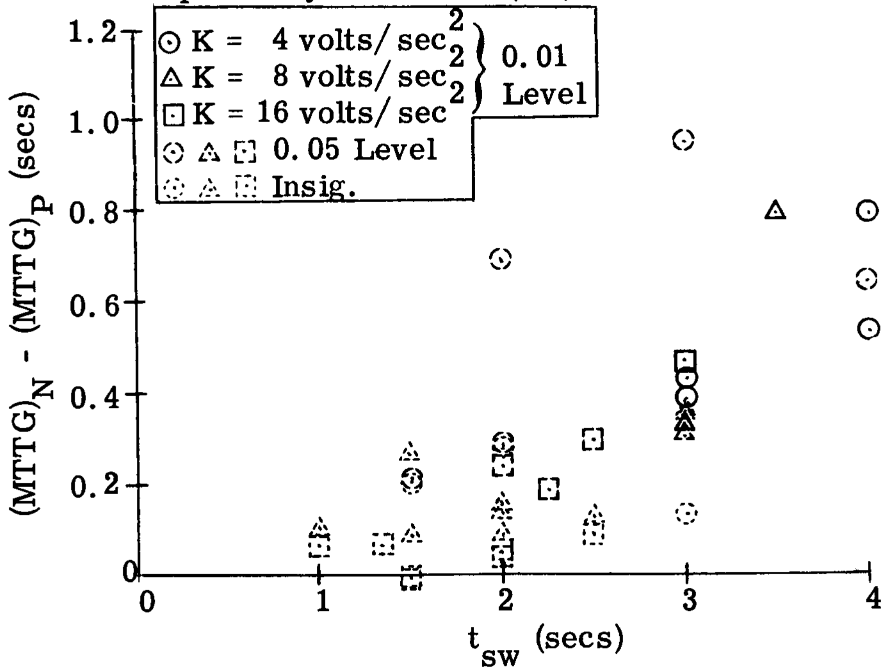


Figure 5.5.4 Difference in MTTG Between Normal Display (N) and On-Line Prediction (P) vs. Switch Time.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Experimental Results

Operator performance in the minimum-time control of a pure inertia system using an exploratory predictive display (as measured by errors in timing of the first control reversal) was found to be highly accurate and independent of any of the system parameters over the ranges investigated. The pure inertia system was varied from that with a relatively high gain and short response time to a moderate gain and response time. Low gains and long response times, as indicated by the results of a pilot study, do not have any detrimental effect on the timing errors. However, the more important system oriented performance measures did show a dependence upon the system parameters, which could be explained by an analytical study of the sensitivity of the performance measures to constant timing errors. Thus the hypothesis that performance evaluation can be based on the response of the overall system rather than just the human operator's behavior was shown to be valid.

The on-line predictive display yielded nearly the same high level of performance as the exploratory predictive display. Though the latter indicated superiority, it was not apparent on a purely statistical basis. The difference in performance can be attributed to the fact that human operator strategy is not as highly constrained with on-line prediction. The fact that only small differences were noted is due to the short amount of time required in the exploring process with on-line prediction. This conclusion therefore should not be extended to situations in which some appreciable time is needed by the operator to determine a proper control change.

Operator performance with the normal display was quite variable, with a tendency towards early switching. The influence of switch time, t_{sw} (defined on page 74), was to cause a general improvement in performance as this time decreased. As a result, it is concluded that the predictive displays offer only marginal improvements when the necessary prediction time is short.

An interesting conclusion concerning the effects of display gain on performance with all the display forms can be made from the results. Since changes in plant gain are equivalent to changes in display gain for fixed values of t_{sw} and T_m, the results plotted vs. t_{sw} with different gains indicated by different symbols can be used for inferences on display gain effects. For example, it can be seen that the gain had no effect on $\frac{|\text{MISS}|}{K/4}$ at a given t_{sw} (see Fig. (5.4.7). Since this measure is the MISS normalized by the display gain, it follows that for a change in display gain, there is no change in the resulting "plant MISS".

Though the subject of this research has been predictive displays as a performance aid, several comments can be made regarding their use as a training aid based on the experience obtained in this experimental effort. With the presentation of predictive information, the initial learning time for operation with the normal display was probably shortened, since the bang-bang optimal control law was more apparent. However, it is doubtful that the eventual trained performance with the normal display would be any better for the following reason: the information required by the operator to make a successful prediction is related to the proper combination of error and error-rate signals and the level of acceleration available. With the predictive display his attention is focused only on a portion of the predicted trajectory which is well away from the present state. Thus he is not concerned with the present error and error-rate combination as he must be with the normal display.

6.2 Extensions of Experimental Results

Though use of predictive displays in any application should be based on complete simulation studies, it is possible to make some qualitative predictions of what the results might be of such studies from the results of this particular experiment. Extensions of this experiment should be made only with the following constraints in mind:

(1) The number of alternative control actions available to the operator must be such that the decision process can be considered to be discrete rather than continuous.

(2) The time available to make a control decision and action is greater than the time required by the operator.

(3) The predictive display format and predictor control program are such that no additional mental predictions are required by the operator in order to effect a nearly optimal control law.

It is not expected that the particular system and display format used here will be exactly duplicated in any application; however, some similarities are present as is briefly pointed out below.

The terminal docking phase of rendezvous between two spacecraft is essentially described by pure inertia dynamics. In the event that this maneuver should be conducted with a stringent time constraint, or in minimum time, it can be expected that a predictive display would be useful. However, the results indicate that the relative speed of the vehicles should be kept low enough so that a large overshoot condition is not encountered. As pointed out earlier, the timing errors by the pilot would not be large, but the sensitivity of the actual terminal state to a timing error is dependent upon the approach speed.

The above considerations for the rendezvous task also are applicable to the terminal phase of lunar landing; as a result, it will not be discussed further.

Attitude control of a space vehicle is also characterized by pure inertia dynamics. While the study by Besco [7] has shown a predictive display to be useful, the experiment reported here indicates that small changes in attitude which may occur in several seconds probably could be accomplished as well without predictive information. The experiment indicated that in tracking the centerline, the predicted coast trajectory was sufficient, and the acceleration paths were not needed. Thus for attitude holding maneuvers, a simple velocity vector display may be as good as a predictive display. However, it should be again noted that the requirement of controlling several dimensions at once increases the importance of predictive information.

The go, no-go decision that must be made in aircraft takeoff is a discrete process. If the takeoff roll is proceeding properly, the predicted takeoff point should not be approaching the last safe takeoff point at all. Otherwise, the pilot would have an indication that something is wrong and may decide to abort early to be on the safe side. At any rate, the necessary mental prediction times are not very short, and some improvements could be found over displays that indicate only present aircraft position and desired lift-off point.

Tracking the glide path in aircraft landing is somewhat analogous to the task of following the centerline in this experiment. Thus, for small deviations from the glide path a velocity vector display might be as valuable as a more complete prediction. Initiation of the flare maneuver on the other hand is similar to the transient portion of the task, in that essentially a discrete decision must be made. (The fact that small adjustments are possible later in the flare is contrary to the analogy however.) Thus, either off-line or on-line prediction could be of value.

These are some of the applications for which inferences can be made from the experimental effort reported here. There are certainly other possibilities as well, but a more complete study of each application is required to identify all the similar operations which satisfy the previously mentioned constraints.

6.3 Recommendations

In Chapter 3, individual problems for specific applications worthy of further study were pointed out. Therefore, they shall not be repeated here. Instead these remarks are confined to problems of general interest.

First, a discussion of direct extensions to the experimental effort reported here is presented:

(1) Comments from the subjects indicated that the complete predictions were of use in the transient response phase, but that a simple velocity vector display was sufficient in tracking the centerline. Thus, it would be of interest to compare the predictive displays to the more simple velocity vector display for this entire task. It can be expected that such a display would show some improvement over the normal display, since the error-rate information is not as subtle.

(2) If the total effort plus a time constraint had been the cost function in this experiment, operator strategy certainly would have been different. It would be of interest to determine just how and under what circumstances predictive information would be useful in such a task. It is also not apparent just how the predictor should be implemented and what display format should be used to eliminate totally any necessary mental predictions, since this is essentially a two-point boundary value problem.

There are several problem areas that can be studied without restriction to specific applications. However, as in this study, selection of the controlled element dynamics and task necessarily must limit extensions of the results. The following is a list of several recommended studies:

(1) The effect on performance when the predictor model is inaccurate is of considerable practical interest. A determination of system performance degradation with decreasing model accuracy, and how the human operator compensates for inaccurate predictions would be the objective of such a study.

(2) Repetition rate and prediction span are somewhat related to the problem of model accuracy, but a study of these characteristics alone is worthwhile. Kelley [22] has noted that desirable prediction spans decrease with increasing vehicle speeds, but other application studies have not noted significant changes in performance for different spans. A more complete understanding of span and repetition rate requirements would hopefully result from such a general research effort.

(3) Selection of display format is somewhat dictated by the specific application. However, the special problems of predictive displays in presenting a future time or distance dimension is in need of further study. Resolving the question between time or distance itself would be of interest.

Another display format problem is concerned with the various cost functions that are used. Since it is probable that desirable display formats are dictated by the task objective, studies directed towards a comparison of formats alone are desirable. In addition, direct display of predicted cost functions should be studied.

(4) The problem of selection of a predictor control program for several applications has been mentioned previously. Since there are many situations in which complex control programs are desired, it would be useful to study in general the implementation of such programs, and how the human operator can participate in the adjustment of the program.

(5) The desire for predictive information is dependent upon the anticipatory abilities of the human operator. Therefore, studies of how the human operator predicts vehicle or system response, and what information he needs to make a prediction would be useful in predictive display development as well as in increasing our understanding of human operator performance. The predictive models as proposed by Sheridan [42] should not be overlooked in such a study.

6.4 Concluding Remarks

The objective of this report has been to provide some guidelines to be used in the consideration of predictive displays from either a basic research or applied point of view. Chapter 2 on the inherent characteristics of predictive display systems hopefully will have given the reader a fundamental understanding of the technique. A complete review of the known literature on predictive displays prompted Chapter 3 which also is intended to provide a starting point for any application being considered. The problems of performance measure selection and influence of plant dynamics were demonstrated in the experimental program which has been reported in Chapters 4, 5 and 6.

The basic substance of each chapter represents a new contribution to the study of predictive display systems. The recommendations for future efforts given in this chapter should suggest that there is room for many more.

Appendix A

INSTRUCTIONS TO SUBJECTS

The purpose of this experiment is to evaluate several different display concepts for manual control of a space vehicle. A large oscilloscope is used to display the motion of the vehicle, which you will control by moving a control stick placed in front of the scope.

The vertical axis of the scope is a time scale, and the horizontal axis is a position scale. A vertical centerline, which does not move, represents the desired path of the vehicle. The vehicle is represented by a point of light which will start at the bottom of the screen and move upwards at a constant speed. This point of light will initially be offset from the centerline, and will move upwards and either towards or away from the centerline at the beginning of a trial. By displacing the control stick, you will cause the point of light to accelerate in the same direction as which you moved the stick. With the control stick in the center, the vehicle, or light point, will not accelerate but travel in a straight line. Note that only one fixed level of acceleration is possible, so moving the stick further from the center will not increase the rate of acceleration.

Your task is to control the vehicle so that it moves to the centerline and travels up the centerline, and to do so as quickly as possible. It is not sufficient to cross the centerline—you must actually follow it.

Your performance depends on how quickly you can reach the centerline and how well you stay on it once you have reached it.

Three types of displays will be considered: normal display, predictive display, and exploratory predictive display.

Normal Display:

All you will see is the point of light representing the present position of the vehicle, and the centerline.

Predictive Display:

In this case a trace will appear on the screen emanating from the light point. This trace shows you the path the point will follow if you keep the control stick in its present position. In this way you can see the effect of the present control input on the future path, i.e., the predicted path.

Exploratory Predictive Display:

Again you will see a trace representing the predicted path. However, now the vehicle, or point of light, will not follow the path unless you squeeze the trigger on the control stick. It is only necessary to briefly press the trigger. After doing so, you can move the control stick so that the predicted path will change, but the point of light will still be following the path you saw when you last pressed the trigger. This way you can look at the future effect of different control inputs before actually applying them to the vehicle, i.e., you can explore inputs before using them.

Notice that if you keep the trigger continuously pressed, you have essentially the normal predictive display discussed above.

How Each Session is Conducted:

You will be seated in front of the oscilloscope in an enclosed booth with your right hand on the control stick. You will be wearing earphones through which you will hear a noise like a waterfall, to eliminate distractions from noises in the laboratory. The experimenter can interrupt this noise to talk with you at any time, and he can always hear you through an intercom.

Each session will be divided into three blocks of three different levels of acceleration. Generally, the higher the level of acceleration, the faster the system responds to control inputs. For each block, you will be given trials with the exploratory predictive display, followed by the plain predictive display, and finally the normal display.

The starting position for each trial will be different, and the rate at which it initially moves towards or away from the centerline will be different. Although these starting conditions will be repeated for each display type, the order in which they are presented will not, so you will not be able to predict each starting point.

Before a trial begins you will have sufficient time to observe the initial position and place the control stick as desired for your initial control input. If the point is initially to the right of the centerline, you will want it to accelerate to the left, so you will move the control stick to the left. You will have no prior warning as to when a trial will start, but the beginning will be immediately noticeable by the upward motion of the point of light. At this point in time then you are to control the vehicle so that it reaches the centerline as quickly as possible, and then stays as close to it as possible. For each trial, there is a certain minimum time in which you can reach the centerline. Four seconds beyond this minimum time the point will stop, signifying termination of the trial. The best you can do then is to meet the centerline in this minimum time and then stay exactly on it for four seconds. Total duration of the trials will range from six to fourteen seconds.

After termination of each trial, you will be informed of how well you did. The experimenter will give you a number which reflects not only how well you did in reaching the centerline in the minimum time, but also how well you were able to follow the centerline. This performance number will have been adjusted so that you can compare your performance between different trials even though the conditions have been changed. The closer this number is to zero, the better you will have performed the task.

Please feel free at any time to ask questions or make comments.

Appendix B

ANALOG COMPUTER SIMULATION

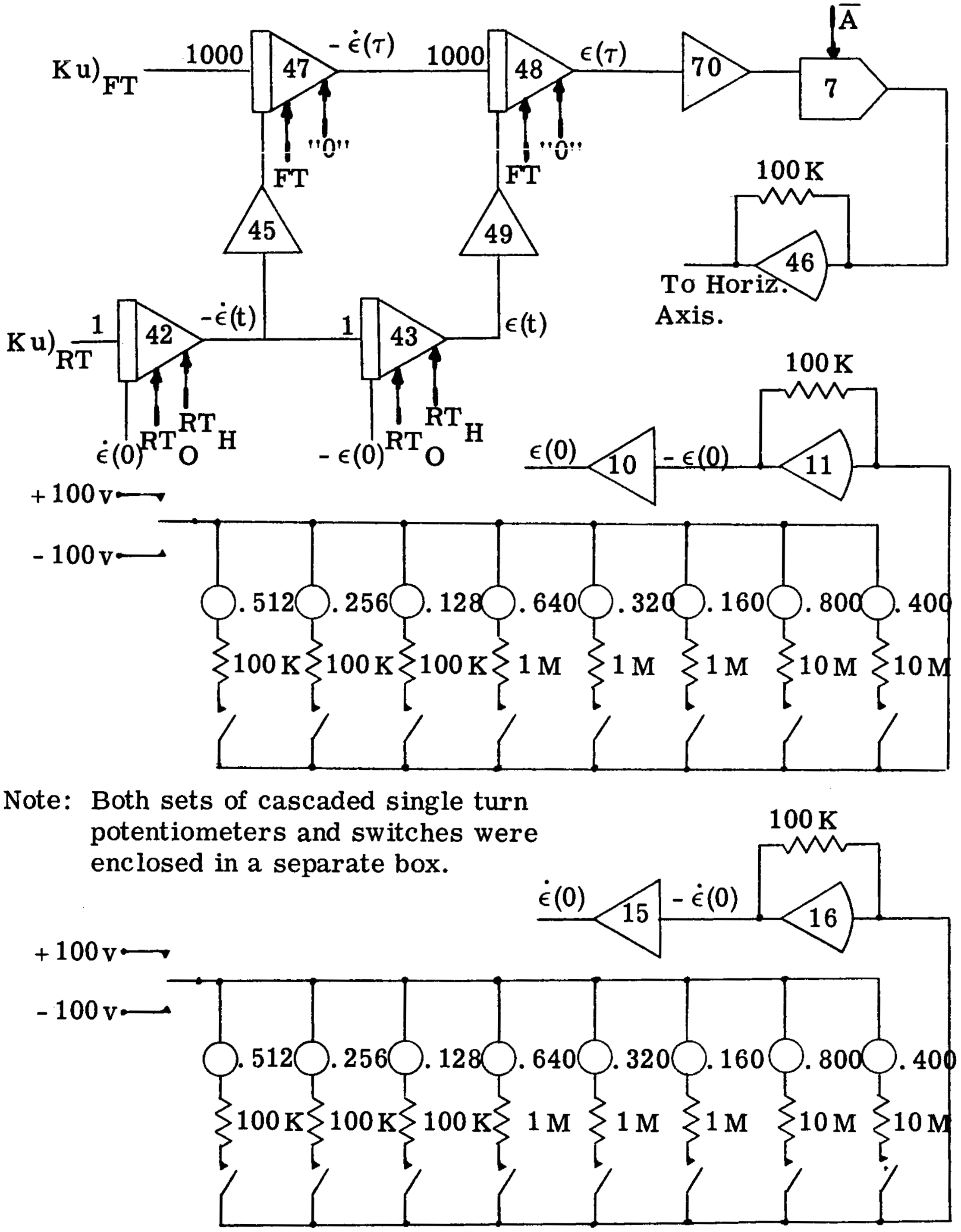
This experiment was conducted in the Simulation Research Laboratory at the University of Michigan using a 90-amplifier analog computer. This computer, which was designed and built at the University of Michigan, has separate patchable logic for integrator model control and analog switch (SPDT reed relays) control. Six analog comparators have logic terminations on the separate logic board.

The circuit diagram in Fig. B.1 was used for the computer simulation. This diagram employs the convention adopted by Simulation Councils, Inc. and reported in the March 1966 issue of the Simulation journal. Additional symbols and logic convention for this computer are noted in the diagram.

Table B.1 is a summary of the initial conditions and independent variables for the thirty-six separate conditions used in the experiment. The setting of initial conditions and operation of data recording equipment was conducted from the experiment monitor's station illustrated in Fig. B.2.

Table B.2 summarizes all the pertinent information concerning display scaling, control stick, etc.

System and Fast-Time Model (Time Scale = 1000 x Real Time):



Note: Both sets of cascaded single turn potentiometers and switches were enclosed in a separate box.

Note: By selecting appropriate switch closures, initial conditions can be supplied in 0.4 volt increments.

Figure B.1 Analog Computer Circuit Diagram.

Three-State Controller:

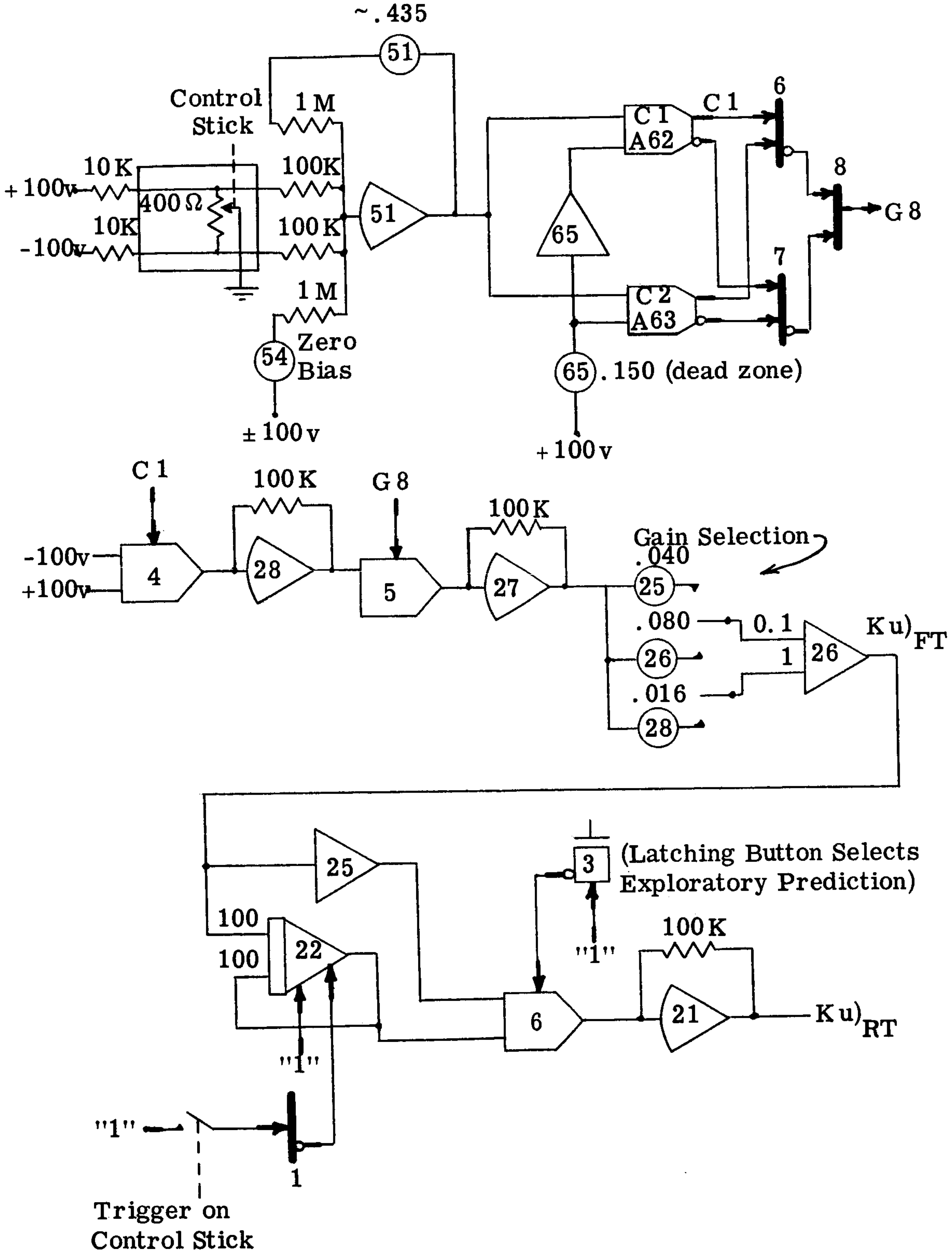
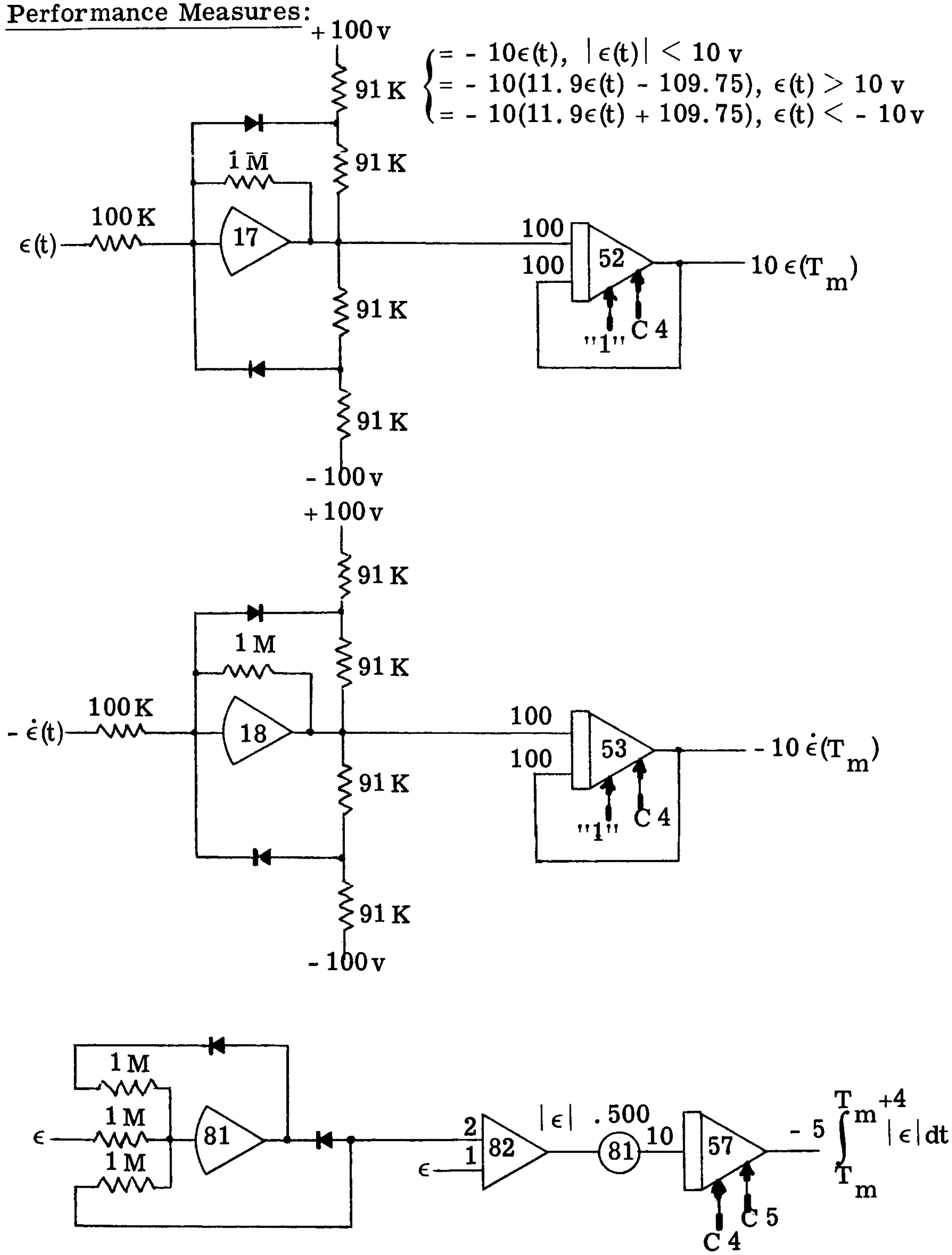


Figure B. 1 (continued.)

Performance Measures:

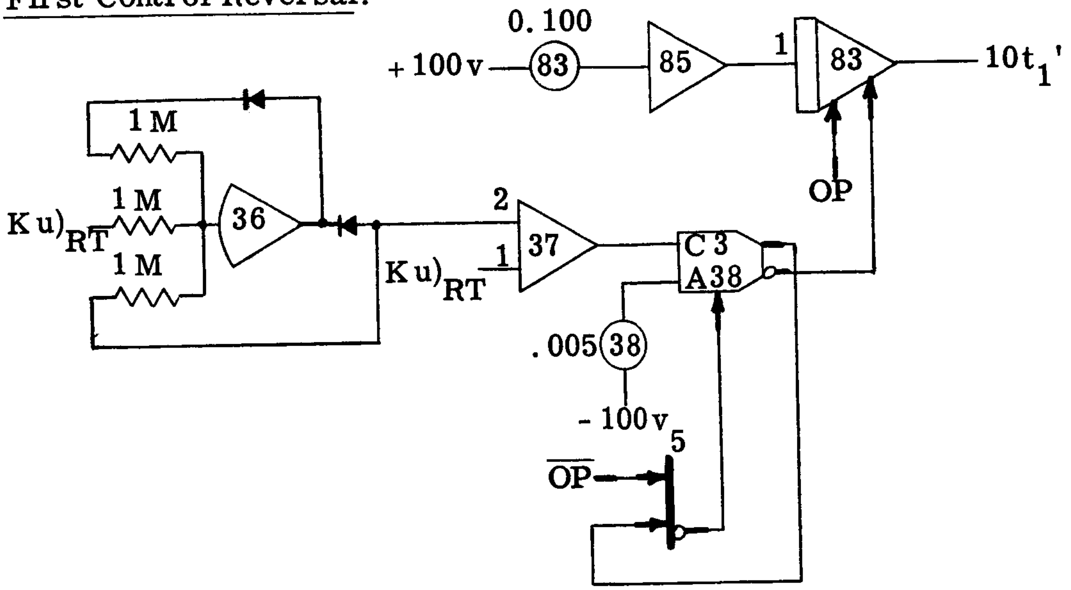


$$\begin{cases} = -10\epsilon(t), & |\epsilon(t)| < 10\text{ v} \\ = -10(11.9\epsilon(t) - 109.75), & \epsilon(t) > 10\text{ v} \\ = -10(11.9\epsilon(t) + 109.75), & \epsilon(t) < -10\text{ v} \end{cases}$$

$$-5\int_{T_m}^{T_m+4} |\epsilon|\,dt$$

Figure B.1 (continued.)

Time Measurement for First Control Reversal:



Centerline and Time Axis Generation:

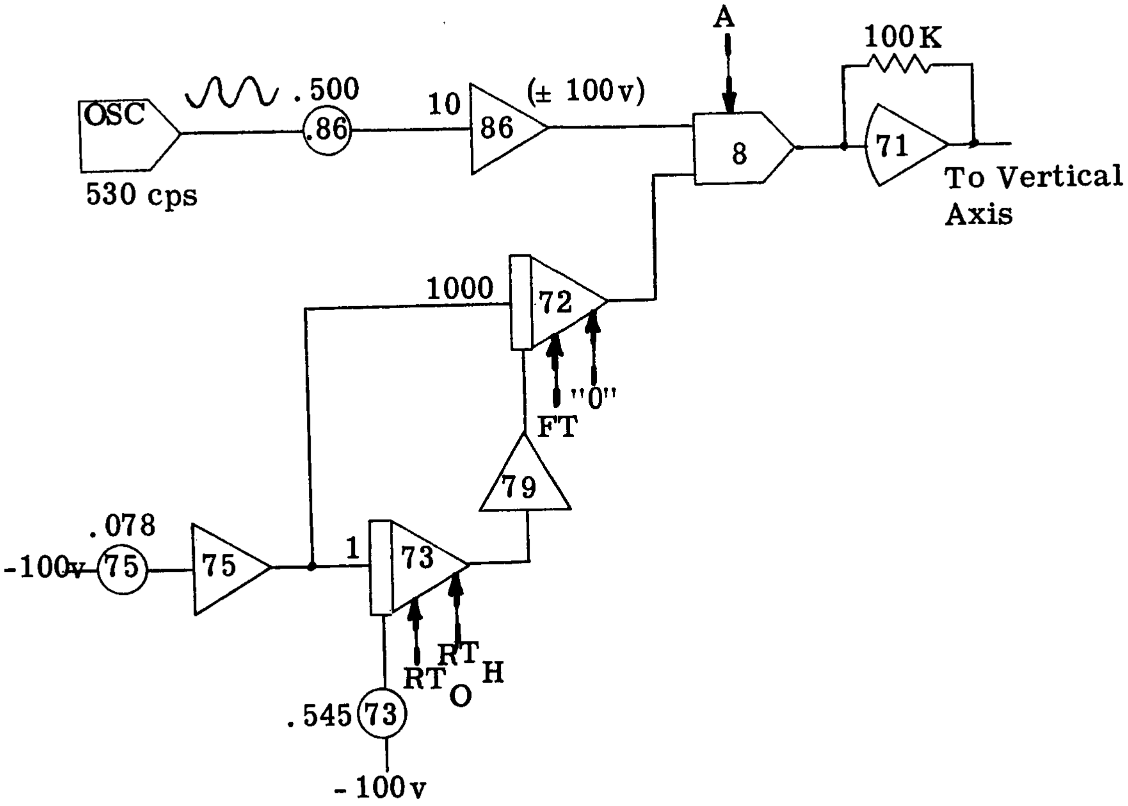
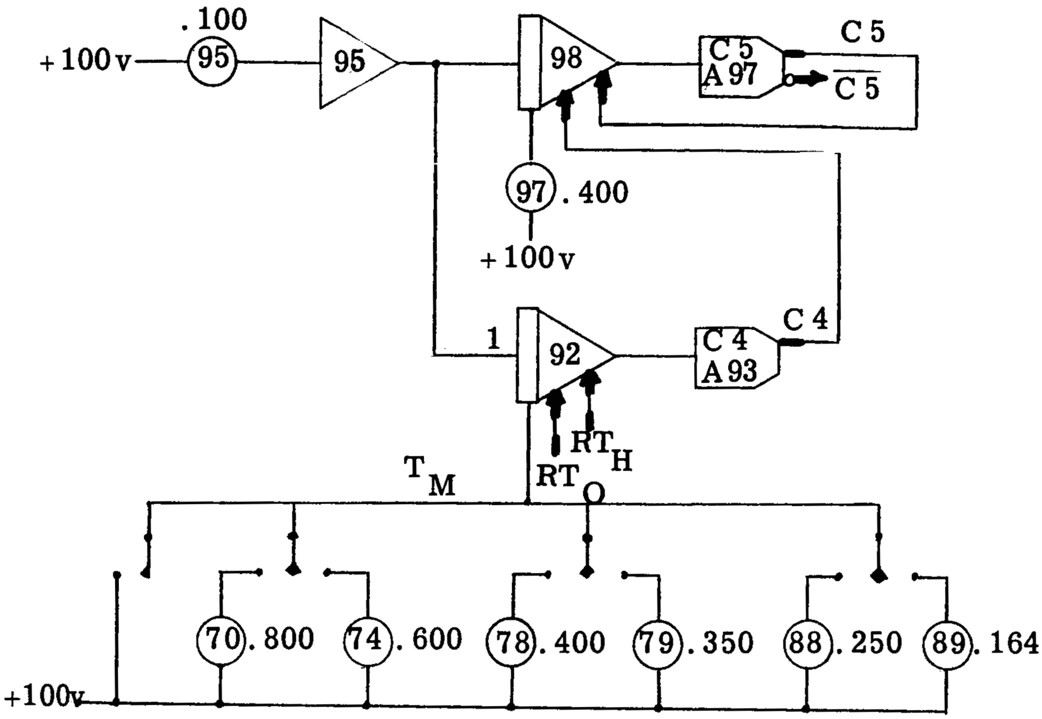


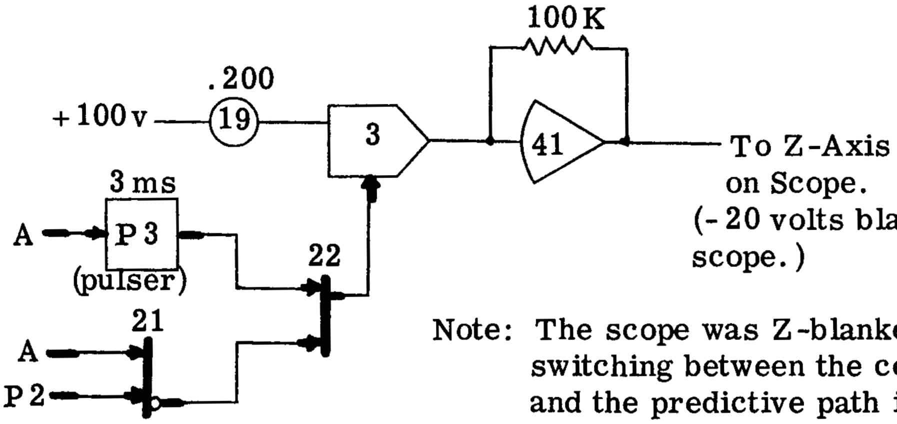
Figure B.1 (continued.)

Timing Integrators:



Note: An error in the setting of potentiometer 89 caused the invalidation of all data for condition 25. The setting shown is the correct value.

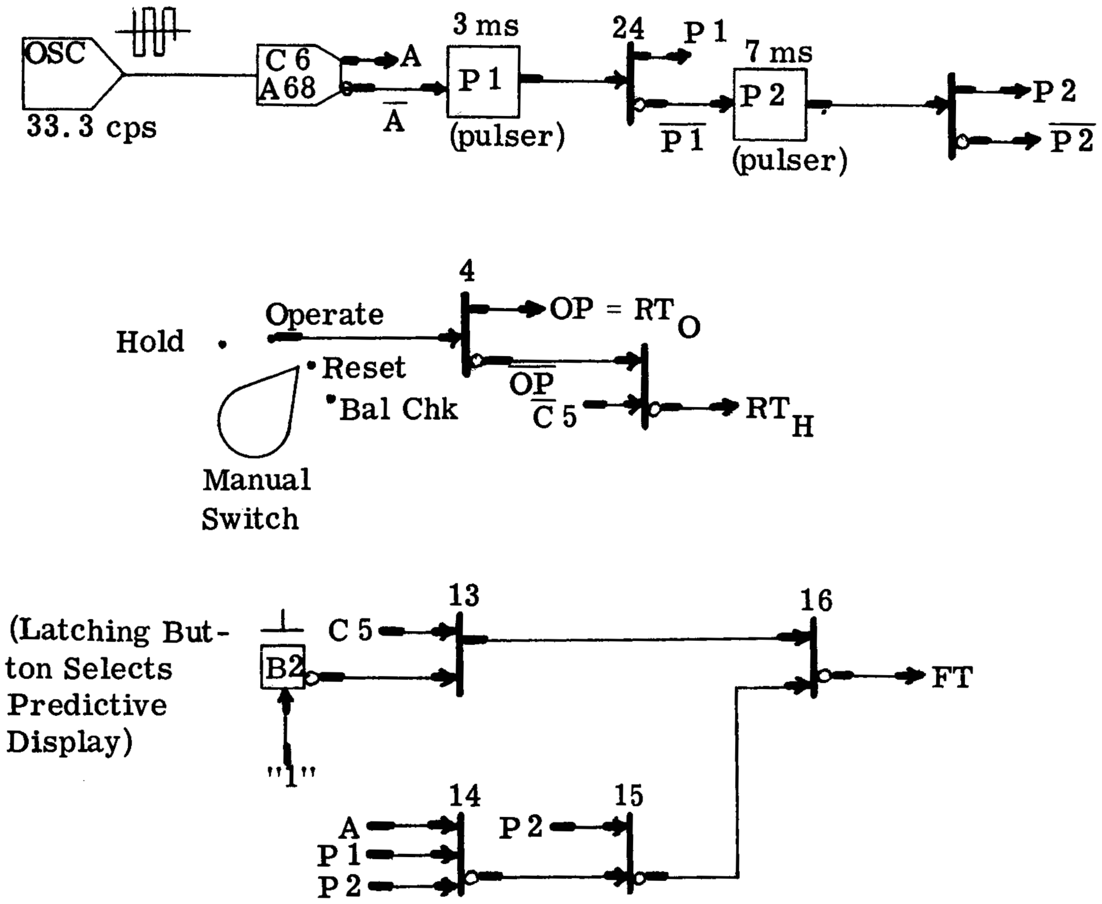
Z-Blanking Circuit:



Note: The scope was Z-blanked during switching between the centerline and the predictive path in order to eliminate spurious traces.

Figure B.1 (continued.)

Real-Time (RT) and Fast-Time (FT) Logic:



Notes:

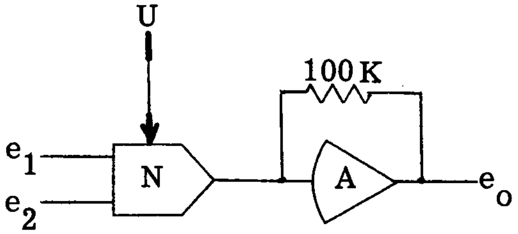
1) Integrator mode control is as follows:

Mode	Left Logic Line (OP)	Right Logic Line (H)
Reset	"0"	"0"
Operate	"1"	"0"
Hold	"1"	"1"

2) All fast-time integrators use 0.01 μfd feedback capacitors. All integrators have 250K initial condition resistors.

Figure B.1 (continued.)

3) Diagram convention for SPDT switches:



$e_o = - e_1$, U = "1"

$e_o = - e_2$, U = "0"

Figure B. 1 (concluded.)

TABLE B.1 INITIAL CONDITIONS AND INDEPENDENT VARIABLES

K (volts/sec^2)	Cond. No.	$\epsilon(0)$ (volts)	$\dot{\epsilon}(0)$ (volts)	V_a (volts/sec)	t_{sw} (sec)	T_m (sec)
4.0	1	8.4	- 2.0	6.0	1.49	2.48
	2	11.6	- 6.0	8.0	2.01	2.51
	3	7.2	4.0	6.1	1.52	4.03
	4	16.0	.0	8.0	2.00	4.00
	5	28.0	- 8.0	12.0	3.00	4.00
	6	8.0	8.0	8.0	2.00	6.00
	7	36.0	.0	12.0	3.00	6.00
	8	56.0	- 8.0	16.0	4.00	6.00
	9	28.0	8.0	12.0	3.00	8.00
	10	64.0	.0	16.0	4.00	8.00
	11	4.0	16.0	12.0	3.00	10.00
	12	56.0	8.0	16.0	4.00	10.00
8.0	13	7.2	4.0	8.1	1.01	2.52
	14	16.8	- 4.0	11.9	1.49	2.48
	15	23.2	- 12.0	16.0	2.01	2.51
	16	14.0	8.0	12.0	1.50	4.00
	17	32.0	.0	16.0	2.00	4.00
	18	56.0	- 16.0	24.0	3.00	4.00
	19	16.0	16.0	16.0	2.00	6.00
	20	72.0	.0	24.0	3.00	6.00
	21	56.0	16.0	24.0	3.00	8.00
	22	14.0	24.0	20.0	2.50	8.00
	23	8.0	32.0	24.0	3.00	10.00
	24	62.4	24.0	28.1	3.51	10.01
16.0	25	7.2	4.0	11.1	.69	1.64
	26	30.0	- 4.0	22.1	1.38	2.51
	27	34.0	- 8.0	24.0	1.50	2.50
	28	46.0	- 24.0	32.0	2.00	2.50
	29	14.0	8.0	16.0	1.00	2.50
	30	94.0	- 40.0	48.0	3.00	3.50
	31	28.0	16.0	24.0	1.50	4.00
	32	64.0	.0	32.0	2.00	4.00
	33	32.0	32.0	32.0	2.00	6.00
	34	62.4	24.0	35.9	2.24	5.98
	35	92.0	16.0	40.0	2.50	6.00
	36	28.0	48.0	40.0	2.50	8.00

Figure B.2 Analog Computer and Experiment Monitor's Station.

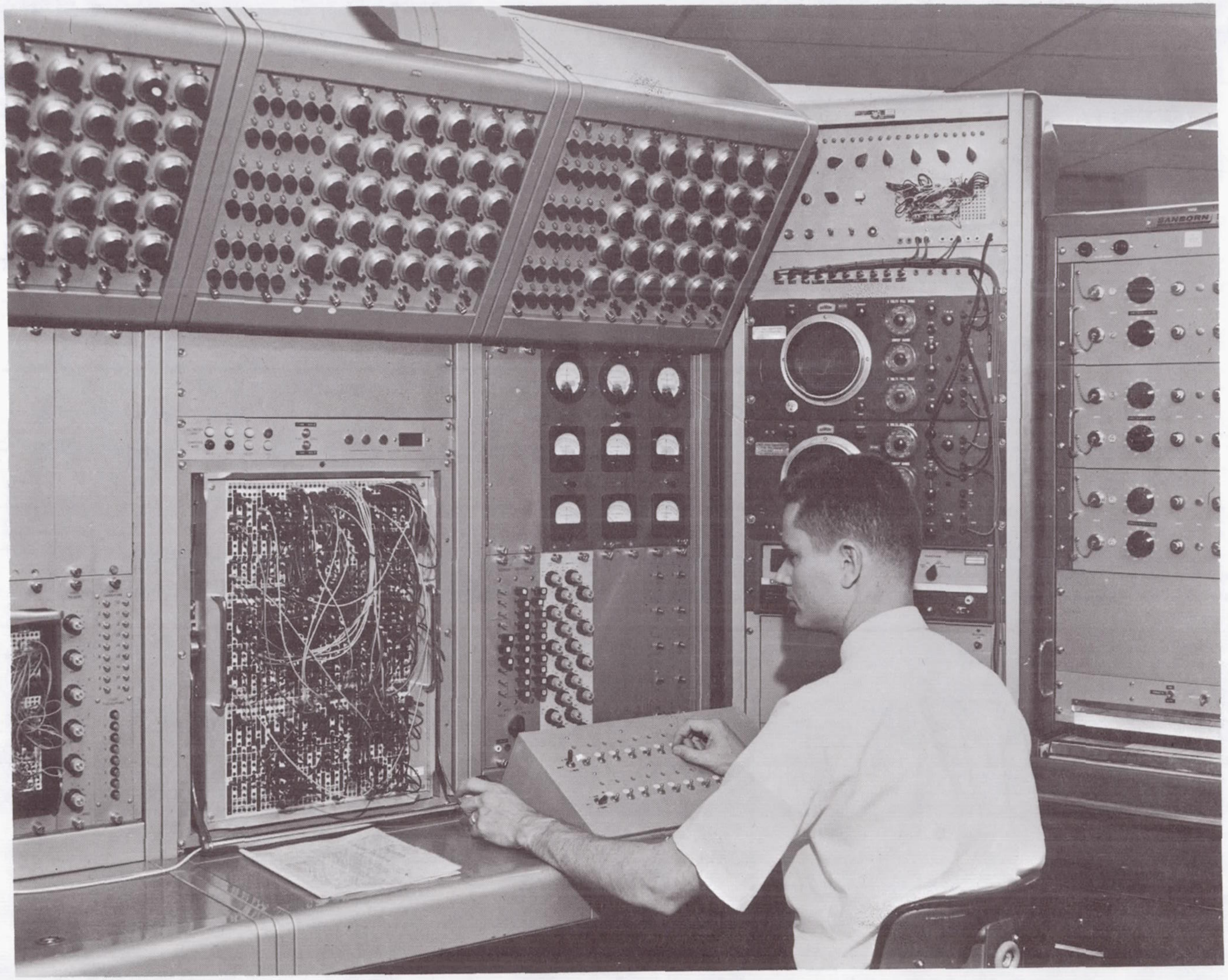


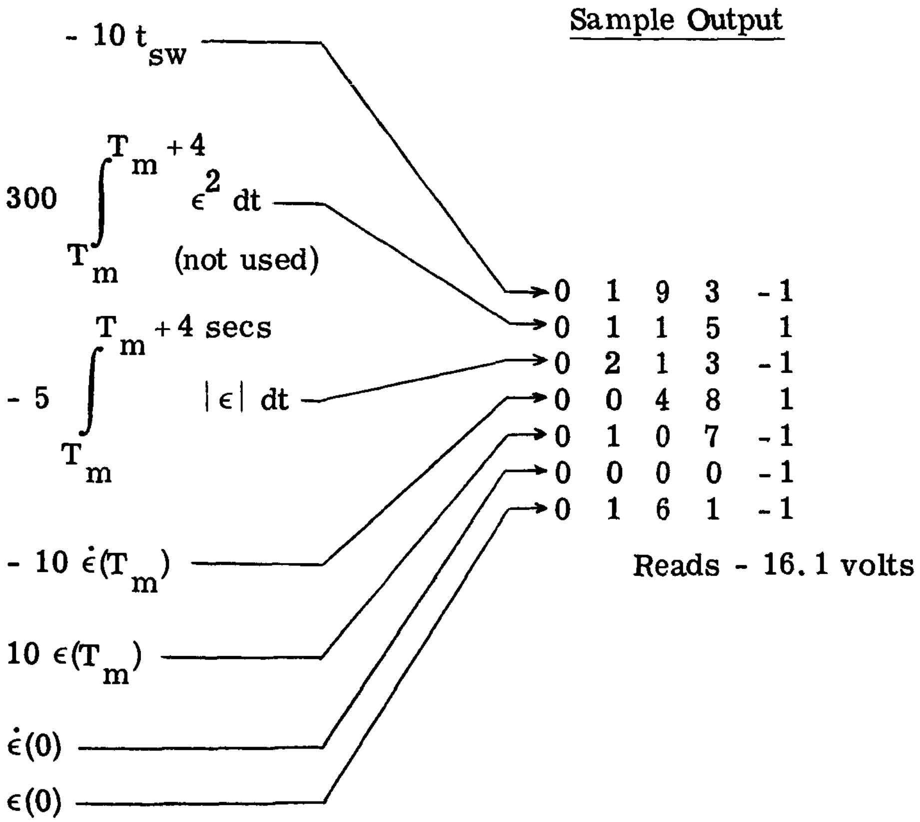
TABLE B. 2

PERTINENT PHYSICAL DATA

OSCILLOSCOPE: Electromec, Model 2140 C; P-4 phosphor; Horizontal axis: 100 volts = 8 inches; Vertical axis (time axis): 14 seconds (109 volts) = 10 inches; Distance of subject's eyes from center of oscilloscope ≈ 26 inches.

CONTROL STICK: U.S. Army Air Forces Type C-1 Autopilot Formation Stick (surplus) with velocity limiter removed; Spring Constant = 2.7 ft-lbs/rad; Total displacement angle ≈ ± 20 degrees; Effective dead zone ≈ ± 3 degrees; Pivot point: ≈ 5 inches below the bottom of the subject's hand.

DATA RECORDING: The following voltages were printed at the end of each trial using a DVM-digital printer combination.



Sample Output

```
0  1  9  3  -1
0  1  1  5   1
0  2  1  3  -1
0  0  4  8   1
0  1  0  7  -1
0  0  0  0  -1
0  1  6  1  -1
```

Reads - 16.1 volts

In addition, the date, subject, gain and display type were recorded on the paper tape by hand.

APPENDIX C

TERMINAL ERROR AND ERROR-RATE DATA FOR FULLY-TRAINED PERFORMANCE

The data presented in Table C.1 is the terminal error and error-rate values in volts for each valid trial for the last six days of testing. A blank entry means that the data for that particular display, day, subject and condition was rejected due to equipment malfunction in the initial condition circuitry. In addition, all data for subject 2 on the twelfth day was rejected due to a long absence between the eleventh and twelfth days for that subject.

This data may be used to re-construct all of the results (other than those for learning) presented in Chapter IV, or to construct new performance measures and statistical tests.

TABLE C.1 Terminal Error and Error-Rate Data.

EXPLORATORY PREDICTION

	DAY 13										DAY 12									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
COND.	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	-.3	-.2	-1.9	-2.9	.2	-1.3	.4	-.8	.4	.2	.3	-.3			-.5	-.4			.1	-.0
2	-.2	-.2	.3	-1.3	.0	-.3	-.3	-.7	-.4	-.3	.0	-.3			-.3	-.4			.1	-.3
3	-.9	-.7	.5	-.6	.1	-.9	.0	-.3	.4	-.5	-.4	-.6			-.6	-.6	.1	-1.2	.3	.1
4	.1	-.0	-.7	-.3	.0	-1.5	.1	-1.0	.0	-.0	-.2	-.4			-.2	-.5	.4	-.2	-1.0	-.6
5	.3	-.2	-1.4	-.5	-.5	-1.2	.2	-1.0	.0	-.0	-.2	-2.0			-.2	-2.6	.6	-.8	-.1	-.1
6	.4	-.2	-.2	-.1	.1	-.1	.2	-1.2	-.4	-.1	.4	-.6			-.2	-.2	.6	-.8	-.3	-.1
7	.2	-.0	.3	-2.0	.1	-.7	.6	-1.4	.7	-.7	.4	-1.0					.5	-1.9	.2	.1
8	-1.9	-.5	-.8	-.2	-1.8	-1.6	.0	-1.6	-.5	-.2	-.5	-1.3			1.0	-.2	.5	-1.3	.8	-.6
9	-.2	-.3	.5	-1.3	-.6	-.5	.1	-1.2	.7	-.0	.6	-.1			.5	-.1	-.2	-2.4	.2	-.0
10	.1	-.6	.1	-1.8	1.1	-1.2	.5	-1.0	.0	-.2	.2	-.5			1.1	-1.7	.7	-1.7	.9	-1.2
11	.3	-.1	-.8	-.3	-.1	.1	.4	-1.2	.2	-.1	.1	.1			.2	-.1	.7	-1.0	-.4	-.3
12	.8	-1.8	-.5	-.0	.9	-1.4	.2	-1.4	-.1	.1	.2	-2.6					1.1	-1.6	-.6	-.0
13	-.2	-.3	-.3	-.5	-.5	-1.0	.2	-1.8	.6	-.1	-.1	-.6			.1	-.5	.1	-.8	-1.0	-1.3
14	-.5	-.3	.2	-3.0	.3	-.4	.2	-1.8	-.5	-.3	-1.4	-1.2			.3	-.4	.5	-2.0	-.7	-.6
15	.4	-1.5	.4	.1	.4	-.6	-.2	-3.4	.2	-.8	-.4	-.8			-.5	-.8	-1.8	-1.7	-1.0	-.8
16	.1	-.7	-.4	-.3	.0	-.7	-.1	-1.1	-1.2	-.9	-.4	-.5			-.1	-.3	.7	-1.9	-1.0	-.8
17	.8	-2.0	-.9	-.4	.0	-3.4	2.4	-5.3	.5	-.6	.3	-4.1			1.3	-.8	1.2	-3.2	-4.4	-5.8
18	-.4	-.1	1.5	-3.3	-11.6	-6.7	-2.9	-1.7	.1	-.1	-1.3	-1.2			1.5	-4.7	1.1	-2.4	-1.0	-.3
19	-.3	-.2	1.3	-1.5	.1	-.4	-1.8	-1.3	.4	-.5	-.2	-1.8			.8	-.8	.4	-1.9	-1.4	-.8
20	.2	-1.9	.6	-.5	-.4	-1.1	.7	-4.5	-.2	-.3	.3	-2.0			-.4	-1.0	1.3	-3.7	.3	-.6
21	.3	-.1	.3	-.1	.4	-.3	-.2	-2.3	-1.4	-.7	-.3	-.7			-.6	-2.5	-.9	-.8	-1.8	-.5
22	.7	-2.4	-1.6	-.6	-.3	-2.0	.4	-1.0	-.7	-.2	1.3	-2.0			.8	-2.6	-.6	-.3	.6	-1.5
23	.9	-.9	2.9	-2.7	.8	-2.5	.2	.2	-.8	-.2	-1.5	-.6			1.8	-1.2	.6	-1.8	-2.8	-.7
24	1.2	-.6	-.2	-.0	1.2	-2.2	.7	-2.1	.5	-.6	-1.2	-1.5			2.5	-2.5	.8	-5.3	.3	-.1
25																				
26	-1.2	-1.1	-.2	-1.9	-.1	-1.1	.6	-.6	-1.5	-1.3	-1.1	-1.9			.7	-4.5			-2.6	-2.2
27	-1.9	-1.3	-1.4	-1.0	-1.6	-2.0	-1.6	-2.0	.1	-1.0	.9	-1.8			.5	-.6	-.2	-1.2	-2.4	-1.6
28	-1.7	-1.0	.8	-3.3	.5	-4.1	.4	-6.6	.5	-.3	-2.0	-1.9			.6	-3.8	1.6	-4.2	-2.4	-1.4
29	-1.3	-1.6	-.7	-4.9	-.6	-1.7	.4	-3.3	-1.4	-1.5	-.4	-1.1			.1	-.5	-.4	-1.3	-1.5	-1.8
30	-1.8	-3.2	.2	-1.7	.5	-3.1	1.5	-3.6	1.5	-.9	-3.1	-2.9			1.3	-2.6	-12.8	-7.3	-2.0	-.7
31	.4	-3.3			-.2	-.8	.0	-.7	-.9	-.6	-.3	-2.0			-.8	-1.2	-2.2	-2.2	-.1	-.4
32	-.3	-2.2	2.8	-4.8	-2.0	-2.4	1.3	-4.7	-1.8	-.9	.0	-1.3			.8	-5.7	1.3	-8.7	-2.2	-1.2
33	2.1	1.3	-2.4	-1.0	.6	-.4	.4	-4.8	.7	-.2	-.8	-4.2			1.0	-4.9	-3.3	-2.0	-.7	-.8
34	-.3	-.1	-1.7	-.4	-.3	-.6	-.3	-4.9	-5.3	-7.7	1.9	-6.8			.2	-.9	.3	-6.8	-1.7	-.5
35	3.9	-5.7	.3	-3.6			1.1	-4.7	-1.1	-1.8	2.7	-4.1			.5	-.9	.2	-4.7	-2.4	-.9
36	-4.0	-1.3	.4	-1.1	1.1	-2.5	1.7	-2.9	-.4	-.3	-.4	-.6			-.3	.1	-1.7	-.6	-.9	-.1

TABLE C.1 Continued.

EXPLORATORY PREDICTION

COND.	DAY 11										DAY 10									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	-.5	-.3	.8	-1.6	.0	-.2	.1	-1.4	.2	-.1	.5	-.4	.1	.1	.7	-.4	.5	-.5	.3	-.1
2	-.9	-.5	.3	-.1	.0	-.2	.3	-.1	.5	-.1	.0	-.1	-.3	-.6					.5	-.1
3	-.4	-.4	.6	-.8	-.1	-1.4	.0	-1.0	-.2	-.4	.1	-.1	.3	-.4	.1	-.1	.8	-.6	.2	-.2
4	-.4	-.2	-.3	-.5	.0	-.2	-1.1	-.5	-.4	-1.4	-.4	-.3	.4	-.2	.6	-.8	.3	-1.2	.5	-.1
5	-.8	-.3	.2	-.4	.5	-.1	.3	-1.0	-.6	-.6	-.4	-.2	1.0	-2.1	-.9	-2.1	.1	-2.1	1.0	-.0
6	-.2	-1.1	.6	-1.9	-1.0	-.5	.3	.2	.3	-.1	.7	-.1	.4	-.8	.0	-.0	1.3	-1.7	-.5	-.3
7	-.3	-.1	-1.1	-1.5	.5	-.2	.7	-2.3	.7	-.2	.7	-.1	1.1	-1.0	.5	-1.9	.6	-2.5	.3	-.3
8	-1.4	-.3	.3	-1.1	1.1	-1.3	.2	-1.9	-.8	-.9	-.2	-1.9	.6	-.2	.4	-.2	.9	-2.8	-1.8	-1.2
9	-.4	-1.8	.1	-2.5	.7	-.1	-1.4	-.4	-.3	-.2	.3	-.1	.6	.3	.0	-1.4			.1	-.2
10	-1.9	-.4	.7	-2.6	1.2	-.1	.3	-1.7	1.2	-1.4	.4	-.0	.6	-.1	.0	.1	.6	-1.4	-.1	-.8
11	-1.0	-1.2	.1	-.0	-1.0	-.2	1.1	-2.0	.0	-.0	.2	-.2	.0	-2.2	-.1	-.2	1.4	-2.7	-.1	-.1
12	-.2	-1.8	.1	-2.4	.7	-.2	-1.8	-.3	-2.0	-.9	-1.1	-.2	.7	-2.5	.1	.1	1.5	-2.4	.7	-.2
13	-.9	-1.2	.4	-.1	-.2	-.6	-.7	-1.0	-.4	-.9	1.0	.5	-.3	-.5	.2	-.0			.4	-.3
14	.4	-1.4	.6	-1.4	-.1	-2.3	.5	-2.2	-1.3	-1.6	-.4	-.2	.8	-.1	-.1	-.2			-.4	-.6
15	-3.5	-1.9	1.2	-1.5	-1.0	-1.0	1.1	-1.1	.0	-1.2	-.4	-.4	1.1	-1.7	-.7	-.5			-.5	-.8
16	.3	-.4	-.9	-3.0	-.2	-.4	.1	-.0	-.6	-1.1	-.8	-.6	.4	-.3	-.6	-.4			-1.3	-1.3
17	-1.1	-.6	-1.3	-1.3	-.9	-1.0	-.7	-.4	.9	-1.3	.9	-.0	-1.7	-.9	.9	-.2			1.3	-1.0
18	.1	-4.1	1.6	-2.8	4.0	-6.3	-1.0	-.4	-.8	-1.4	-.1	-.1	1.2	-1.3	.7	.1			1.1	-.3
19	.2	-2.1	.2	-1.5	.5	-1.9	-.4	-2.4	.2	-.6	-.3	-.1	.7	-.7	.9	-.8			-.4	-.4
20	-2.3	-.8	-1.3	-2.7	-.3	-.8	.0	-4.6	-.5	-1.2	1.7	-.2	.7	-.5	1.4	-.4			-.4	-1.6
21	-.6	-2.1	1.8	-1.2	.5	-2.0	1.1	-3.7	-2.3	-1.3	1.3	-1.7	.5	-.4	.6	-2.6			-.1	-.5
22	-2.0	-1.0	.4	-2.6	-1.5	-.7	-.9	-.2	1.2	-.6	.2	-.2	.1	-2.1	1.4	-1.5			.2	.1
23	-.6	-.0	.4	-1.3	-.5	-.0	.5	.2			1.8	-2.5	1.7	-2.6	.6	-.3			-1.6	-1.1
24	-.7	-.3	2.5	-2.5			.8	-1.0	-.4	-.9	.8	-.0	.0	.1	.6	.3			.7	-.8
25																				
26	-1.3	-1.8	-2.4	-2.9	.0	-2.7	-.7	-.8	-.4	-1.3	-.5	-.7			-.7	-.8	-2.0	-3.1	-2.0	-2.6
27	-.9	-1.1	-.2	-1.0	-6.0	-8.4			-1.4	-1.8	.5	-.0	.5	-.4	.2	-.2	.4	-2.4	2.7	-.5
28	-.7	-1.0			-3.0	-2.3	.4	-.0	-1.8	-2.1	-.3	-5.3	-1.3	-.7	1.2	-2.1	1.1	-7.7	1.2	-.4
29	.5	.4	-1.4	-2.1	-.1	-.5	1.4	-4.1			1.0	-.9			.0	-.2	-2.2	-2.3	-.2	-.9
30	.8	-3.5	2.8	-5.8	-.4	-1.1	-1.0	-.4	-2.2	-2.1	-8.3	-2.9	-3.6	-1.2	1.4	-1.1	1.5	-2.0	3.0	-1.8
31	.3	-1.5	-2.9	-2.7	-.2	-.6	2.3	-3.2	-.9	-1.2	-2.0	-1.5	-.9	-.6	-1.3	-.8	.5	-.2	-1.9	-1.9
32	-1.2	-1.3	-1.0	-1.8	-.2	-1.1	-1.4	-4.1	.4	-2.4	1.3	-2.6	.8	-.6	.8	-3.2	1.7	-7.1	-2.4	-3.0
33	-2.1	-.8	1.8	-2.0	.4	-.6	-1.9	-1.0	.0	-.2	.0	-.2	.8	-2.0	1.6	-2.6	.4	-5.1	1.6	-.2
34	-.7	.1	1.6	-8.9	.6	-.2	-.5	-5.3	.5	-.3	3.1	-2.2	-3.2	-1.0	1.2	.4	1.3	-.0	-.1	-.6
35	-1.9	-1.4	2.6	-2.8	1.3	-4.8	-.9	-2.4	-4.3	-3.1	-1.1	-.5			1.1	-.9	.2	-6.9	-3.8	-4.3
36	-3.7	-1.2	1.3	-1.9	.9	-1.0	-2.4	-.9	1.2	-5.3	.5	.1	-3.5	-1.2	1.9	-.7	2.4	-4.3	1.8	-.0

TABLE C.1 Continued.

EXPLORATORY PREDICTION

COND.	DAY 9										DAY 8									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	-.3	-.2			.0	-1.5	.5	-1.1	-.6	-.8	-.2	-.1			.0	-.0	.6	.1	.7	-1.0
2	-.8	-.5			-.6	-.4	.7	-2.0			.2	-.4			.1	-1.1	.7	-2.5	.4	-2.3
3	-.5	-.5	.6	-1.0	.2	-1.3	.3	.1	.1	-1.9	.0	-.2	-.3	-.4	-.1	-.2	.1	-1.2	-.1	-.2
4	-1.2	-.6	.0	-.1	.0	-.1	-.3	-1.9	-.7	-.6	-1.3	-.7	.0	-.1	.0	-.1	.0	-.8	-.1	-.1
5	-1.5	-.6	.8	-.7	.6	-.0	.0	-1.7	-.2	-.4	-.4	-.2	.7	-.3	-.5	-.2	.7	-2.5	.0	-.0
6	-.2	-.1	.5	-.3	.0	-.0	1.5	-1.4	-.8	-.4	.3	-.3	-.4	-.2	.7	-.3	-.1	-1.5	-.2	-.1
7	.1	-.3	1.2	-1.1	-.1	-.1	.4	-.2	-.1	-.4	-.5	-.2	-.6	-.2	.2	-.0	.1	-1.8	-.1	-.0
8	-.3	-1.3	1.2	-1.6	-.7	-.2	-1.2	-.3	.9	-.2	-1.3	-.4	.3	-.5	.8	-.1	.8	-.4	1.2	-.0
9	-1.2	-.6	-1.5	-.7	.5	-1.0	.7	-1.2	-.8	-.5	.3	-.4	.4	-.4	-.6	-.8	.5	-1.1	-.3	-.1
10	.0	-1.5	1.4	-.7	-.1	-.0	.1	-1.0	-.5	-.6	-.4	-.1	-2.5	-2.0	.6	-1.7	.6	-2.7	.1	-.0
11	-1.0	-.2	.7	.3	.0	-.0	.6	-1.4	.0	-.0	.1	-1.6	-.3	-.0	-.2	-.2	.3	-1.8	.2	.2
12	-1.8	-2.6	-1.6	-1.3	-.2	-.1	-.6	-.1	.0	-.3	-.3	-.1	.5	-.2	.3	-1.5	.3	-2.0	.1	-.2
13	-.5	-.8	.0	-.2	-.1	-.3	.5	-1.1	-.1	-.5	-.8	-1.1	-.7	-1.0	-.2	-.4	.5	-3.3	-.4	-.6
14	.0	.1	.7	-1.9	-.7	-.5	.7	-.7	-1.8	-1.5	.7	-1.2			-.4	-.2	.3	-.7	-.6	-.3
15	-1.1	-1.3	.9	-.3	.7	-.3			-.6	-.9	.2	-2.4			.4	-.0	-.3	-.6	-1.1	-.7
16	-.2	-.4	.6	-.6	.1	-.3			-1.3	-1.1	.4	-2.2	-.7	-1.5	.0	-.3	.1	-3.5	.3	-.1
17	-1.1	-.6	-.6	-.4	.7	-.6	.3	-3.4	-.1	-.6	.5	.2	1.3	-2.3	.7	-.2	.8	-2.4	.4	-.0
18	.4	-1.0	1.3	-3.4	.4	-.1	-1.5	-2.5	1.2	-.4	-1.8	-.6	-2.3	-.9	-.7	-.3	-1.1	-.4	1.2	-.3
19	.1	.1	1.0	-3.0	.2	-.1	-.3	-1.1	.0	-.2	.6	-3.0	-.6	-.3	.6	-.5	.5	-1.9	.1	-.1
20	-1.9	-.6	-.8	-.3	.2	-3.3	-2.6	-.9	-1.0	-1.0	1.3	-.3	-2.7	-.9	1.1	-2.0	.8	-3.6	.2	-.1
21	.7	-1.1	.3	-2.2	-.2	-.2			-.6	-.6	2.2	-1.9	-.7	-.1	.3	-4.8	1.0	-2.6	.5	-.4
22	.6	-.8	1.5	-1.6	-.1	-.2	-1.7	-.6	.1	-.0	1.0	-1.5	1.0	-1.3	-1.6	-.8	-.2	-3.2	-1.2	-.3
23	-.6	-.2	.6	-.8	-1.4	-.4	-.7	-1.4	.8	-.3	-3.1	-1.7	-1.0	-.3	.1	-.1	-1.4	-.3	1.5	-.0
24	-3.7	-2.1	-1.6	-.3	.2	-.0	-.4	-.1	-2.7	-1.2	1.2	-3.3	.5	-1.2	-.8	-.4			1.2	-2.3
25																				
26	-1.3	-1.3	.2	-.2	-.9	-.9	-2.5	-2.2	-2.1	-2.6	1.5	-2.4	-.2	-.4	3.7	-10.0	.6	-2.4	.0	-.7
27	-1.7	-1.3	1.0	-4.3	-.6	-.5	-.1	-1.5	-.5	-1.1	-2.3	-1.7	-.8	-.7	-1.4	-1.1	1.4	-4.4		
28	-5.4	-2.9	.4	-.0	-.4	-3.4	-2.1	-6.5	-2.7	-2.1	1.5	-1.3	1.6	-7.0	-3.6	-2.2	-4.7	-2.5	2.2	-1.1
29	-.7	-.7	-.1	-.2	-1.7	-1.9	-.9	-3.4	-2.5	-3.1	-.1	-1.4	-2.0	-4.5	.6	-3.1	.8	-.3	.2	-1.3
30	-5.4	-1.8	3.9	-3.0	.2	-1.7	-4.2	-1.5	.9	-.8	-10.4	-3.7	.6	-1.1	1.4	-3.0	1.8	-8.6	-2.4	-.9
31	.1	.5	2.1	-3.9	-1.6	-1.1	-6.3	-7.1	-.3	-.7	.3	-.2	.8	-3.7	-.1	-.3	.1	-3.3	-.8	-.6
32	-2.4	-1.2	-.5	-.4	-1.0	-.6	-.2	-.2	-1.6	-1.8	1.1	-2.8	-1.4	-9.2	.5	-.8	.6	-1.4	.6	-.8
33	2.0	-2.3	.0	-.1	-4.5	-2.3	.6	-2.7	-2.7	-1.6	-2.2	-1.3	.3	-5.8	.6	.1	-.8	-4.8	-.1	-.8
34	-3.3	-1.1	-1.4	-.3	-1.1	-.1	-1.1	-.2	1.1	-1.9	1.9	-4.6	-3.5	-1.2	-.4	-.3	-1.7	-.6	3.5	-3.4
35	-.2	-5.2	3.3	-2.8	.3	-.1	-.9	-3.1	-.6	-1.2	-.1	-.5	-2.4	-.9	-2.5	-1.1	-2.1	-.8	3.4	-2.5
36	-5.0	-1.8	1.5	-5.1	.5	-3.9	.5	-3.3	1.8	-2.1	-1.8	-.9	-.2	-4.7	1.2	-1.1	2.0	-6.3	1.3	-.2

TABLE C.1 Continued.

ON-LINE PREDICTION

	DAY 13										DAY 12									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
COND.	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	.8	-.4	.1	-.9	1.4	-1.7	.3	-2.3	.5	-1.9					.1	-1.0	.3	-2.1	.0	-2.4
2	.2	-.4	-.1	-1.8	.2	-1.0	-1.3	-.9	.1	-.5	.3	-.6			-2.9	-1.9	.1	-2.7	.0	-.8
3	.6	-1.3	.8	-1.2	.9	-2.1	.4	-2.1	-.5	-.4	.7	-.7			.5	-1.5	1.4	-3.0	.1	-.3
4	1.1	-1.7	.4	-.7	.7	-2.1	.1	-1.1	.1	-.5	1.0	-3.0			.7	-2.1	1.3	-3.4	.4	-1.2
5	-1.4	-1.8	-.5	-1.1	-.4	-.6	-5.5	-2.3	.3	-.7	.0	-1.0			-.1	-1.0	-.9	-1.4	-.4	-1.1
6	.2	-.4	1.8	-1.8	.8	-2.2	.9	-2.6	.3	-.4	.9	-2.3			.4	-1.2	-.3	-1.0	-.1	-.5
7	.5	-1.5	-.1	-1.3	.4	-1.3	.3	-1.3	.2	-.2	.2	-1.6			.0	-1.5	-.2	-1.7	-.3	-.5
8	-1.0	-1.4	-.2	-2.4	.3	-1.7	.3	-2.8	.0	-.8	.2	-1.7			.6	-1.6	-2.1	-1.9	.4	-1.6
9	1.5	-3.6	-.1	-3.6	.3	-1.4	-1.1	-1.9	-.1	-.3	.1	-2.1			.4	-1.5	1.0	-2.3	-.9	-.2
10	1.0	-1.8	-.2	-.3	-.5	-1.5	.0	-1.0	.4	-.2	.3	-2.0			.6	-1.6	-.3	-2.4	-.2	-.7
11	.6	-1.3	.7	-1.8	.0	-1.6	.2	-1.4	.2	-.5	.0	-.7			.2	-.3	-.1	-3.0	.0	-1.1
12	-.1	-3.5	.3	-1.9	-.4	-1.0	-.4	-1.7	.1	-.8	.4	-1.3			.6	-1.3	.4	-.5	-.3	-.7
13	1.6	-2.0	1.0	-1.5	.5	-2.5	-.1	-1.7	-.6	-.9	1.2	-.6			.6	-2.0	-.2	-2.4	.6	-1.5
14	.6	-1.9	.2	-1.1	.4	-2.9	-.1	-1.9	.0	-2.2	2.3	-4.0			.3	-2.6	-.2	-1.5	-.2	-2.5
15	.2	-3.4	.5	-2.6	.2	-1.8	.3	-2.3	.3	-1.4	.9	-1.7			1.4	-5.1	-.4	-3.6	-.8	-.7
16	1.2	-2.3	1.6	-3.3	.1	-1.8	.0	-.8	.1	-2.0	-2.9	-3.2			.3	-2.0	-.2	-3.1	.1	-.4
17	-.8	-1.4	-1.8	-2.0	.6	-4.3	-1.2	-4.2	-.2	-.9	-1.4	-3.6			.4	-2.6	.6	-2.3	-.6	-1.4
18	.2	-4.9	1.6	-4.1	.6	-4.6	.8	-2.7	-1.7	-1.9	1.2	-4.1			1.0	-3.7	-.4	-1.3	-.3	-2.0
19	1.7	-4.0	-.7	-4.3	.5	-3.2	-.6	-2.6	1.8	-4.1	1.2	-4.5			.3	-2.3	-.1	-2.5	-1.3	-1.1
20	.6	-2.4	.7	-4.0	1.1	-5.1	-1.1	-2.7	.0	-.7	1.5	-3.9			.9	-3.7	.2	-1.7	-2.3	-.9
21	.6	-3.3	-.2	-2.5	.9	-3.6	.1	-.9	-.9	-1.0	-7.4	-4.5			.7	-3.0	.7	-1.8	-1.9	-1.5
22	-7.4	-3.9	-.2	-2.9	-.6	-2.4	.4	-3.4	-.5	-1.1	2.0	-3.3			.0	-1.7	.1	-.9	-.3	-1.0
23	.1	-2.1	2.4	-3.4	-.2	-1.9	-1.5	-1.3	-.2	-1.5	2.3	-6.1			.4	-1.9	.8	-4.4	.1	-.9
24	.6	-1.2	1.7	-6.4	.5	-2.6	.1	-.8	-.4	-1.3	.3	-2.2			1.3	-4.4	.4	-3.0	.0	-.6
25																				
26	3.5	-6.3	1.4	-3.4	.5	-3.6	2.2	-10.4	-.1	-5.1	.6	-5.8			1.6	-4.7	1.5	-6.8	2.2	-9.1
27	1.6	-12.8	-1.7	-6.9	1.5	-5.6	1.6	-12.8	.3	-7.2	3.3	-10.4			.8	-1.7	.1	-8.1	-.4	-1.4
28	-.8	-2.6	-2.3	-2.5	.4	-4.6	-.2	-3.2	-.5	-1.7	1.0	-4.7					1.7	-2.0	-1.7	-3.1
29	.9	-1.3	.8	-2.0	1.0	-3.6	-.4	-5.3	-.1	-1.2	2.7	-3.0			.8	-3.6	-1.5	-4.7	.8	-3.7
30	-.2	-1.6	-6.0	-2.8	.8	-4.3	1.9	-5.2	-1.0	-1.2	.2	-3.8					-.2	-3.2	-.2	-.8
31	1.7	-3.8	1.9	-10.0	-.1	-3.0	1.0	-1.4	.8	-2.3	1.0	-2.6			.9	-3.2	-.3	-4.4	-2.8	-2.7
32	-6.1	-5.0	1.8	-6.6	.8	-5.0	4.5	-11.6	-.7	-2.0	-7.1	-7.6			2.4	-7.8	1.5	-5.1	-2.1	-2.6
33	7.2	-12.8	1.4	-10.4	.0	-4.5	-.9	-5.7	-.9	-.2	.4	-4.6			-1.1	-3.5	.8	-6.2	-2.4	-1.0
34	-.3	-4.7	1.3	-7.2	1.6	-8.3	1.8	-5.1	-2.0	-2.1	.2	-6.5			.6	-4.1	-2.2	-5.1	-.6	-2.3
35	.2	-6.4	-2.9	-7.8	-.1	-5.6	.9	-6.4	-1.3	-6.3	2.5	-9.9			.8	-5.5	.6	-6.0	-1.1	-3.3
36	-.4	-5.6	2.6	-4.9	.3	-3.2	-12.8	-8.2	-.4	-1.2	.1	-2.2					-2.2	-5.6	-3.8	-1.7

TABLE C.1 Continued.

ON-LINE PREDICTION

COND.	DAY 11										DAY 10									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	.9	-1.9	-.7	-.6			.2	-1.9	1.0	-1.9	.6	-1.8	.5	-.8	.5	-1.6	.2	-1.6	.4	-1.4
2	-.4	-.7	.4	-.1	.2	-1.1	-2.7	-1.5	.3	-.3	.0	-1.4	-1.2	-.7	.3	-.8	-1.1	-.6	.3	-.4
3	1.1	-1.6	.8	-1.3			.4	-1.5	.2	-1.4	1.0	-1.3	.7	-1.6	.5	-1.3	.4	-1.2	.0	-.9
4	.6	-2.2	.4	-1.8	1.2	-2.7	-.3	-.5	.1	-.9	1.4	-2.4	1.1	-1.1	.0	-1.8	.1	-.9	-.4	-1.3
5	-.3	-1.1	.8	-3.1	.0	-.4	-1.7	-1.8	-.5	-1.2	-2.7	-1.2	1.1	-2.0	-.4	-.3	-.4	-3.2	.1	-1.4
6	1.1	-1.2	1.8	-2.4	.6	-2.1	.2	-1.0	.0	-.6	2.3	-3.0	.3	-1.4	.8	-2.3	2.3	-2.8	.6	-.7
7	.3	-1.9	-.4	-2.3	.6	-1.9	.4	-1.6	-.3	-1.1	-3.9	-2.2	-1.0	-.3	.0	-1.4	.6	-1.0	.1	-.6
8	-.3	-.6	-1.5	-1.6	.7	-2.4	-.7	-.3	-3.1	-2.7	.6	-1.1	-.2	-1.4	.4	-.7	.6	-1.7	-.3	-1.2
9	.0	-2.1	-.7	-3.1	1.1	-2.1	.2	-.3	.7	-1.4	1.0	-1.4	.5	-.9	.3	-1.1	-2.0	-3.1	-.3	-1.5
10	.4	-1.4	-1.8	-2.2	1.0	-2.4	-.1	-1.5	.4	-1.2	.6	-1.1	.1	-1.1	.3	-.6	-.2	-1.9	-.3	-.9
11	.2	-1.0	.7	-1.9	1.8	-3.0	.6	-1.4	-.2	-.4	.3	-1.4	1.0	-.6	.8	-1.8	.4	-1.0	-.1	-.2
12	.1	-.9	.5	-2.2	.5	-1.8	.1	-3.5	-1.2	-1.9	-2.6	-1.2	-.6	-1.2	1.1	-2.2	.5	-.3	.4	-.8
13	1.2	-2.2	1.3	-.2	1.6	-1.8	.0	-1.9	-1.8	-3.3	1.9	-1.7	1.0	-2.9	.7	-2.6			.3	-1.2
14	1.7	-3.0	.1	-3.5	.1	-1.3	.2	-2.2	-.2	-1.9	.6	-3.7	-.3	-.9	.7	-2.7			.5	-1.2
15	-1.1	-.9	-.8	-3.7	.1	-3.1	.2	-.1	.6	-1.1	.1	-.7	-1.3	-1.4	.7	-3.0			-1.0	-1.1
16	1.5	-3.6	1.7	-5.3	.5	-3.5	1.2	-2.6	.2	-1.0	.8	-.3	.2	-2.5	1.0	-2.9			-.7	-2.3
17	2.0	-5.8	.5	-2.6	.9	-3.5	.1	-2.9	.2	-.8	-.2	-1.8	.5	-.9	.5	-2.0			-.4	-1.7
18	.1	-1.8	1.8	-4.3	1.7	-4.4	.4	-.6	-2.5	-1.9	-3.3	-2.7	1.6	-2.4	1.1	-3.9			-.5	-3.7
19	-.6	-3.4	1.5	-5.8	1.3	-4.4	.6	-2.2	-.8	-2.1	.1	-2.2	1.0	-3.2	1.3	-4.7			-.1	-.9
20	1.1	-4.8	.8	-3.7	.9	-3.2	-1.5	-2.3	-.1	-1.8	-3.0	-3.3	.2	-2.5	.4	-3.3			.1	-1.7
21	-.4	-1.5	-.5	-3.8	.6	-4.9	-1.8	-1.4	-1.5	-1.8	.7	-3.1	1.6	-3.1	.2	-2.7			.1	-2.3
22	-.6	-1.1	-.5	-1.8	.2	-3.2	1.0	-4.0	-.7	-3.0	.9	-4.3	8.2	-8.9	2.3	-4.3			.5	-1.7
23	-1.0	-1.7	.8	-4.6	.5	-2.8	.2	-.2	-.1	-.5	-2.2	-1.0	-2.7	-1.9	.5	-4.3			-.4	-7.0
24	-.7	-1.6	-.2	-4.2	.7	-3.1	-.6	-2.4	.0	-1.4	-1.1	-2.0	-4.6	-1.4	.4	-3.0			-.3	-1.4
25																				
26	-.5	-3.0	1.8	-5.0	.6	-2.9	.4	-3.3	1.0	-9.9	.2	-3.0	2.5	-5.9	2.8	-4.1	1.1	-4.3	-3.2	-9.6
27	3.1	-9.3	2.9	-10.4	2.1	-6.9	3.6	-12.8	-1.5	-8.3	1.8	-1.8	3.2	-8.4	2.9	-6.5	1.5	-6.8	.2	-4.2
28	5.6	-3.2	2.4	-5.2	1.0	-3.3	-3.6	-3.4	.3	-2.9	.8	-4.8	.6	-4.1	2.1	-6.2	-2.9	-1.6	-1.8	-3.3
29	-.1	-1.4	.5	-3.5	.4	-1.9	2.3	-8.3	1.0	-1.5	-1.9	-2.1	1.6	-5.4	1.5	-3.7	2.7	-5.8	.1	-.6
30	-3.2	-4.7	1.4	-5.8	.1	-3.9	-14.0	-4.7	-.1	-4.6	-.4	-4.1	-10.4	-4.2	1.0	-4.8	-12.8	-4.3	-.6	-2.0
31	.3	-3.3	1.6	-5.6	.5	-5.2			-.3	-7.1	-1.4	-4.1	1.5	-9.4	1.1	-3.3	1.4	-2.2	-.3	-2.7
32	.1	-4.2	-4.5	-10.4	1.6	-5.6	-.6	-4.0	-.4	-5.4	-2.2	-5.3	-1.3	-6.2	1.9	-7.6	-1.2	-4.4	-1.0	-3.4
33	4.4	-7.9	1.6	-5.2	.6	-5.0	-.8	-1.3	-.3	-1.1	1.7	-4.6	-3.3	-10.4	-.2	-1.5	.0	-6.5	-1.6	-2.4
34	5.6	-.3	1.1	-7.3	1.9	-8.6	-1.5	-4.2	.4	-3.2	1.6	-5.0	-4.4	-4.3	.7	-3.2	1.2	-3.8	-2.4	-2.7
35	.4	-4.6	.6	-7.2	.6	-5.2	-1.1	-3.4	-.1	-4.0	1.2	-5.0	-3.4	-5.6	-4.8	-2.4	-.1	-2.4	.5	-2.9
36	-2.0	-2.9	1.0	-5.7	1.1	-4.3	-2.6	-4.3	-1.2	-.9	1.5	-3.1	.4	-3.9	.2	-4.0	-1.6	-3.4	-.9	-1.6

TABLE C.1 Continued.

ON-LINE PREDICTION

	DAY 9										DAY 8									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
COND.	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	.7	-2.0	.8	-2.4	.3	-2.0	-.2	-1.6	-.2	-1.6	.3	-2.1	-.5	-1.9	.8	-.8	.2	-.9	.7	-.9
2	-1.2	-.8	1.0	-1.5	-1.1	-.9	.1	-.8	-.1	-.6	-.4	-1.3	-.5	-.6	.5	-1.1	.1	-1.0	-.6	-.6
3	1.1	-2.3	.5	-4.3	.4	-2.0	1.7	-2.8	.2	-.9	.4	-2.4	.9	-1.0	.9	-2.1	1.4	-2.1	.5	-.8
4	-.9	-1.5	1.9	-3.0	.2	-.8	1.0	-2.6	.0	-.2	1.0	-2.7	.2	-.7	1.0	-.9	.5	-2.8	.2	-.3
5	.1	-1.8	-.6	-.6	.3	-1.2	.0	-.7	-.6	-1.7	-.7	-.8	-.7	-1.9	.2	-1.8	.5	-1.0	1.0	-.6
6	1.2	-3.0	2.1	-2.6	.3	-1.1	.7	-1.5	.1	-.9	1.5	-3.1	1.4	-2.0	.1	-3.0	.6	-1.2	.4	-.6
7	.5	-2.0	-4.3	-3.9	-.3	-1.2	.1	-1.8	.2	-.6	-.3	-2.3	-.6	-1.8	.2	-1.3	1.0	-1.8	-.3	-.6
8	.2	-1.7	.6	-1.7	.5	-2.6	-1.6	-.7	-1.4	-1.9	-.1	-1.5	-2.3	-1.2	-.3	-1.1	-.7	-2.7	-1.1	-1.7
9	-.3	-.8	1.0	-2.4	.1	-1.6	-1.1	-.9	-.8	-1.3	.1	-1.6	.4	-1.3	.9	-2.2	.7	-3.1	.6	-.2
10	-.6	-1.8	-.7	-.7	.0	-1.4	-3.5	-.9	-.4	-1.6	-9.2	-3.1	-.2	-2.2	.8	-3.0	.1	-1.6	.3	-.4
11	.5	-1.3	1.4	-3.1	.2	-.7	.0	-1.4	-.5	-.1	-1.4	-2.6	-.3	-.9	.4	-.9	1.3	-2.0	.4	-.2
12	1.3	-3.3	1.3	-3.5	.4	-2.1	.4	-2.2	.4	-1.2	.1	-2.1	.4	-1.4	.4	-1.5	-.3	-2.1	.8	-.8
13	.5	-.8	.5	-.7	1.0	-2.8	1.0	-4.0	-.2	-1.7	3.9	-3.1	.2	-2.6	1.0	-1.7	1.8	-3.4	.5	-1.2
14	2.5	-2.5	1.1	-4.2	-.1	-2.3	9.9	-8.1	.4	-2.7	-.3	-2.0	1.8	-3.1	.5	-2.9	.5	-3.2	.3	-.2
15	-.8	-.7	.2	-.4	3.3	-4.8	-1.1	-1.5	-.3	-1.8	.1	-2.3	1.2	-1.4	-1.0	-1.1	-2.0	-1.2	-.7	-.9
16	1.1	-3.2	1.7	-4.8	-.1	-1.7	2.3	-6.7	-1.3	-1.9	1.9	-4.2	1.9	-5.4	2.0	-4.1	1.5	-5.1	-2.0	-1.3
17	-.4	-1.2	.5	-2.4	.3	-2.2	.8	-1.5	-.3	-1.6	-.2	-2.8	.1	-.8	.1	-2.6	-.8	-2.9	.0	-.5
18	-2.7	-3.2	.7	-3.5	-.4	-2.9	-.2	-4.2	-1.6	-2.7	.7	-4.1	.4	-2.0	.3	-1.5	-1.6	-2.6	-.3	-1.1
19	.1	-1.7			1.0	-3.1	1.9	-3.7	-.1	-.2	1.1	-6.1	-1.1	-1.8	1.7	-3.3	1.9	-5.8	.4	-1.1
20	-8.6	-4.0	-1.2	-2.8	.7	-3.7	-2.2	-1.6	-.5	-1.6			.6	-2.8	.5	-2.9	.5	-2.0	.4	-.5
21	-.4	-1.6	1.6	-5.9	-.4	-2.3	3.3	-6.8	-1.4	-1.4	.1	-1.1	.8	-1.8	.6	-2.4	.1	-2.8	-3.0	-2.4
22	2.0	-4.4	1.6	-3.5	.8	-3.4	-1.5	-2.0	.0	-1.2	-.3	-2.6			.2	-3.9	1.4	-4.1	.6	-1.8
23	1.3	-4.5	.2	-.9	-.1	-2.1	1.8	-5.9	-3.2	-3.7	-.3	-1.6			1.0	-2.0	1.0	-1.3	-.1	-.8
24	.3	-1.8	1.2	-4.2	.4	-2.9	-.2	-.3	-.5	-.9	-.9	-1.0	-1.5	-1.8	.8	-2.3	-1.8	-.9	-.5	-.5
25																				
26	-.5	-6.2	2.6	-5.3	2.2	-6.1	.4	-5.1	-2.6	-8.3	5.9	-6.0	.1	-2.1	1.0	-5.9	2.5	-5.1	-.9	-5.5
27	4.1	-6.7	1.2	-7.0	3.7	-5.1	1.4	-5.4	3.8	-11.6	3.9	-10.4	7.9	-9.3	1.9	-7.5	-3.8	-6.2	-3.1	-7.9
28	.2	-4.0	2.0	-7.4	1.4	-6.3	-.2	-3.1	-2.2	-1.9	2.1	-.0	-.5	-1.7	1.0	-6.9	4.4	-16.4	.4	-4.1
29	3.7	-1.2	-1.9	-4.1	1.8	-6.8	.3	-5.5	.1	-2.4	1.4	-2.9	.5	-4.8	1.8	-3.9	5.4	-5.7	.9	-.5
30	-2.1	-2.7	-2.0	-1.6	-1.0	-1.2	-1.9	-2.2	-.8	-1.2	-6.2	-2.2	1.1	-3.7	.5	-4.6	-1.0	-.5	1.5	-1.7
31	-.5	-5.6	1.6	-4.6	1.3	-4.3	1.2	-5.7	1.2	-4.3	2.4	-10.0	-2.3	-5.3	2.4	-3.6	-1.2	-4.8	-.4	-1.2
32	2.4	-6.2	3.7	-9.4	.2	-7.6	.2	-6.0	-.1	-3.1	.8	-6.1	7.7	-8.6	.6	-4.0	4.5	-4.7	-4.6	-2.4
33	-.7	-1.8	.1	-3.9	-1.4	-1.6	-.7	-2.1	.0	-2.9	.2	-8.7	-2.7	-5.0	-2.9	-4.2	.7	-2.1	1.9	-.6
34	-.6	-6.9	1.0	-3.8	3.1	-9.7	6.2	-12.8	.7	-3.6	.7	-1.5	-4.1	-2.8			.6	-7.7	1.1	-3.6
35	-.2	-4.5	-7.3	-4.5	.0	-4.2	.7	-2.7	-.3	-4.7	-3.2	-2.6	-2.3	-4.1	.4	-4.7	-3.0	-2.2	.7	-5.8
36	.8	-5.6	.5	-6.3	.1	-2.6	-.7	-3.8	-3.2	-1.2	.6	-5.4	-8.9	-8.4	1.4	-5.1	-1.3	-4.6	-3.3	-2.9

TABLE C. 1 Continued.

NO PREDICTION

COND.	DAY 11										DAY 10									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	.9	-2.6	-.2	-.5	-.2	-.0	-1.2	-.8	-.1	-1.2	.4	.3	.5	-2.0	-.2	-.1	-.2	-1.7	-.6	-.6
2	-.7	-.4	-3.1	-2.0	.3	-.1	-2.0	-1.1	-1.3	-1.0	-2.6	-1.4	-2.6	-1.5	-.1	-.3	-3.0	-1.7	-3.7	-2.4
3	.3	-1.5	-.7	-.8	.7	-.7	-2.0	-1.6	-1.4	-1.3	.8	.4	-.5	-.4	-.4	-.4	1.2	-2.6	-2.5	-2.1
4	.1	-1.7	.5	-.1	1.1	-1.2	.7	-3.2	.1	-.5	-.6	-.3	-1.4	-.7	1.6	-.5	1.1	-.4	1.3	-2.3
5	1.9	-.9	-8.9	-3.7	.3	-1.9	-6.0	-2.1	.6	-.1	-9.2	-3.4	-10.4	-3.8	-5.7	-2.9	-4.5	-1.6	-2.7	-1.3
6	1.4	-2.6	-1.4	-1.6	.5	-1.8	.9	.5	-1.7	-1.0	-.5	-.2	-3.7	-1.9	-2.0	-.9	1.7	-1.4	-1.0	-.6
7	-.1	-2.6	-5.8	-3.4	-1.4	-2.1	-.2	-1.8	1.4	-1.2			-2.2	-.7	.9	-1.6	-1.3	-.4	-2.2	-1.2
8	1.5	-3.6	-8.5	-3.6	2.0	-2.7	-6.7	-1.7	2.2	-3.4	-.5	-2.7	-.1	-3.0	-2.0	-.5	-4.4	-1.1	.5	-.7
9	.8	-1.9	1.4	-3.3	1.3	-2.7	3.5	-4.2	1.3	-2.4	5.6	-3.2	1.8	-1.6	1.6	-3.6	1.4	-2.9	-.2	-.3
10	1.6	-2.2	-4.3	-1.7	1.2	-2.9	-.1	-2.6	3.4	-2.8	.7	-2.0	-9.4	-2.4	1.2	-2.5	1.1	-2.8	1.1	-2.0
11	-.2	-1.7	1.7	-1.1	.8	-1.9	3.3	-4.3	2.0	-.8	2.3	-5.2	1.7	-1.7	1.2	-2.2	1.6	-3.3	-.7	-.1
12	1.5	-3.4	-4.2	-1.3	1.1	-1.3	-10.4	-2.7	-3.1	-1.2	-.3	-2.6	-5.3	-1.2	-.6	-3.1	2.7	-1.1		
13	.6	.4	1.1	-5.9	.4	-2.3	-2.2	-2.6	-.9	-1.4	-.8	-1.1	1.5	-4.0	-.7	-1.0			-.4	-1.1
14	1.9	-3.3	-1.4	-1.5	1.5	-1.5	3.6	-3.9	1.5	-7.4	-.4	-4.8	-.7	-.4	-.1	-.6			2.9	-8.9
15	.9	.3	-1.0	-1.1	1.4	-3.3	-.5	-.4	3.3	.6	-3.7	-2.1	-.1	-.2	.5	-2.3			-.8	-1.0
16	2.4	-3.6	3.2	-1.8	-.1	-2.8	1.3	.8	-2.0	-2.1	1.9	-4.0	1.4	.9	1.2	-2.0			1.1	.4
17	2.6	-1.6	2.9	-4.3	.1	-2.2	-9.0	-4.9	-.8	-1.0	-.9	-2.4	3.8	-2.3	1.6	-3.1			4.6	-2.3
18	5.3	-7.6	.0	-2.4	5.6	-5.9	1.9	-1.6	3.7	-4.5	-.9	-.4	-17.6	-6.2	.3	.1			1.8	-9.4
19	2.9	-2.5	2.2	-6.3	1.1	.4	2.5	-3.1	-2.7	-1.9	2.2	-2.4	-1.0	-.3	1.0	-2.7			2.2	-4.7
20	5.2	-4.8	1.2	-6.5	.9	-2.6	.3	.1	2.0	-.3	2.7	-9.4	-1.4	-4.8	3.7	-4.1			1.7	-5.2
21	.0	-1.9			.9	-5.1	-.9	-2.6	2.4	.1	3.3	-7.0	-15.2	-5.2	.5	-5.4			.4	-.4
22	2.0	-1.8	2.1	-4.3	1.5	-3.0	-.4	-.0	-7.3	-3.3	2.5	-6.3	5.2	-1.2	1.5	-1.4			-3.4	-1.4
23	-3.3	-.9	2.3	-7.3	1.4	-2.7	.3	.2	.0	.3	2.9	-4.1	.2	.2	.0	-2.7			3.1	-2.6
24	3.8	-5.3	-3.0	-5.7	1.3	-5.3	-2.8	-5.2	-3.1	-1.4	1.7	-4.6	-27.1	-8.0	1.4	-2.8			.7	-6.3
25																				
26	4.9	-1.2	5.9	-4.0	2.1	-.2	2.1	1.0	-.3	-1.3	1.7	-5.9	5.2	-5.4	-.6	-.7	.8	-11.6	1.0	-.2
27	6.1	-2.6	6.8	-12.8	2.4	-6.4	4.1	-3.1	6.0	-4.1	5.2	-6.3	7.1	-8.6	1.5	-4.7	5.0	-7.5	2.6	-10.0
28	2.6	-2.2	-.3	-1.1	2.1	-4.2	1.0	-.4	4.2	-4.8	4.8	-3.2	3.1	-8.4	1.3	-2.6	4.2	-3.0	-5.8	-4.1
29	2.4	-4.8	.8	.1	.6	-1.5	-1.5	-1.6	2.5	-4.3	-1.7	-1.9	4.7	-4.5	.6	-1.6	-1.0	-1.1	-2.0	-2.8
30	6.2	-10.4	-17.6	-9.0	-3.7	-2.3	-1.1	-.5	5.6	-.6	7.0	-6.9	-14.0	-7.4	1.5	-3.2	-14.0	-8.3	5.6	-4.4
31	-1.2	-1.4	.7	.3	1.2	-3.3	.6	.4	-2.1	-2.1	1.6	-6.2	1.5	-15.2	-2.0	-2.9	1.7	-.6	2.2	-9.0
32	5.4	-9.3	.4	-10.0	1.9	-5.5	-.8	-11.6	5.3	-3.9	5.1	-15.2	.5	-8.4	2.3	-8.2	7.5	-12.8		
33	7.6	-10.4	4.6	-9.5	3.2	-5.1	8.4	-14.0	4.1	-14.0	-3.9	-2.1	4.8	-2.7	-5.1	-2.6	9.9	-3.2	-6.4	-3.6
34	3.6	-5.2	14.0	-15.2	-5.7	-3.0	-7.3	-2.9	4.7	-5.5	2.6	-8.4	1.1	-6.8	2.9	-8.7	8.5	-6.8	-.1	-.6
35	3.8	-8.2	.6	-3.6	4.6	-8.8	-1.3	-.4	7.8	-8.0	6.0	-5.6	9.4	-9.8	2.5	-4.8	8.6	-8.4	2.5	-.1
36	-10.4	-4.4	1.6	-8.8	-6.1	-3.4	4.0	-8.5	6.6	-2.3	-11.6	-4.6	-.6	-9.2	-4.5	-3.3	7.7	-5.3	6.6	-11.6

TABLE C. 1 Continued.

NO PREDICTION

	DAY 13										DAY 12									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
COND.	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	-.4	-.9	-.1	-.0	-.8	-2.6	.9	-2.9	-.8	-.5	-1.9	-1.6			-.2	-2.8	1.2	-2.8	.0	-.1
2	.5	-.3	-3.6	-2.0	.0	-.3	-1.9	-1.7	-2.3	-1.3	-1.9	-1.3			1.9	-1.3	-2.2	-1.5	-2.7	-1.5
3	1.8	-1.0	.5	.2	-.7	-.8	-.1	-.3	-.3	-.3	1.6	-.4			-.2	-.4	.3	-2.4	1.3	-2.2
4	1.4	-1.7	1.7	.2	.7	-1.2	.5	-.2	.0	-1.3	2.0	-1.3			1.4	-2.2	.6	-.1	.3	-.1
5	1.0	-1.6	-.1	-4.4	.9	-.9	-.1	-2.9	-.1	-.0	-2.2	-2.4			-1.5	-.9	-3.6	-3.1	-.8	-2.7
6	.0	.1	1.3	-1.3	.7	-1.0	1.0	-1.3	1.8	.1	.1	-.7			-.2	-.2	2.1	-3.8	-.9	-.4
7	-.1	-.0	-1.1	-.3	.4	-1.6	.9	-4.0	-2.7	-.9	1.8	-2.7			.1	-.4	-2.0	-1.1	1.0	.2
8	3.3	-3.7	-.4	-.1	1.5	-1.9	-1.7	-1.9	.9	-1.7	3.6	-5.6			1.1	-1.9	1.6	-1.0		
9	1.1	-3.8	-1.0	-.3	1.8	-3.3	3.0	-3.0	-2.7	-.8	1.3	-2.4			1.1	-.5	-.1	-2.6	1.2	-.1
10	-2.1	-.5	.5	.2	2.0	-3.6	-3.4	-1.5	-.2	-3.2	-.1	-2.9			.2	-2.6	.5	-1.3	.1	-1.1
11	2.1	-1.2	1.1	-2.5	1.6	-2.0	.8	-1.2	-1.6	-.5	1.2	-2.3			-3.4	-1.1	1.9	-.8	2.0	-2.9
12	3.3	-3.5	-1.7	-.3	.8	-2.2	.2	-2.2	.6	.3	-1.7	-.9			1.6	-4.3	.1	-2.0	.4	-2.6
13	1.2	-3.5	-.8	-1.0	.6	-2.3	.7	-.5	1.1	-.6	1.7	-2.0			.0	-.5	-3.7	-5.1	.5	.3
14	.8	-.5	-1.6	-1.1	.5	-2.8	1.4	-2.2	2.4	-1.9	1.3	-2.2			-1.7	-1.6	2.2	-4.4	1.5	-7.5
15	-2.6	-1.6	-.4	-.3	.6	-4.8	.8	-5.4	-1.2	-.8	-7.0	-4.5			.9	-.0	-1.9	-1.7	1.8	-2.1
16	.8	-3.5	.7	.4	1.3	-3.4	-.6	-.8	.4	-.3	1.3	-.8			-1.4	-.9	1.8	-.5	-1.3	-1.0
17	2.6	-2.8	-.6	-3.4	1.1	-4.0	3.1	-5.1	-1.6	-.8	1.2	-6.2			1.8	-1.9	-1.5	-1.4	2.2	-3.2
18	.7	-6.9	-3.7	-1.3	-.1	-.7	3.3	-6.4	2.8	-5.5	2.9	-9.2			1.8	-3.8	-.8	-3.3	.4	-7.4
19	-.7	-3.4	-1.7	-.9	.4	-.2	3.4	-3.1	2.3	-3.0	1.4	-4.1			-.2	-1.0	-.5	-.6	1.3	-3.3
20	3.3	-4.1	-.3	-4.4	3.5	-9.5	-.6	-3.9	1.4	-7.5	8.5	-5.6			.2	-7.7	.7	-3.6	.9	.2
21	3.2	-6.0	-4.1	-1.3	3.7	-7.4	3.6	-7.5	.3	-4.1	3.5	-3.3			-.3	-3.9	-1.0	-3.5	2.7	.5
22	2.4	-2.6	-2.2	-.8	1.8	-2.8	2.5	-4.6	2.4	-3.9	1.8	.8			.4	.2	1.9	.1	-.9	-.3
23			-2.7	-.7	2.0	-2.5	3.5	-5.7	-5.7	-1.7	3.0	-6.4			-1.2	-3.8	-3.8	-1.0	-1.7	-.3
24	3.6	-5.9	7.6	-5.7	-5.9	-3.4	.5	-4.1	5.7	-2.8	3.3	-3.4			4.2	-8.0	-1.0	-3.5	2.8	-1.3
25																				
26	2.7	-6.9	4.6	-8.8	2.3	-6.9	2.5	-5.8	3.6	-3.2	3.8	-1.5			.9	-3.3	2.9	-6.8	2.1	-10.4
27	-2.4	-7.3	6.8	-8.3	2.6	-4.4	7.3	-14.0	1.9	1.2	5.3	-11.6			1.1	-.1	-.1	-3.5	2.1	-11.6
28	4.4	-3.7	.7	-7.6	2.0	-10.0	3.9	-10.0	1.7	-8.8	1.0	-.4			-.1	-.9	3.9	-5.3	-.9	-.7
29	-.1	-5.8	3.6	1.3	-.1	-1.1	.7	-1.6	-.3	-2.3	.7	.1			1.9	-3.3	1.4	.6	-2.0	-2.3
30	4.7	-3.5	-6.4	-2.2	2.3	-8.6	-10.4	-4.9	7.3	-11.6	-6.5	-4.1			-6.5	-3.5	-11.6	-5.1	-6.4	-2.2
31	3.0	-4.1	1.9	-7.2	2.5	-3.7	1.4	-.3	-3.2	-2.1	2.3	.9			2.0	-3.3	1.1	.2	3.3	-3.1
32	3.8	-8.3	5.5	-9.2	7.4	-9.8	4.6	-10.4	-1.2	-.6	7.7	-11.6			3.5	-11.6	5.6	-2.8	.6	.2
33	.2	-8.4	1.6	-7.4	-5.6	-3.1	6.2	-3.0	-1.8	-.6	-7.2	-7.3			-3.9	-2.2	-1.1	-5.6	-3.3	-1.4
34	.8	-.8	3.0	-11.6	1.7	-4.9	2.5	.5	1.5	-5.3	-1.7	-4.2			2.3	-12.8	8.7	-10.4	3.2	1.5
35	3.7	-8.4	10.4	-4.3	-6.1	-3.9	6.5	-5.8	4.9	-6.6	8.9	-15.2			3.2	-8.0	12.8	-8.1	3.7	-11.6
36	-5.3	-1.8	-4.9	-5.2	3.7	-10.4	5.4	-7.7	-1.6	-.3	1.3	.5			-3.3	-1.1	1.2	-7.9	3.4	-.0

TABLE C.1 Concluded.

NO PREDICTION

	DAY 9										DAY 8									
	SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5		SUBJECT 1		SUBJECT 2		SUBJECT 3		SUBJECT 4		SUBJECT 5	
COND.	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE	ERROR	ERROR RATE
1	-.2	-2.1	-1.1	-.7	.0	-.6	1.2	-3.2	1.1	.3	.8	-.1	.3	.3	-.5	-2.3	-.3	-2.2	-1.5	-1.0
2	.0	-.6	.0	-.1	-.5	-.7	-2.4	-1.3	-3.5	-2.2	-2.8	-1.6	-1.4	-.8	-1.2	-.7	.0	-1.4	-4.0	-2.2
3	1.0	-1.3	1.1	-3.3	1.3	-1.8	.2	-.0	-.1	-.3	.2	-2.8	1.1	-3.0	.8	-.7	.3	.1	.5	-.2
4	-2.0	-1.1	1.0	-2.4	.1	-1.3	-.5	-.3	2.2	-3.6	1.6	-1.1	2.0	-3.6	1.1	-1.7	-3.1	-1.6	-1.5	-.8
5	-1.8	-.6	-1.7	-.6	-1.5	-1.4	-8.1	-3.0	2.7	-.0	-.5	-.2	-8.2	-2.9	.6	-1.1	2.0	-4.5	-1.8	-.6
6	.3	-1.7	.6	-1.6	.3	-.0	1.0	.5	1.6	-2.2	1.5	-1.0	-2.8	-1.5	.4	-1.2	1.0	-2.2	-.6	-.3
7	2.6	-2.2	-.2	-.1	-.2	-1.9	2.5	-.7	.9	-.0	-1.2	-3.9	.3	-4.8	2.1	-3.3	-.2	-1.2	1.5	-1.8
8	1.3	-2.3	.8	-2.2	.1	-2.8	-8.4	-2.2	.4	-4.3	-4.3	-2.6	2.3	-.9	2.2	-2.3	-6.1	-1.6	-10.4	-4.6
9	1.9	-1.7	.8	-4.0	.3	-1.3	-2.8	-1.5	.9	-3.8	2.7	-2.8	1.9	-3.5	1.4	-2.2	.0	-.0	2.6	-2.4
10	2.6	-4.3	-3.2	-.8	-3.3	-.8			1.2	-.1	2.4	-4.4	-7.3	-1.9	-2.0	-2.0	-12.8	-3.2	3.6	-4.7
11	1.5	-2.7	-2.3	-.7	1.4	-2.5	.6	-2.0	1.5	-3.1	-.2	-2.0	.1	.1	-.8	-.4	3.0	-1.8	2.4	-3.7
12	2.9	-4.4	2.6	-3.7	-1.5	-.3	-3.8	-.9	2.3	-4.3	-2.5	-1.9	-14.0	-3.7	2.3	-3.9	4.5	-2.5	-4.1	-1.0
13	.5	-1.7	1.2	-3.0	.4	-.9	-.9	-1.2	.1	-.3	3.0	-2.3	1.0	-6.1	.7	-.9	.8	-3.5	.4	-.5
14	1.5	-2.9	-2.4	-1.5	1.8	-2.2	.9	-1.8	.9	-.0	.6	-5.0	1.1	-.6	.1	-.0	-.2	-.1	2.3	-2.5
15	-.1	-1.0	.0	-.1	.4	-2.2	2.1	-3.6	-1.0	-1.0	1.5	.6	-.1	-.3	.9	-2.7	1.1	.4	1.5	-.3
16	-.9	-.6	1.5	-4.5	.0	-1.6	3.0	-.9	.9	-1.0	4.3	-5.1	2.5	-5.6	.6	-2.6	-2.2	-1.5	1.7	-1.0
17	2.6	-4.1	3.2	-4.4	.2	-1.4	2.5	-3.3	1.8	-2.7	2.2	-.2	.5	-9.6	.6	-3.8	2.4	-2.6	1.1	-4.2
18	.7	-5.8	3.9	-2.5	.6	-1.6	4.7	-1.4	3.6	-5.1	4.7	-7.7	2.7	-3.9	2.9	-2.9	.0	-3.0	3.9	-4.4
19	1.0	-2.6	3.2	-3.1	.4	.2	2.1	-3.9	1.2	.5	3.3	-1.8	1.2	-3.5	-3.3	-1.9	1.8	-6.6	2.6	-5.1
20	3.7	-3.5	-.4	-.1	3.3	-5.8	1.2	-4.2	2.7	-7.3	5.5	-6.1	2.3	-.2	1.7	-3.9	3.6	-2.1	3.7	-4.5
21	3.3	-7.5	1.8	-3.2	-.6	-2.4	-.7	-2.4	-1.8	-1.1	4.5	-3.7	1.0	-6.5	2.3	-4.3	1.1	-1.6	3.4	-5.3
22	3.4	-3.2	.9	-2.6	3.1	-4.0	7.4	-2.1	2.1	.6	2.4	-3.3	1.1	-2.8	3.0	-4.0	2.9	-4.2	2.9	-4.6
23	-1.2	-.4	-1.7	-.5	1.8	-6.8	2.6	-3.5	-6.7	-2.1	-3.1	-5.6	-.3	-4.2	-6.1	-2.2	3.6	-5.4	.9	.2
24	1.4	.4	-14.0	-3.9	1.8	-2.6	.5	-1.2	-4.4	-1.7	6.3	-8.5	-1.4	-5.6	3.1	-3.4	-6.6	-1.8	3.7	-5.9
25																				
26	5.6	-3.5	4.8	-7.0	3.2	-5.8	4.7	-5.2	1.2	-6.7	2.5	-3.6	3.7	-5.3	-.4	-3.7			1.8	-9.8
27	2.6	-2.6	3.1	.5	4.1	-7.9	8.0	-11.6	3.1	-10.4	5.8	-7.5			2.2	-5.3	4.7	-3.2	7.2	-10.4
28	-1.7	-.8	.3	-.0	.3	-1.9	-3.0	-1.7	4.1	-1.1	1.6	.7	-.4	-.4	3.9	-2.9	2.9	1.3	-.8	-.5
29	2.2	-5.5	1.6	-5.6	.9	-1.9	3.1	-7.0	-1.0	-1.4	-.1	-.2	4.3	-5.2	2.3	-5.8	3.5	1.4	2.3	-5.8
30	2.3	.8	2.0	-4.7	1.2	-3.9	-2.8	-1.0	1.3	-.5	-6.6	-2.3	-4.8	-1.7	-6.5	-2.3	-14.0	-4.9	5.0	-1.5
31	2.5	-6.9	3.2	-3.0	.4	-2.9	3.4	-8.6	1.6	-6.2	1.5	-5.9	5.0	-4.3	1.9	-4.8	.2	.1	-.1	-.1
32	2.3	-6.0	4.7	-8.0	1.1	-7.7	5.1	-5.1	-1.6	-1.8	1.9	-7.1	4.7	-5.2	5.0	-7.9	3.3	-4.1	4.5	-12.8
33	-.1	-8.8	8.9	-6.5	1.3	-4.0	.4	.2	4.0	-4.4	2.0	-6.6	-2.9	-1.5	.9	-6.0	5.8	-9.6	3.4	1.3
34	-4.6	-1.7	9.5	-11.6	-6.4	-2.5	3.9	-9.8	4.9	-8.4	3.4	-3.4	-6.1	-2.4	1.0	-4.8	9.1	-8.2	-2.0	-.5
35	7.8	-9.3	10.4	-15.2	5.1	-5.3	11.6	-10.4	4.9	-10.0	-1.3	-.7	4.2	-8.7	-2.8	-1.3	5.5	-3.8	4.8	-3.5
36	.4	-2.5	-11.6	-4.9	3.3	-5.5	5.6	-6.0	8.4	-8.3	4.6	-6.9	1.4	-8.2	-4.7	-4.4	4.7	-12.8	8.1	-3.0

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