MANUAL CONTROL OF REMOTE MANIPULATORS: EXPERIMENTS USING ANALOG SIMULATION

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FOREWORD

This work was initiated by the Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted by Ritchie, Inc., Dayton, Ohio, under Contract No. AF33(615)-1456, "Remote Manipulator Controls Research" with Dr. Sidney Seidenstein, Senior Associate, the principal investigator for Ritchie, Inc. Mr. William N. Kama, Maintenance Design Branch, was the AMRL contract monitor. The work was performed in support of Project No. 8171, "Aerospace Support Equipment for Nuclear Application," and Task No. 817105, "Human Engineering for Remote Handling Systems." The contract effort was initiated in February 1964 and completed in March 1965.

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This technical report has been reviewed and is approved.

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ABSTRACT

An analog simulation of a remote manipulator system with two degrees-of-freedom in motion was developed. It was then used in a series of three experiments designed to investigate operator performance as a function of control mode, manipulator dynamics and task requirements. Experiment I investigated the following independent variables: (1) control mode (fixed vs. proportional rate), (2) maximum rates of motion, four levels, (3) manipulator dynamics, two levels: (involving mass, damping, motor, and drive characteristics), (4) target size or final positioning error tolerance, two levels, (5) criterial time, i.e., the duration final arm position had to be maintained once achieved, two levels, and (6) distance from starting point to target, three levels. Experiment II studied position control rather than rate control and included the same variables as in experiment I, except that only one level of "dynamics" was investigated. In experiment III operator performance was assessed under conditions which enabled the operator to select either of two discrete rates of simulated manipulator motion. Four combinations of rates were used. The other variables were as in experiment II. Dependent variables for each experiment were travel time, adjustment time, time on target and total task time. Experiment I indicated that increasing the complexity of system dynamics produced a decrement in operator control performance, which was greater for the fixed rate control. Best overall performance was attained with the proportional rate control. In the case of fixed rate control, the best overall performance was obtained with a rate of motion of 9.32 cm/sec. Contrasting the results obtained in experiment II (position control) with the fixed rate and proportional rate data of experiment I revealed a clear superiority for the position control. Experiment III revealed that a two-level fixed rate control afforded no overall advantage in performance as compared to an optimum single level of rate control.

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SECTION I

INTRODUCTION

The development and design of remote manipulative devices has received relatively little attention from the engineering psychologist. Where studies were performed, they generally involved task variables extraneous to the manipulator characteristics *per se*. The purpose of the present project was to experimentally study various characteristics of manipulator control systems. This was accomplished through the development and utilization of a two degrees-of-freedom analog simulation of a rectilinear rate controlled manipulator. A series of experiments was performed to assess the effects of both machine variables and task variables on manipulator system performance. The feasibility of the simulation approach was demonstrated and the requirements and techniques for developing a more sophisticated simulation were outlined.

HISTORICAL BACKGROUND

The field of remote handling has been defined and described by Clark (ref 7, 8) in terms of devices and techniques which permit performance of manipulation tasks in a hostile environment. Manipulation, sensation, locomotion, communication from hostile to safe environment, communication from system to man, and providing power are given as the several remote handling functions. The methods available for performing these functions involve "protective clothing, barriers, remote control (remote prime movers), direct control (motorized prime mover), and programmed systems (automatic)".

The earliest of the sophisticated general purpose remote manipulators were developed in conjunction with the requirement for experimentation with radioisotopes. The master-slave manipulator evolved to meet the requirements of relatively precise and delicate operations typical of a chemical laboratory. Such master slave manipulators are limited largely by their load capability and the fact that operation of such systems is inherently fatiguing. They do, however, provide force feedback, isomorphism between master and slave, and are position control systems.

Powered manipulators were developed to overcome the load limit factors. These were generally developed from "off the shelf" hardware, and were designed in a manner which generally resulted in separate control of each motion, although they were not entirely free of cross-coupling problems. No force feedback *per se* was available.

Rate control was generally utilized with the loop being closed by visual feedback through the operator.

Several servo operated master slave manipulators were developed. Handyman (ref 7) was a later development in powered manipulators which incorporated force feedback. The Handyman operator "wears" a harness which follows his motions and transmits commands to the slave. Forces on the slave end are fed back to the operator through force reflecting servo loops with adjustable gains. Thus, this device incorporates isomorphic position control with force reflection.

Valuable insights into the remote manipulator control problems were derived from discussion with R. C. Goertz (ref 14, 15) of Argonne National Laboratories. Goertz is concerned with flexible general purpose manipulators. These devices are used to perform nondestructive maintenance and repair of complex equipment, in the operation of chemical, physical, and analytical laboratory equipment. Goertz believes such tasks can best be performed by a master-slave, servo driven, force reflecting manipulator. He believes that "velocity-controlled" manipulators are unsuited for these complex and delicate tasks. His analysis of the manipulator task is as follows:

a. Each operation is essentially preceded by a collision.

b. Mass should be low to avoid damage to the colliding components.

c. When contact with an object is made degrees of freedom are lost. The operator no longer freely controls the path of the arm. Control of this path is transferred to the object being operated upon. The path the manipulator can now take is defined by the path the object can follow and the terminal point of the arm.

d. The manipulator must have sufficient freedom to accommodate to the path to which it is constrained. In other words, there must be some compliance in the arms and the joints of the manipulator.

e. Frequently, prior to contact with an object and the subsequent loss of degrees of freedom, vision is also lost. The arm, in making contact with the part to which it is being affixed, obscures the object of interest.

f. Control of force, and not control of position, is necessary to operate efficiently.

g. To obtain control of forces, as well as the fidelity to permit operation by feel in the event of loss of visual feedback, frequency response of the feedback system is quite important. Transmission and reflection of higher frequency components would permit operation through the kinesthetic and proprioceptive senses to supplement visual feedback, and would allow control of force levels, accommodation to the required force level, and knowledge of results of damage.

It is generally true that master-slave manipulators are capable of being used to accomplish more precise and delicate operations than are rectilinear rate manipulators. It was taken as a working hypothesis that the analysis of differences between master-slave and rectilinear rate manipulators would yield clues as to what variables might make significant contributions to man-machine system performance. An analytical comparison of these two classes of manipulators led to the following conclusions:

a. Control order: Master-slave manipulators are position-control systems. All others are basically rate-controlled systems; either fixed level or proportional.

b. Controller-effector relationship: Master-slaves have integrated controller configurations permitting the operator to make simultaneous complex motions requiring only that he position his hand. In this sense they resemble a pantograph. Rectilinear manipulators employ independent orthogonal control of each degree of freedom. The control device usually bears little spatial resemblance to the manipulator side. Operation requires complex, multi-axis programming by the user.

c. Rates of motion: Master-slave rates of motion are mechanically limited only by inertia and friction, both generally low. Rate manipulators have maximum speeds determined by motor size, gearing, and desired load capability. In rate controlled manipulators, rates of motion average about 5.0 meters/min. For space and recovery operations, this tradeoff may be inappropriate, resulting in increased performance time and operator fatigue. Speeds are also limited because the high load, high speed capability represents a hazard which may not be adequately controlled by the operator.

d. Feedback characteristics: Master-slave manipulators incorporate tactual-kinesthetic force feedback, somewhat degraded by the mechanism, as well as visual feedback. Rectilinear-rate manipulators provide no tactual-kinesthetic force feedback.

e. Precision of control: Master-slave manipulators provide very fine control capabilities. The accuracy, precision, and magnitude of possible movements is largely determined by the operator within the limits of the mechanical or electromechanical system. Rectilinear rate manipulators, because of their electrical and mechanical characteristics, cannot be positioned or moved with the same degree of precision.

f. Compliance: Master-slave manipulators exhibit some degree of compliance, either in their structure, or through feedback to the operator's arm which permits the man-machine system to accommodate to the complex paths which must be followed.

Each of these characteristics probably makes some contribution to the apparent superiority of master-slave type manipulators over existant versions of the rectilinear arm.

In addition to design features, described above, task variables which interact with the manipulator characteristics must also be studied. Task variables are defined as the required physical operations which the manipulator arm must perform. They involve:

a. Transport: moving from one location to another, where no limits exist on accuracy.

b. Adjust: fine adjustments required subsequent to a "ballistic" transport motion in order to terminate the movement within some desired area.

c. Orient: addition of restricting attitude as well as position. Not only must a move be made from A to B, where B is a limited area, but some specific orientation about point B is required.

d. Grasp: manipulator is brought into contact with an object, and the magnitude and direction of forces are controlled.

More complex tasks involve combinations of these operations with additional time and path restrictions.

Other variables of concern are:

a. Dynamics of the controlled element: This includes factors such as system order, forms of aiding, and characteristics due to the nature and combination of the mechanical and electrical elements comprising the manipulator.

b. Controller configuration: Of concern here is the physical configuration of the man-controller interface which includes not only factors such as size, shape, and location of controls but also the spatial congruency between control degrees of freedom and manipulator degrees of freedom in a manner analogous to stimulus-response compatibility.

c. Information transfer: This category involves variables related to the presentation of information concerning the task situation and includes sensory modulators and feedback techniques developed to permit various forms of feedback.

RELEVANT PSYCHOLOGICAL LITERATURE

Based on the foregoing material and a review of the literature, an analysis of remote manipulation tasks was made.

Remote manipulation, though a skilled motor task, cannot properly be called a tracking task. Skilled performance is characterized by a requisite spatial-temporal patterning of behavior. In tracking, this patterning is determined primarily by the nature of the task (forcing function). In other skills, the operator is the basic determiner of this spatial-temporal pattern, while the task may determine spatial positions which must be attained.

For tracking tasks, targets are presented to the operator according to some program or forcing function. In remote manipulation, on the other hand, the operator chooses not only the target object, but commonly, the order in which he will approach that object among other objects which may be present.

All tracking tasks are to some degree path-constrained. A tracking operator must follow the movements, of, or take a minimum path to, the target in continous and discrete tracking tasks, respectively.

There is generally a time constraint in both discrete and continuous tracking. In both tracking modes, the operator tries to spend as little time as possible away from the target or the target's path.

In remote manipulation, there is usually no such time constraint. The operator may choose the most advantageous speed to approach the manipulation target, depending upon such circumstances as emergencies, time-based chemical and nuclear reactions which must be begun and terminated remotely, and frequently, only at his own pace. Generally then, he has more flexibility in both spatial and temporal programming.

In summary, tracking may be contrasted to remote manipulation by the degree of task structuring imposed by the stimulus situation. These differences may not always be clear and distinct in "real life". The experimental literature, however, exaggerates the differences simply as a result of the necessity for systematic control of variables. A detailed review of the tracking literature revealed relatively little information specific to the remote manipulator task, largely because continuous forcing functions are usually employed in this research.

REVIEW OF FINDINGS: RELEVANT REMOTE MANIPULATOR CONTROL LITERATURE

Remote manipulation consists not only of a series of consecutive equipment maneuvers, but also of a series of operator-oriented tasks which are independent of the task of monitoring the control characteristics of the manipulation equipment. This latter series of tasks consists of sighting the target, judging the best path of approach, approaching the target, controlling speed to minimize under-and-over-shoot error, orientating the claw for the manipulation task, and final adjustment.

1) Judging best path for approaching target:

There have been no studies concerning optimal target approach methods for remote manipulation tasks. Several sources, however, discuss the use of lateral rotation and angular indexing ot slave arms in master-slave configuration and indicate that there may be difficulty in performing manipulations when slave hand motions are more than 90 degrees out of phase with controller motion in any axis. Also, speed of performance increases with angular indexing speed at far, rather than near distances (ref 2), indicating that paths may be chosen which incorporate angular indexing movements to some advantage.

2) Approaching target and controlling speed to minimize under-and-over-shoot error:

Though there have been no reported studies on approach and slowdown aspects of manipulation tasks, there is a considerable body of research on discrete radar display tracking tasks. Most of these studies have concentrated on determining optimal control-display ratio (gain) for discrete tasks in which the operator moves an indicator to various points on a cathode ray tube (CRT) (directly with his hand or using a joystick) as quickly as possible, minimizing overshoot and adjustment corrections once the target spot on the scope is reached. The major findings of this research are as follows:

a. Gain, or control-display ratio, is the most important factor in speed-accuracy control. Less important are control stick length and reversal of controls.

Optimal gain ratios vary between 2.5:1 and 3:1 for midrange joystick movement (ref 13), (ref 17).

b. Defining gain as the ratio of velocity of the cursor (in radians at the observers eye) to the angular movement of the control stick, (radians at pivot), Gibbs (ref 13) found a U-shaped curve for time-to-complete-tasks plotted against gain. Hammerton (ref 16) using the same gain measure, obtained a logarithmic monotonically increasing curve of time-to-completion against gain. The reasons for this conflicting evidence for the U-curve relationship may lie in the fact that Gibbs varied gain and lag but held maximum control excursion constant, whereas Hammerton varied amount of excursion and kept maximum attainable speed constant. For these and other considerations, such as difference in scoring procedures in the two studies, the gain/movement time/accuracy inter-relationship remains to be fully explored.

c. Gibbs (ref 13) found a gain x lag interaction which greatly affected target acquisition and holding time in the position and velocity control modes. For position control, optimal control display ratio changed rapidly with changes of lag at values of less than 0.2 sec., but this curve flattened when lag was increased above this value.

d. For the velocity control mode, an increase in either gain or lag alone tended to degrade performance, but an increase of both together may balance out. An increase of lag may filter undesirable effects of limb tremor resulting from high gain, and increasing gain may compensate for reduction of speed caused by lag (ref 13).

e. Use of two hands on a control stick yields quicker fine adjustments once the target has been reached, but use of one hand yields quicker coverage of long distances (ref 13).

f. Maximum cursor velocities when using a rolling ball control apparatus are a function of both target distance and direction, increasing almost linearly with distance (ref 22).

3) Orientation for manipulating task:

No material was found on best ways to orient a manipulator claw to perform various tasks.

4) Adjustment:

Information on manipulator performance in handling objects *per se*, is limited to studies done by Crawford and Kama on psychophysical aspects of weight judgment in manipulator lifting tasks (ref 9, 10, 11), and one attempt to devise an index of overall task difficulty made by Sheridan and Ferrell (ref 24). Their index of difficulty is given as:

$$I = \log_2 \frac{2 \times \text{distance moved}}{\text{Final tolerance}}$$

Their results showed a consistent increase in performance time as a function of the index of difficulty. The form of the relationship remained the same but absolute time level increased as lags were introduced.

5) Control dynamics:

a. Control characteristics

Bahrick (ref 1), summarizing variables which influence the proprioceptive control of movements, hypothesized that, (1) the elasticity constant of a control should affect ability to perceive and control positions, (2) the damping constant should affect control of rate, and (3) the amount of inertia should affect the control of acceleration. Since his paper dealt mainly with previous work done on positioning responses in discrete tasks, these hypotheses may prove fruitful.

Jenkins (ref 17) found that C/D ratio affected time to make a setting more than inertia, friction, backlash, setting tolerance, or control size, for both knobs and levers. There has been some work done (ref 11), (ref 13), (ref 23), in both discrete and continuous tracking tasks that shows that the operator expects a linear, rather than a nonlinear, cursor response to his control movements. Rogers (ref 22) notes that the operator moves his control at a velocity proportional to the expected excursion of the display cursor. Rogers (ref 22) proposes designing systems which optimize the control display ratio, using the fact that system gain is a function of control velocity. Thus the output will move further in response to a fast control input than it will in response to a slow control input. He named this process "adaptive aiding", and found that discrete tracking performance was considerably improved when it was incorporated into the control loop for a radar operator's target acquisition task.

b. Spatial arrangement of controls

There have been no general studies done on optimal arrangements of remote manipulator controls. Clark (ref 7) feels that the principal criteria of a control console should be ease and comfort of operation over considerable periods of time, unambiguous presentation of data, and natural means of actuating the commanded limits. Also, the range of effective performance of a seated, rather than standing operator has been found to be approximately one-third the inherent work range of a master-slave manipulator (ref 4).

Crawford (ref 12) studied the effects of a joystick vs. multiple lever controls on operator performance utilizing a rectilinear rate manipulator. He reports superior performance with the joystick control, but practice tended to decrease differences. We interpret this in terms of a lighter task load on the operator with the joystick since the stick permits the integration of several discrete motions.

c. Information requirements within control loop

Work done on the need for force, kinesthetic, and proprioceptive feedback in remote manipulation is limited to hardware evaluation; there are no general published studies in this area. There is some indication (ref 3) that Northrop is now conducting experiments which have tentatively shown that back pressures or force feedback from control arms may not be required for all degrees of freedom.

SECTION II

EXPERIMENT RATIONALE

EXPERIMENTAL APPROACH

The goal of this research program is to develop design principles which would refine and improve control capabilities for powered manipulator systems. Because of the large number of variables involved, and because of the difficulty and expense of designing and constructing actual manipulators with different or variable characteristics, it was decided to develop a general purpose analog simulation of a remote manipulator as a primary research tool. Simulation would permit the study of many variables, over wide ranges, without the need for redesign and machining of costly equipment. It was anticipated that this approach would provide an understanding of the functional relationships in rectilinear rate manipulators, permit the establishment of design criteria for improving system performance, and clarify the significance of many factors which contribute to system performance.

Limitations of the simulation approach were recognized. However our goal was to obtain an understanding of the basic functional relationships among variables without necessarily requiring that absolute levels of performance correspond to those obtained with actual manipulators. The necessity of ultimately validating the analog findings was also recognized. This can be done for selected conditions on existing remote manipulators.

An analysis of the remote manipulator control task showed the operator to be primarily responsible for determining the space-time pattern of activities. He is constrained only by (1) the discrete physical locations of objects, (2) the operations to be performed, and (3) the characteristics of the manipulator being used. This differs from most tracking tasks where a specific space-time path defines the task requirements.

Basic to the remote handling task are the distance which a manipulator arm traverses, the precision with which terminal position must be achieved (the target size), and the duration of time for which this position must be maintained (criterial time). Control order (position or rate) and overall system gain are basic variables determining control system characteristics.

A series of experiments was conceived to explore some basic relationships among the variables described above. The experiments began with a simple representation of the manipulator as a dot on the face of a cathode ray tube (CRT). The position of this dot relative to a fixed target circle on the CRT was controlled through either a fixed rate or a proportional rate controller. In a later simulation the analog representation of the manipulator dynamics was more sophisticated, and the manipulator arm was represented as an "L" shaped figure on the CRT. This work constituted Experiment I.

Experiment II used the simpler simulation as described above to investigate performance with a position control system.

Experiment III, also used the simpler simulation to investigate performance with a two level fixed rate control.

EXPERIMENT I

Purpose

Experiment I was conceived to investigate the functional relationships among the following variables:

1. control mode
2. rate of arm motion
3. distance from starting point to target
4. target size
5. criterial time.

A sixth variable, complexity of the dynamic simulation, was included to provide a baseline from which to assess the form and magnitude of the functions obtained with a more complex simulation. The experimental design used is shown in table I.

Apparatus

The remote manipulator task was simulated using an analog computer and a 21" oscilloscope. Either a dot on the CRT or two lines at a right angle juncture represented the arm. A circle represented target size and position. The operator was required to operate a two-axis controller to maneuver the dot from the initial position into the target circle. A detailed description of the apparatus, the equations of motion, and operating procedures are given in appendix I.

Independent Variables

The following three variables relating to machine characteristics were investigated.

TABLE I

Matrix of Experimental Conditions: Experiment 1

				Simple		Complex	
				FR*	PR**	FR*	PR**
R_1	D_1	S_1	T_1				
			T_2				
		S_2	T_1				
			T_2				
	D_2	S_1	T_1				
			T_2				
		S_2	T_1				
			T_2				
	D_3	S_1	T_1				
			T_2				
		S_2	T_1				
			T_2				
R_2	Same as R_1						
R_3	Same as R_1						
R_4	Same as R_1						
				Subjects #1 - 8		Subjects #9 - 16	

Note: The four sub-experiments on this study (indicated by the columns) were conducted over a period of seven (7) months requiring the use of different subjects for the evaluation of the simple and the complex dynamics. For analytical purposes it was possible to combine the experiments as indicated into a single analysis (appendix II).

*Fixed rate control

**Proportional rate control

1) Control Mode: Rates of manipulator arm motion were either proportional to stick deflection (proportional rate) or were set at one level (fixed rate) upon stick activation.

2) Rates of Motion: Four levels were used. These were defined as the maximum rates obtainable in a single axis upon controller activation. With the fixed rate control (FR) the rate of motion was obtained immediately upon control activation. With the proportional rate controller (PR), this rate of motion was obtained upon maximum control deflection.

3) Dynamic Complexity: Two levels of complexity were employed. The simple dynamics condition represented a situation of minimum dynamic complexity and the highest possible degree of abstraction, e.g., output rates were a simple function of input magnitude. The manipulator arm was represented by a dot (appendix I). This was envisioned as a baseline condition. The complex dynamics (appendix I) were selected to represent the electro-mechanical characteristics of a manipulator such as the General Mills 300. Thus, the system response was not a simple function of input magnitude, but was affected by factors such as the mass of the arm, the length of the arm segments, the spring constants, damping factor, backlash, resiliency, etc. The arm was represented as two line segments at a right angle juncture (appendix I, figure 13).

The following three variables relating to task characteristics were investigated.

1) Distance from Initial Position to Target: It has been shown in other research (ref 22) that travel is essentially constant across a range of distances since the operator imparts a velocity to the system which varies approximately with the expected excursion. We wished to determine whether this result would hold for rate manipulator systems and, also, to evaluate the interaction of distance with the other variables. Three levels of this variable were used.

2) Target Size: This variable was used to represent two levels of positioning accuracy, required after the travel motion was accomplished. In a real situation it would represent the tolerances to which a manipulator must be operated. Two levels of this variable were used.

3) Criterial Time: In many cases after a manipulator attains a position it is required to remain in that position for a discrete period of time. This requirement was represented by criterial time. Two levels of this variable were used.

The specific values for the levels of each factor described above are given in table II.

TABLE II

Experimental Conditions: Experiment I

Rates of Motion

	cm/sec	in/sec	deg/sec
R_1	1.27	.50	.23
R_2	9.32	3.67	1.75
R_3	17.35	6.83	3.25
R_4	25.40	10.00	4.76

Distance

	centimeters	inches	degrees
D_1	11.35	4.47	2.13
D_2	21.39	8.42	4.00
D_3	36.63	14.42	6.52

Target Size

	centimeters	inches	degrees
S_1	.64	.25	.12
S_2	1.27	.50	.25

Criterial Time	seconds
T_1	1
T_2	4

Control Modes

Fixed Rate: Operation of the off-on controller in either axis produced a fixed rate of manipulator arm motion given by R_1, R_2, R_3, or R_4 above.

Proportional Rate: Rate of arm motion in each axis was proportional to stick deflection from zero to a maximum rate given by R_1, R_2, R_3 or R_4 above.

Dynamics (see appendix I)

Simple: Output rates were a simple function of input magnitude.

Complex: Output rates were a function of input magnitudes, system mass, damping, and motor characteristics.

Subjects and Procedure

Subjects were paid male volunteers from a local university. Each subject served for two experimental sessions. Eight subjects performed under the simple dynamics conditions; eight others performed under the complex dynamics conditions. In each session each subject was put through a randomized sequence of 48 conditions. Half the subjects used fixed rate control during the first session and proportional rate control during the second session. The order was reversed for the other subjects.

Each condition was run for three trials, but the data used in the analysis was taken only from the third trial under each condition. This procedure was used to minimize the effects of transferring from one condition to the next.

Dependent Variables

In keeping with the exploratory nature of these studies, four dependent variable measures were taken. They were 1) travel time, 2) adjustment time, 3) total time, and 4) time on target (T.O.T.). These four measures are described and illustrated in appendix I. The travel and adjustment scores were expected to reflect any differential effects of the independent variables on these two basic components of response. The sum of travel and adjustment times results, of course, in the total time score. The T.O.T. score was included in the belief that it might reflect the ability of subjects to maintain the manipulator arm within the target area for the criterial period.

Results

Table III presents a summary of the terms significant in the analyses of variance for each of the four measures used, e.g., travel time, adjustment time, T.O.T., and total time. The 1% level of confidence was used for acceptance of significant differences. Appendix II presents the complete analysis of variance summary tables.

When an experimental treatment results in a group of means which an analysis of variances shows to differ significantly among themselves it is appropriate to determine the specific nature of these differences. For this purpose we employed the Tukey test of honestly significant differences (ref 25). For purposes of presenting the results of this test, means are rank ordered by magnitude. Means which do not differ significantly from one another are joined by underlining. The 1% level of confidence was always used for the Tukey HSD test.

Control Mode: The main effect of control mode was significant for the adjustment and total scores. The mean values are given below.

	Fixed Rate	Proportional Rate
Adjustment	2.12	.79
Total	11.65	10.17

Superior adjustment performance was attained with the proportional control system. This effect is due largely to the superior fine control offered by the proportional system.

Dynamics: A significant main effect of dynamics was found for travel, adjustment and total scores. Performance deteriorated as the control task was made more difficult through the introduction of more complex dynamics. The mean values obtained are as follows.

	Travel	Adjustment	Total
Simple	8.40	1.07	9.47
Complex	10.52	1.83	12.35

Rate: The main effect of rate was significant for each measure. The results are plotted in figure 1 for the travel, adjustment, total time, and T.O.T. scores. Tukey HSD tests were performed on the means. These results are presented in table IV.

The Tukey HSD test essentially indicates that no significant differences exist as a function of rate beyond the R_2 level. Both the adjustment and T.O.T. scores increase as a function of rate although successive means do not differ significantly. For the total score, R_4 is significantly different from R_1 and from R_2 and R_3 indicating an upturn at high rates and a U-shaped relationship. The increase at high rates comes partially from an increase in travel time and partially from an increase in adjustment time (figure 1). The shape of the function can be explained in terms of the difficulty of making precise movements when control rate is too high. Precise responses are required both to attain the target circle area which can influence travel time, and to remain within it, which is revealed in the adjustment time score. The U-shaped function follows the results obtained by Gibbs (ref 13).

Distance: The analysis indicated significant differences in travel and total scores as a function of distance. For each measure all means differed from one another as indicated by the Tukey HSD test. The mean values (derived from tables VIII and IX) are plotted in figure 2. The relationship is largely determined by the physical

TABLE III

Summary of Terms in the Analyses of Variance
for Experiment 1, Significant at the 1% Level of Confidence

Source	Travel Time	Measure Adjustment Time	Time on Target	Total Time
Control Mode		xx		xx
Dynamics	xx	xx		xx
Subjects	xx			xx
Rate	xx	xx	xx	xx
Distance	xx			xx
Size	xx			xx
Time			xx	
CM x Dy				xx
CM x Ss	xx			xx
CM x R	xx	xx		xx
CM x D	xx			
Dy x R	xx			xx
Dy x S	xx	xx	xx	xx
D x R	xx			xx
CM x Dy x R	xx			xx
CM x R x D	xx			

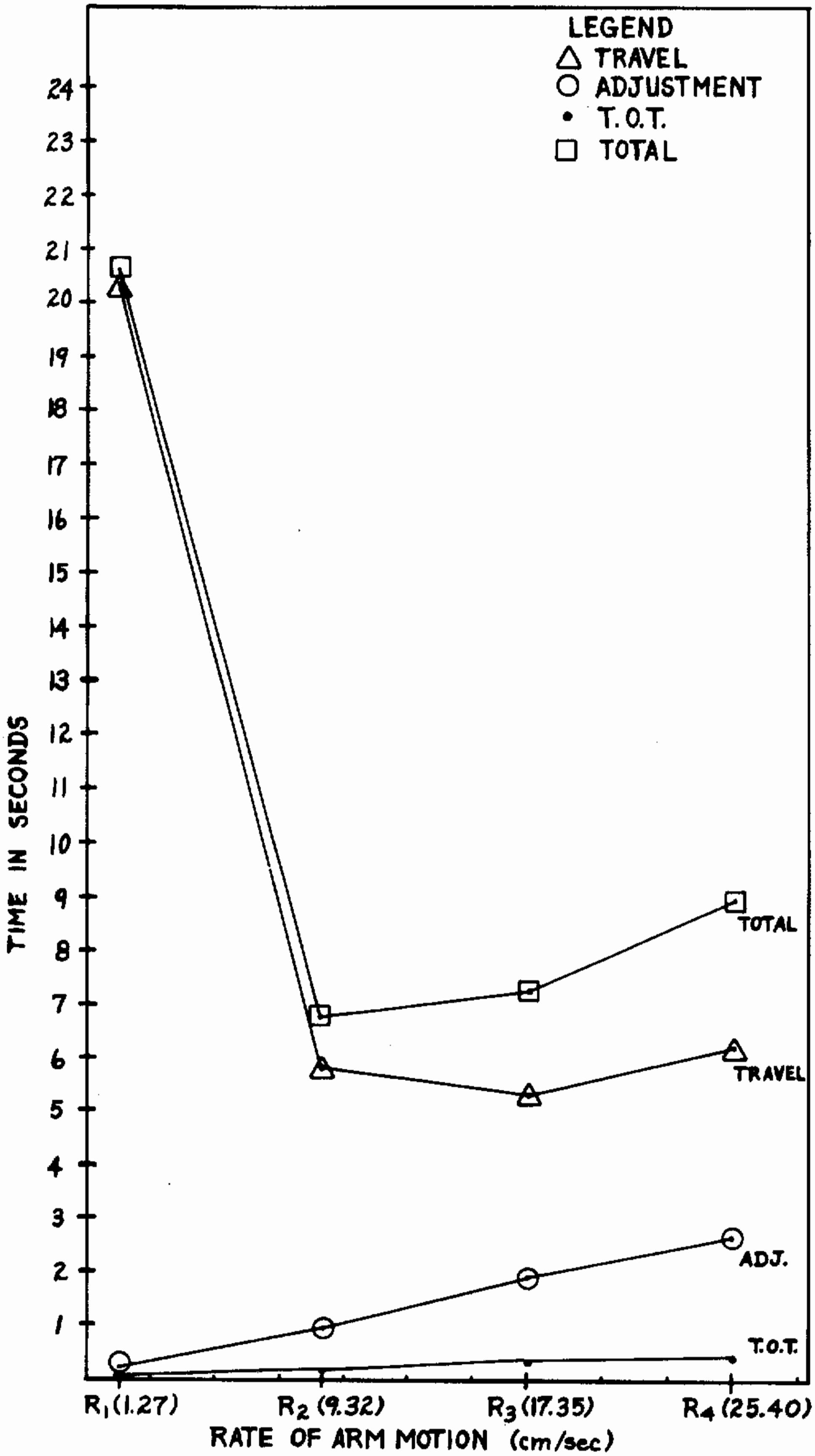

Fig. 1. Mean Travel, Adjustment, Time on Target, and Total Time Scores as a Function of Rate.

TABLE IV

Travel, Adjustment, T.O.T., and Total Time Means, and Tukey HSD Test of Significant differences for the Main Effect of Rate

Travel	R_1	R_4	R_2	R_3
	20.43	6.26	4.79	5.35
Adjustment	R_4	R_3	R_2	R_1
	2.72	1.94	.96	.19
T. O. T	R_4	R_3	R_2	R_1
	.42	.37	.23	.08
Total	R_1	R_4	R_3	R_2
	20.62	8.98	7.28	6.76

Note: On this and all subsequent tables of Tukey HSD tests, the underlined Means are not significantly different.

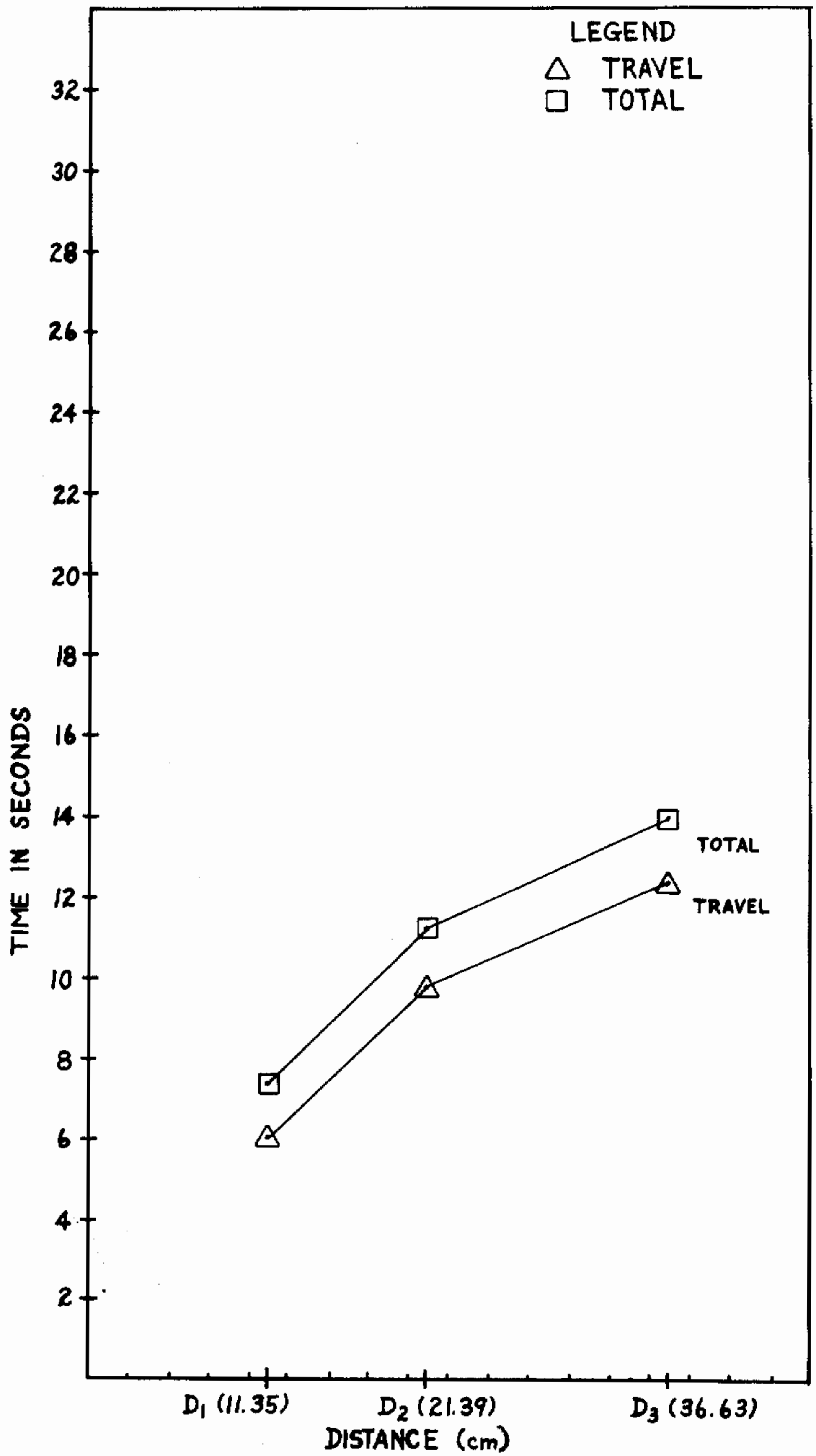

Fig. 2. Mean Travel and Total Time Scores as a Function of Distance.

limits of traversing the various distances. The total score is approximately equal to travel time plus a constant which would be adjustment time.

Size: Significant differences were found in travel and total time scores as a function of target size. The obtained mean values in seconds are shown below.

	Travel	Total
S_1	9.74	10.14
S_2	9.18	11.68

The lower travel times for S_2, e.g., the larger target, are understandable in terms of the ease of hitting the target and terminating the travel time period.

Time: The effect of criterial time was significant only in terms of the T.O.T. measure. Time on target was scored as time within the target area minus the criterial time required for problem termination. This measure was generally sensitive to the effects of experimental adjustments involving target size and criterial time. Its value is questionable since the obtained relationships are not logically consistent.

Control Mode x Dynamics: A significant interaction of control mode and dynamics for the total score was indicated by the analysis of variance. Means and results of the Tukey HSD test are presented below.

Complex/FR	Complex/PR	Simple/PR	Simple/FR
13.68	<u>11.03</u>	<u>9.92</u>	<u>9.62</u>

The most difficult condition, e.g. complex dynamics with fixed rate control, differ from all others. As was also shown previously by the main effect term of dynamics, performance is superior with simple dynamics. Where the control task is more complex, proportional rate control is superior.

Control Mode x Rate: The interaction of control mode and rate was found to be significant for the travel, adjustment and total time scores. The means are presented in table V, and plotted in figure 3.

The Tukey HSD test on the travel time means indicated that the means for PR/R_2 PR/R_3 and PR/R_4 did not differ significantly from one another. All other means for this interaction differed significantly from one another and from PR/R_2, PR/R_3 and PR/R_4 means.

For both control modes (figure 3), travel performance improves markedly with an increase in rate from R_1 to R_2. Performance with the proportional rate system is not significantly affected by increases beyond R_2 (9.32 cm/sec, 3.67 in/sec) while

TABLE V

Travel, Adjustment, and Total Time Means
as a Function of Rate and Control Mode

		R_1	R_2	R_3	R_4
Travel Time					
	FR	18.35	6.01	6.04	7.74
	PR	22.52	5.58	4.66	4.79

(PR1 FR1 FR4 FR3 FR2 PR2 PR4 PR3)

		R_1	R_2	R_3	R_4
Adjustment Time					
	FR	.14	1.27	3.02	4.04
	PR	.24	.66	.85	1.39

(FR4 FR3 PR4 FR2 PR3 PR2 PR1 FR1)

		R_1	R_2	R_3	R_4
Total Time					
	FR	18.48	7.27	9.06	11.78
	PR	22.76	6.24	5.51	6.18

(PR1 FR1 FR4 FR3 FR2 PR2 PR4 PR3)

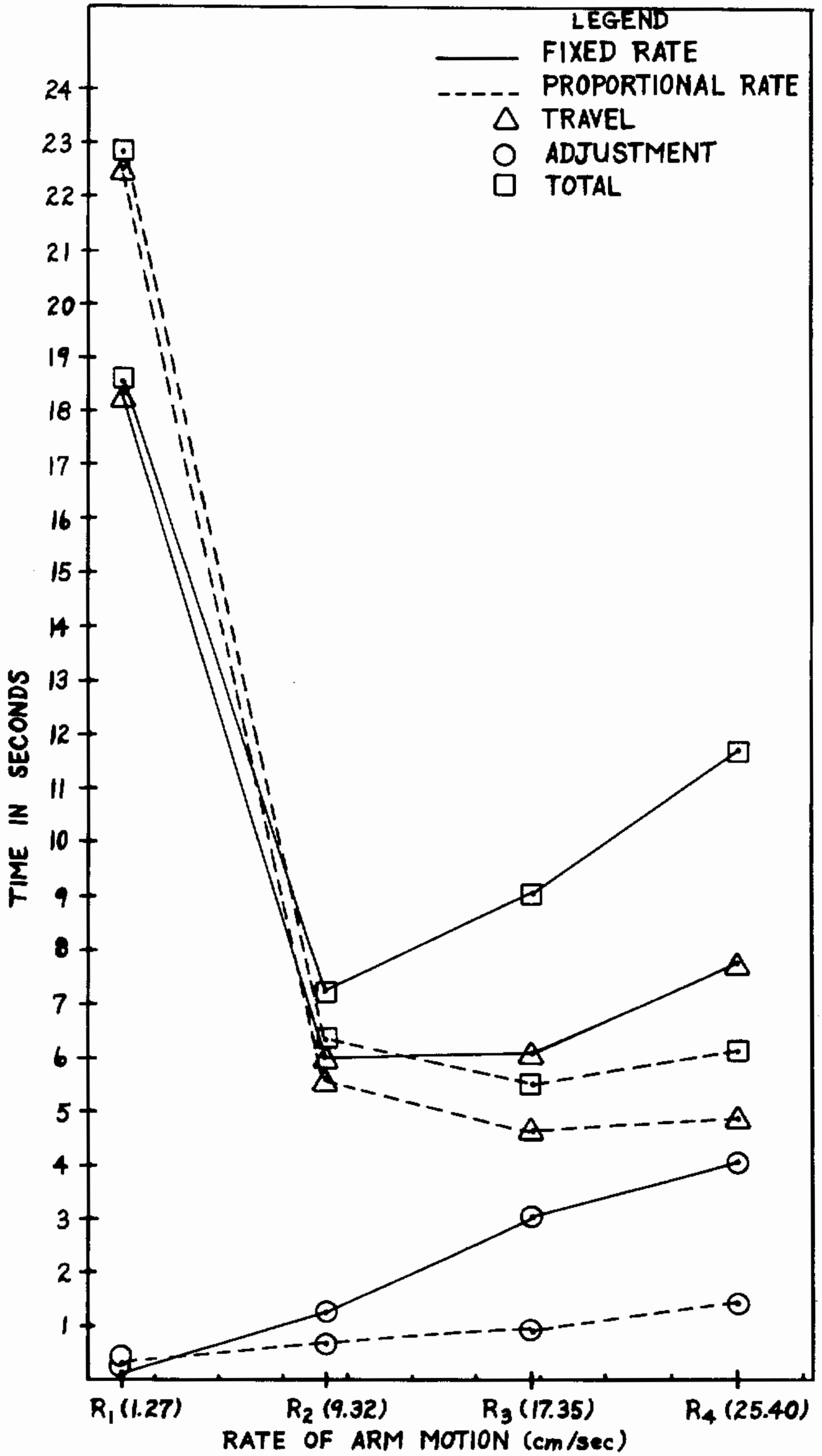

Fig. 3. Mean Travel, Adjustment, and Total Time Scores as a Function of Control Mode and Rate.

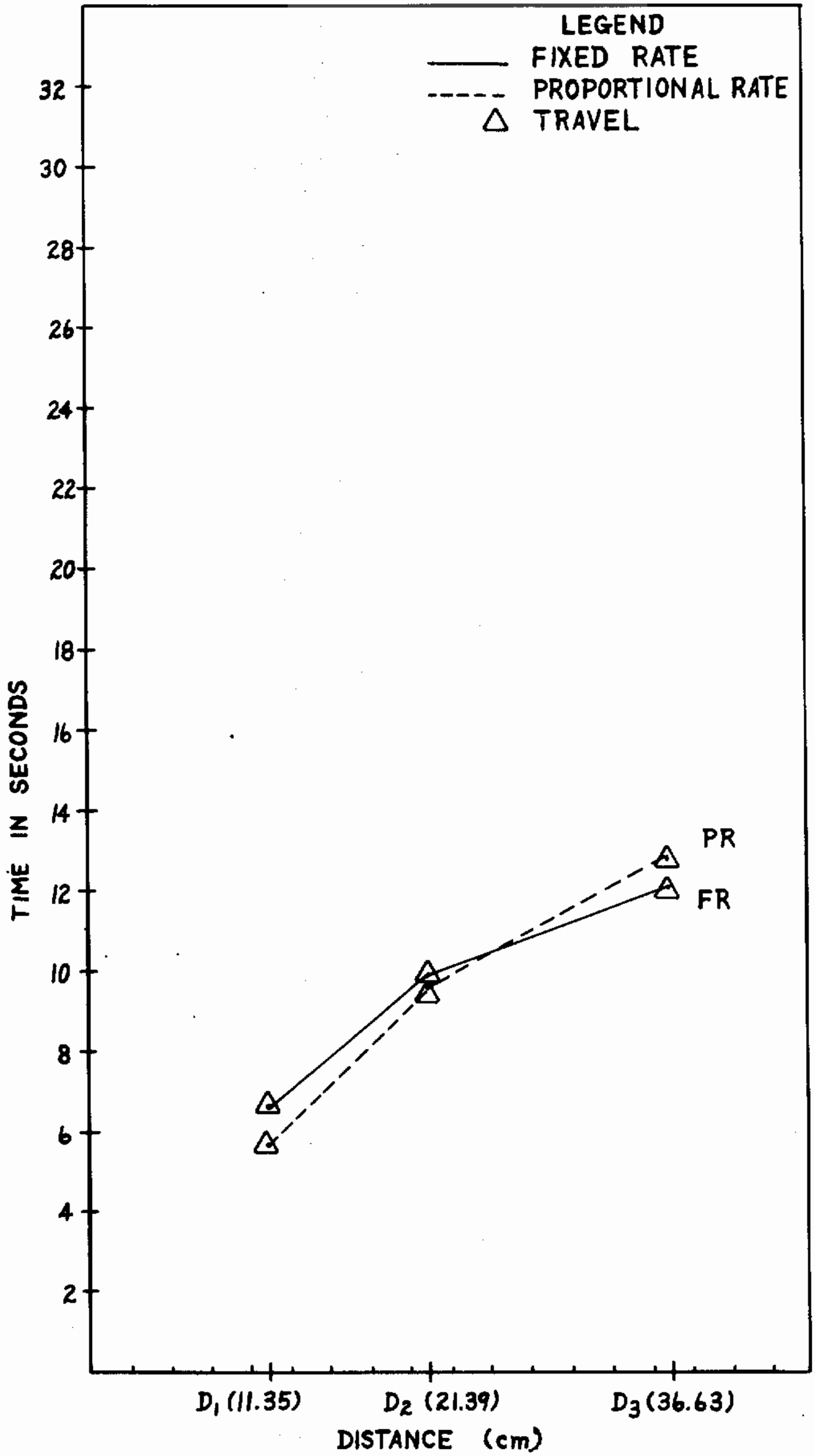

Fig. 4. Mean Travel Time as a Function of Control Mode and Distance.

performance with the fixed rate system degrades as the rate is increased from R_3 (17.35 cm/sec, 6.83 in/sec) to R_4 (25.40 cm/sec, 10.00 in/sec). Performance with the fixed rate system yielded a U-shaped relationship while the proportional rate system yielded asymptotic performance beyond R_2.

Figure 3 also shows essentially linear increases in adjustment time for both the fixed rate and proportional rate systems, with the slope being about twice as steep for the fixed rate system. The Tukey HSD test yielded no significant differences among the proportional rate means, but the means for FR/R_3 and FR/R_4 differed significantly from one another and from all other means. Adjustment time increases at higher rates of motion when fixed rate control is utilized.

The total scores as a function of control mode and rate are presented in figure 3. Here the U-shaped function for fixed rate control is evident. Within the proportional rate mode, R_1 differs from R_2, R_3, and R_4 indicating an asymptotic function. The fixed rate and proportional rate curves differ at each point except R_2 indicating the proportional control is inferior at low rates of motion but becomes superior as rate of motion is increased.

Control Mode x Distance: The interaction of control mode and distance was found to be significant for the travel time score. The mean values are presented below and plotted in figure 4.

	D_1	D_2	D_3
Fixed Rate	6.68	9.83	11.99
Prop. Rate	5.65	9.64	12.86

The Tukey HSD test shows that the means for the control modes differ from one another at D_1 and D_3 and the differences between distances are all significant. When distance increases, travel time increases more rapidly for proportional rate control than for fixed rate control. As with the distance main effect, the basic relationship can be explained in terms of the time required to physically traverse the required distance. The times do not increase linearly with distance indicating that some other factor, perhaps response time, enters into the obtained relationship.

Dynamics x Rate: The interaction of dynamics and rate was significant for travel and total scores. The mean values are presented in table VI and plotted in figure 5. For the travel score, the Tukey HSD test revealed that within each control mode the R_1 mean differed from those of R_2, R_3, and R_4 which did not differ among themselves. Between control modes, R_1 means did not differ while all others did. This indicates that at the lowest rate, R_1, dynamic complexity had no significant

TABLE VI

Travel and Total Time Means as a Function of Control Mode, Dynamics, and Rate

		R_1	R_2	R_3	R_4
Travel Time					
	FR	18.50	4.69	4.16	5.47
Simple	PR	21.56	5.09	3.93	3.77
	$\overline{M}$	20.03	4.89	4.05	4.62
	FR	18.19	7.32	7.91	10.00
Complex	PR	23.47	6.07	5.38	5.80
	$\overline{M}$	20.83	6.70	6.65	7.90
Total Time					
	FR	18.61	5.50	5.99	8.37
Simple	PR	21.88	5.72	4.61	4.96
	$\overline{M}$	20.25	5.66	5.30	6.67
	FR	18.36	9.04	12.13	15.18
Complex	PR	23.64	6.66	6.41	7.40
	$\overline{M}$	21.0	7.85	9.27	11.29

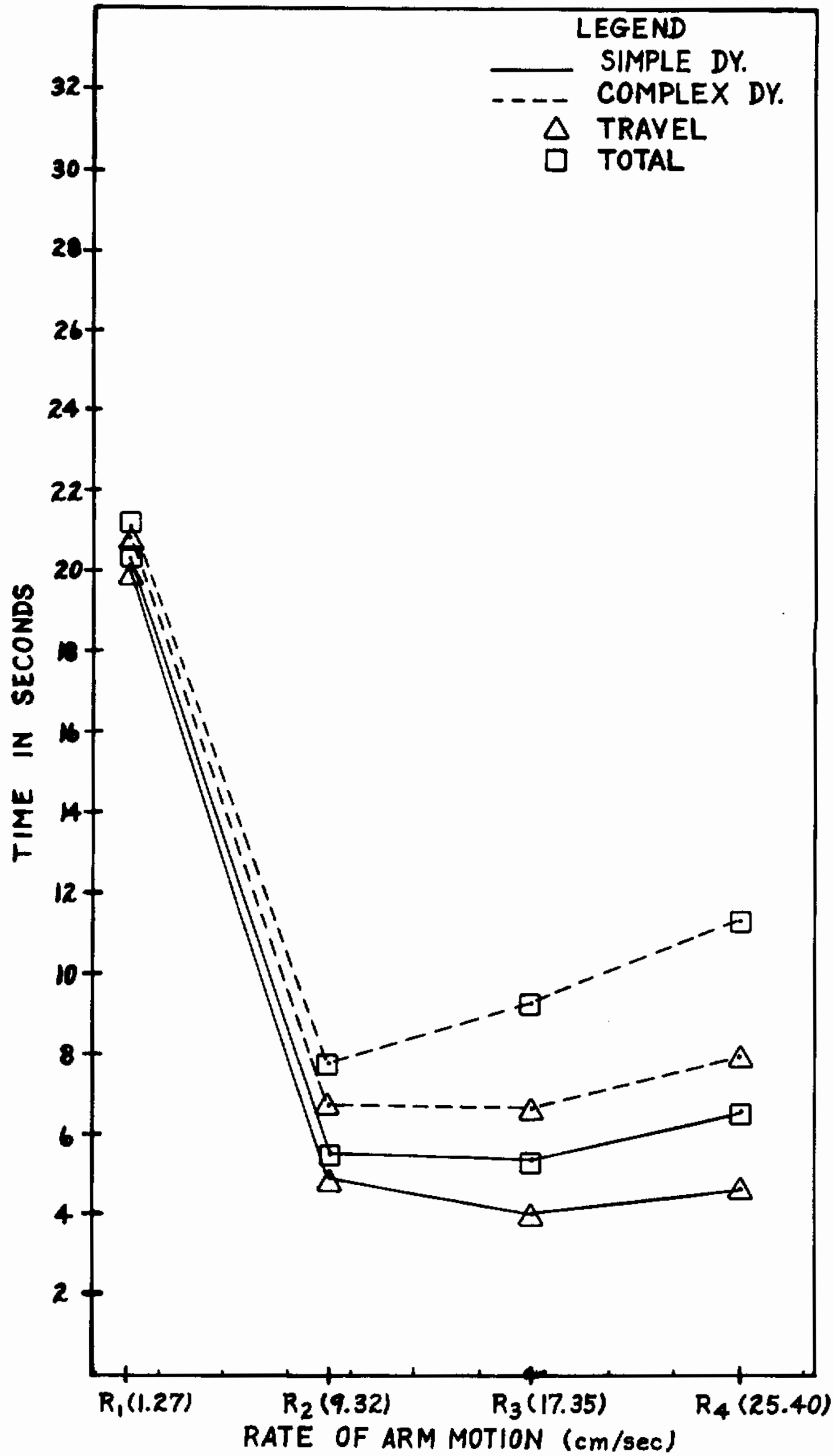

Fig. 5. Mean Travel and Total Time Scores as a Function of Dynamics and Rate.

effect. For each control mode, performance was asymptotic as a function of rates above R_2 and was clearly superior with the simple dynamics. Apparently the basic effect of rate does not change markedly as a function of complexity, since the curve forms are similar but the absolute level of performance varies.

The findings for the total time score are somewhat more complicated. With the complex dynamics, all means differ significantly from one another. With the simple dynamics, R_1 differs from R_2, R_3, and R_4 which do not differ from one another. Thus, the complex function may be described as U-shaped while the simple one is asymptotic. Between control modes, only the R_4 means differ indicating an upturn in the complex curve. It appears that the U-shaped relation can be expected as a function of increasing task complexity, and is probably due to the fine adjustment requirements of the task which are not compatible with high levels of fixed rate control.

Dynamics x Distance: The interaction of dynamics and distance proved significant for the total time score. The obtained means are as follows.

	D_1	D_2	D_3
Simple	6.44	9.28	12.69
Complex	8.34	13.24	15.48

The Tukey HSD test indicates that all means for the complex dynamics differ from one another. For the simple dynamics D_1 and D_2 differ from D_3. Between dynamics, at each distance, all differences are significant. Performance time increases for both systems, but increases more sharply over the short distances for the complex system.

Dynamics x Size: The interaction of dynamics and size was significant for all four measures. The means and the results of the Tukey HSD tests are presented in table VII.

For the travel, adjustment, and T.O.T. scores, differences as a function of dynamics occur only with the small target, S_1. With simple dynamics, performance with S_1 is superior. With complex dynamics, the reverse is true. For the travel score, differences due to size were significant with both sets of dynamics. For the total score, target size produced significant differences with both simple dynamics, and the complex dynamics. There is also a reversal of order. With simple dynamics, performance under S_1 conditions is always superior. With complex dynamics, performance under S_2 conditions is superior. No ready explanation of this is apparent.

Rate x Distance: The interaction of rate and distance was significant for the travel and total scores. The means for the travel scores are presented in table VIII

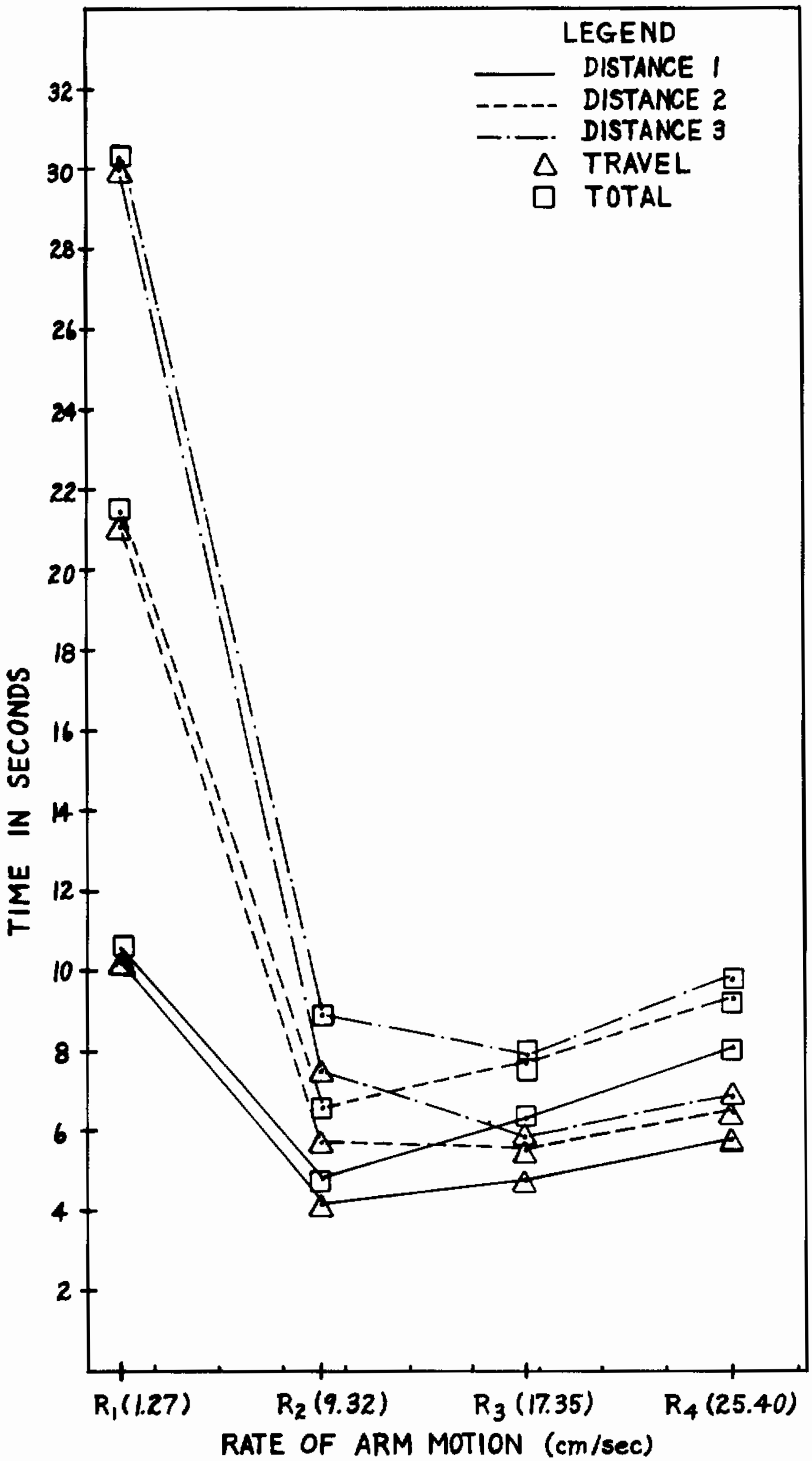

Fig. 6. Mean Travel and Total Time Scores as a Function of Distance and Rate.

Table VII

Travel, Adjustment, T.O.T., and Total Time
Means as a Function of Dyanmics and Size

Travel Time

S_1/S	S_2/S	S_2/C	S_1/C
7.83	8.96	9.39	11.64

Adjustment Time

S_1/S	S_2/C	S_2/S	S_1/C
.60	1.54	1.13	2.53

Time on Target

S_1/S	S_2/C	S_2/S	S_1/C
.10	.22	.31	.46

Total Time

S_1/S	S_2/S	S_2/C	S_1/C
8.43	10.50	10.52	14.17

TABLE VIII

Travel Time Means as a Function of
Distance, Control Mode and Rate

		R_1	R_2	R_3	R_4
	FR	9.57	4.47	5.50	7.18
D_1	PR	10.72	3.90	3.98	4.01
	$\overline{M}$	10.15	4.19	4.74	5.60
	FR	18.85	5.75	6.49	8.34
D_2	PR	23.45	5.66	4.62	4.83
	$\overline{M}$	21.15	5.70	5.55	6.53
	FR	26.62	7.80	6.12	7.78
D_3	PR	33.39	7.18	5.37	5.52
	$\overline{M}$	30.00	7.49	5.73	6.65

TABLE IX

Total Time Means as a Function
of Rate and Distance

	R_1	R_2	R_3	R_4
D_1	10.45	4.73	6.31	8.04
D_2	21.34	6.61	7.77	9.32
D_3	30.07	8.93	7.76	9.57

and those for the total score are presented in table IX. The values are plotted in figure 6. For the travel score, the means for D_1, D_2, and D_3 at R_1 differ among themselves and are different from all means at R_2, R_3, and R_4, which do not differ with the exception of D_1 differing from D_3 at R_2. With low rates of motion, the difference in distance to be travelled significantly affects travel time. This is a limitation imposed by the maximum rate of motion available to traverse a fixed distance. Where rates are high enough so that no appreciable time difference would be required to traverse the physical distance, performance differences are not significant. If we were to examine travel time in excess of minimum possible, a measure which reflects the human's contribution, we would find this increases with increasing rate, and the percentage of time in excess of minimum possible increases even more rapidly.

The comparison of total score means by the Tukey HSD test indicates a relationship similar to that described for the travel score. Here D_1/R_1, D_2/R_1, and D_3/R_1 differ from one another. The D_1 curve has significant differences between R_1 and R_2, between R_2 and R_4, but not between R_1 and R_4. Also, D_1/R_2 differs significantly from D_2/R_2. The distance curve is clearly U-shaped indicating a marked decrement in performance with increasing rate, which is only partially attributable to the travel score.

Although the adjustment scores were not significantly different, it is probable that they contributed markedly to producing the significant total score. It has been previously shown that adjustment time increases with increased rate. It has also been suggested that the difficulty of hitting a target at higher rates contributes to higher travel scores. Thus, the relationships obtained as a function of distance and rate may be understood in terms of (1) a limitation imposed by minimum possible transit times, and (2) the difficulty of making fine responses with higher rate levels.

Distance x Time: Significant differences among total time means were determined by the analysis of variance. The mean values are given below.

	D_1	D_2	D_3
T_1	7.69	11.16	13.55
T_2	7.05	11.72	14.67

According to the Tukey HSD test, within each criterial time all means differ from one another. No significant effects of criterial time within a given distance were noted.

Control Mode x Dynamics x Rate: The interaction of control mode x dynamics x rate was significant for both travel and total scores. The mean values are presented in table VI and plotted in figures 7 and 8. The Tukey HSD comparison of means for the travel score revealed that within each control mode/dynamics condition, R_1 differed from all other rates. For the fixed rate/complex condition R_4 differed from

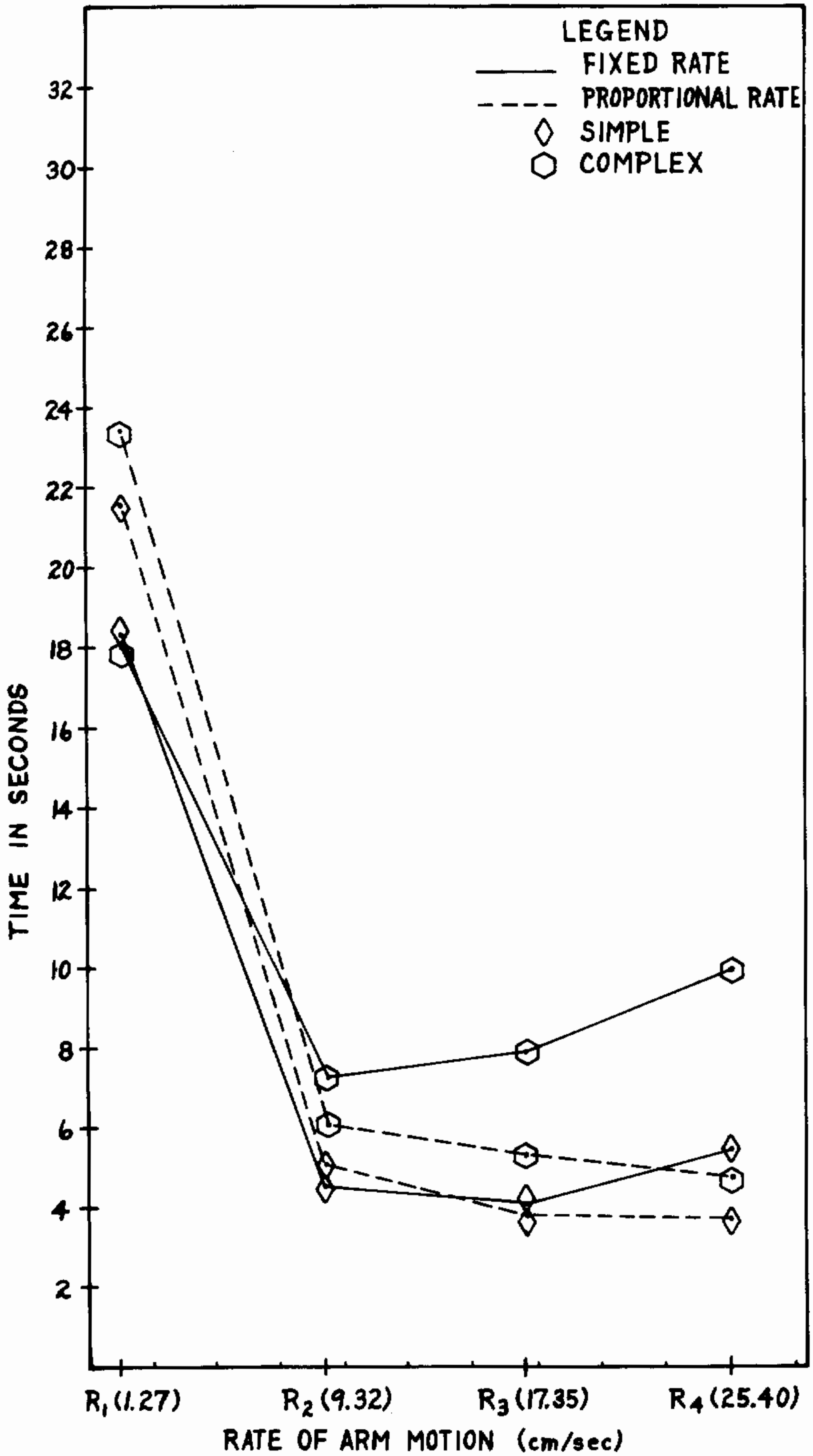

Fig. 7. Mean Travel Time Scores as a Function of Control Mode, Dynamics, and Rate.

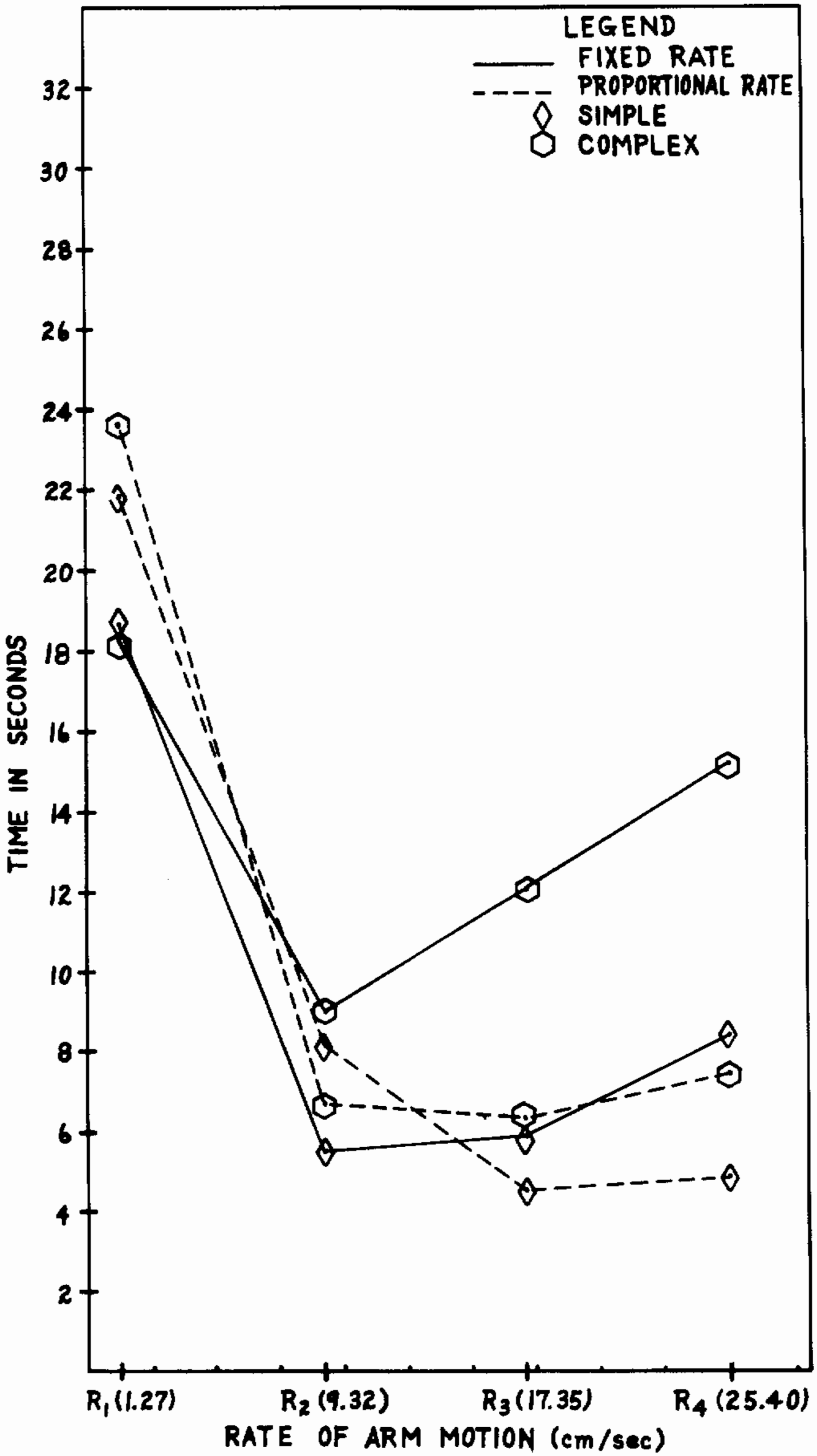

Fig. 8. Mean Total Time Scores as a Function of Control Mode, Dynamics, and Rate.

R_2 and R_1, indicating a significant increase in score at R_4. For the other curves, R_2, R_3, and R_4 did not differ. At R_1, the proportional control modes differed significantly from the fixed control modes. At R_2, the two fixed modes differed as a function of dynamics, and for R_3 and R_4 the fixed rate/complex mode differed significantly from all others. An examination of figure 7 will indicate that the fixed rate/complex curve appears different from the others and is generally U-shaped while the others are generally asymptotic.

The total scores reveal a similar set of relationships. Within the fixed rate/complex curve, R_1 differs from R_2 and R_3 but not from R_4. R_3 and R_4 differ from R_2. Thus, R_2 represents a minimum and a definite U-shaped relationship prevails. Within each of the other curves, R_1 differs significantly from R_2, R_3, and R_4, which do not differ from one another, indicating asymptotic relationships.

Comparison between curves at R_1 shows the proportional control modes differ from the fixed control modes, and at R_2, R_3, and R_4 the fixed rate/complex curve differs from all others. At R_4, the mean for proportional rate/simple is also significantly different from all others. Thus, in terms of total score, the U-shaped relationship for fixed rate/complex is repeated. There is, in addition, some evidence for an upturn of the fixed rate/simple, and proportional rate/complex curves. These results again indicate that higher rates are detrimental and appear to interact as a function of task complexity.

Control Mode x Rate x Distance: The interaction of control mode, rate, and distance was significant for the travel time score. Means are presented in table VIII and plotted in figure 9. Tukey HSD tests were performed to compare means within each control mode/distance condition across rates, and to compare between control mode/distance combinations at each rate. The fixed rate/D_1 curve is U-shaped as shown by the lack of significant differences between the R_1, R_3, and R_4 values, and the significant difference between them and the R_2 value. The other curves all show the R_1 value to differ significantly from the R_2, R_3, and R_4 values, which do not differ among themselves within each curve.

At R_1, the fixed rate/D_3, and proportional rate/D_2 means do not differ, nor do the fixed rate/D_2 and the proportional rate/D_1 means. At R_2, the proportional rate/D_1 mean differs from the D_3 means for both control modes and the fixed rate/D_1 and D_3 means differ. At R_3, only proportional rate/D_1 and fixed rate/D_3 differ. At R_4, the relationship among means is given below.

FR/D_2	FR/D_3	FR/D_1	PR/D_3	PR/D_2	PR/D_1
8.34	7.78	7.18	5.52	4.83	4.01

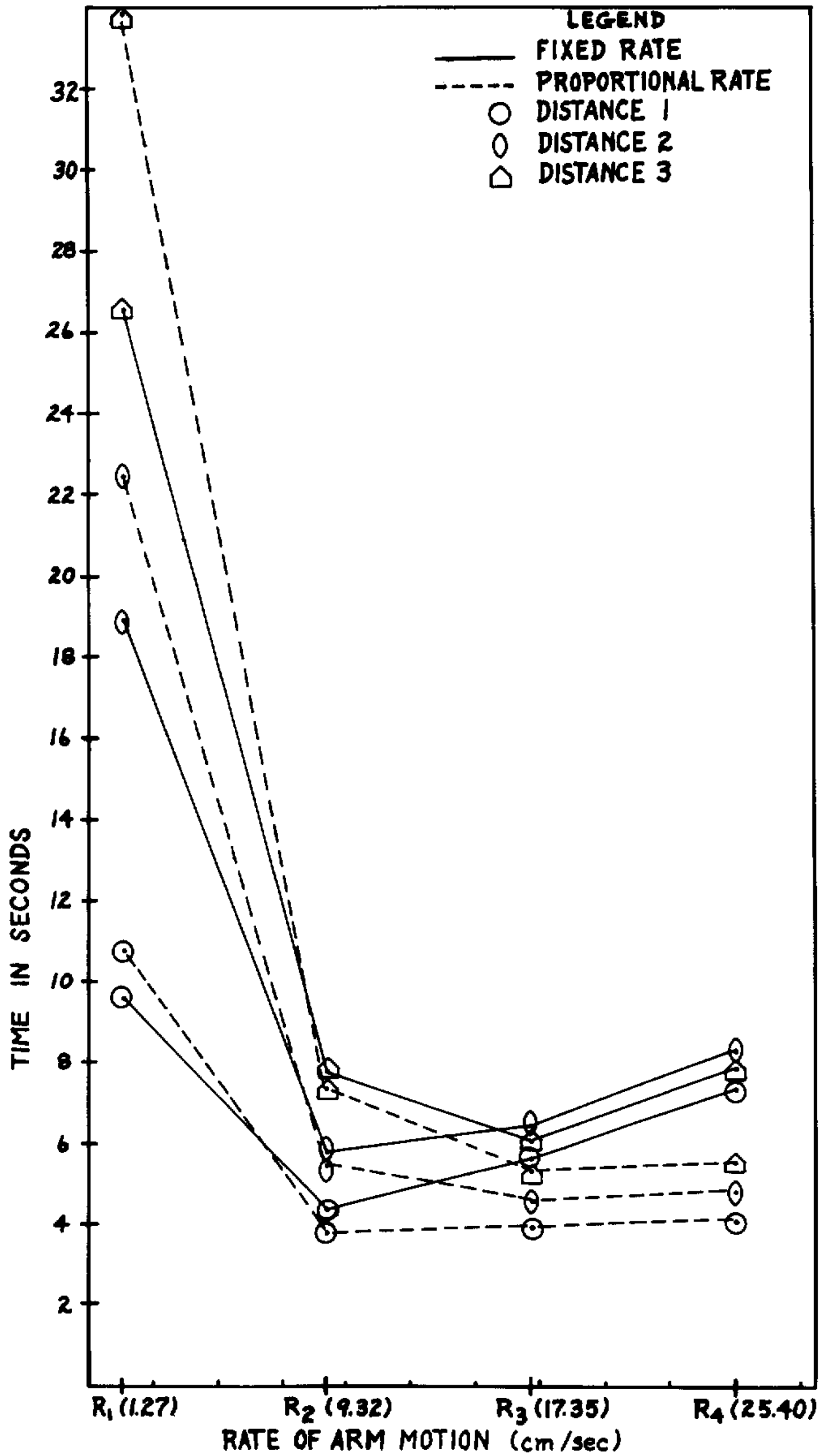

Fig. 9. Mean Travel Time Scores as a Function of Control Mode, Distance, and Rate.

TABLE X

Mean Adjustment and Total Time as a Function of Dynamics, Rate, and Size

	Simple R_1	Simple R_2	Simple R_3	Simple R_4	Complex R_1	Complex R_2	Complex R_3	Complex R_4
Adjustment Time								
S_1	.36	.22	.73	1.43	.23	1.50	3.74	4.66
S_2	.39	1.32	1.78	2.66	.09	.82	1.51	2.13
Total Time								
S_1	19.75	4.58	4.18	5.21	21.31	9.53	11.82	13.86
S_2	20.79	6.74	7.37	8.11	20.32	5.99	6.71	8.71

There is substantial separation of the fixed rate and proportional rate curves. There is evidence then, that the fixed rate curves are U-shaped and the proportional rate curves are asymptotic. In addition, distance seems the primary determinant of differences at the low rates and control mode appears to produce the differences at the highest rates.

Dynamics x Rate x Size: Significant differences were obtained for the dynamics x rate x size interaction for adjustment and total time scores. These values are presented in table X. For the simple/S_1 data, the Tukey HSD test showed that the adjustment time means do not differ significantly as a function of rate. For the simple/S_2 data, R_1 and R_4 differ, other means do not. The same holds for the complex/S_2 data. For the complex/S_1 data, R_1 and R_2, which are not different, differ from R_3 and R_4, which are not different. At R_4, the complex/S_1 mean differs from the complex/S_2 and simple/S_1 means. No other differences were found. The complex dynamics clearly yield the higher adjustment scores. It is understandable that the complex system with the small target (S_1) would yield the highest scores, particularly at high rates, as it is the most difficult task. It is not clear why the simple/S_1 condition yielded the lowest scores.

For the total scores, the R_1 means for each dynamic/size combination differ from those for R_2, R_3, and R_4; between means at R_2, the complex/S_1 mean differs from the others and at R_3 and R_4 there are no differences as a function of dynamics for S_2, but these means differ from both S_1 means. The S_2 curves do not differ at any rate while the S_1 curves show marked differences at R_2, R_3, and R_4. It would appear that the smaller size target provides a more sensitive measure of total performance although the contribution of the adjustment times are not logically resolved.

Dynamics x Rate x Time: The adjustment and total time mean values for the interaction of dynamics x rate x time, which was significant, are presented in table XI and the results of the Tukey HSD test are indicated for each dynamics/time combination. For the adjustment score, with the exception of the simple/T_2 combination, there is a general significant increase as a function of rate. Comparisons between means at each rate indicate no differences for R_1, R_2, or R_3. At R_4, the complex/T_1 mean differs significantly from all others, which do not differ.

For the total score, the R_1 means for each dynamic/time combination differ from the R_2, R_3, and R_4 means. The curves for the simple dynamics are essentially level beyond R_2 while an upturn is indicated for the complex dynamics. At R_1, there are no differences among the four curves. At R_2, the two extreme means, simple/T_1 and complex/T_2, differ from R_3 and R_4. The complex means differ from the simple means. With the complex dynamics, an increase in score occurs as a function of increasing rate.

TABLE XI

Mean Adjustment and Total Time as a Function of Dynamics, Rate, and Time

	Simple				Complex			
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4
Adjustment time								
T_1	.20	.44	1.03	2.46	.15	1.11	2.57	2.26
T_2	.23	1.10	1.47	1.63	.17	1.21	2.68	4.53
Total time								
T_1	20.28	5.15	5.89	7.02	21.41	7.47	8.90	10.16
T_2	20.21	6.17	5.66	6.30	20.71	8.05	9.63	12.42

TABLE XII

Mean Travel and Total Time Scores as a Function of Rate, Distance and Time

		R_1	R_2	R_3	R_4	M
Travel time						
T_1	D_1	10.34	3.90	5.17	5.89	
	D_2	22.01	5.46	5.07	7.23	
	D_3	29.95	7.27	6.19	6.79	
T_2	D_1	9.96	4.48	4.33	5.34	
	D_2	20.61	5.94	6.04	7.80	
	D_3	30.08	7.72	5.66	6.50	
Total time						
T_1	D_1	10.84	4.41	6.55	8.95	7.69
	D_2	21.71	6.31	8.98	7.62	11.16
	D_3	30.03	8.22	6.65	9.30	13.35
T_2	D_1	10.31	4.54	6.07	7.28	7.05
	D_2	20.94	6.90	8.00	11.02	11.72
	D_3	30.14	9.88	8.87	9.79	14.69

Dynamics x Size x Time: The T.O.T. measure produced a significant dynamics x size x time interaction. Mean values are presented below.

	Simple		Complex	
	T_1	T_2	T_1	T_2
S_1	.09	.11	.26	.66
S_2	.10	.45	.15	.26

The Tukey HSD test showed the complex means were significantly different from all the simple means with the exception of S_2/T_2. The interaction criterial time is marked by the high S_2/T_2 mean for the simple case and the high S_1/T_2 time for the complex case. The latter would be logical to expect due to the smaller target and longer required criterial time.

Rate x Distance x Time: This interaction was significant for the travel and total scores. The means are presented in table XII. For each D/T curve the Tukey HSD showed the R_1 value differed from those for R_2, R_3, and R_4. At R_1, the values for each distance do not differ as a function of time. At R_2, the D_3 means are significantly higher than the D_1 or D_2 means. At R_4, the D_2/T_2 mean differs from the D_1/T_2 mean.

For the total scores, the R_1 values for each curve differ from each other. For the D_1/T_1 curves, the R_4 value also differs from R_2 and R_3 as is also the case with the D_2/T_2 curve. At R_2, R_3, and R_4, no differences were found.

The results appear to be primarily determined by the distance and rate variables and no logical or consistent effect can be attributed to criterial time variable.

<u>Higher Order Interactions</u>

The analysis revealed several significant fourth and fifth order interactions. In general, the nature of the higher order differences is small. The same general trends as shown previously could be derived from the data. A detailed examination is possible for the interested reader through examination of the tables included in appendix III. Since the available studentized range tables are limited to 20 means we were unable to perform Tukey HSD tests of individual means except in the case of the control mode x dynamics x size x time interaction for T.O.T. where the number of means is 16.

EXPERIMENT II

This experiment was designed to investigate performance with a position control. When position control is used, a displacement of the controller results in a displacement of the controlled element. The ratio of input to output is termed gain. For purposes of the present study gain was defined as the ratio of the angular displacement of the manipulator arm, (in degrees of visual angle at the observer's eye) to the angular displacement of the hand controller about its axis (ref 13).

The functional relationships among the following variables were investigated.

1. gain
2. distance from starting point to target
3. target size
4. criterial time

Apparatus

The apparatus was identical to that employed in the simple, proportional rate conditions of experiment I. The manipulator was represented by a dot on the display and the target was a circle. A spring centered two axis proportional hand controller was used to provide control inputs to the analog simulator. Full deflection of the control from center (±30 degrees) produced maximum apparent arm displacements of 6.65°, 7.12°, 7.50° and 8.07° in visual angle at the operator's eye. Viewing distance was 304.80 cm (10 feet). A detailed description of the apparatus is given in appendix I.

Independent Variables

The following independent variables were investigated. Specific values for each level of each variable are presented in table XIII.

1. gain ratio of angular excursion of the manipulator arm (in degrees of visual angle) to maximum possible angular control deflection
2. distance from starting point to target
3. target size
4. criterial time

The task variables, distance, size, and criterial time were identical to those investigated in experiment I. The range of gains studied was limited due to constraints imposed by the display screen size, obtainable controller deflection, and the desire to maintain viewing distance, target size and other physical conditions similar to those in experiment I.

TABLE XIII

Experimental Conditions: Experiment II
Position Control, Simple Dynamics

Gain

	centimeters	inches	degrees
G_1	33.56	14	$6.65^\circ/30^\circ$
G_2	38.10	15	$7.12^\circ/30^\circ$
G_3	40.64	16	$7.58^\circ/30^\circ$
G_4	43.18	17	$8.07^\circ/30^\circ$

Distance

	centimeters	inches	degrees
D_1	7.18	2.83	1.35°
D_2	11.35	4.47	2.13°
D_3	16.05	6.32	3.02°

Target Size

	centimeters	inches	degrees
S_1	.64	.25	$.12^\circ$
S_2	1.27	.50	$.25^\circ$

Criterial Time

		seconds
T_1	=	1
T_2	=	4

Subjects and Procedures

Subjects were paid male volunteers from a local university. Each subject served for one experimental session during which he performed under a randomized sequence of all 48 conditions.

Each condition was run for three trials. The data used in the analysis was taken from the third trial under each condition to minimize the effects of transferring from one condition to the next.

Dependent Variables

The four dependent variables measured were: (1) travel time, (2) adjustment time, (3) total time, and (4) time on target (T.O.T.). These four measures are described in appendix I.

The experimental design used for analysis is presented in table XIV.

Results

The results of experiment II are summarized in table XV. The table indicates those terms in the analysis of variance which were significant at the 1% level of confidence. Complete summary tables for each are presented in appendix IV.

Variation in target size produced statistically significant differences in the travel, adjustment, T.O.T., and total time scores. A variation in criterial time produced significant differences in adjustment and total time scores. A significant interaction between size and criterial time was also found for the adjustment time score. The mean values are given in table XVI.

The smaller target size (S_1) resulted in lower scores for each measure; e.g. travel, adjustment, T.O.T. and total time. It was originally hypothesized (1) that S_2, the larger target, would produce lower scores for travel time because it was easier to hit and thereby would terminate the travel period sooner, and (2) that adjustment time would be lower for S_2 because it would be easier to stay within the larger target. We have been unable to explain this reversal in direction of the obtained effect after carefully eliminating the possibility of error due to data recording or data processing procedures.

The different criterial times, i.e. the duration for which the subject had to remain continuously on target after initial acquisition, produced significant differences in adjustment and total time scores. The subject had to remain on target for 1 second (T_1) or 4 seconds (T_2). The values in table XVI reflect the adjustment times in excess of these durations. Thus the amount of adjustment in excess of the minimum required was higher the longer the subject was required to remain on target. On a percentage

TABLE XIV

Summary Table: Basic Experimental Design

Source of variation	d.f.
Gain (Rate for experiment III)	3
D (Travel distance)	2
S (target size)	1
T (criterial time)	1
G x S	3
R x D	6
G x T	3
S x D	2
S x T	1
D x T	2
G x S x D	6
G x S x T	3
G x D x T	6
S x D x T	2
G x S x D x T	6
Error (within cells)	336
Total	383

TABLE XV

Summary of Terms in the Analyses
of Variance for Experiment II
Significant at the 1% Level of Confidence

Source	Measure: Travel Time	Adjustment Time	Time on Target	Total Time
Gain				
Distance				
Size	x	x	x	x
Time		x		x
G x D				
G x S				
G x T				
D x S				
S x T		x		
G x D x S				
G x D x T				
G x S x T				
G x D x S x T				

TABLE XVI

Means for Terms Significant in the Analyses of Variance, Experiment II

		Measure			
		Travel Time	Adjustment Time	Time on Target	Total Time
Target Size	S_1	1.30	.21	.12	1.51
	S_2	1.96	1.72	.87	3.68
Criterial Time	T_1		.58		2.19
	T_2		1.34		3.00

Target Size x Criterial Time (Adjustment Score)

	T_1	T_2
S_1	.13	.29
S_2	1.04	2.39

basis, the ratio of time in excess of criterial time to criterial time, e.g. (.58/1.00, 1.34/4.00) indicates that proportionately less excess time was spent in adjustment as the required absolute time increased (58% for T_1 as compared to 34% for T_2).

The difference in total time scores as a function of criterial time is attributed to the contribution to overall time score made by the adjustment portion of the task.

The position control system used was quite sensitive to control inputs. Small input motions produced relatively large arm displacements. The range of gains, and the initial target arm separation distances were small. Thus the travel time means were not expected to be sensitive to these experimental treatments. The different requirements for precise adjustments imposed by the two target sizes and the two criterial times did produce statistically significant differences in the adjustment time measure which was expected to reflect the capability for fine manipulative performance. With the position control system the subject was required to actively maintain the arm within the target area for the entire criterial time period. With the rate control systems returning the control to center would stop all arm motion.

Performance with position control may be compared with that using rate control. Scores for the simple dynamics with fixed and with proportional rate control derived from experiment I, are given below.

	Time in Seconds		
	Travel	Adjust.	Total
Fixed Rate	8.21	1.41	9.62
Proportional Rate	8.59	.73	9.92
Position	1.63	.97	2.65

Clearly the superior overall performance with the position control system is due to the low travel times. There are differences in the average distances for experiment I and those used in experiment II (tables XIII and XIV) but they are probably too small to account for all of the travel time differences. In terms of performing fine adjustments position control is slightly inferior to proportional rate. Fixed rate control is poorest.

Proportional rate control appears to provide the capability for fine adjustment. In addition by increasing rate of motion, travel time may be significantly reduced. This would be a simpler design approach than attempting to implement a position control system. Neither suggestion fully solves the problem of impact with objects at high rates of motion.

EXPERIMENT III

The results obtained with the fixed rate controller (experiment I) suggested that greater control flexibility might be obtained if the operator could choose at will either of two fixed rates of arm motion. Such a system would be easier to implement than a proportional control system and yet might result in improved performance as compared to a single fixed rate.

This experiment investigated the functional relationships among the following variables:

1. rates of motion
2. distance from starting point to target
3. target size
4. criterial time.

Apparatus

The apparatus was basically the same as that used in the simple, fixed rate conditions of experiment 1. The manipulator was represented by a dot on the display and the target was a circle. The control was a spring centered 2 axis on-off stick with a locking thumbswitch. Depressing the thumbswitch changed the rate of arm motion from a higher level to the lower level for each rate combination used. Return to the higher rate of motion could be obtained by using the index finger to depress a button on the side of the control stick. Constraints imposed by the apparatus influenced the selection of levels of rate.

Independent Variables

The variables studied are described below. Specific values used for each level of each combination are presented in table II, except for new rates defined below.

Rates of Motion: Each level of this variable represented a combination of two rates of arm motion made available to the operator. For each rate condition either of the two rates could be selected by operating the control as described above. The specific values available with the apparatus were 1.27, 9.32, 10.41 and 25.40 cm/sec. These were designated as low, medium, and high rates of motion. The values 9.32 and 10.41 were considered equivalent. The conditions studied were:

R_A	low/medium	(1.27/10.41 cm/sec)
R_B	low/high	(1.27/25.40 cm/sec)

R_C medium/high (9.32/25.40 cm/sec)

R_D medium/medium (9.32/10.41 cm/sec)

The following variables were identical to those studied in experiment I (see table II).

1. distance from starting point to target
2. target size
3. criterial time.

Thus the task was the same as in previous experiments.

Subjects and Procedure

Subjects were paid male volunteers from a local university. Each subject served for one experimental session during which he was put through a randomized sequence of all 48 conditions.

Subjects were instructed to initiate travel motion using the higher rate. When they had acquired the target they were to depress the thumbswitch and engage the lower rate level. Each subject was run through three trials on each of the 48 experimental conditions. As in the other experiments, the score was taken from the third trial. This procedure was used to minimize the effects of transferring from one condition to the next.

Dependent Variables

Four dependent variables were measured. They are 1) travel time, 2) adjustment time, 3) total time, and 4) time on target (T.O.T.). These four measures are described in appendix I.

The experimental design used for analysis is identical to that used in experiment II (table XIV).

Results

The summary of terms in the analysis of variance, significant at the 1% level of confidence, is presented in table XVII. Mean values are presented in table XVIII.

These data have been examined for systematic trends and the following conclusions can be drawn:

1) The effect of traversed distance is reflected in the increasing mean travel scores as a function of distance. To a lesser degree this appears in the total score.

2) No significant differences in travel time appeared as a function of the rate combinations. If it is assumed that Ss, following instructions, used the higher rate for travel, then the average high rate level used was 17.78 cm/sec (7.00 in/sec). The three highest fixed rate levels of experiment I, average to 6.7 in/sec, or a roughly comparable value. The mean travel time in experiment I (17.02 cm/sec) for these three rate levels is 4.80 seconds. Here it is 5.24 seconds, or slightly higher. Availability of two level control did not facilitate travel performance except as it made higher rates of travel available, and eliminated the very long travel times at low rates.

The significant effect of rate on adjustment score is indicated by the mean adjustment score for R_C (table XVIII). In R_C where no low speed was available and a sizeable change in rate resulted from activation of the thumbswitch adjustment scores are substantially higher than for R_A, R_B, and R_D.

The adjustment scores obtained with two level rate may be compared to the adjustment time data for experiment 1 (fixed rate control). In experiment I there was a significant increase in adjustment time as rate increased, e.g.:

R_1	.11
R_2	.81
R_3	1.8
R_4	2.9
M	1.45

TABLE XVII

Summary of Terms in the Analysis of Variance
for Experiment III, Significant at the 1% Level of Confidence

	Measure		
	Travel Time	Adjustment Time	Total Time
Rate		xx	xx
Distance	xx		xx
Size	xx	xx	xx
Time			
R x D	xx		xx
R x S		xx	xx
R x T	xx		
D x S			
D x T			
S x T			
R x D x S			
R x D x T			
R x S x T			
D x S x T			
R x D x S x T			

TABLE XVIII

Means for Terms Significant in
the Analysis of Variance, Experiment III

	R_A	R_B	R_C	R_D	$\overline{M}$
Travel Time					
			Rate x Distance		
D_1	4.15	4.76	5.06	4.54	4.63
D_2	5.55	5.61	6.09	4.53	5.44
D_3	6.44	4.90	4.92	6.41	5.67
$\overline{M}$	5.38	5.09	5.35	5.16	
			Rate x Time		
T_1	5.33	5.39	4.86	4.61	5.04
T_2	5.73	4.80	5.84	5.72	5.45
			Size		
		S_1 4.69		S_2 5.80	
Adjustment Time					
			Rate x Size		
S_1	.29	.40	.78	.96	.62
S_2	.52	.47	2.94	1.36	1.32
$\overline{M}$	.40	.43	1.86	1.16	
Total Time					
			Rate x Distance		
D_1	4.34	5.38	6.08	5.95	5.44
D_2	6.09	5.86	8.96	5.63	6.64
D_3	6.90	5.31	5.70	7.37	6.32
$\overline{M}$	5.78	5.52	7.21	6.32	
			Rate x Size		
S_1	5.40	5.13	5.15	5.50	
S_2	6.15	5.91	9.28	7.13	

In the present study the mean adjustment score was .97. This marked difference in adjustment time is attributable to use of the low rate for fine adjustment. The major contribution of a two level control is that it allows the operator a low rate for use in the fine adjustment task. This effect is reflected in the total time scores.

4. The R_C condition yielded the highest total score. The Tukey HSD test indicates that R_A and R_B do not differ. R_C and R_D differ from each other and from R_A and R_B. The R_B condition appears best overall, affording adequate speed without excessive sensitivity.

In general, two level fixed rate control can offer advantages above single level fixed rate controls in reducing adjustment time. However, proper selection of a single value, e.g. of about 10 cm/sec, offers a superior overall solution.

CONCLUSIONS

Use of the simulation technique yielded a systematic set of relationships regarding most of the major variables studied. In general the relationships obtained for the simple dynamics either held for the complex dynamics, or changed in a direction logically related to the change in level of task difficulty. Within the limits of the two degrees-of-freedom simulation, the mechanics of manipulator motion could be realistically displayed. The use of the analog technique readily permits modification of manipulator characteristics other than rate of motion or control mode. Once the basic simulation is established, experimental modification of many parameters will be possible.

Task Variables

The criterial time variable did not produce any significant systematic differences and appears of little value in future experimentation.

Variation in target size produced some logical relationships and some illogical ones. With rate control there is evidence that smaller targets, being harder to hit initially, produce higher travel times. There is also evidence that higher adjustment scores result because of the difficulty of remaining on the smaller target. The opposite was found with position control, and this finding is logically inconsistent. A further check of the effects due to size is recommended because of the inconsistencies uncovered. In addition, if we are concerned with precision, this variable or some criterion which establishes tolerance requirements should be included.

The effects due to distance are primarily a result of the maximum available manipulator rates of travel. For any distance a curve of travel time vs rate of travel will show a rapid initial drop followed by a gradual leveling and subsequently only a slight decrease in travel time as rate increases. The selection of an appropriate maximum rate of manipulator travel will depend in part on the average distances traversed and the cost in time. Distance is a variable which has little significance for operator performance per se, although it is highly significant for overall system performance.

Dependent Variables

Of the measures employed, time on target yielded little information of value and is not recommended for future use. Travel and total scores yield the greatest amount of information. The total score sometimes reflects the additive effect of differences in travel and adjustment score where the relatively small contribution of adjustment time would not produce a difference. The adjustment time score appears to reflect the fine manipulation responses and its retention is recommended for analytical reasons as it frequently points to the explanation for findings revealed by the total score.

Machine Variables

Two variables, control mode and rate of motion, are of interest as manipulator design parameters. For the distances studied the optimum rate of arm motion appears to be in the region of 4 in/sec (10.16 cm/sec). Below this value excessive time is required to perform travel functions. Above this value, no significant improvement performance is realized, and with the fixed rate system particularly, decrements occur.

The proportional rate system is generally superior, except at very low rates where fixed rate is better. In the region of 4 in/sec (10.16 cm/sec), differences between control modes are minor. For higher rates of motion, proportional control is increasingly desirable as fixed rate performance begins to deteriorate markedly (fig. 6). The difference between proportional rate and fixed rate control is clearly indicated for the complex dynamics as shown in figure 8. Proportional rate permits high travel speeds as well as slow motion for fine adjustments.

These conclusions are drawn with the understanding that several significant problems must be considered. A major one is the problem of collision with the target object. The present experiment yielded no data on the rate of motion at target impact with the possible exception of that inferred from long adjustment times and long T.O.T. It is apparent, however, that proportional control will yield better operator control over this factor. In addition, proportional control permits the operator to select a range of rates and durations of approach to a target. Fixed rate control permits only 0°, 90°, or 45° motions from any two degrees of freedom. Flexibility appears to be of increasing importance as task complexity increases.

The data on position control are inadequate at present. Only simple dynamics were studied, and the range of gains utilized was inadequate to yield significant results.

Two level fixed rate control can offer advantages above single level fixed rate controls in reducing adjustment time. However, proper selection of a single value, (about 10 cm/sec) offers a superior overall solution.

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APPENDIX I

EXPERIMENTAL APPARATUS AND MANIPULATOR SIMULATION

Simple Dynamics: The critical aspects of a simple remote manipulator task, requiring travel and adjustment movements, were simulated using an analog computer and a 21 inch oscilloscope. A dot on the display represented the end of a manipulator arm. A circle represented target size and position. The task required the operator to maneuver the dot, in two degrees of freedom, from its initial position into the target area represented by the circle. A functional block diagram of the experimental apparatus is shown in figure 10.

The arm end point was arranged to be placed in any one of 35 initial positions. The operator moved the arm, using either positional control, proportional rate control, or fixed rate control, as shown in figure 11. The target could be located in any of 5 positions and its size could be adjusted in steps from a diameter of 1/4 inch to 2 inches. Based on position comparison logic, the scoring circuitry measured four dependent variables: travel time, adjustment time, time on target, and total time. These are illustrated and defined in figure 12.

To initiate a trial, the experimenter established the experimental conditions; target size, target position, arm position, control dynamics, system gain, and criterial time. Pressing a reset button cleared the timing circuits and turned on the display of target and arm. When the subject was ready, he initiated the trial by depressing a foot switch which unlocked the timing circuitry and allowed him to control the manipulator arm. When criterial time on target was achieved, the timing circuitry automatically stopped and the display was blanked.

The apparatus consisted of (1) a GEDA computer for simulating the dynamics and initial positions, (2) relays and switches for the operator console and computer control, and (3) a 2 channel time-sharer and TR48 computer for display generation and scoring logic. A 21" oscilloscope was used to display the arm and target. Time was measured with four standard electric timers.

Complex Dynamics: The complex dynamics simulation represented a two dimensional translational manipulator. The arm segments were assumed to have compliance with internal damping; masses were assumed to be concentrated at the ends of the arms; and a simulation of the motor and drive characteristics was included. In particular, the horizontal carriage motion was assumed to be driven by a motor and an irreversible screw. Except for the modified dynamics and the represention of the manipulator

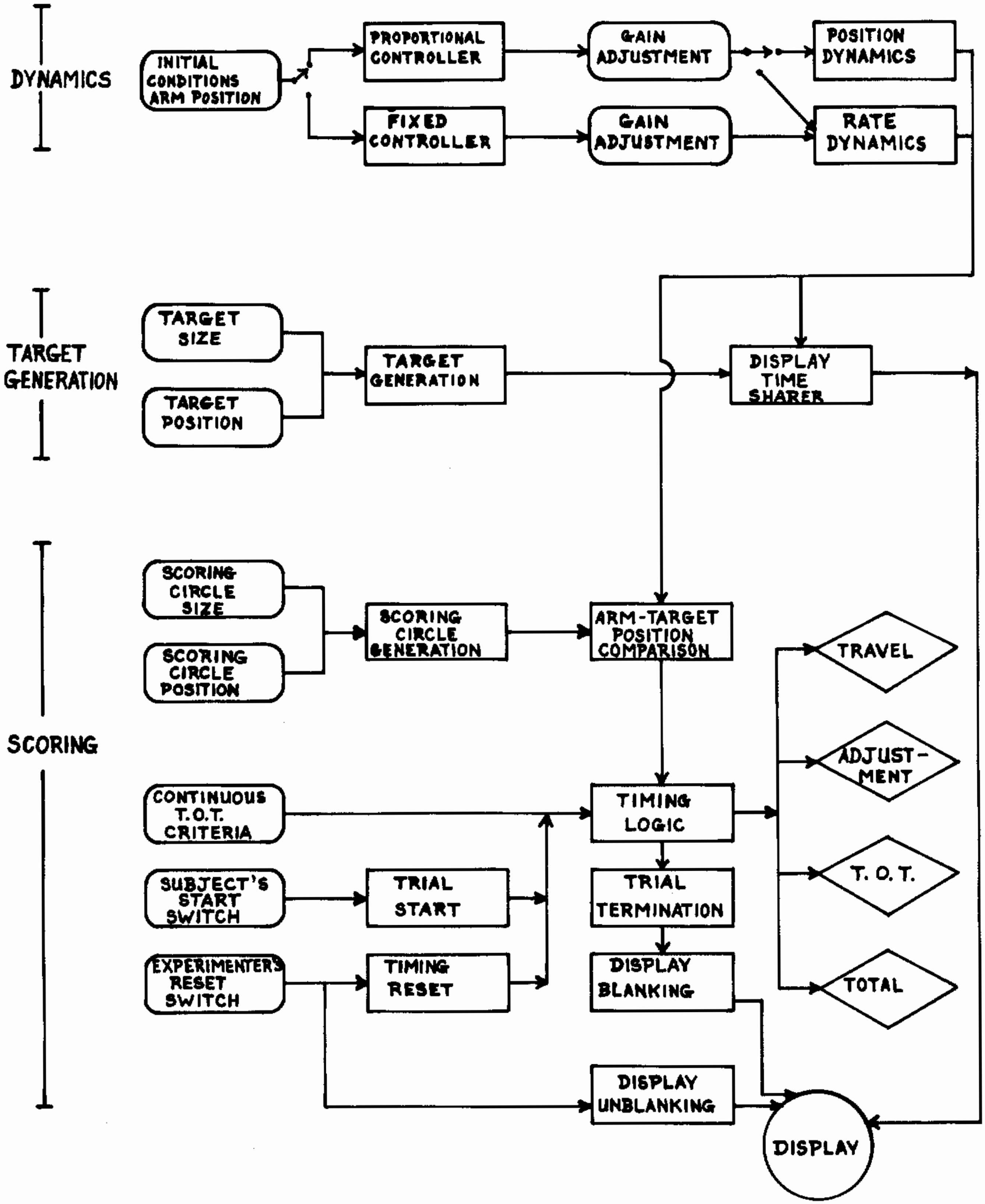


Fig. 10. Configuration of the Experimental Apparatus for the Remote Manipulator Task.

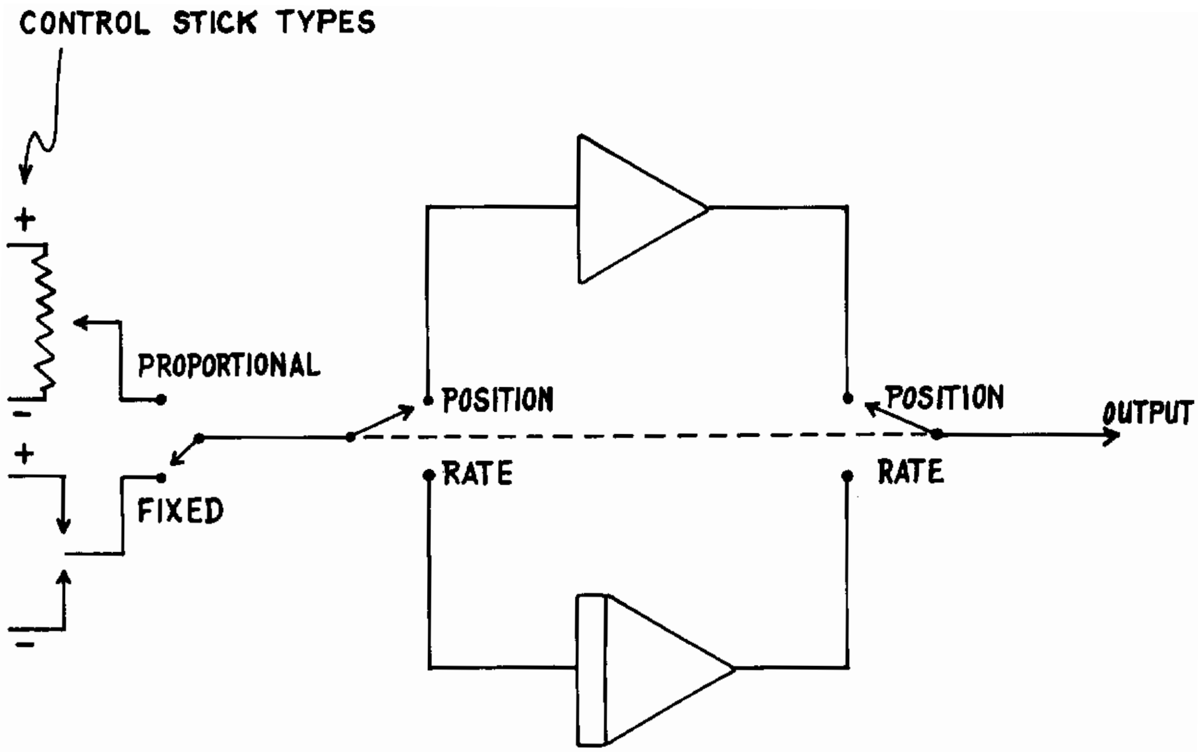


Fig. 11. Functional Analog Computer Diagram of the Simple Manipulator Dynamics.

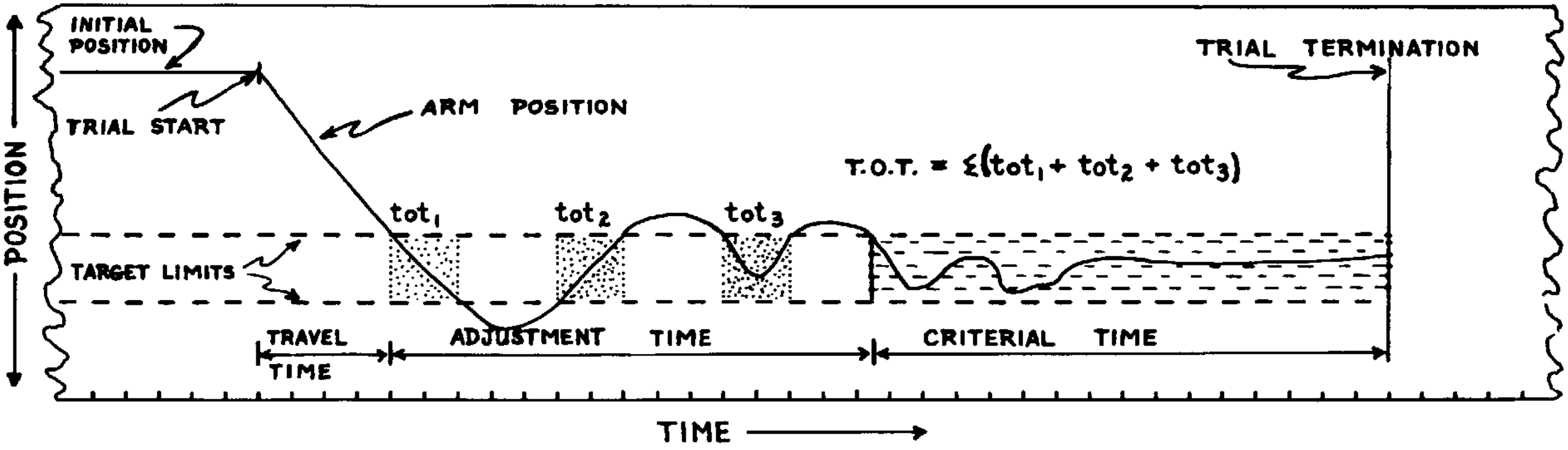


Fig. 12. Hypothetical Strip Chart Record of Discrete Tracking Response.

The X axis represents time. The Y axis represents position of the arm in the Y axis of the display. The parallel dashed lines indicate the Y limits of the target. The distance between the lines corresponds to target diameter.

Dependent Variables are:

1. Travel Time: Time from initiation of response to first entry into target area.
2. Manipulation Time: Time from first entry into target area until attainment of continuous criterial time.
3. Total Time: Scored from initiation of run until termination of trial.
4. Time On Target: Cumulative time spent within the target area during manipulative period.

Criterial time, an independent variable, is defined as the time the subject must continuously remain within the target area in order to complete the trial. It is subtracted from Manipulation, Time On Target, and Total Time scores.

arm by two lines (fig. 13), all other conditions were as with the simple dynamics.

To gain an understanding of the mechanics of remote manipulator arms, and to establish the analog computer requirements, the scope of this study was limited to the dynamics of rectilinear motion in two dimensions. Based on this decision, an analysis was made of the various mechanical movements to be expected in the general classes of driven moving arms with mass and elasticity. Mathematical equations were developed for the displacement obtained for a time varying input force and a tentative analog computer schematic was obtained. This schematic was expanded in the case of the horizontal motion and simplified in the case of the vertical motion.

The general arm and drive used for analysis is shown in figure 14. Note the following:

Arm: The mass of the arm is assumed to be concentrated at each end of its length (M_2 and M_3) and the arm has a spring constant (K_{23}) and an internal damping (B_{23}). Distances of translation are designated as X_2 and X_3 for M_2 and M_3, respectively.

Drive: The drive mechanism is a simple motor and gearing system, shown here as a belt drive. The system is considered as a whole with an effective mass of M_1 and a damping B_1. The output translation is designated X_1. The system backlash, δ, and resiliency, K_1, are considered as at the interface between the drive and the driven arm. Note that this is a reversible gearing system. The reaction of the arm is fed back directly to the motor and is not absorbed in thrust bearings as in an irreversible screw drive. Consideration was given to this in a later analysis.

The equation of motion of the end of the arm, mass M_3, is as follows:

$$M_3 \ddot{X}_3 + B_{23} (\dot{X}_3 - \dot{X}_2) + K_{23} (X_3 - X_2) = 0$$

The equation of motion of the upper end of the arm, mass M_2, has to have additional forms since the backlash must be considered:

When $(X_2 - X_1) \leq 0$

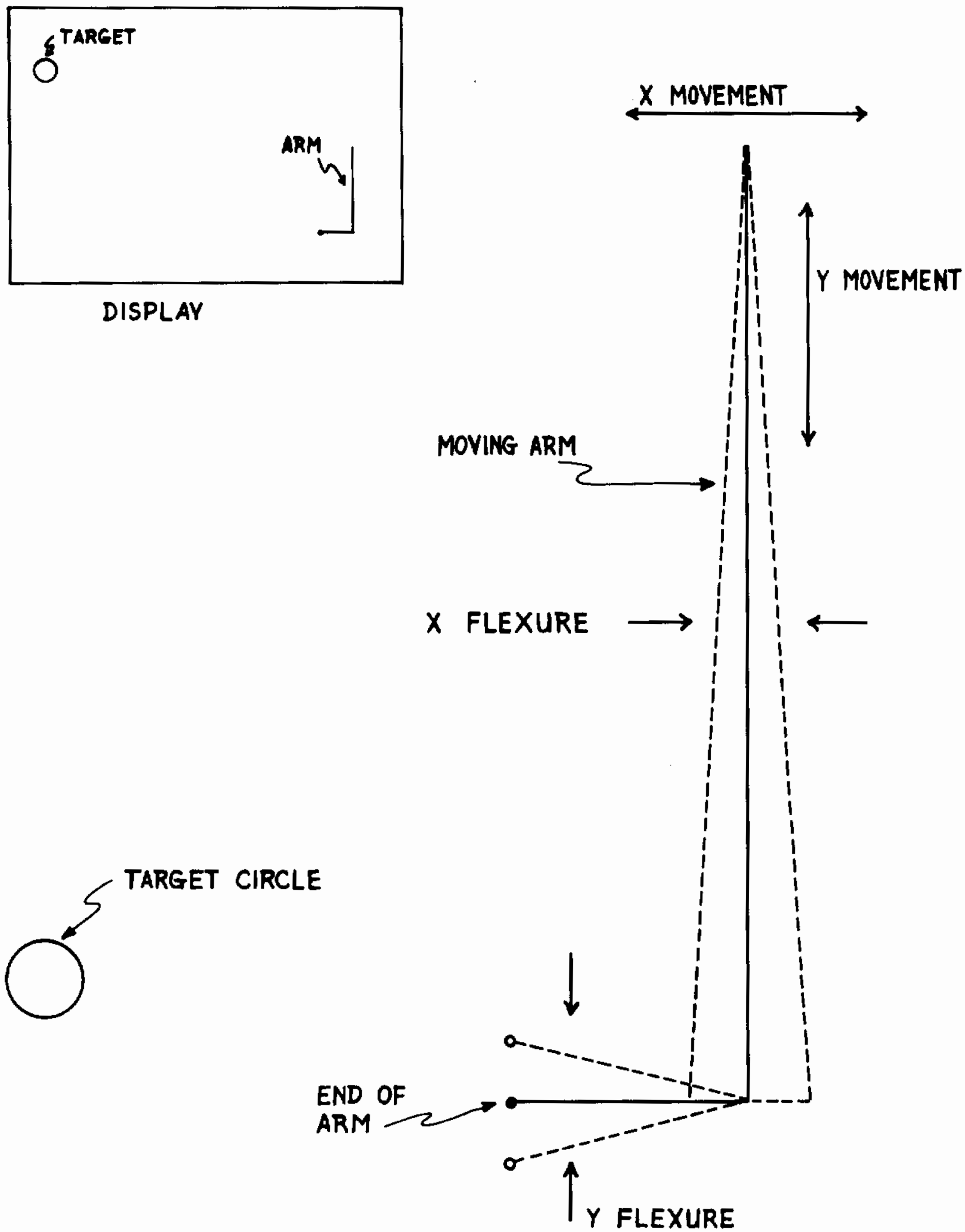


Fig. 13. Sketch of Simulated Manipulator Arm.

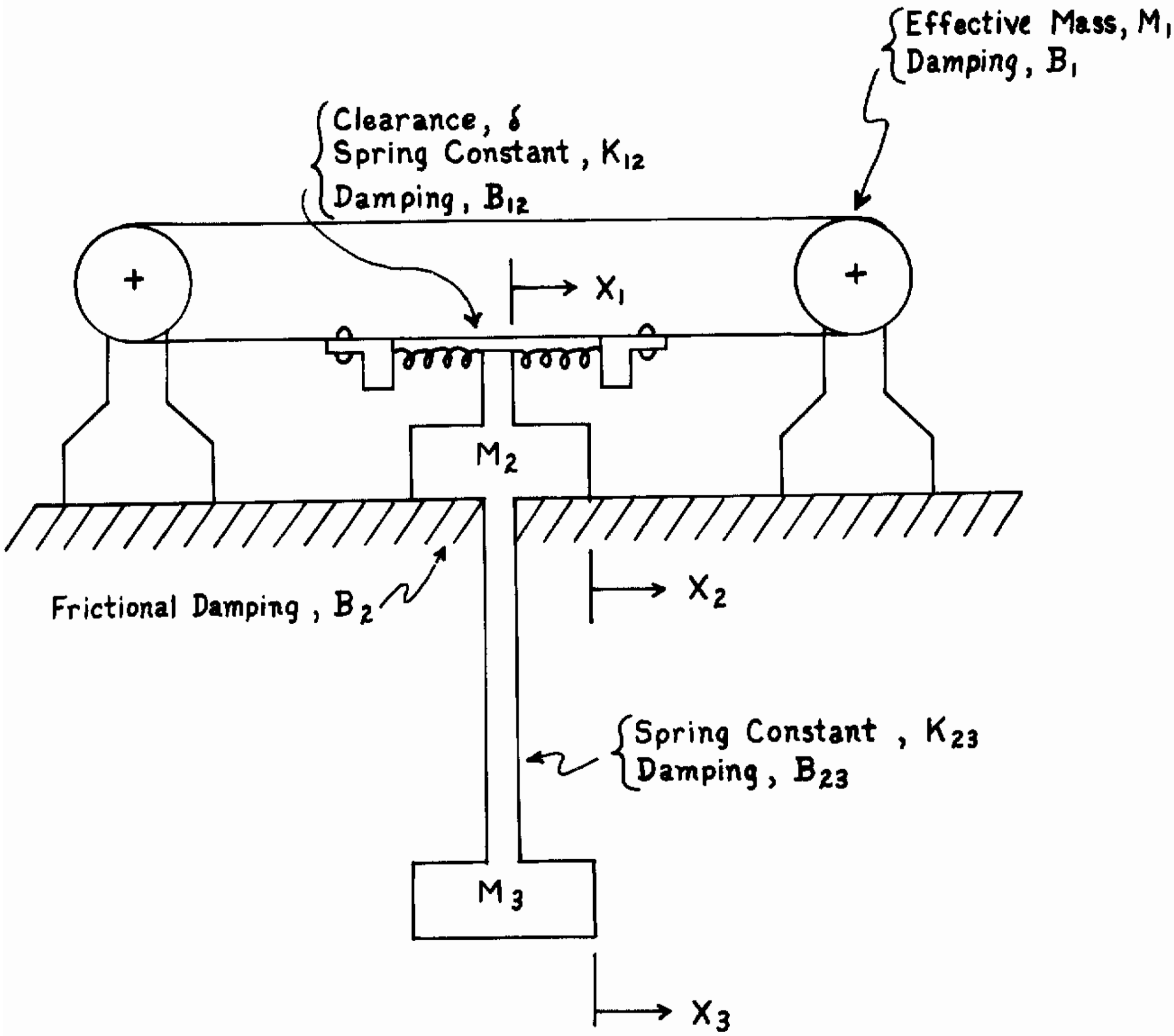


Fig. 14. Manipulator Arm and Drive System used in Analysis of Dynamics.

$$M_2 \ddot{X}_2 + B_{23} (\dot{X}_2 - \dot{X}_3) + B_{12} (\dot{X}_2 - \dot{X}_1) + K_{23} (X_2 - X_3) + K_{12} (X_{12} - X_1) = 0$$

When $0 \leq (X_2 - X_1) \leq \delta$

$$M_2 \ddot{X}_2 + B_{23} (\dot{X}_2 - \dot{X}_3) + K_{23} (X_2 - X_3) = 0$$

When $(X_2 - X_1) \geq \delta$

$$M_2 \ddot{X}_2 + B_{23} (\dot{X}_2 - \dot{X}_3) + B_{12} (\dot{X}_2 - \dot{X}_1) + K_{23} (X_2 - X_3) + K_{12} (X_2 - X_1 - \delta) = 0$$

The drive mechanism equations are as follows:

When $(X_2 - X_1) \leq 0$

$$M_1 \ddot{X}_1 + B_{12} (\dot{X}_1 - \dot{X}_2) + B_1 \dot{X}_1 + K_{12} (X_1 - X_2) = F_g$$

When $0 \leq (X_2 - X_1) \leq \delta$

$$M_1 \ddot{X}_1 + B_1 \dot{X}_1 = F_g$$

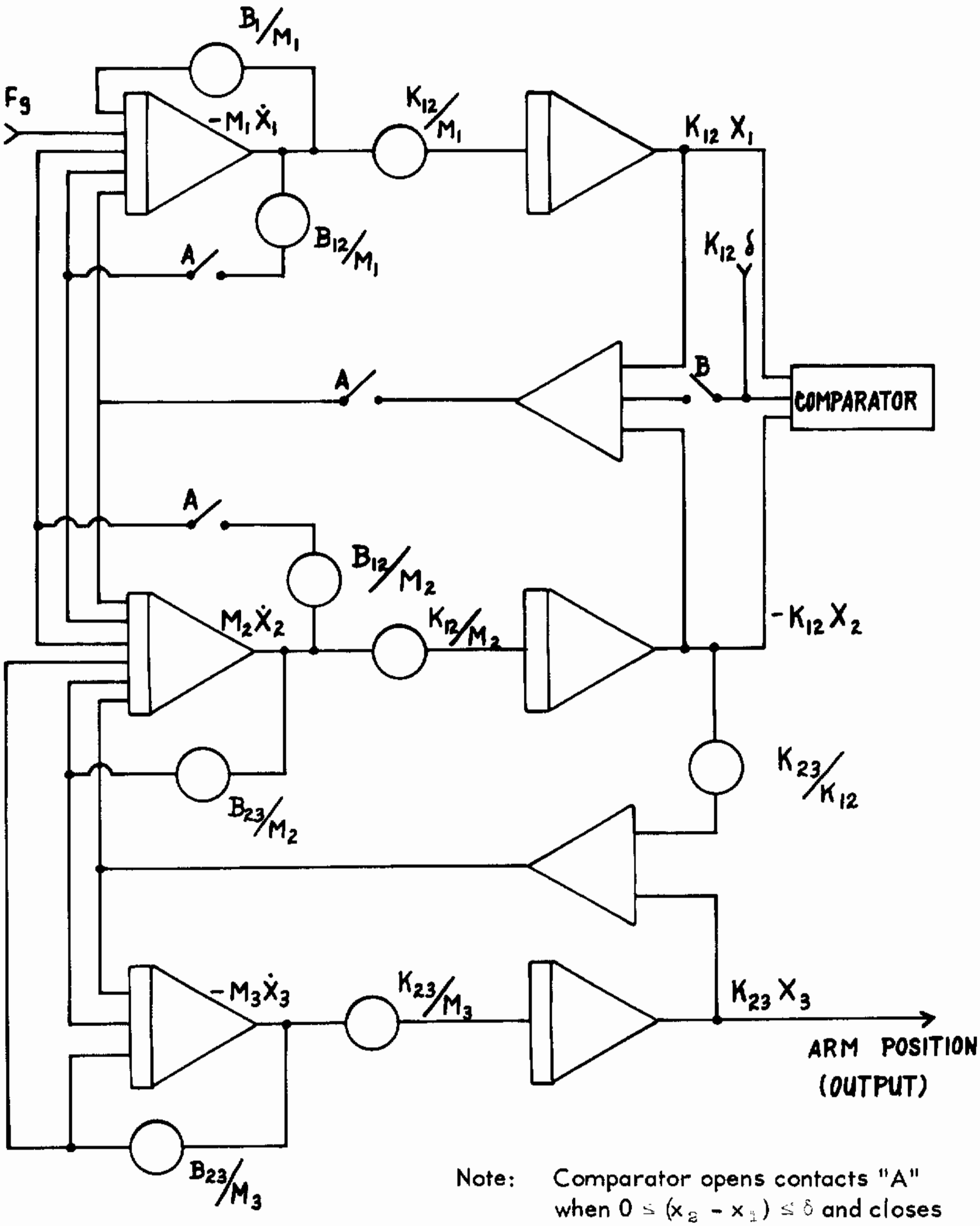
When $(X_2 - X_1) \geq \delta$

$$M_1 \ddot{X}_1 + B_{12} (\dot{X}_1 - X_2) + B_1 \dot{X}_1 + K_{12} (X_1 - X_2 + \delta) = F_g$$

Here F_g is the equivalent "generated" force of the motor of the drive system. In general, this could be any input, programmed to represent the type of motor and controller combination desired.

A functional analog diagram of these equations is shown in figure 15.

The actual implementation on the analog computer for the horizontal arm recognized the irreversible screw effect. Thus, the motor could drive the load, but



Note: Comparator opens contacts "A" when $0 \leq (x_2 - x_1) \leq \delta$ and closes contact "B" when $(x_2 - x_1) \geq \delta$

Fig. 15. Functional Analog Computer Diagram of Complex Manipulator Dynamics.

the load could not drive the motor. In addition, it was assumed that the load forces were negligible to the motor, and these feedbacks were eliminated. The screw was assumed to be compliant and to have some backlash. The effect of the screw on the load (locking action) was accomplished by adding heavy damping to the X_2 integrator at the time this effect was needed. The actual circuitry is shown in figure 16. Here switch "A" closed whenever the extra damping was necessary. The criteria for the extra damping was based on the physical requirements that whenever the X_1 and X_2 rates and the difference between X_1 and X_2 were of the same sign (same direction), the screw should lock and prevent further motion of the upper end of the arm. Thus, if the screw drive and the upper end of the arm were travelling in the same direction and the carriage attempted to move ahead of the drive, the irreversible effect would lock the carriage (through extra damping).

The following Boolean truth table illustrates the logic used.

$\dot{x}_1$	$\dot{x}_2$	x_2-x_1	A	B	C	ABC	$\bar{A}\bar{B}\bar{C}$	D
Pos	Pos	Pos	0	0	0	0	1	1
Pos	Pos	Neg	0	0	1	0	0	0
Pos	Neg	Pos	0	1	0	0	0	0
Pos	Neg	Neg	0	1	1	0	0	0
Neg	Pos	Pos	1	0	0	0	0	0
Neg	Pos	Neg	1	0	1	0	0	0
Neg	Neg	Pos	1	1	0	0	0	0
Neg	Neg	Neg	1	1	1	1	0	1

Thus $D = ABC + \bar{A}\,\bar{B}\,\bar{C}$

In this table, zero was assigned to a positive value and one to a negative value of the variable. In addition, A is equivalent to X_1 rate, B is equivalent to X_2 rate, and C is equivalent to $X_2 - X_1$. The function D is the resulting contact closing condition (when equal to one).

The actual logic was resolved on the GEDA computer using high gain amplifiers limited to plus or minus 20 volts as flip-flop comparators. Figure 17 illustrates the computer diagram in a simplified form. The following table of output voltage conditions indicates the method of operation.

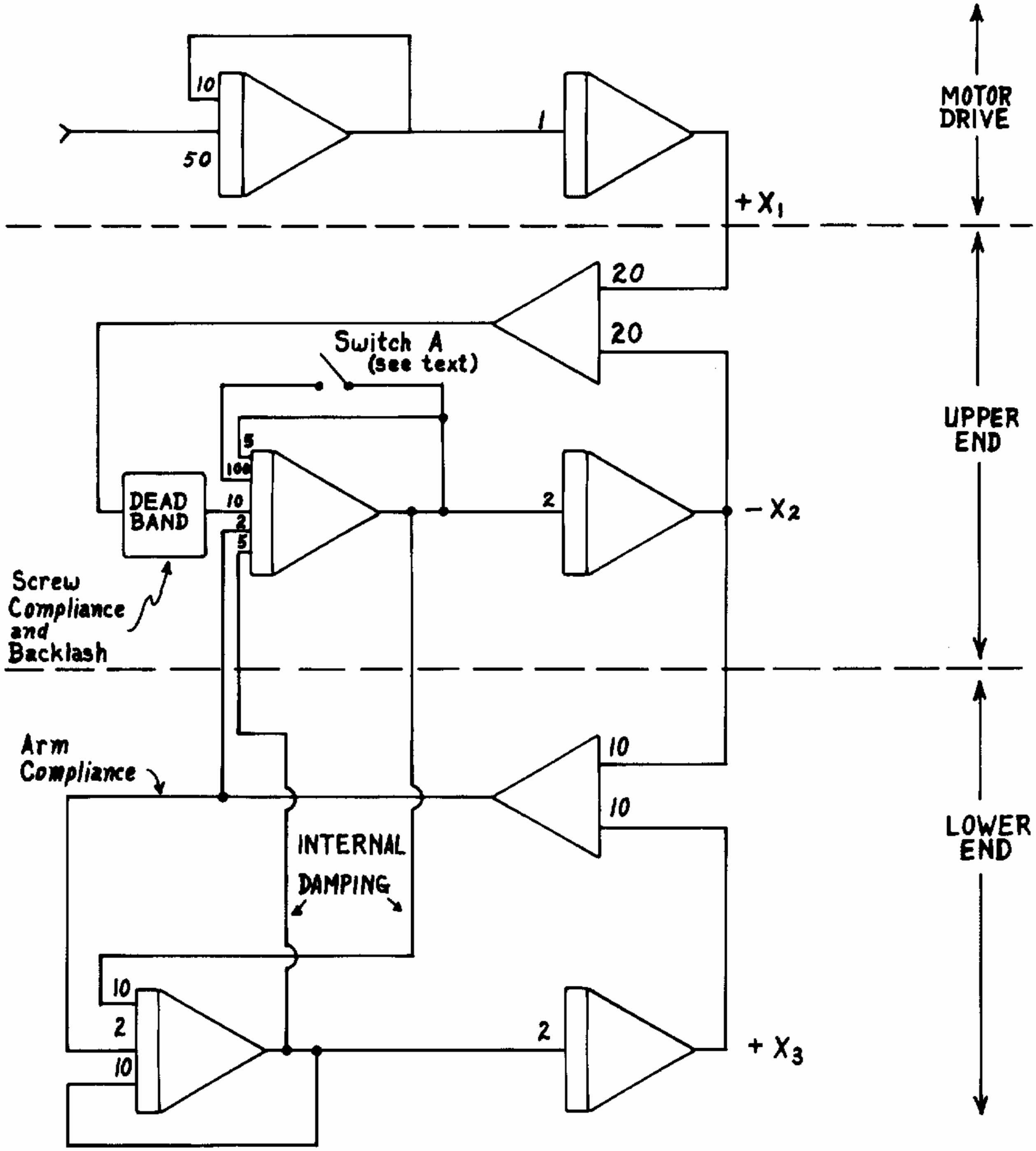


Fig. 16. Computer Diagram, Horizontal Axis.

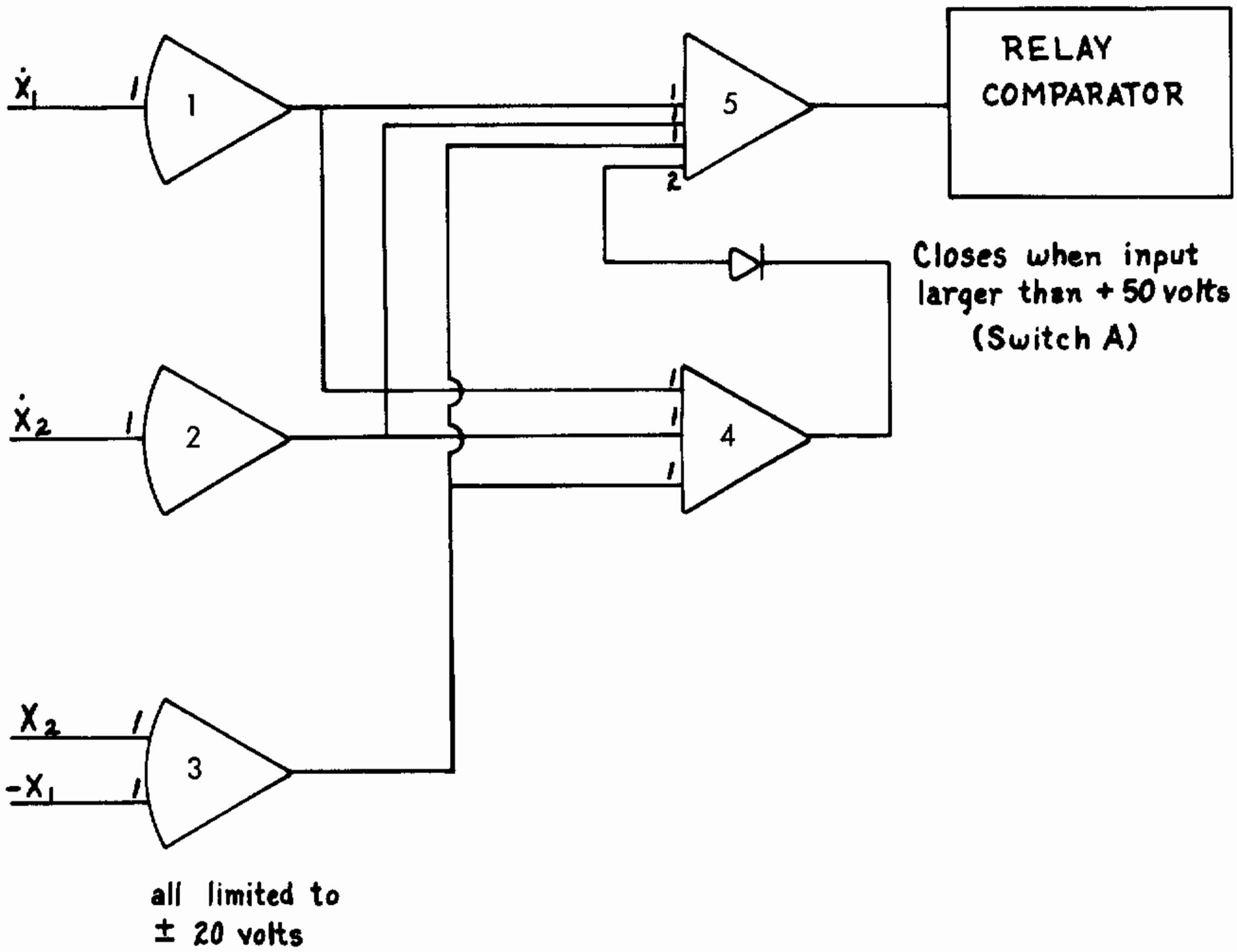


Fig. 17. Comparator Diagram, Irreversible Screw.

$\dot{x}_1$	$\dot{x}_2$	$x_2 - x_1$	Amplifier Output (Volts) 1	2	3	4	5	Relay Comparator
Pos	Pos	Pos	-20	-20	-20	+60	+60	Closed
Pos	Pos	Neg	-20	-20	+20	+20	+20	Open
Pos	Neg	Pos	-20	+20	-20	+20	+20	"
Pos	Neg	Neg	-20	+20	+20	-20	+20	"
Neg	Pos	Pos	+20	-20	-20	+20	+20	"
Neg	Pos	Neg	+20	-20	+20	-20	+20	"
Neg	Neg	Pos	+20	+20	-20	-20	+20	"
Neg	Neg	Neg	+20	+20	+20	-60	+60	Closed

The equipment utilized a GEDA computer for the dynamics and irreversible screw amplifiers. A specially built 4 channel time sharer was used to control the display on the 21 inch oscilloscope as well as control the operate-reset relays on the TR48 computer, which was used for scoring logic. The high integrating rate mode of this computer was used to generate the lines on the oscilloscope display representing the vertical and horizontal arms of the arm. This display is illustrated in figure 13.

APPENDIX II

ANALYSIS OF VARIANCE SUMMARY TABLES: EXPERIMENT I

ANALYSIS PROGRAM

A computer program, BMD02V-Analysis of Variance, developed at UCLA was used to analyze the data from these experiments.

The experimental design, previously shown contained seven variables. These variables were control mode, dynamics, subjects, rate, distance, size, and criterial time. The computer analysis considers each variable to be completely crossed with all other variables. However, this was not the case in the present design. The "subjects" variable was nested within the "dynamics" variable. As a result evaluations were made on the basis of the information presented in the appendix of the BMD02V program stating "how to obtain a nested or partially nested analysis of variance table given a fully crossed analysis of variance table."

ESTIMATED MEAN SQUARES FOR DETERMINING F RATIOS

The problem of determining the proper estimated mean square for each variable in the analysis, and therefore, the appropriate denominators for the F ratios is simplified by assumption that all independent variables considered in the analysis, with the exception of subjects, were "fixed" variables. "Fixed" variables are ones that are "determined by some systematic non-random procedure" (ref 25). The appropriate error mean squares for those variables that could be tested in this analysis are shown in the summary tables of the analysis of variance. These error mean squares were determined using the method described on pages 195 through 197.

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* = $P < .05$
** = $P < .01$

Table XIX
Summary Table, Analysis of Variance, Experiment I, Travel Time Score

Source	df	Error Term	SS	MS	F
Control Mode	1	CM x Ss/Dy	8.11	8.11	--
Dynamics	1	Ss/Dy	1725.93	1725.93	14.26**
Subjects/Dy	14	None	1694.16	121.01	
Rate	3	Ss/Dy x R	61832.23	20610.74	2366.33**
Distance	2	Ss/Dy x D	10234.95	5117.48	719.76**
Size	1	Ss/Dy x S	120.53	120.53	10.52**
Time	1	Ss/Dy x T	30.11	30.11	4.43
CM x Dy	1	CM x Ss/Dy	106.30	106.30	1.92
CM x Ss/Dy	14	None	775.13	55.37	
CM x R	3	CM x Ss/Dy x R	2698.75	899.58	94.89**
CM x D	2	CM x Ss/Dy x D	210.70	105.35	23.10**
CM x S	1	CM x Ss/Dy x S	43.14	43.14	3.30
CM x T	1	CM x Ss/Dy x T	0.24	0.24	--
Dy x R	3	Ss/Dy x R	326.69	108.90	12.50**
Dy x D	2	Ss/Dy x D	69.83	34.91	4.91*
Dy x S	1	Ss/Dy x S	1101.18	1101.18	96.09**
Dy x T	1	Ss/Dy x T	4.79	4.79	--
Ss/Dy x R	42	None	365.87	8.71	
Ss/Dy x D	28	None	199.13	7.11	
Ss/Dy x S	14	None	160.47	11.46	
Ss/Dy x T	14	None	95.26	6.80	
R x D	6	Ss/Dy x R x D	15960.96	2660.16	244.95**
R x S	3	Ss/Dy x R x S	18.67	6.23	--
R x T	3	Ss/Dy x R x T	45.61	15.20	2.47

Table XIX (2)

Source	df	Error Term	SS	MS	F
D x S	2	Ss/Dy x D x S	12.00	6.00	1.09
D x T	2	Ss/Dy x D x T	58.58	29.29	3.22
S x T	1	Ss/Dy x S x T	8.68	2.68	--
CM x Dy x R	3	CM x Ss/Dy x R	351.02	117.01	12.34**
CM x Dy x D	2	CM x Ss/Dy x D	14.96	7.48	1.64
CM x Dy x S	1	CM x Ss/Dy x S	66.57	66.57	5.09*
CM x Dy x T	1	CM x Ss/Dy x T	5.78	5.78	--
CM x Ss/Dy x R	42	None	398.03	9.48	
CM x Ss/Dy x D	28	None	127.65	4.56	
CM x Ss/Dy x S	14	None	182.97	13.07	
CM x Ss/Dy x T	14	None	157.91	11.28	
CM x R x D	6	CM x Ss/Dy x R x D	352.49	58.75	5.50**
CM x R x S	3	CM x Ss/Dy x R x S	32.08	10.69	1.70
CM x R x T	3	CM x Ss/Dy x R x T	37.25	12.42	2.12
CM x D x S	2	CM x Ss/Dy x D x S	3.47	1.74	--
CM x D x T	2	CM x Ss/Dy x D x T	32.05	16.03	1.08
CM x S x T	1	CM x Ss/Dy x S x T	3.18	3.18	--
Dy x R x D	6	Ss/Dy x R x D	67.16	11.19	1.03
Dy x R x S	3	Ss/Dy x R x S	91.40	30.47	3.71*
Dy x R x T	3	Ss/Dy x R x T	16.06	5.35	--
Dy x D x S	2	Ss/Dy x D x S	32.14	16.07	2.91
Dy x D x T	2	Ss/Dy x D x T	19.76	9.88	1.08

Table XIX (3)

Source	df	Error Term	SS	MS	F
Dy x S x T	1	Ss/Dy x S x T	1.18	1.18	--
Ss/Dy x R x D	84	None	912.02	10.86	
Ss/Dy x R x S	42	None	345.34	8.22	
Ss/Dy x R x T	42	None	258.78	6.16	
Ss/Dy x D x S	28	None	154.69	5.52	
Ss/Dy x D x T	28	None	255.19	9.11	
Ss/Dy x S x T	14	None	110.17	7.87	
R x D x S	6	Ss/Dy R x D x S	82.95	13.83	2.12
R x D x T	6	Ss/Dy x R x D x T	151.10	25.18	3.07**
R x S x T	3	Ss/Dy x R x S x T	29.44	9.81	1.03
D x S x T	2	Ss/Dy x D x S x T	30.29	15.14	1.12
CM x Dy x R x D	6	CM x Ss/Dy x R x D	198.70	33.12	3.10**
CM x Dy x R x S	3	CM x Ss/Dy x R x S	68.89	22.96	3.65*
CM x Dy x R x T	3	CM x Ss/Dy x R x T	9.57	3.19	--
CM x Dy x D x S	2	CM x Ss/Dy x D x S	7.90	3.95	--
CM x Dy x D x T	2	CM x Ss/Dy x D x T	16.47	8.24	--
CM x Dy x S x T	1	CM x Ss/Dy x S x T	0.07	0.07	--

Table XIX (4)

Source	df	Error Term	SS	MS	F
CM x Ss/Dy x R x D	84	None	896.76	10.68	
CM x Ss/Dy x R x S	42	None	264.37	6.29	
CM x Ss/Dy x R x T	42	None	246.69	5.87	
CM x Ss/Dy x D x S	28	None	175.94	6.28	
CM x Ss/Dy x D x T	28	None	414.88	14.82	
CM xSs/Dy x S x T	14	None	75.61	5.40	
CM x R x D x S	6	CM x Ss/Dy x R x D x S	130.98	21.83	3.53**
CM x R x D x T	6	CM x Ss/Dy x R x D x T	64.95	10.82	2.10
CM x R x S x T	3	CM x Ss/Dy x R x S x T	12.18	4.06	--
CM x D x S x T	2	CM x Ss/Dy x D x S x T	13.91	6.95	--
Dy x R x D x S	6	Ss/Dy x R x D x S	18.07	3.01	--
Dy x R x D x T	6	Ss/Dy x R x D x T	49.47	8.24	1.00
Dy x R x S x T	3	Ss/Dy x R x S x T	30.28	10.09	1.06
Dy x D x S x T	2	Ss/Dy x D x S x T	46.18	23.09	1.71
Ss/Dy x R x D x S	84	None	546.68	6.51	
Ss/Dy x R x D x T	84	None	689.64	8.21	
Ss/Dy x R x S x T	42	None	401.07	9.55	
Ss/Dy x D x S x T	28	None	378.23	13.51	

Table XIX(5)

Source	df	Error Term	SS	MS	F
R x D x S x T	6	Ss/Dy x G x D x S x T	119.59	19.93	1.93
CM x Dy x R x D x S	6	CM x Ss/Dy x R x D x S	60.94	10.16	1.64
CM x Dy x R x D x T	6	CM x Ss/Dy x R x D x T	64.48	10.75	2.08
CM x Dy x R x S x T	3	CM x Ss/Dy x R x S x T	44.95	14.98	1.45
CM x Dy x D x S x T	2	CM x Ss/Dy x D x S x T	6.06	3.03	--
CMxSs/DyxRxDxS	34	None	519.06	6.18	
CMxSs/DyxRxDxT	84	None	433.23	5.16	
CMxSs/DyxRxSxT	42	None	433.85	10.33	
CmxSs/DyxDxSxT	28	None	376.81	13.46	
CM x R x D x S x T	6	CMxSs/DyxRxDxS	90.84	15.14	1.82
Dy x R x D x S x T	6	Ss/Dy x R x D x S x T	93.09	15.51	1.50
Ss/Dy x R x D x S x T	84	None	869.79	10.35	
CMxDyxRxDxSxT	6	CMxSs/DyxRxDxSxT	83.44	13.91	1.68
CMxSs/DyxRxDxSxT	84	None	696.85	8.30	
TOTAL	1535		112604.10		

Table XX
Summary Table, Analysis of Variance, Experiment I, Adjustment Time Score

Source	df	Error Term	SS	MS	F
Control Mode	1	CM x Ss/Dy	677.91	677.91	22.25**
Dynamics	1	Ss/Dy	223.83	223.83	9.74**
Subjects/Dy	14	None	321.75	22.98	
Rate	3	Ss/Dy x R	1410.77	470.26	32.48**
Distance	2	Ss/Dy x D	44.14	22.07	1.80
Size	1	Ss/Dy x S	20.08	20.08	1.48
Time	1	Ss/Dy x T	46.67	46.67	5.27*
CM x Dy	1	CM x Ss/Dy	161.00	161.00	5.28*
CM x Ss/Dy	14	None	426.62	30.47	
CM x R	3	CM x Ss/Dy x R	481.89	160.63	13.76**
CM x D	2	CM x Ss/Dy x D	25.57	12.79	--
CM x S	1	CM x Ss/Dy x S	6.17	6.17	--
CM x T	1	CM x Ss/Dy x T	35.60	35.60	6.11*
Dy x R	3	Ss/Dy x R	146.34	48.78	3.37*
Dy x D	2	Ss/Dy x D	76.27	38.13	3.12
Dy x S	1	Ss/Dy x S	520.56	520.56	38.25**
Dy x T	1	Ss/Dy x T	28.79	28.79	3.25
Ss/Dy x R	42	None	608.09	14.48	
Ss/Dy x D	28	None	342.41	12.23	
Ss/Dy x S	14	None	190.53	13.61	
Ss/Dy x T	14	None	123.94	8.85	
R x D	6	Ss/Dy x R x D	55.63	9.27	1.46
R x S	3	Ss/Dy x R x S	58.51	19.50	1.71
R x T	3	Ss/Dy x R x T	23.39	7.80	--

Table XX (2)

Source	df	Error Term	SS	MS	F
D x S	2	Ss/Dy x D x S	6.01	3.01	--
D x T	2	Ss/Dy x D x T	66.60	33.30	4.07*
S x T	1	Ss/Dy x S x T	0.19	0.19	--
CM x Dy x R	3	CM x Ss/Dy x R	50.99	17.00	
CM x Dy x D	2	CM x Ss/Dy x D	38.88	19.44	1.19
CM x Dy x S	1	CM x Ss/Dy x S	20.99	20.99	2.01
CM x Dy x T	1	CM x Ss/Dy x T	0.00	0.00	--
CM x Ss/Dy x R	42	None	490.15	11.67	
CM x Ss/Dy x D	28	None	457.77	16.35	
CM x Ss/Dy x S	14	None	146.10	10.44	
CM x Ss/Dy x T	14	None	81.64	5.83	
CM x R x D	6	CM x Ss/Dy x R x D	46.39	7.73	--
CM x R x S	3	CM x Ss/Dy x R x S	6.80	2.27	--
CM x R x T	3	CM x Ss/Dy x R x T	19.45	6.48	--
CM x D x S	2	CM x Ss/Dy x D x S	10.82	5.41	--
CM x D x T	2	CM x Ss/Dy x D x T	47.21	23.61	2.32
CM x S x T	1	CM x Ss/Dy x S x T	21.96	21.96	2.13
Dy x R x D	6	Ss/Dy x R x D	33.59	5.60	--
Dy x R x S	3	Ss/Dy x R x S	158.28	52.76	4.62**
Dy x R x T	3	Ss/Dy x R x T	211.57	70.52	6.54**
Dy x D x S	2	Ss/Dy x D x S	3.72	1.86	--
Dy x D x T	2	Ss/Dy x D x T	22.21	11.11	1.36

Table XX (3)

Source	df	Error Term	SS	MS	F
Dy x S x T	1	Ss/Dy x S x T	0.65	0.65	--
Ss/Dy x R x D	84	None	535.12	6.37	
Ss/Dy x R x S	42	None	479.85	11.42	
Ss/Dy x R x T	42	None	452.55	10.78	
Ss/Dy x D x S	28	None	510.90	18.25	
Ss/Dy x D x T	28	None	229.30	8.19	
Ss/Dy x S x T	14	None	206.06	14.72	
R x D x S	6	Ss/Dy R x D x S	39.87	6.64	--
R x D x T	6	Ss/Dy x R x D x T	186.89	31.15	2.15
R x S x T	3	Ss/Dy x R x S x T	68.09	22.70	2.26
D x S x T	2	Ss/Dy x D x S x T	10.07	5.04	--
CM x Dy x R x D	6	CM x Ss/Dy x R x D	42.81	7.13	--
CM x Dy x R x S	3	CM x Ss/Dy x R x S	20.37	6.79	--
CM x Dy x R x T	3	CM x Ss/Dy x R x T	56.85	18.95	1.37
CM x Dy x D x S	2	CM x Ss/Dy x D x S	1.22	0.61	--
CM x Dy x D x T	2	CM x Ss/Dy x D x T	28.62	14.31	1.41
CM x Dy x S x T	1	CM x Ss/Dy x S x T	76.49	76.49	7.40*

Table XX (4)

Source	df	Error Term	SS	MS	F
CM x Ss/Dy x R x D	84	None	855.26	10.18	
CM x Ss/Dy x R x S	42	None	297.87	7.09	
CM x Ss/Dy x R x T	42	None	581.52	13.85	
CM x Ss/Dy x D x S	28	None	538.89	19.25	
CM x Ss/Dy x D x T	28	None	284.91	10.18	
CM xSs/Dy x S x T	14	None	144.57	10.33	
CM x R x D x S	6	CM x Ss/Dy x R x D x S	78.58	13.10	1.03
CM x R x D x T	6	CM x Ss/Dy x R x D x T	163.52	27.25	1.82
CM x R x S x T	3	CM x Ss/Dy x R x S x T	9.93	3.31	--
CM x D x S x T	2	CM x Ss/Dy x D x S x T	6.85	3.42	--
Dy x R x D x S	6	Ss/Dy x R x D x S	32.25	5.38	--
Dy x R x D x T	6	Ss/Dy x R x D x T	69.48	11.58	--
Dy x R x S x T	3	Ss/Dy x R x S x T	12.58	4.19	--
Dy x D x S x T	2	Ss/Dy x D x S x T	11.76	5.88	--
Ss/Dy x R x D x S	84	None	764.00	9.10	
Ss/Dy x R x D x T	84	None	1216.45	14.48	
Ss/Dy x R x S x T	42	None	422.60	10.06	
Ss/Dy x D x S x T	28	None	360.22	12.86	

Table XX (5)

Source	df	Error Term	SS	MS	F
R x D x S x T	6	Ss/Dy x G x D x S x T	61.13	10.19	--
CM x Dy x R x D x S	6	CM x Ss/Dy x R x D x S	23.30	3.88	--
CM x Dy x R x D x T	6	CM x Ss/Dy x R x D x T	94.80	15.80	1.06
CM x Dy x R x S x T	3	CM x Ss/Dy x R x S x T	47.05	15.68	2.16
CM x Dy x D x S x T	2	CM x Ss/Dy x D x S x T	0.21	0.11	--
CMxSs/DyxRxDxS	34	None	1064.95	12.68	
CMxSs/DyxRxDxT	84	None	1255.34	14.94	
CMxSs/DyxRxSxT	42	None	305.23	7.27	
CmxSs/DyxDxSxT	28	None	316.70	11.31	
CM x R x D x S x T	6	CMxSs/DyxRxDxS	62.57	10.43	--
Dy x R x D x S x T	6	Ss/Dy x R x D x S x T	65.47	10.91	--
Ss/Dy x R x D x S x T	84	None	1226.44	14.60	
CMxDyxRxDxSxT	6	CMxSs/DyxRxDxSxT	53.51	8.92	--
CMxSs/DyxRxDxSxT	84	None	1107.66	13.19	
TOTAL	1535		22479.14		

Table XXI
Summary Table, Analysis of Variance, Experiment I, Time on Target Score

Source	df	Error Term	SS	MS	F
Control Mode	1	CM x Ss/Dy	0.00	0.00	--
Dynamics	1	Ss/Dy	6.65	6.65	7.64*
Subjects/Dy	14	None	12.23	0.87	
Rate	3	Ss/Dy x R	25.96	8.65	12.72**
Distance	2	Ss/Dy x D	1.25	0.62	--
Size	1	Ss/Dy x S	0.15	0.15	--
Time	1	Ss/Dy x T	15.50	15.50	25.41**
CM x Dy	1	CM x Ss/Dy	0.56	0.56	1.06
CM x Ss/Dy	14	None	7.37	0.53	
CM x R	3	CM x Ss/Dy x R	4.06	1.35	3.75*
CM x D	2	CM x Ss/Dy x D	0.11	0.06	--
CM x S	1	CM x Ss/Dy x S	0.10	0.10	--
CM x T	1	CM x Ss/Dy x T	3.44	3.44	6.49*
Dy x R	3	Ss/Dy x R	5.05	1.68	2.47
Dy x D	2	Ss/Dy x D	1.21	0.61	--
Dy x S	1	Ss/Dy x S	19.91	19.91	51.05**
Dy x T	1	Ss/Dy x T	0.90	0.90	1.48
Ss/Dy x R	42	None	28.75	0.68	
Ss/Dy x D	28	None	23.13	0.83	
Ss/Dy x S	14	None	5.45	0.39	
Ss/Dy x T	14	None	8.55	0.61	
R x D	6	Ss/Dy x R x D	4.22	0.70	1.21
R x S	3	Ss/Dy x R x S	2.50	0.83	1.66
R x T	3	Ss/Dy x R x T	6.06	2.02	3.74*

Table XXI (2)

Source	df	Error Term	SS	MS	F
D x S	2	Ss/Dy x D x S	0.00	0.00	--
D x T	2	Ss/Dy x D x T	0.94	0.47	--
S x T	1	Ss/Dy x S x T	0.06	0.06	--
CM x Dy x R	3	CM x Ss/Dy x R	0.17	0.06	--
CM x Dy x D	2	CM x Ss/Dy x D	2.53	1.26	1.34
CM x Dy x S	1	CM x Ss/Dy x S	4.06	4.06	7.66*
CM x Dy x T	1	CM x Ss/Dy x T	0.27	0.27	--
CM x Ss/Dy x R	42	None	15.10	0.36	
CM x Ss/Dy x D	28	None	26.39	0.94	
CM x Ss/Dy x S	14	None	7.36	0.53	
CM x Ss/Dy x T	14	None	7.46	0.53	
CM x R x D	6	CM x Ss/Dy x R x D	5.76	0.96	2.23*
CM x R x S	3	CM x Ss/Dy x R x S	0.60	0.20	--
CM x R x T	3	CM x Ss/Dy x R x T	5.19	1.73	3.84*
CM x D x S	2	CM x Ss/Dy x D x S	5.05	2.52	3.65*
CM x D x T	2	CM x Ss/Dy x D x T	0.68	0.34	--
CM x S x T	1	CM x Ss/Dy x S x T	0.07	0.07	--
Dy x R x D	6	Ss/Dy x R x D	1.58	0.26	--
Dy x R x S	3	Ss/Dy x R x S	3.41	1.14	2.28
Dy x R x T	3	Ss/Dy x R x T	3.62	1.21	2.24
Dy x D x S	2	Ss/Dy x D x S	1.35	0.67	--
Dy x D x T	2	Ss/Dy x D x T	0.31	0.15	--

Table XXI (3)

Source	df	Error Term	SS	MS	F
Dy x S x T	1	Ss/Dy x S x T	6.81	6.81	10.81**
Ss/Dy x R x D	84	None	48.73	0.58	
Ss/Dy x R x S	42	None	21.06	0.50	
Ss/Dy x R x T	42	None	22.77	0.54	
Ss/Dy x D x S	28	None	21.20	0.76	
Ss/Dy x D x T	28	None	18.76	0.67	
Ss/Dy x S x T	14	None	8.80	0.63	
R x D x S	6	Ss/Dy R x D x S	1.44	0.24	--
R x D x T	6	Ss/Dy x R x D x T	2.66	0.44	--
R x S x T	3	Ss/Dy x R x S x T	2.48	0.82	1.82
D x S x T	2	Ss/Dy x D x S x T	0.10	0.05	--
CM x Dy x R x D	6	CM x Ss/Dy x R x D	2.00	0.33	--
CM x Dy x R x S	3	CM x Ss/Dy x R x S	4.43	1.48	32.9*
CM x Dy x R x T	3	CM x Ss/Dy x R x T	0.12	0.04	--
CM x Dy x D x S	2	CM x Ss/Dy x D x S	0.18	0.09	--
CM x Dy x D x T	2	CM x Ss/Dy x D x T	2.84	1.42	1.89
CM x Dy x S x T	1	CM x Ss/Dy x S x T	4.20	4.20	9.33**

Table XXI (4)

Source	df	Error Term	SS	MS	F
CM x Ss/Dy x R x D	84	None	36.17	0.43	
CM x Ss/Dy x R x S	42	None	19.08	0.45	
CM x Ss/Dy x R x T	42	None	19.09	0.45	
CM x Ss/Dy x D x S	28	None	19.28	0.69	
CM x Ss/Dy x D x T	28	None	20.89	0.75	
CM xSs/Dy x S x T	14	None	6.33	0.45	
CM x R x D x S	6	CM x Ss/Dy x R x D x S	4.51	0.75	1.27
CM x R x D x T	6	CM x Ss/Dy x R x D x T	7.97	1.33	2.66*
CM x R x S x T	3	CM x Ss/Dy x R x S x T	1.31	0.44	--
CM x D x S x T	2	CM x Ss/Dy x D x S x T	1.89	0.94	1.81
Dy x R x D x S	6	Ss/Dy x R x D x S	3.29	0.55	1.10
Dy x R x D x T	6	Ss/Dy x R x D x T	1.08	0.18	--
Dy x R x S x T	3	Ss/Dy x R x S x T	3.28	1.09	2.42
Dy x D x S x T	2	Ss/Dy x D x S x T	1.52	0.76	1.73
Ss/Dy x R x D x S	84	None	42.31	0.50	
Ss/Dy x R x D x T	84	None	47.26	0.56	
Ss/Dy x R x S x T	42	None	18.90	0.45	
Ss/Dy x D x S x T	28	None	12.35	0.44	

Table XXI (5)

Source	df	Error Term	SS	MS	F
R x D x S x T	6	Ss/Dy x G x D x S x T	2.28	0.38	--
CM x Dy x R x D x S	6	CM x Ss/Dy x R x D x S	4.24	0.71	1.20
CM x Dy x R x D x T	6	CM x Ss/Dy x R x D x T	1.84	0.31	--
CM x Dy x R x S x T	3	CM x Ss/Dy x R x S x T	4.59	1.53	3.06*
CM x Dy x D x S x T	2	CM x Ss/Dy x D x S x T	0.10	0.05	--
CMxSs/DyxRxDxS	34	None	49.89	0.59	
CMxSs/DyxRxDxT	84	None	42.17	0.50	
CMxSs/DyxRxSxT	42	None	20.88	0.50	
CmxSs/DyxDxSxT	28	None	14.68	0.52	
CM x R x D x S x T	6	CMxSs/DyxRxDxS	1.35	0.22	--
Dy x R x D x S x T	6	Ss/Dy x R x D x S x T	2.43	0.40	--
Ss/Dy x R x D x S x T	84	None	36.85	0.44	
CMxDyxRxDxSxT	6	CMxSs/DyxRxDxSxT	3.70	0.62	--
CMxSs/DyxRxDxSxT	84	None	53.07	0.63	
TOTAL	1535		948.30		

Table XXII

Summary Table, Analysis of Variance, Experiment I, Total Time Score

Source	df	Error Term	SS	MS	F
Control Mode	1	CM x Ss/Dy	834.30	834.30	7.44*
Dynamics	1	Ss/Dy	3192.84	3192.84	10.35**
Subjects/Dy	14	None	4318.80	308.49	
Rate	3	Ss/Dy x R	49316.23	16438.74	845.18**
Distance	2	Ss/Dy x D	11584.58	5792.29	428.42**
Size	1	Ss/Dy x S	239.00	239.00	5.79*
Time	1	Ss/Dy x T	151.76	151.76	4.89*
CM x Dy	1	CM x Ss/Dy	528.94	528.94	4.72*
CM x Ss/Dy	14	None	1570.12	112.15	
CM x R	3	CM x Ss/Dy x R	5239.46	1746.49	75.61**
CM x D	2	CM x Ss/Dy x D	90.22	45.11	2.75
CM x S	1	CM x Ss/Dy x S	81.94	81.94	3.26
CM x T	1	CM x Ss/Dy x T	30.05	30.05	1.55
Dy x R	3	Ss/Dy x R	888.80	296.27	15.23**
Dy x D	2	Ss/Dy x D	276.15	138.08	10.21**
Dy x S	1	Ss/Dy x S	3135.96	3135.96	75.97**
Dy x T	1	Ss/Dy x T	57.07	57.07	1.84
Ss/Dy x R	42	None	816.90	19.45	
Ss/Dy x D	28	None	378.63	13.52	
Ss/Dy x S	14	None	577.90	41.28	
Ss/Dy x T	14	None	434.86	31.06	
R x D	6	Ss/Dy x R x D	14629.42	2438.24	122.03**
R x S	3	Ss/Dy x R x S	103.63	34.54	2.18
R x T	3	Ss/Dy x R x T	117.09	39.03	2.14

Table XXII (2)

Source	df	Error Term	SS	MS	F
D x S	2	Ss/Dy x D x S	34.94	17.47	1.12
D x T	2	Ss/Dy x D x T	210.38	105.19	7.36**
S x T	1	Ss/Dy x S x T	1.45	1.45	--
CM x Dy x R	3	CM x Ss/Dy x R	648.51	216.17	9.36**
CM x Dy x D	2	CM x Ss/Dy x D	32.38	16.19	--
CM x Dy x S	1	CM x Ss/Dy x S	162.32	162.32	6.46*
CM x Dy x T	1	CM x Ss/Dy x T	5.62	5.62	--
CM x Ss/Dy x R	42	None	970.28	23.10	
CM x Ss/Dy x D	28	None	459.54	16.41	
CM x Ss/Dy x S	14	None	351.73	25.12	
CM x Ss/Dy x T	14	None	270.84	19.35	
CM x R x D	6	CM x Ss/Dy x R x D	344.71	57.45	2.32*
CM x R x S	3	CM x Ss/Dy x R x S	23.28	7.76	--
CM x R x T	3	CM x Ss/Dy x R x T	14.65	4.88	--
CM x D x S	2	CM x Ss/Dy x D x S	4.64	2.32	--
CM x D x T	2	CM x Ss/Dy x D x T	52.39	26.19	--
CM x S x T	1	CM x Ss/Dy x S x T	41.85	41.85	2.36
Dy x R x D	6	Ss/Dy x R x D	106.36	17.73	--
Dy x R x S	3	Ss/Dy x R x S	482.18	160.73	10.17**
Dy x R x T	3	Ss/Dy x R x T	294.62	98.21	5.39**
Dy x D x S	2	Ss/Dy x D x S	55.45	27.72	1.77
Dy x D x T	2	Ss/Dy x D x T	0.25	0.12	--

Table XXII (3)

Source	df	Error Term	SS	MS	F
Dy x S x T	1	Ss/Dy x S x T	3.59	3.59	--
Ss/Dy x R x D	84	None	1678.04	19.98	
Ss/Dy x R x S	42	None	664.08	15.81	
Ss/Dy x R x T	42	None	764.80	18.21	
Ss/Dy x D x S	28	None	437.94	15.64	
Ss/Dy x D x T	28	None	400.16	14.29	
Ss/Dy x S x T	14	None	424.41	30.31	
R x D x S	6	Ss/Dy R x D x S	225.50	37.58	2.09
R x D x T	6	Ss/Dy x R x D x T	570.12	95.02	4.17**
R x S x T	3	Ss/Dy x R x S x T	152.56	50.85	2.54
D x S x T	2	Ss/Dy x D x S x T	32.98	16.49	--
CM x Dy x R x D	6	CM x Ss/Dy x R x D	351.86	58.64	2.36*
CM x Dy x R x S	3	CM x Ss/Dy x R x S	73.19	24.40	1.87
CM x Dy x R x T	3	CM x Ss/Dy x R x T	47.92	15.97	--
CM x Dy x D x S	2	CM x Ss/Dy x D x S	15.16	7.58	--
CM x Dy x D x T	2	CM x Ss/Dy x D x T	26.57	13.28	--
CM x Dy x S x T	1	CM x Ss/Dy x S x T	72.06	72.06	4.06

Table XXII (4)

Source	df	Error Term	SS	MS	F
CM x Ss/Dy x R x D	84	None	2084.27	24.81	
CM x Ss/Dy x R x S	42	None	548.06	13.05	
CM x Ss/Dy x R x T	42	None	794.55	18.92	
CM x Ss/Dy x D x S	28	None	497.15	17.76	
CM x Ss/Dy x D x T	28	None	999.78	35.71	
CM xSs/Dy x S x T	14	None	248.30	17.74	
CM x R x D x S	6	CM x Ss/Dy x R x D x S	270.71	45.12	2.15
CM x R x D x T	6	CM x Ss/Dy x R x D x T	321.48	53.58	2.51*
CM x R x S x T	3	CM x Ss/Dy x R x S x T	13.97	4.66	--
CM x D x S x T	2	CM x Ss/Dy x D x S x T	16.94	8.47	--
Dy x R x D x S	6	Ss/Dy x R x D x S	83.04	13.84	--
Dy x R x D x T	6	Ss/Dy x R x D x T	145.61	24.27	1.06
Dy x R x S x T	3	Ss/Dy x R x S x T	28.70	9.57	--
Dy x D x S x T	2	Ss/Dy x D x S x T	99.53	49.76	2.85
Ss/Dy x R x D x S	84	None	1512.71	18.01	
Ss/Dy x R x D x T	84	None	1914.53	22.79	
Ss/Dy x R x S x T	42	None	839.08	19.98	
Ss/Dy x D x S x T	28	None	487.95	17.43	

Table XXII (5)

Source	df	Error Term	SS	MS	F
R x D x S x T	6	Ss/Dy x G x D x S x T	309.16	51.53	5.42**
CM x Dy x R x D x S	6	CM x Ss/Dy x R x D x S	26.50	4.42	--
CM x Dy x R x D x T	6	CM x Ss/Dy x R x D x T	148.85	24.81	1.16
CM x Dy x R x S x T	3	CM x Ss/Dy x R x S x T	29.83	9.94	--
CM x Dy x D x S x T	2	CM x Ss/Dy x D x S x T	5.16	2.58	--
CMxSs/DyxRxDxS	34	None	1766.48	21.03	
CMxSs/DyxRxDxT	84	None	1791.01	21.32	
CMxSs/DyxRxSxT	42	None	657.76	15.66	
CmxSs/DyxDxSxT	28	None	813.42	29.05	
CM x R x D x S x T	6	CMxSs/DyxRxDxS	234.50	39.08	1.98
Dy x R x D x S x T	6	Ss/Dy x R x D x S x T	268.61	44.77	4.71**
Ss/Dy x R x D x S x T	84	None	798.07	9.50	
CMxDyxRxDxSxT	6	CMxSs/DyxRxDxSxT	168.41	28.07	1.43
CMxSs/DyxRxDxSxT	84	None	1654.25	19.69	
TOTAL	1535				

APPENDIX III

MEANS FOR SIGNIFICANT HIGHER ORDER INTERACTIONS: EXPERIMENT I

TABLE XXIII

Travel Time Means, Experiment 1, as a Function of Control Mode, Dynamics, Rate, and Distance

Fixed Rate

		R_1	R_2	R_3	R_4
Simple	D_1	9.73	3.30	3.94	5.11
	D_2	18.47	4.82	4.25	4.93
	D_3	27.30	5.96	4.30	6.38
Complex	D_1	9.41	5.64	7.06	9.26
	D_2	19.22	6.68	8.73	77.55
	D_3	25.95	9.63	7.92	9.18

Proportional Rate

		R_1	R_2	R_3	R_4
Simple	D_1	10.82	3.14	3.14	3.30
	D_2	21.77	5.00	3.83	3.96
	D_3	32.10	7.13	4.81	4.06
Complex	D_1	10.62	4.66	4.82	4.72
	D_2	25.13	6.31	5.40	5.70
	D_3	34.67	7.23	5.93	6.98

TABLE XXIV

Time on Target Means, Experiment 1, as a Function of Control Mode, Dynamics, Size, and Time

		Fixed Rate		Proportional Rate	
		S_1	S_2	S_1	S_2
T_1	Simple	.10	.19	.08	.02
	Complex	.34	.24	.19	.06
T_2	Simple	.15	.30	.07	.59
	Complex	.50	.34	.82	.19

TABLE XXV

Travel Time Means, Experiment 1, as a Function of Control Mode, Rate, Distance, and Size

		Fixed Rate				Proportional Rate			
		R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4
S_1	D_1	9.28	5.00	6.00	8.10	10.56	4.07	4.31	3.98
	D_2	19.73	5.30	7.30	9.49	23.49	6.40	4.63	4.73
	D_3	26.79	8.54	6.90	7.28	33.51	7.39	5.48	5.41
S_2	D_1	9.86	3.94	4.97	6.27	10.88	3.73	3.65	4.04
	D_2	17.96	6.20	5.68	6.99	23.41	4.92	4.60	4.92
	D_3	26.46	7.06	4.58	8.27	33.26	6.98	5.26	5.63

TABLE XXVI

Total Time Means, Experiment 1,
as a Function of Rate,
Distance, Size, and Time

			R_1	R_2	R_3	R_4
T_1	S_1	D_1	10.62	4.59	7.36	10.57
		D_2	22.73	6.75	8.04	6.73
		D_3	29.86	9.66	7.51	8.60
	S_2	D_1	11.07	4.23	5.74	7.33
		D_2	20.70	5.87	9.93	8.51
		D_3	30.20	6.78	5.80	10.10
T_2	S_1	D_1	9.90	5.29	6.54	7.79
		D_2	21.04	6.55	8.86	14.15
		D_3	30.51	9.48	9.72	9.71
	S_2	D_1	10.72	3.80	5.61	6.77
		D_2	20.84	7.26	7.14	7.89
		D_3	29.77	10.28	8.02	9.87

Table XXVII

Total Time Means, Experiment I, as a Function of Dynamics, Rate, Distance, Size, and Time

			Simple R_1	Simple R_2	Simple R_3	Simple R_4	Complex R_1	Complex R_2	Complex R_3	Complex R_4
T_1	S_1	D_1	9.86	2.94	4.14	6.59	11.38	6.25	10.58	13.95
		D_2	20.22	4.28	3.52	4.07	25.25	9.23	12.56	9.40
		D_3	28.93	6.64	4.18	5.31	30.81	12.68	10.84	11.89
	S_2	D_1	12.24	3.94	6.53	8.57	9.91	4.52	4.95	6.10
		D_2	20.19	6.28	11.53	6.48	21.21	5.46	8.33	10.55
		D_3	30.24	6.86	5.42	11.10	29.95	6.70	6.18	9.10
T_2	S_1	D_1	9.62	3.09	4.28	4.47	10.18	7.49	8.80	11.11
		D_2	20.06	4.50	3.53	6.46	22.03	8.60	14.20	21.84
		D_3	29.81	6.02	5.47	4.40	31.21	12.95	13.97	15.03
	S_2	D_1	11.20	4.78	4.18	6.56	10.25	2.82	7.04	6.99
		D_2	20.40	7.16	7.87	7.69	21.29	7.36	6.42	8.09
		D_3	30.20	11.44	8.68	8.28	29.34	9.12	7.36	11.47

APPENDIX IV

ANALYSIS OF VARIANCE SUMMARY TABLES: EXPERIMENT II

Table XXVIII

Summary Table, Analysis of Variance,
Experiment II, Travel Time Score

Source	df	SS	MS	F
Gain	3	4.45	1.48	1.87
Distance	2	1.28	0.64	--
Size	1	41.40	41.40	52.23**
Time	1	0.31	0.31	--
G x D	6	5.28	0.88	1.11
G x S	3	1.02	0.34	--
G x T	3	0.72	0.24	--
D x S	2	0.52	0.26	--
D x T	2	0.62	0.31	--
S x T	1	1.15	1.15	1.45
G x D x S	6	3.68	0.61	--
G x D x T	6	4.68	0.78	--
G x S x T	3	6.70	2.23	2.82*
D x S x T	2	1.09	0.55	--
G x D x S x T	6	2.46	0.41	--
Within	336	266.28	0.79	
TOTAL	383	341.63		

* = $P < .05$
** = $P < .01$

Table XXIX

Summary Table, Analysis of Variance,
Experiment II, Adjustment Time Score

Source	df	SS	MS	F
Gain	3	13.10	4.37	--
Distance	2	3.14	1.57	--
Size	1	217.13	217.13	46.58**
Time	1	54.85	54.85	11.76**
G x D	6	21.70	3.62	--
G x S	3	10.69	3.56	--
G x T	3	6.92	2.31	--
D x S	2	9.32	4.66	--
D x T	2	0.79	0.40	--
S x T	1	33.23	33.23	7.13**
G x D x S	6	17.97	2.99	--
G x D x T	6	31.29	5.21	1.12
G x S x T	3	8.16	2.72	--
D x S x T	2	1.25	0.62	--
G x D x S x T	6	54.73	9.12	1.96
Within	336	1566.14	4.66	
TOTAL	383	2050.40		

Table XXX

Summary Table, Analysis of Variance, Experiment II, Time on Target Score

Source	df	SS	MS	F
Gain	3	11.40	3.80	1.70
Distance	2	3.17	1.58	--
Size	1	54.50	54.50	24.41**
Time	1	12.57	12.57	5.63*
G x D	6	13.66	2.28	1.02
G x S	3	6.82	2.27	1.02
G x T	3	5.27	1.76	--
D x S	2	4.39	2.19	--
D x T	2	2.81	1.40	--
S x T	1	5.60	5.60	2.51
G x D x S	6	19.02	3.17	1.42
G x D x T	6	5.10	0.85	--
G x S x T	3	8.84	2.95	1.32
D x S x T	2	2.40	1.20	--
G x D x S x T	6	8.35	1.39	--
Within	336	750.21	2.23	
TOTAL	383	914.11		

Table XXXI

Summary Table, Analysis of Variance,
Experiment II, Total Time Score

Source	df	SS	MS	F
Gain	3	6.03	2.01	--
Distance	2	5.62	2.81	--
Size	1	448.14	448.14	77.21**
Time	1	63.38	63.38	10.92**
G x D	6	36.90	6.15	1.06
G x S	3	5.14	1.71	--
G x T	3	10.54	3.51	--
D x S	2	12,11	6.05	1.09
D x T	2	0.27	0.14	--
S x T	1	22.02	22.02	3.80
G x D x S	6	33.37	5.56	--
G x D x T	6	38.92	6.49	1.12
G x S x T	3	24.93	8.31	1.43
D x S x T	2	0.25	0.13	--
G x D x S x T	6	48.15	8.03	1.38
Within	336	1950.24	5.80	
TOTAL	383	2706.00		

APPENDIX V

ANALYSIS OF VARIANCE SUMMARY TABLES: EXPERIMENT III

Table XXXII

Summary Table, Analysis of Variance,
Experiment III: Travel Time Score

Source	df	SS	MS	F
Rate	3	5.65	1.88	--
Distance	2	76.68	38.34	7.47**
Size	1	117.52	117.52	22.90**
Time	1	15.66	15.66	3.05
R x D	6	123.28	20.55	4.00**
R x S	3	30.30	10.10	1.97
R x T	3	46.10	15.37	2.99*
D x S	2	2.75	1.38	--
D x T	2	2.41	1.20	--
S x T	1	0.67	0.67	--
R x D x S	6	37.01	6.17	1.20
R x D x T	6	32.10	5.35	1.04
R x S x T	3	15.92	5.31	1.03
D x S x T	2	8.61	4.30	--
R x D x S x T	6	28.65	4.77	--
Within	336	1724.06	5.13	
TOTAL	383	2267.36		

Table XXXIII

Summary Table, Analysis of Variance, Experiment III: Adjustment Time Score

Source	df	SS	MS	F
Rate	3	137.71	45.90	9.24**
Distance	2	10.39	5.20	1.05
Size	1	49.78	49.78	10.02**
Time	1	1.25	1.25	--
R x D	6	53.46	8.91	1.79
R x S	3	67.49	22.50	4.53**
R x T	3	32.60	10.87	2.19
D x S	2	6.35	3.18	--
D x T	2	11.68	5.84	1.18
S x T	1	8.56	8.56	1.72
R x D x S	6	16.74	2.79	--
R x D x T	6	29.48	4.91	--
R x S x T	3	21.96	7.32	1.47
D x S x T	2	3.24	1.62	--
R x D x S x T	6	17.74	2.96	--
Within	336	1669.53	4.97	
TOTAL	383	2137.96		

Table XXXIV

Summary Table, Analysis of Variance,
Experiment III: Total Time Score

Source	df	SS	MS	F
Rate	3	160.72	53.57	6.20**
Distance	2	113.41	56.70	6.56**
Size	1	320.27	320.27	37.05**
Time	1	8.06	8.06	--
R x D	6	206.94	34.49	3.99**
R x S	3	181.85	60.62	7.01**
R x T	3	64.99	21.66	2.51
D x S	2	7.36	3.68	--
D x T	2	4.98	2.49	--
S x T	1	4.44	4.44	--
R x D x S	6	49.52	8.25	--
R x D x T	6	66.01	11.00	1.27
R x S x T	3	1.30	0.43	--
D x S x T	2	19.83	9.91	1.15
R x D x S x T	6	53.20	8.87	1.03
Within	336	2904.72	8.65	
TOTAL	383	4167.62		

APPENDIX VI

APPLICATION OF AN INDEX OF GAIN TO THE REMOTE MANIPULATOR SIMULATION

The size, distance, and rate variables, all of which are distance related measures, can be treated in terms of the visual angles subtended at the eye of the observer. Studies have indicated that it is meaningful to treat gain as the ratio of control stick angular excursion to angular excursion of the display element at the eye of the operator (ref 13). Viewing distance has a marked effect on the apparent rate and extent of motion of a stimulus.

To be consistent with the use of a gain index, it is necessary and logical to treat target size and the distance to be traversed in terms of visual angle rather than in terms of size or linear translation. By converting to angular measures, it is possible to treat a variety of parameters consistently, in angular terms, and to generalize to other situations on this basis.

The computation of appropriate gain values was accomplished by first determining typical manipulator rates of motion and target viewing distance. A survey of performance specifications for six different rate controlled manipulators yielded the following parameter values:

Av. carriage rate in X, Y	86.36 cm/sec	(17 fpm)
Range of carriage rates in X, Y	30.48 - 152.40 cm/sec	(6-30 fpm)
Average maximum X travel	188.82 cm	(6 feet)
Average maximum Y travel	152.40 cm	(5 feet)
Average maximum velocity of arm segments	1.3 rpm	

Converting these figures from linear to angular values, and assuming a 304.80 cm (10 ft) viewing distance, yielded ranges of .05 to 3.0 deg/sec at the eye as representing the slowest and the fastest rates at which current manipulators operate. Since the available control stick had an angular excursion of 30 degrees, the gain for the current system was established as G = angular rate at the eye in degrees per second/angular excursion of the control, or 3/30 = .1. At a viewing distance of 304.80 cm this was represented on the display by an arm which moved across the scope face at 13.24 cm/sec (6 in/sec) for a maximum 30 degree stick deflection.

If a different viewing distance was used, the linear rate of the arm on the display surface would have to be modified to give the required angular rate. By decreasing viewing distance, it is possible to increase the angular separation of arm and target.

With the position control system the logic of determining gain and other variables in angular terms is similar; gain is the ratio of arm displacement in degrees of visual angle to angular stick displacement. However, with position control, separation of arm and target on the display must be less than the distance which the arm will travel upon full excursion of the cursor, otherwise it is not possible to reach the target. Gain is then limited to values obtainable with the available stick excursion and by the requirement that this excursion produce arm travel which is greater than or equal to the target-arm separation distance. Maximum physical separation of target and arm is limited by the size of the available CRT display. In other words, arm travel must be greater than target-arm separation, and gain values are limited to values where

$$\text{gain} = \frac{\text{an angle} > \text{target-arm separation}}{\text{stick excursion } (30^\circ)}$$

For a viewing distance of 304.80 cm and maximum physical target-arm separation of 38.10 cm (15 in), the resultant angular target-arm separation is approximately 7° and the gain is $7^\circ/30^\circ$, or .23. If viewing distance is increased, both target-arm angular separation and gain decrease in direct proportion to distance.

In summary, by considering parameters in terms of angular values, it is possible to study the analog of a wide variety of sizes and distances because angular size for any practical gain value is not limited by the target-arm separation distance which can be displayed on the scope. With rate control, rates of arm motion on the display can be adjusted to compensate for any viewing distance so as to maintain the same angular rate at the eye. Maximum target-arm separation is set independently and is limited only by size of the display. With position control, gain and target-arm separation are simultaneously affected by the interaction of viewing distance, scope size, angular excursion of the control, and desired gain level.

In establishing the experimental situation, the viewing distances, size of the display elements, and angular rates of motion were scaled so that the resultant angular travel at the retina of the observer would be representative of the angular size and rates of motion at which actual manipulators operate.

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13. ABSTRACT

An analog simulation of a remote manipulator was developed and used to investigate operator performance as a function of machine design parameters. Independent variables included control order, rate of motion, manipulator dynamics, positioning error tolerance, distance traversed, and duration for which final arm position had to be maintained. Dependent variables were travel time, adjustment time, time on target and total task time. Principal results were as follows: Increasing the complexity of system dynamics produced a decrement in operator performance which was greater for fixed rate than for porportional rate control. Proportional rate control was found to be superior to fixed rate control afforded no advantage over the optimum single level of rate control.

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