STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

June 1967

Final Report | Covering the Period 24 May 1966 to 24 May 1967

TACTUAL PERCEPTION: EXPERIMENTS AND MODELS

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Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA

CONTRACT NAS2-3649

SRI Project 6070

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FOREWORD

This report was prepared by Stanford Research Institute under Contract NAS 2-3649, monitored at Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, by Dr. Robert Linebarger. Dr. James Bliss was Project Leader.

While the author is responsible for the material contained in this report, certain sections are primarily the work of others and are so indicated. In addition, we would like to acknowledge the contributions of A. F. Ferrera, who helped develop the interface system for computer control of the tactile experiments, and J. R. Duke, who constructed electronic interfaces for several systems peripheral to the computer.

ABSTRACT

Experiments in tactile perception, tactile and visual tracking behavior, and tactile and visual choice reaction time are described. Results from an experiment on tactile perception of sequentially presented point stimuli indicate that content errors (responses that are incorrect regardless of what order they are in) are constant as the interstimulus interval is increased up to 200 ms, and that sequence errors (errors caused only by responding in an incorrect order) decrease exponentially with interstimulus interval. The total error can be expressed as a linear sum of a constant, representing the content error, and a decaying exponential function of interstimulus interval (with a time constant of less than 100 ms), representing the sequential error.

In the tracking experiments comparisons were made between tracking performance when an airjet stimulator moved horizontally across the forehead and when it moved along the palmar side of the hand and index finger. Performance appeared to be about equal in these two cases. A comparison of performance with a contacting tactile stimulus and a visual display revealed essentially the same phase characteristics for both displays, but less gain and more remnant power with the tactile display.

Results from "critical" tracking with both visual and tactile displays indicated a greater effective time delay with the tactile display and no significant difference between tracking with the visual display only and tracking with both the visual and tactile displays used simultaneously.

In the reaction-time experiments subjects could receive either tactile or visual stimuli, or both simultaneously, on any one trial. In a simple reaction-time experiment in which only one response was

required, the tactile and visual reaction times were approximately equal. However, in the two-choice version of the experiment, response times were appreciably longer, and the probability of an error was greater with the tactile stimuli than with the visual stimuli. When both tactile and visual stimuli were presented simultaneously, significantly shorter reaction times were obtained than with either stimulus alone. These results are consistent with a model which assumes that the sensory input channels are independent of each other and that subjects tend to respond to the first perceived stimulus.

Five Appendices describe developments on new techniques and facilities for conducting a wide variety of experiments on tactile perception, which range from presentation of multiple point stimuli to analyses of describing functions in tracking experiments. The key item in these facilities is a LINC-8 computer, which will control, in a time-shared mode, the presentation of the stimuli, and record and analyze the responses.

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I INTRODUCTION

by J. C. Bliss

The high-performance capability of the tactile channel makes it a good contender for practical application. Examples of potential applications for tactile displays are situations in which vibration and high acceleration might severely limit visual function, cases where so many visual displays require attention that transferring some of this information to other sensory channels can improve overall performance, and applications where non-electrical displays have engineering and safety advantages.

A primary goal of our research effort over the past few years has been the development of information-processing models of the tactile channel with which we can correlate our experimental findings and with which special tactile display equipment can be designed. In addition, development of tactile perception models should also contribute to the general area of sensory communication, increasing our understanding of vision, audition, and multisensory interactions.

In the course of this research, we have developed airjet and piezoelectric tactile stimulators and an on-line digital computer system for experiment control. We have also used these facilities to obtain experimental results on spatial and temporal characteristics of the tactile channel with stationary patterned stimuli (Bliss, Crane, Link, and Townsend, 1966), moving patterned stimuli (Bliss, Crane, and Link, 1966), and multiple point stimuli (Bliss, Crane, Mansfield, and Townsend, 1966). Also, tactile displays for compensatory tracking have been developed and operator describing functions have been determined with these tactile displays (Bliss, 1966, and Seeley and Bliss, 1966), and with analogous visual displays for comparison.

This report covers a one-year research effort on additional work along these lines. Objectives of this additional work include the further determination of spatial and temporal information-processing characteristics of the tactile modality, to compare these characteristics with vision, to study interactions between the tactile sense and vision, and to study interactions between sensory perception and motor functions. The body of this report covers the work toward these objectives. In addition, there are five Appendices which describe techniques and instrumentation we have developed for on-line computer control of experiments.

In Sec. II, an experiment is described whose results reveal new information about the spatial and temporal information processing characteristics of the tactile modality. In this experiment, point tactile stimuli were applied to the interjoint regions of the fingers one at a time. The subject's task was to name the locations stimulated in the order stimulated. The analyses of the results indicate that as content errors (responses that are incorrect regardless of what order they are in) are constant as the interstimulus interval is increased up to 200 ms, and that sequence errors (errors caused only by responding in an incorrect order) decrease exponentially with interstimulus interval. These two types of error are independent. The total error can be expressed as a linear sum of a constant, representing the content error, which is different for each subject, and a decaying exponential function of interstimulus interval, representing the sequential error, which is nearly the same for all subjects. These results specify certain temporal properties of the tactile channel with which any model must be consistent.

In Sec. III, experimental comparisons between tactual and visual tracking performance are compared. First, several different tactile displays are compared, with a rubbing or contacting stimulus moving along the palmar side of the hand and index finger giving the best results. A comparison of performance with this tactile display versus a visual display revealed that the tactile performance had equal bandwidth, but less gain than the visual performance. The remnant data are examined for evidence of a periodic sampler nonlinearity, but no such evidence is found.

Also in Sec. III, performance on the "critical" tracking task with visual and tactile displays is compared. The subject's effective time delay with the visual display was shorter than with the tactile display, and there was no significant difference in the effective time delay with the visual display only and with both displays used simultaneously. These results are consistent with the conclusions of the reaction-time experiment described in Sec. IV and suggest a model in which (1) the sensory input channels are independent, (2) subjects respond to the first perceived stimulus, and (3) the time taken to respond consists of an input distribution characteristic of the sensory channel plus a motor time corresponding to the direction of the response.

These data, combined with results from our previous experiments, are summarized and corresponding models suggested in Sec. IV. Finally, the Appendices describe several developments on running of on-line-computer-controlled experiments.

II PERCEPTION OF SEQUENTIALLY PRESENTED POINT STIMULI

by J. C. Bliss, J. W. Hill, and P. K. Mansfield

A. GENERAL

The transmission of information in the tactile sense is limited by both spatial and temporal interactions. That is, the presentation of point stimuli either simultaneous with, or in close temporal proximity to, another tactile point stimulus will affect the accuracy of perceiving that stimulus. Recent experiments performed in this laboratory have examined the effects of these interactions on tactile perception.

In one study (Bliss, Crane, Mansfield, and Townsend, 1966), spatial interaction was investigated by presenting subjects with from two to twelve simultaneous jets of air to any of the 24 different interjoint regions of their fingers and measuring their accuracy in reporting the stimulated locations. Subjects were able to report from 3 to 7 positions correctly; however, their performance in reporting only one portion of the stimulus field indicated that as many as 11 out of 12 positions are actually available.

Somewhat earlier, a study was performed (Bliss, Crane, Link, and Townsend, 1966) to determine the conditions in which temporal interactions interfere with performance. Presenting pairs of alphabetic shapes sequentially to the same anatomical location on the hand, these investigators found (1) an increase in letter reversals for very short interstimulus intervals, and (2) a greater backward-masking effect for small interstimulus and stimulus-on intervals, and a greater forward-masking effect for longer interstimulus and stimulus-on intervals.

The information obtained from these experiments has been used to suggest models for tactile perception, based on masking and interference phenomena, which are similar to models, such as Sperling's (1963), for visual memory tasks. Sperling, for example, speaks of three major intervals: (1) a read-in interval of 50 to 100 ms during which stimuli tend to summate and superimpose; (2) an interval immediately following, during which a second stimulus can cancel or replace the first stimulus before it is read out; and (3) a later interval of reduced interference.

The experiment described in this section was designed to investigate further the perception of sequentially presented tactile stimuli. However, instead of using alphabetic shapes presented sequentially to the same anatomical location, the stimuli consisted of brief jets of air to any of the 24 interjoint regions of the fingers (thumbs excluded). The subjects' task was to report the regions stimulated. In this sense, this experiment is more analogous to the earlier one on simultaneous stimulation.

To gain additional insight into the nature of possible masking phenomena, each subject was asked, in separate tests, to rate each stimulus sequence on how much apparent motion it produced. In relation to an epochal model, a subject ought to perceive motion if the successive point stimuli are within adjacent temporal epochs.

Investigations of the perception of tactile apparent motion are not new. Boring (1942) reports several early studies of apparent movement between two successively stimulated skin loci, but as Sherrick and Rogers (1966) state, those studies rarely quantified the variable of interest, such as stimulus duration or interstimulus interval. Moreover, the nature of the stimulus, produced by dropping a weight on the skin and retrieving it electromagnetically, left much to be desired. Sumby (1965) indicated the most critical variable for vibrotactile apparent motion to be the time interval between stimuli. Kotovsky and Bliss (1963), asking their subjects to report which of two airjets came on first and how much apparent motion they felt, found that increasing the overlap time of the pulses beyond 0.2s caused a drop in accuracy.

In the present study, the time interval between stimuli was varied from a simultaneous condition up to a 200-ms interval, while the stimulus duration remained constant at 10 ms.

B. METHOD

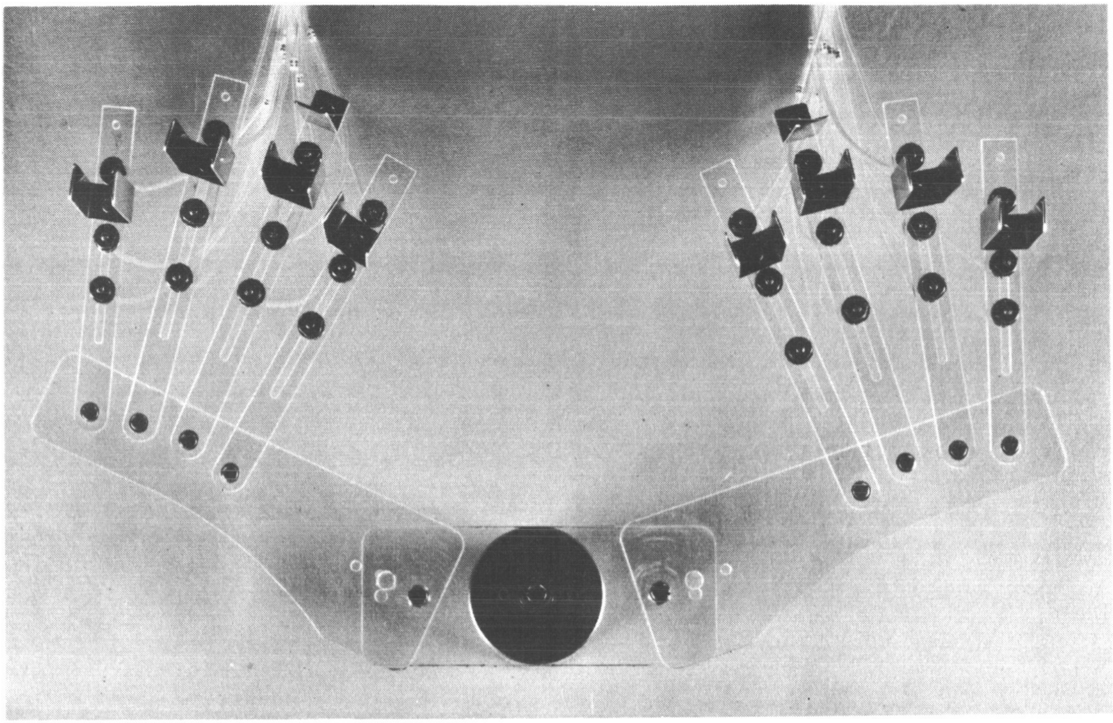
1. Apparatus

The experiment was carried out under control of a CDC 8090 computer system, which was used to store stimulus patterns and the sequence in which the patterns were to be presented (Bliss and Crane, 1964). This system was designed for use with up to 96 tactile or visual stimulators. Only 24 tactile stimulators were used in this experiment, one for each of the 24 interjoint regions of the fingers (thumbs excluded). The palmar sides of the fingers were suspended about 1/8 inch above the airjet stimulators shown in Fig. 1. The subjects' arms were supported from wrist to elbow, permitting the hands to be suspended in this manner for extended periods without fatigue. Each subject had his own set of airjet stimulators, which was initially adjusted to his hands and never reset unless he requested that a particular jet be readjusted. This ensured better constancy in the positioning of the airjets from session to session.

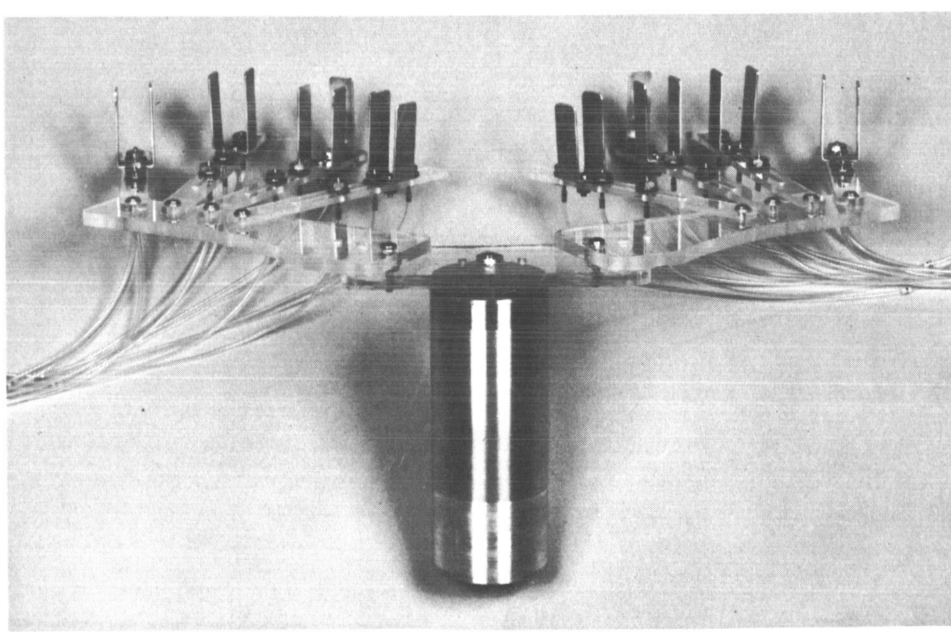
Each jet of air was formed by a 0.031-inch outlet nozzle under control of a high-speed electromagnetic valve. The air-pressure pulse, measured 1/8 inch directly above the airjet outlet, was about 3 psi, with a rise and fall time of about a millisecond and an overall pulse width of about 2.5 ms. A 200-c/s pulse-repetition rate was used through the experiments. Thus, all stimulators were simultaneously turned on and off 2 or 3 times during the 10-ms stimulus-presentation time. The advantages of airjet stimulation for this investigation were that relatively uniform stimulation was produced over nonuniform cutaneous surfaces and that stimulator spacing could be easily adjusted.

2. Subjects

Five male subjects were used. Subjects B and L were high school seniors, N was a college freshman, S, a college junior, and G, a graduate student. N had been totally blind from birth; G became blind seven years ago. None of the subjects had ever participated in an experiment of this nature.



(a) TOP VIEW



(b) SUBJECT'S VIEW

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FIG. 1 APPARATUS FOR HOLDING AIRJET NOZZLES BELOW THE 24 INTERJOINT REGIONS OF THE FINGERS

3. Procedure

On any one trial, 2 or 3 stimulation points were randomly selected (by the computer) out of the possible 24 interjoint locations, and the corresponding stimulators then activated, one at a time, for 10 ms. The time interval (T_i) between the offset of the first stimulator and the onset of the second stimulator, and (when $n = 3$) between the offset of the second and the onset of the third stimulator, was one of the following: (1) -10ms (that is, the 2 or 3 points were simultaneously activated); (2) 2 ms; (3) 50 ms; (4) 100 ms; (5) 200 ms. Except in the simultaneous condition, the same interjoint position could be stimulated repetitively in a single trial. In any one session, the number of positions stimulated, n, in each trial was constant and known by the subject, while T_i was constant but unknown. All positions were stimulated an equal number of times per session.

After each stimulus, the subject orally reported the locations perceived in the order of their occurrence, using the alphabetic labels shown in Fig. 2. Each response was typed into the control computer by the experimenter, and after a fixed delay of 2s, the next stimulus was automatically presented. There was no fixed time within which a subject was forced to respond. Verbal feedback was given after each response during training only.

Each subject participated in one 40-minute session a day, five days a week, for four weeks. The first ten days were devoted to training the subjects, in the hope that their performance at the task would reach asymptote before testing began. The number of trials per training session was selected so that the session would be completed within 40 minutes. For the testing sessions, the number of trials for each value of n (at each value of T_i) was chosen to allow the variance for the mean number correct per n-value to remain constant across all values of n (in this case, for $n = 2$ and $n = 3$). (Specifically, the number of trials per session was set so that the probability that the mean number correct per value of n would exceed the true mean by more than

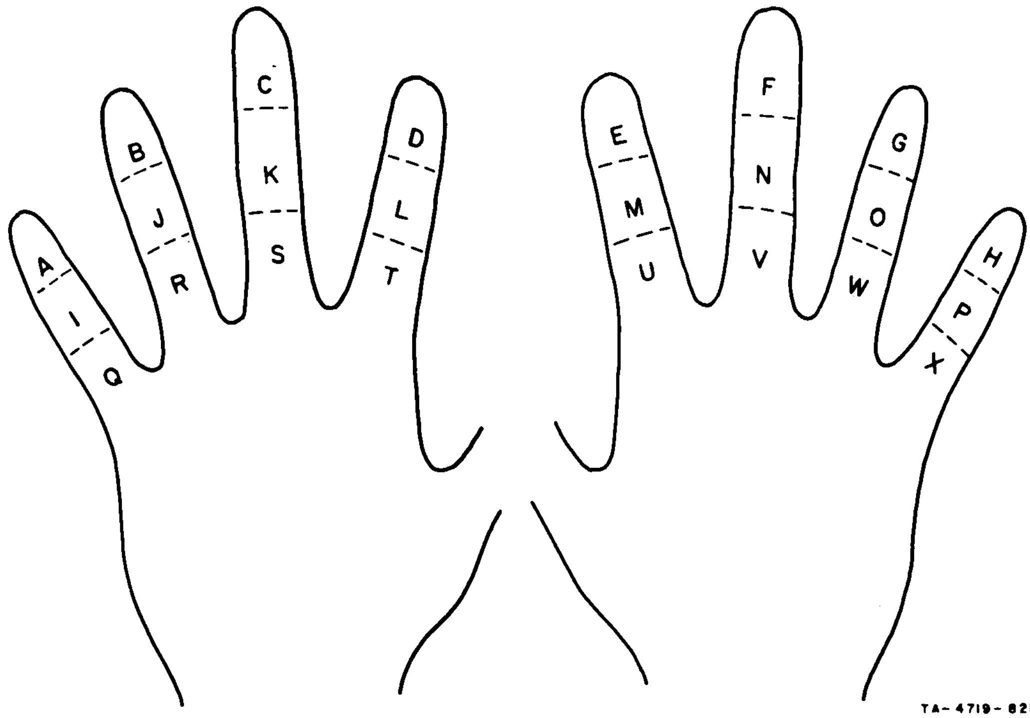

FIG. 2 FINGER LABELING FOR TWO HANDS

0.3 stimulus position was ≤ 0.1). The resulting training and testing schedule is shown in Table I.

In addition to the scheduled tests, during the last two weeks a third test was run each day. This test was the same as one of the two scheduled tests run that day, but the subject was instructed not to report the positions perceived but to rate each stimulus on how much apparent motion was produced by the stimulus. The subjects were instructed to rate the stimuli from 1 to 10, basing their judgments on how smooth the motion appeared and how much of the area between the stimulated positions appeared to be covered by the "moving" stimulus.

C. RESULTS AND DISCUSSION

1. Apparent Motion

The degrees of motion perceived by the subjects for stimuli separated by each of the time intervals are pictured in Figs. 3 and 4.

Table I

TRAINING AND TESTING SCHEDULE

<table>
<tr><th colspan="21">Training</th></tr>
<tr><td>Day</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">4</td><td colspan="2">5</td><td colspan="2">6</td><td colspan="2">7</td><td colspan="2">8</td><td colspan="2">9</td><td colspan="2">10</td></tr>
<tr><td>n</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">3</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">3</td><td colspan="2">3</td></tr>
<tr><td>T_i</td><td colspan="2">100</td><td colspan="2">-10</td><td colspan="2">50</td><td colspan="2">200</td><td colspan="2">2</td><td colspan="2">50</td><td colspan="2">100</td><td colspan="2">-10</td><td colspan="2">2</td><td colspan="2">200</td></tr>
<tr><td>No. trials</td><td colspan="2">144</td><td colspan="2">144</td><td colspan="2">120</td><td colspan="2">120</td><td colspan="2">144</td><td colspan="2">144</td><td colspan="2">144</td><td colspan="2">120</td><td colspan="2">120</td><td colspan="2">120</td></tr>
<tr><td>Hand</td><td colspan="2">left</td><td colspan="2">right</td><td colspan="2">left</td><td colspan="2">right</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td></tr>
<tr><th colspan="21">Testing</th></tr>
<tr><td>Day</td><td colspan="2">11</td><td colspan="2">12</td><td colspan="2">13</td><td colspan="2">14</td><td colspan="2">15</td><td colspan="2">16</td><td colspan="2">17</td><td colspan="2">18</td><td colspan="2">19</td><td colspan="2">20</td></tr>
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<tr><td>T_i</td><td>-10</td><td>100</td><td>2</td><td>50</td><td>200</td><td>-10</td><td>200</td><td>100</td><td>50</td><td>2</td><td>-10</td><td>100</td><td>200</td><td>2</td><td>50</td><td>200</td><td>50</td><td>100</td><td>-10</td><td>2</td></tr>
<tr><td>No. trials</td><td>60</td><td>60</td><td>60</td><td>60</td><td>60</td><td>88</td><td>88</td><td>88</td><td>88</td><td>88</td><td>88</td><td>88</td><td>88</td><td>88</td><td>88</td><td>60</td><td>60</td><td>60</td><td>60</td><td>60</td></tr>
<tr><td>Hand</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td><td colspan="2">both</td></tr>
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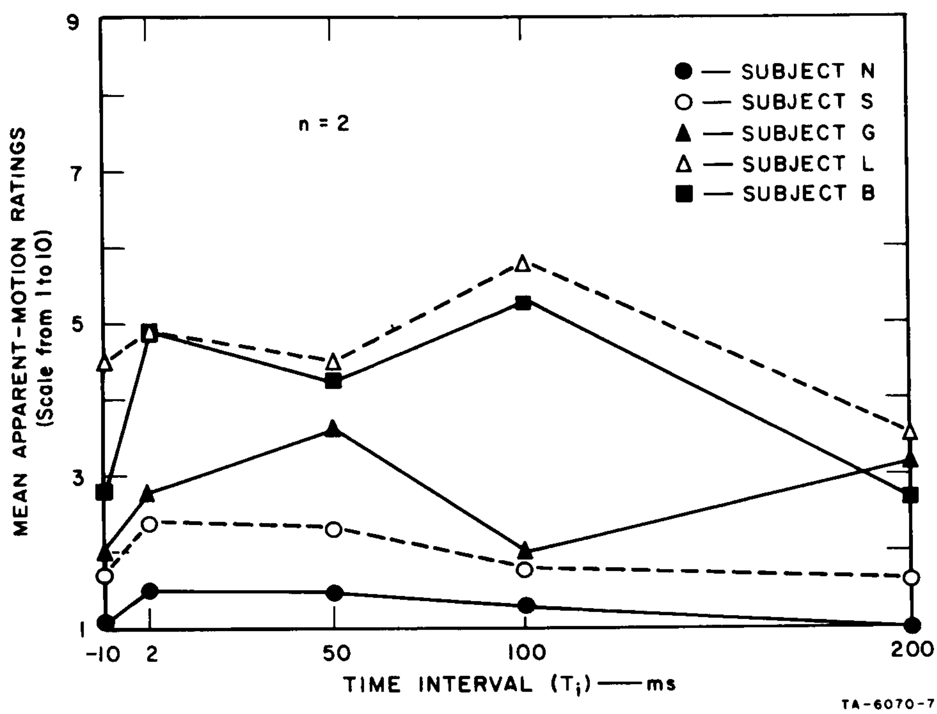

FIG. 3 MEAN APPARENT-MOTION RATINGS AT EACH TIME INTERVAL, FOR n = 2 SESSIONS (The −10 ms interval is the simultaneous condition.)

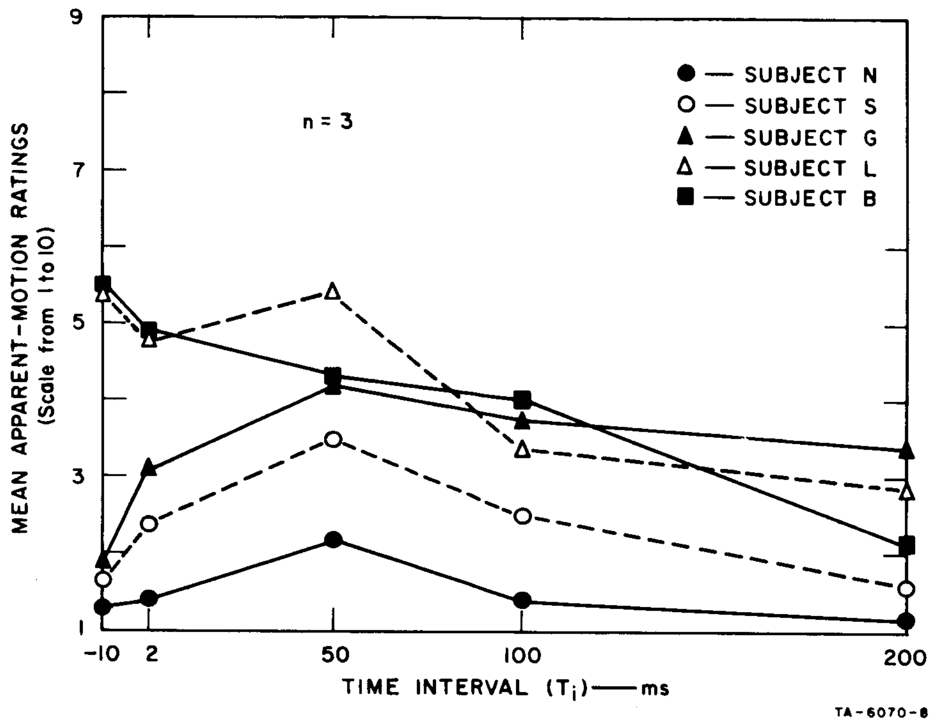

FIG. 4 MEAN APPARENT-MOTION RATINGS AT EACH TIME INTERVAL, FOR n = 3 SESSIONS

Figure 3 represents those sessions in which the stimuli consisted of two positions stimulated, while Fig. 4 represents the n = 3 sessions. Immediately apparent from the plots is the amount of variability among subjects, which could be due either to real differences in the amount of motion perceived by each of them, or to differences among them in what they considered to be "little" or "much" motion.

From Fig. 3 it can be seen that on the average, subjects perceived about the same amount of motion in stimuli separated by 2, 50, or 100 ms. Stimuli separated by any of these intervals produced more apparent motion than those either occurring simultaneously or separated by 200 ms. Of interest is the fact that all but one subject perceived some degree of motion even in the simultaneous and the 200-ms-interval cases.

Figure 4 shows that when three locations are stimulated, subjects reported more sensation of movement with an interval of 50 ms than with any other interval. Again, all subjects but Subject N reported some apparent motion at all time intervals.

These results are somewhat in accordance with the results of Kotovsky and Bliss (1963) and Sumby (1965), who found apparent motion most prevalent for stimuli temporally separated by 50 to 150 ms, which would place the stimuli in adjacent read-in intervals. The fact that the present results showed some apparent motion for simultaneous stimuli as well as for stimuli separated by 200 ms may be attributable to the vague standard used by the subjects in deciding what was "a little" or "a lot" of motion.

2. Error Analysis

Turning now to the analysis of response errors,* the number of errors was counted for each stimulus in a sequence (1st and 2nd for

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* This analysis was prepared by John Hill and constitutes a preliminary report on an analysis being carried out as part of a doctoral dissertation at Stanford University. While this data analysis was supported under NIH Grant NB 06412 at Stanford University, the experiment was designed and performed at Stanford Research Institute under Contract NAS 2-3649.

n = 2; and 1st, 2nd, and 3rd for n = 3) for each subject. The types of errors were classified according to the following definitions:

(1) Total Error: The fraction of erroneous stimulus-response pairs out of the total number of stimulus-response pairs. That is, unless the i^{th} response correctly identified the i^{th} stimulus, an error was counted.

(2) Content Error: The fraction of the total number of stimuli that were not correctly identified by any of the responses in a trial.

(3) Sequential Error: The total error minus the content error.

For example, the response sequence BAE to the stimulus sequence ABC contains three total errors, one content error, and two sequence errors.

An analysis of variance was performed on the data to evaluate the significant effects of the five subjects, the five different inter-stimulus intervals (T_i), and two or three stimuli sequence positions (SSP) on total and content error. The data are counts of discrete responses and hence obey a multinomial distribution which is approximately normally distributed. Since many error fractions are close to zero, the arcsin transformation was used on the error fractions in order to meet the equal variance assumptions of the analysis. The results of the analysis are given in Tables II and III. The important features of the analysis are as follows:

(1) The total error for different values of T_i is significantly different for both n = 2 and n = 3.

(2) The content error for different values of T_i is not significantly different, and the data therefore indicate that content error does not vary with T_i.

(3) The content error (and the total error for n = 3) at different positions in the stimulus sequence is significantly different. Thus, the error varies with position in the subject's response sequence. This result is in agreement with Bliss, Crane, Mansfield, and Townsend (1966; Fig. 7) for simultaneous point stimuli, and with Bliss, Crane, Link, and Townsend (1966) for sequential patterned stimuli.

Table II

SUMMARIES OF ANALYSIS-OF-VARIANCE OF ARCSIN TOTAL ERROR

Source	df	MS	F	p	
Between Subjects (S)	4	0.04415			n = 2
T_i	4	0.87339	>100	<0.001	
T_i × S	16	0.00855			
SSP	1	0.00228	2.96	--	
SSP × S	4	0.00077			
T_i × SSP	4	0.00090	1.32	--	
T_i × SSP × S	16	0.00068			
Between Subjects (S)	4	0.11504			n = 3
T_i	4	0.98664	60.2	<0.005	
T_i × S	16	0.01639			
SSP: Linear	1	0.15075	18.82	<0.005	
SSP: Remainder	1	0.12045	15.07	<0.005	
SSP × S	8	0.00801			
T_i × SSP	8	0.00673	1.44	--	
T_i × SSP × S	32	0.00468			

Table III

SUMMARY OF ANALYSIS-OF-VARIANCE OF ARCSIN CONTENT ERROR

Source	df	MS	F	p	
Between Subjects (S)	4	0.17517			n = 2
T_i	4	0.01012	1.60	--	
T_i × S	16	0.00634			
SSP	1	0.03900	17.98	<0.025	
SSP × S	4	0.00217			
T_i × SSP	4	0.00993	1.88	--	
T_i × SSP × S	16	0.00526			
Between Subjects (S)	4	0.30534			n = 3
T_i	4	0.00791	1.28	--	
T_i × S	16	0.00615			
SSP: Linear	1	0.06164	9.22	<0.025	
SSP: Residual	1	0.00046	--	--	
SSP × S	8	0.00669			
T_i × SSP	8	0.00646	1.11	--	
T_i × SSP × S	32	0.00580			

(4) The interaction terms T_i X SSP are all insignificant; therefore, the data indicate that the error for each subject is the linear sum of two independent terms. This result is in contrast to our results reported in Bliss, Crane, Link, and Townsend (1966), in which a greater percentage of first-response errors were obtained with patterned tactile stimuli for short interstimulus intervals and a greater percentage of second-response errors were obtained for long interstimulus intervals.

The average values of total error and content error for both n = 2 and n = 3 as a function of T_i are given in Figs. 5 and 6. All of the data reported are corrected for probability of guessing the content (but not sequence) according to a model similar to that reported in Bliss, Crane, Mansfield, and Townsend (1966). However, this correction makes at most only a 2-percent increase in error rate and thus is negligible. The graphs of Figs. 5 and 6 are an average over all five subjects and all stimulus sequence positions.

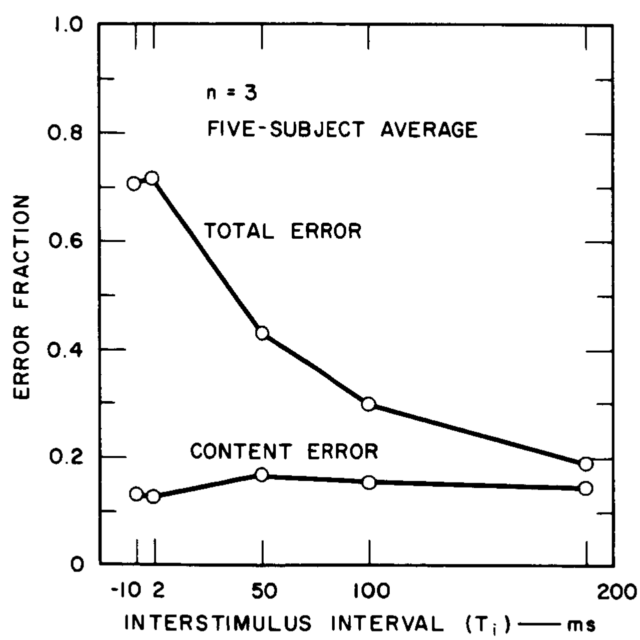


FIG. 5 AVERAGE TOTAL AND CONTENT ERRORS AS A FUNCTION OF INTERSTIMULUS INTERVAL FOR n = 3

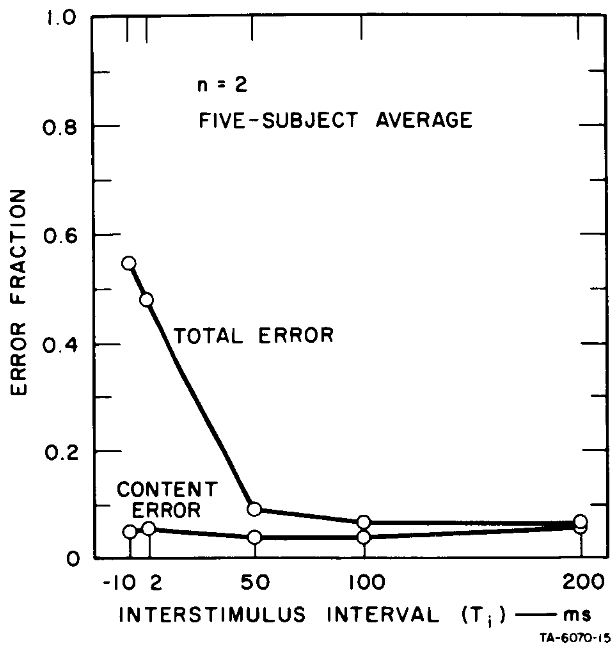


FIG. 6 AVERAGE TOTAL AND CONTENT ERRORS AS A FUNCTION OF INTERSTIMULUS INTERVAL FOR n = 2

For n = 3, the SSP mean square can be represented by a linear portion and an orthogonal quadratic portion. The linear portion is significant in both total- and content-error calculations, while the quadratic term is significant only in the total-error calculation. This quadratic term occurs because of the high total error in the middle sequence position, a result similar to that found by Bliss, Crane, Link, and Townsend (1966) with patterned tactile stimuli. The total and content error for each SSP, averaged over all values of T_i are shown in Fig. 7 for both n = 2 and n = 3.

In all of the analyses, the interaction term between SSP and T_i is not significant. Hence, the total error can be simply represented by a linear sum of three factors, one due to each subject E(S), one due to each interstimulus interval $E(T_i)$, and one due to the stimulus sequence position E(SSP). That is, the total error, E_T, is given by

$$E_T = E(S) + E(T_i) + E(SSP) + \epsilon \tag{1}$$

where ϵ is the error associated with the measurement. In most of the experiments, ϵ is normally distributed with mean equal to zero and a standard deviation (σ_ϵ) of 0.07.

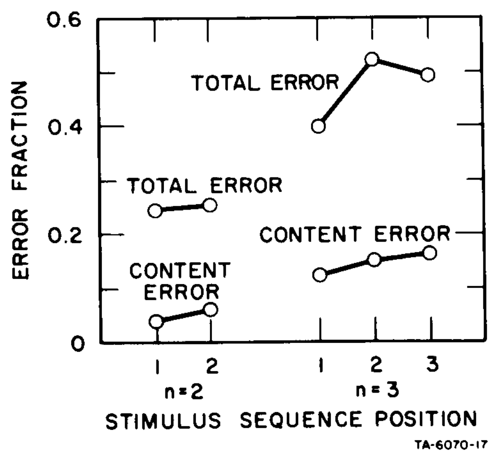


FIG. 7 TOTAL ERROR AND CONTENT ERROR AVERAGED OVER ALL STIMULUS DELAYS AS A FUNCTION OF STIMULUS SEQUENCE POSITION (SSP)

To investigate the error further, the sequential error was obtained by subtracting the content error from the total error for each SSP, subject, and value of T_i. A regression analysis of the sequence data was made using different types of curves: linear, hyperbolic, and exponential. The best fit was obtained with the exponential curves. The regression curves shown in Fig. 8 explain a significant portion of the error variation due to the different values of T_i. In fact, the very small amount of residual variance from the curves leaves little evidence to suggest that these regression lines are not the true model for the data. Summaries of the analysis of variance for the regression lines, with measured regression variance and residual variance, are given in Table IV. Other curves that were used to fit the data gave not only a significant regression, but a significant residual as well; thus, they were not complete in this sense.

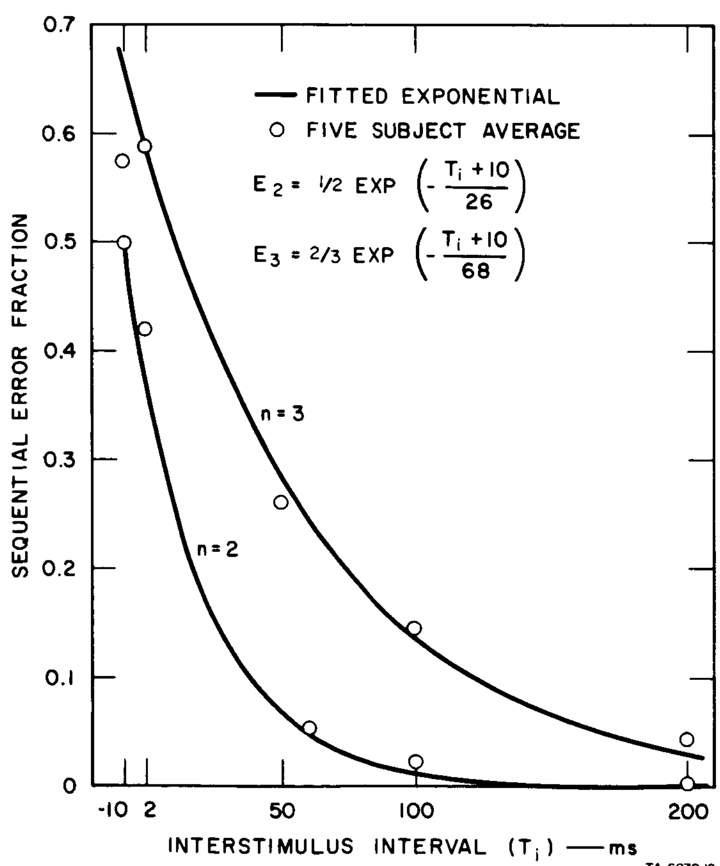


FIG. 8 EXPONENTIAL REGRESSION CURVES FITTED TO SEQUENCE ERROR DATA

Table IV

ANALYSIS-OF-VARIANCE FOR REGRESSION ON SEQUENCE ERROR

Source	n = 2				n = 3			
	df	MS	F	p	df	MS	F	p
Between T_i	4				4			
Due to regression	1	2.2926	653	<0.001	1	3.6368	330	<0.001
Residual	3	0.0052	1.47	--	3	0.0153	1.39	--
$T_i \times S$	16	0.0035			16	0.0110		

If the $E(T_i)$ error component of Eq. (1) is replaced by the exponential model, then the total error can be represented by the formula

$$E_T = E(S) + \frac{n - 1}{n} \operatorname{Exp}\left(-\frac{T_i + 10}{\tau}\right) + E(SSP) + \epsilon \tag{2}$$

where τ is a constant depending on n. This modeling process could be carried further. The error that depends on the stimulus sequence positions, E(SSP), could be expressed as the sum of a linear and a quadratic term, if such results were deemed important.

The subjects can be compared as a group by comparing their values of E(S). It is suspected, for example, that Subject N, because of travel fatigue and difficulty in concentrating, had a significantly higher error rate than the other subjects. This hypothesis is tested on the content error for the n = 2 condition by the one-way analysis of variance summarized in Table V.

Table V

SUMMARY OF ANALYSIS-OF-VARIANCE OF
SUBJECTS' CONTENT ERROR RATES FOR n = 2

Source	df	MS	F	p
Subject N	1	0.12934	36.6	<0.01
Between Other Subjects	3	0.00353		

Using the data from this experiment, we can compute the percentage of erroneous responses, where an erroneous response is a response pattern that contains at least one content error. We can then compare the error rates on this experiment with those of an experiment by Alluisi, Morgan, and Hawkes (1965), in which multiple electrically excited stimuli were presented. [Since simultaneous presentation was used both in Alluisi's experiment and in this sequential experiment (T_i = -10 ms condition), the performance in the two studies can be compared.] Figure 9 shows the percentage of erroneous patterns of each experiment. Both error means for n = 2 are about the same, but Alluisi's error rate is about 50 percent higher for 3 loci (n = 3). A lower error rate in Alluisi's experiment might have been predicted, since the subjects were guessing from a smaller field of stimuli (6 instead of 24). However, certain differences between the two experiments, such as the location of the stimulators and the type of stimulation, might account for the differences in the results.

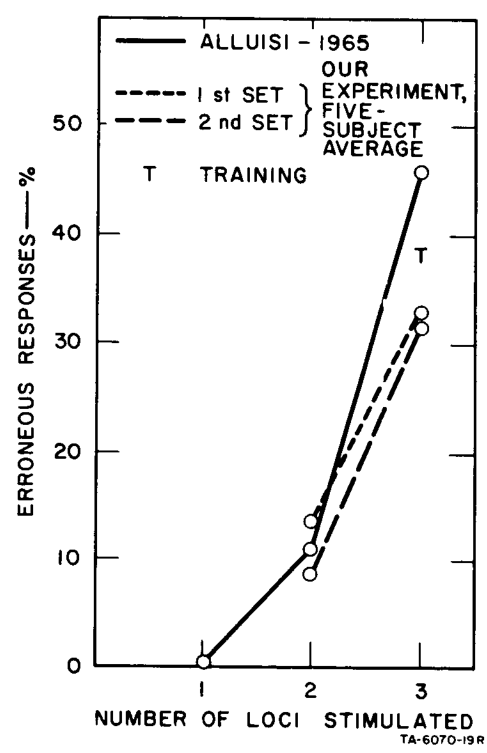


FIG. 9 COMPARISON OF PERFORMANCE IN OUR EXPERIMENT (T_i = 10 ms condition) WITH PERFORMANCE IN ALLUISI'S EXPERIMENT (Alluisi, 1965)

The maximum possible information that could be transmitted using Alluisi's patterns is 3.9 bits for n = 2 and 4.3 bits for n = 3. Our results show that the 24-position stimulus pattern, on the other hand, transmits at least 7.3 bits for n = 2 and 8.1 bits for n = 3.

Another important method of evaluating the ability of subjects on tactile tasks is to measure the amount of information they transmit. Like error rate, information can be divided into two separate parts: (1) content information (depends on the content of the response); and (2) sequence information (depends on the order or sequence in which the responses are given). A means of measuring or bounding information in tactile patterns has been developed by J. Hill (1967). Content information can be bounded from below, and sequence information can be estimated.

Using Hill's method, the content information was given a lower bound for each subject, and for each value of T_i, on the second set of n = 2 and n = 3 sessions. These results, averaged across values of T_i, are shown in Table VI. Like any other random variable, an analysis of variance can be performed on the information bounds to find their significant features. The results of the analysis are summarized in Table VII. Like the content error, content information is a constant over different values of T_i.

Table VI

LOWER BOUNDS ON CONTENT INFORMATION

(in bits)

Subject:	S	N	L	G	B	Average
n = 2	7.78	5.92	7.56	7.28	7.98	7.30
n = 3	9.10	5.60	9.60	6.98	9.48	8.14

Table VII

SUMMARY OF ANALYSIS-OF-VARIANCE OF

CONTENT INFORMATION ON SECOND n = 2, n = 3 SESSIONS

Source	n = 2				n = 3			
	df	MS	F	p	df	MS	F	p
Subjects (S)	4	13.3314			4	15.8006		
T_i	4	0.0554	<1	--	4	0.2966	1.56	--
S × T_i	16	0.1701			16	0.1893		

Though content information varies greatly from subject to subject, sequence information is relatively constant for all the subjects. The sequence information for the second set of trials, for all five subjects averaged together, is given in Fig. 10. The interesting feature of

Fig. 10 is that the initial slopes of the information versus T_i are about the same for both the n = 2 and n = 3 conditions, indicating that there may be an intrinsic limit on the rate of tactile information intake. The slopes of the sequence-information rate are about 17 bits/s, or one bit/60 ms. The content and total information transmitted by the subjects are summarized in Fig. 11. The figure also shows the information contained in the stimulus H(S). It should be kept in mind that these are lower bounds on the information transmitted and that H(S) is an upper bound.

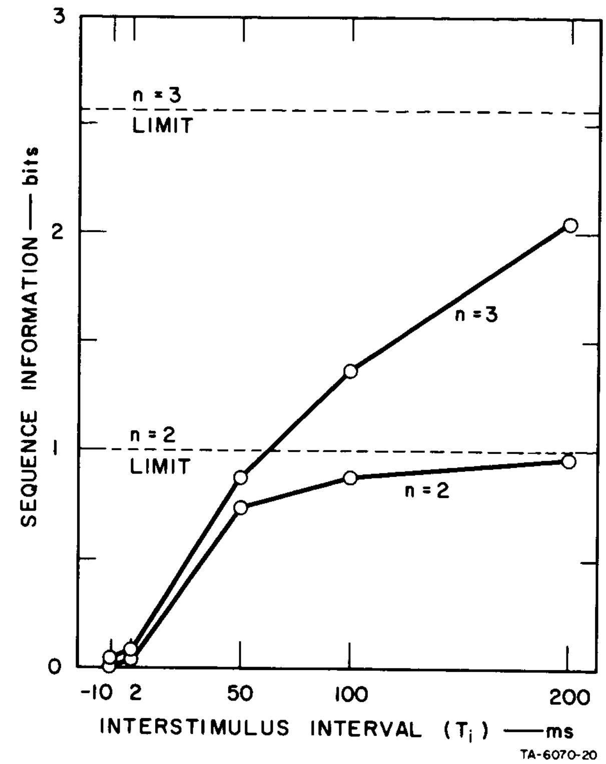


FIG. 10 AVERAGE SEQUENCE INFORMATION AS A FUNCTION OF INTERSTIMULUS INTERVAL T_i

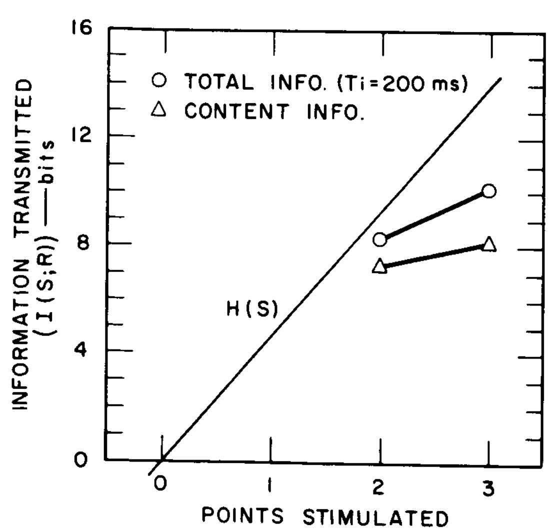


FIG. 11 TOTAL AND CONTENT INFORMATION TRANSMITTED

In conclusion, this analysis has pointed out several results important to the development of a model for tactual perception. It has been shown that content error is not related to the time interval separating point stimuli (at least for intervals less than 200 ms), but is related to the position in the subject's response sequence. Furthermore, as interstimulus time is increased, the subject's error rates for correct sequential responding decrease exponentially with a time constant of about 26 ms for two stimuli presented, and about 68 ms for three stimuli presented. Regarding the transmission of information, the data from this experiment indicate an information intake rate for short interstimulus intervals of about 17 bits/s. There is some indication of an intrinsic limit on the rate of tactile information intake.

D. FUTURE EXPERIMENTATION

The results from the above investigation suggest the following plans for a future experiment. The data have suggested certain modifications, and these have been incorporated into the plans. For instance, large values of n (the number of points stimulated in a single trial) seem desirable; thus, n will be either 4 or 6, instead of 2 or 3, as in the last experiment. It will be especially interesting to learn whether the initial tactile-information intake rate of about 17 bits/s, found with the $n = 2$ and $n = 3$ conditions, will continue to hold true as n is increased. In addition, the results suggested that a somewhat different choice of intervals between any two successive point stimulations would permit more accurate curve fitting. In a future experiment, the intervals (T_i) will be 5, 16.66, 50, 100, and 200 ms.

Future experimental plans involve three other phases, all with simultaneous rather than sequential presentation of tactile stimuli. These phases also are extensions of earlier investigations completed in this laboratory. In the first of these phases, called whole-reporting, subjects receive from 2 to 12 simultaneously presented stimuli, and report as many correct stimuli as they can. The number of correctly reported items defines the subject's so-called span of attention or immediate memory (e.g., see Miller, 1956). This span has been estimated to be 3 to 4 items in one of our earlier experiments, while in analogous studies employing a visual task, the span typically ranged from 4 to 7 items (Miller, 1956; Sperling, 1960).

In the whole-report phase, the method is to be the same as that described by Bliss (25 April 1966; Sec. 5), with the following modifications:

(1) Reducing the stimulus presentation time from 100 ms to 2.5 ms. (This means there will be only a single pulse from the airjets, which normally pulsate at 200 c/s.)

(2) Relabeling the finger positions so that each of the three rows reads across from A to H. Earlier results indicate that subjects show more accuracy in perceiving points stimulated in the top row (A-H) than in the bottom row (Q-X). In order to attribute this result to increased sensitivity in the fingertips and not to increased difficulty in reporting positions in the bottom row (because of their less familiar letter labels), all three rows will now be identically labelled.

(3) Eliminating reinforcement (which consisted of presenting the original stimulus after the subject responded) during testing. Previous subjects generally agreed that reinforcement was most helpful during training; also, there was some evidence that the fingers had not fully recovered from the long reinforcement (1-1/3 to 3 seconds) by the time the next stimulus was presented.

(4) Increasing the inter-trial duration from 2 to 4 seconds. Allison (1962) has shown that 4 seconds is adequate for full recovery of all components of the evoked response occurring within 300 ms of nerve and finger stimulation.

Another phase will involve a sampling, or partial-report, procedure. Several investigators of short-term visual memory (Sperling, 1960; Averbach and Coriell, 1961), to bypass the immediate-memory limitation discovered in whole-reporting, have employed sampling procedures and have found that subjects, at the time of stimulus presentation and for a few tenths of a second afterward, have more information available than they can later report. Analogously, we performed a sampling or partial-report tactile stimulation experiment in which subjects were signaled, after various delays, to report the stimulated points from only one of the three rows of points. Under this method, the results indicated that subjects had more information available than indicated by a whole-report, averaging one additional stimulus position available out of twelve. Two subjects performed considerably better than the average. One of these, an early blind subject, averaged about

8 points correctly perceived out of 12 on whole-report, and over 11 points available out of 12 on partial-report.

The paradigm for this phase is also described by Bliss (1966; Sec. 5). In addition to the changes listed above, which are true for the entire experiment, there will be two additional differences between a future experiment and the earlier partial-report experiment: (1) only the $k = 4$, $n = 12$ condition (four stimulated positions in each row) will be used; (2) there will be an increase in the number of trials in each of the six time-interval conditions, from 132 to 264 trials. This increase is expected to add to the stability of the results in each condition.

The final phase will consist of a partial-report procedure with an additional masking stimulus introduced. At some designated time, following the stimulus but preceding the response, all 24 positions will be briefly stimulated. The effect of this masking stimulus on the tactile short-term memory will be investigated.

III COMPARISONS BETWEEN TACTILE AND VISUAL TRACKING BEHAVIOR

By J. C. Bliss and P. K. Mansfield

A. FURTHER ANALYSIS OF DESCRIBING FUNCTION DATA

In our previous report (Bliss, 1966) we describe a series of tracking experiments with visual and tactile displays. By varying the sense modality employed (i.e., visual, tactile, or both) with continuous command signals and pure-gain vehicle dynamics, our aim has been to isolate the sensory factors contributing to performance and to obtain a valid comparison between the visual and tactile senses for tracking tasks.

The system for measuring describing functions consisted of a CDC 8090 computer with A/D and D/A conversion channels and display and response apparatus. The computer was programmed to generate a command signal consisting of a sum of the eight sinusoids shown in Table VIII. The computer then cross-correlated either the subject's error signal or the subject's response signal with a cosine and a sine function at each of these frequencies plus eight more frequencies shown in Table IX. Further calculations by the computer transformed these cross-correlations into an amplitude and a phase component at each of the sixteen measurement frequencies.

Table VIII

COMPOSITION OF COMMAND SIGNAL

Frequency c/s	Frequency rad/s	Amplitude
0.0261	0.164	1.0
0.0436	0.274	1.0
0.0960	0.603	1.0
0.2440	1.53	1.0
0.4270	2.68	1.0
0.6730	4.23	1.0
1.25	7.85	0.25
2.30	14.45	0.25

The display apparatus consisted of a servopositioned airjet stimulator which moved horizontally across the forehead or the palmar side of the hand over a range of about 4.5 inches. In the

Table IX

MEASUREMENT FREQUENCIES NOT CONTAINED IN COMMAND SIGNAL

Frequency	
c/s	rad/s
0.165	1.04
0.845	5.31
1.10	6.98
1.38	8.71
1.51	9.47
1.64	10.3
1.80	11.3
2.05	12.9

forehead case, the analogous visual display was obtained by placing a mirror in front of the subject so that he could see the position of the airjet nozzle. In the hand case, the visual counterpart was obtained by having the subject watch the airjet nozzle directly. In both cases a pointer was provided to give a visual zero reference.

Figure 12 shows the control loop containing the subject. Since the dynamics of the display servo system were not negligible, two methods were used, in the course of the experiments, to find the subject's open-loop describing function. In the first, the error and response spectra were measured. The error spectrum was multiplied by the measured transfer function of the servo to obtain the display spectrum. Then the amplitude of each response component was divided by the amplitude of the display component at the corresponding command frequency to obtain the subject's gain $|Y|$ and phase $(\angle Y)$ at that frequency (ω). In the second method, the display signal was measured directly from the feedback potentiometer of the display servo.

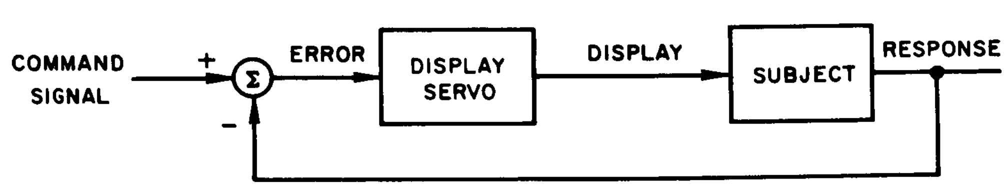


FIG. 12 CONTROL LOOP CONTAINING SUBJECT

The calibration of the system and the describing functions obtained are given in the previous report (Bliss, 1966). Further discussion of the data will be given below.

1. Comparison of Forehead and Hand Tactile Displays

Three subjects were used in the experiments, all in their early twenties. Previous to testing, each subject was given from 12 to 30 (depending on his mean-square error scores) two-minute trials, during which (on alternate trials) the display was changed from visual to tactile. Testing consisted of three four-minute trials at each display condition for each subject.

Figure 13 shows the forehead and hand tactile results averaged over the three subjects. The differences between these two curves are less than one standard deviation, except near the crossover frequency, where the difference is slightly more than one standard deviation. Thus these differences are hardly significant, and it appears that forehead stimulation and hand stimulation resulted in approximately equal performance.

2. Comparison Between Visual and Tactile Performance

The best performance with a tactile display was obtained on the hand when the airjet nozzle was turned off, but allowed to contact the skin. Figure 14 shows a comparison between this tactile-contact condition and visual performance for one subject. The amplitude differences are significant, but the phase curves are practically identical. Thus, our tentative results, based on one subject, suggest that with tangential as well as normal forces on the skin, the tactile performance has equal bandwidth, but less gain, than the visual performance.

3. Mean-Square Error and Display Measurements

The computer also calculated the mean-square error and display for each run. Tables X and XI show these results, averaged over three sessions, for each subject and each condition of the experiment.

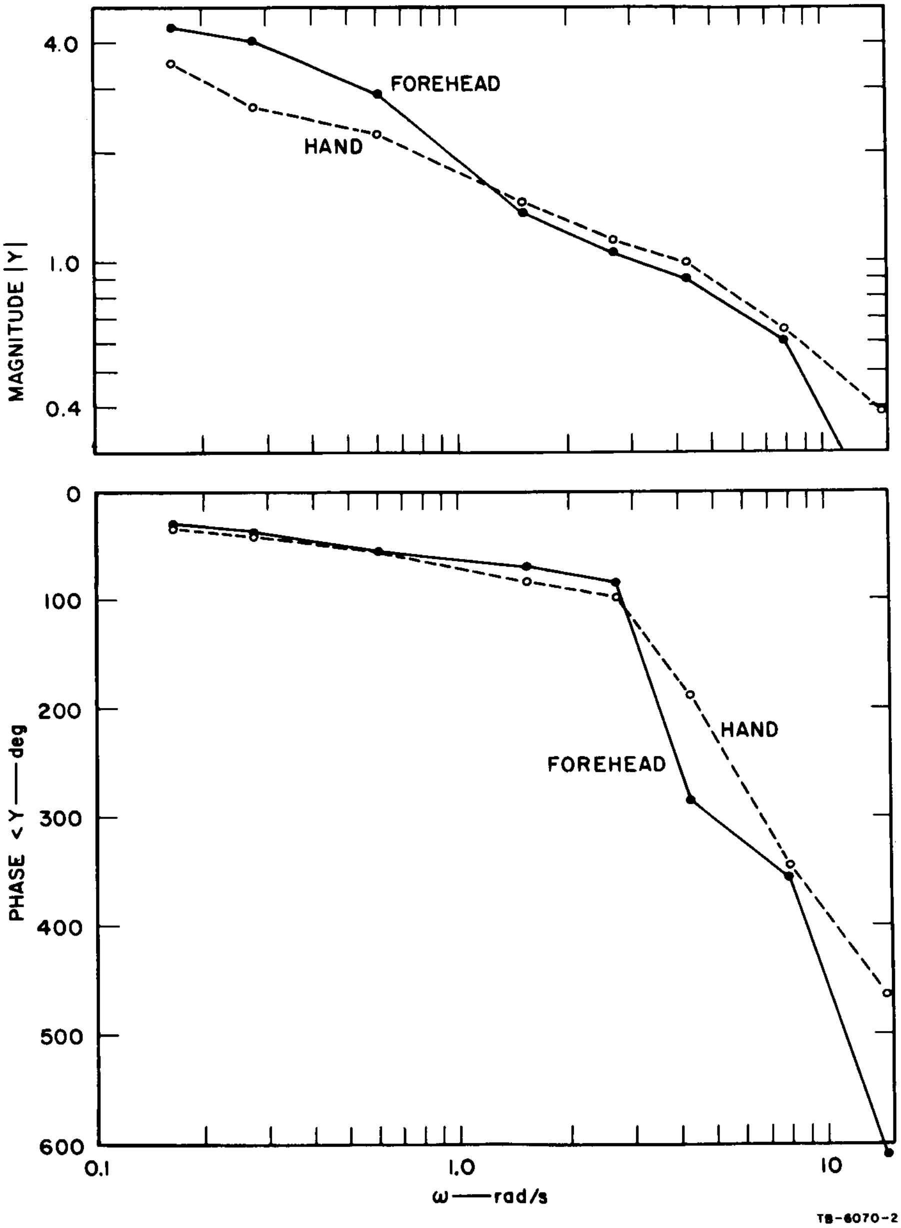


FIG. 13 DESCRIBING FUNCTIONS FOR HAND AND FOREHEAD TACTILE DISPLAYS (200-c/s airjet)

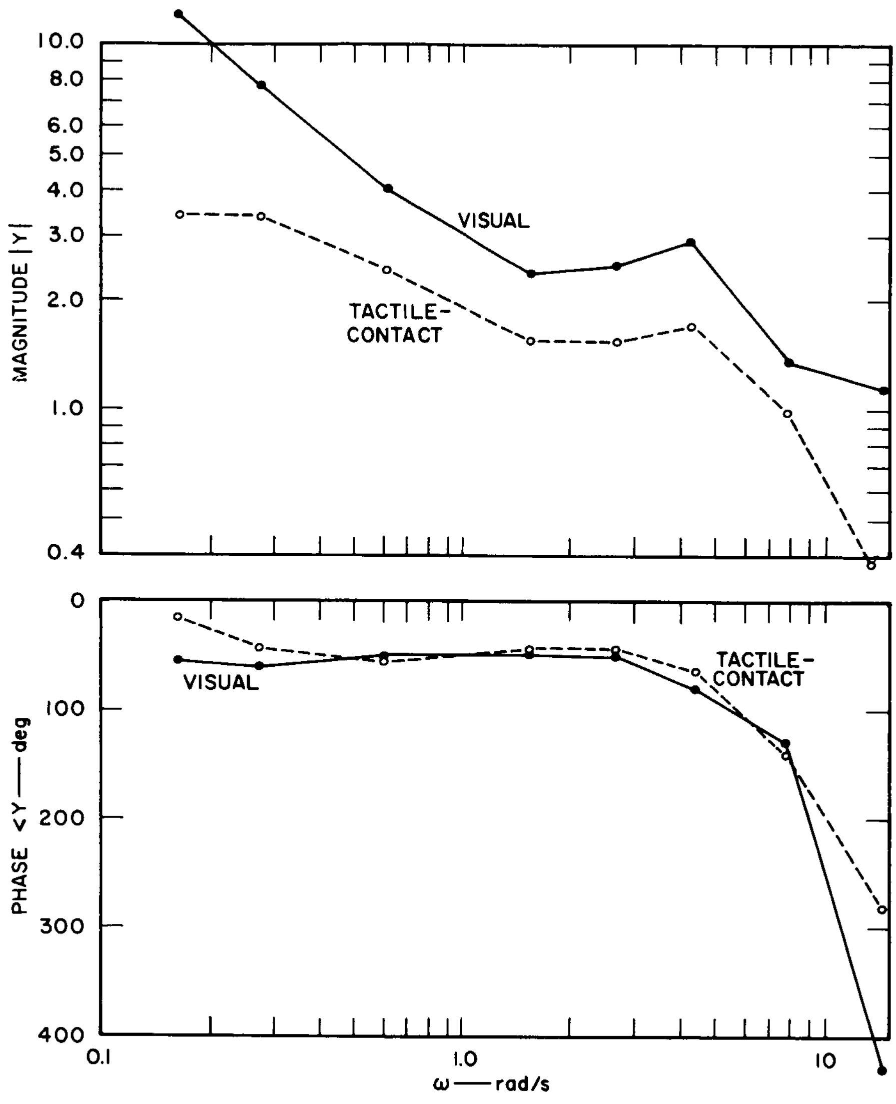


FIG. 14 DESCRIBING FUNCTIONS FOR VISUAL AND TACTILE (Hand-Contacting Stimulus) DISPLAYS

Table X

AVERAGE MEAN-SQUARE ERROR FOR EACH SUBJECT AND VISUAL, TACTILE, AND BOTH DISPLAY CONDITIONS (ARBITRARY UNITS)

Subject	Visual	Tactile (Forehead--200 c/s)	Both
1	2.32	4.91	1.84
2	2.06	5.69	2.10
3	2.63	5.88	2.40
Average	2.33	5.49	2.11

Table XI

AVERAGE MEAN-SQUARE DISPLAY SIGNAL FOR EACH SUBJECT AND VISUAL AND TACTILE DISPLAY CONDITIONS

Subject	Visual	Tactile			
		200 c/s	70 c/s	40 c/s	Contact
1	1.58	3.04	3.06	5.39	3.80
2	1.63	4.04	--	--	--
3	1.94	11.3	--	--	--
Average	1.72	6.13	--	--	--

Tactile mean-square error was generally about twice the visual mean-square error. The one anomalous result was with Subject 3, who produced a tactile (hand display) mean-square error of more than five times his visual mean-square error.

Even though the describing function results indicate superior performance under the tactile-contact condition, the mean-square error values for the 200 cs and 70 cs conditions were lower.

In general there was less mean-square error when both displays were used simultaneously than with either display alone.

4. Remnant Data

There have been a number of suggestions that a model for the human operator should include a nearly periodic sampler (e.g., Bekey, 1962). The following quotation from McRuer, *et al.* (1965) explains the effect of this hypothesis on the output spectrum:

> "With the line spectrum forcing function, nonlinearities in the operator would be expected to result in output spectrum peaks which are harmonically related to the forcing function frequencies. Constant-rate sampling on the part of the operator will also tend to produce recurring peaks and valleys in the output spectrum. If the sampler is precisely periodic at a frequency ω_s, output spectral lines would be expected at frequencies $\omega_n \pm m\omega_s$, m = 0, 1, 2, 3 .... Slight variations in sampling rate over a measurement run would tend to slur the lines into peaks."

To examine our data with regard to this hypothesis, the output spectra from single runs for each subject were plotted as shown in Figs. 15 through 17. The forcing-function frequencies are shown as line spectra. The other measurement frequencies were chosen in the region around half the expected sampling frequency, to coincide with Bekey's "sampling peak." For this reason, only the region between 4 and 15 rad/s is plotted. The output spectra at ω_7 and ω_8 are uncorrected for the fact that the forcing-function amplitude at these frequencies was only one fourth that at the lower frequencies.

These data fail to show any stable, clearly defined peaks that could be attributed to a periodic sampling nonlinearity. The power at remnant frequencies is generally less than that at the nearby forcing-function frequencies. Moreover, the remnant curves are certainly not reproducible from run to run.

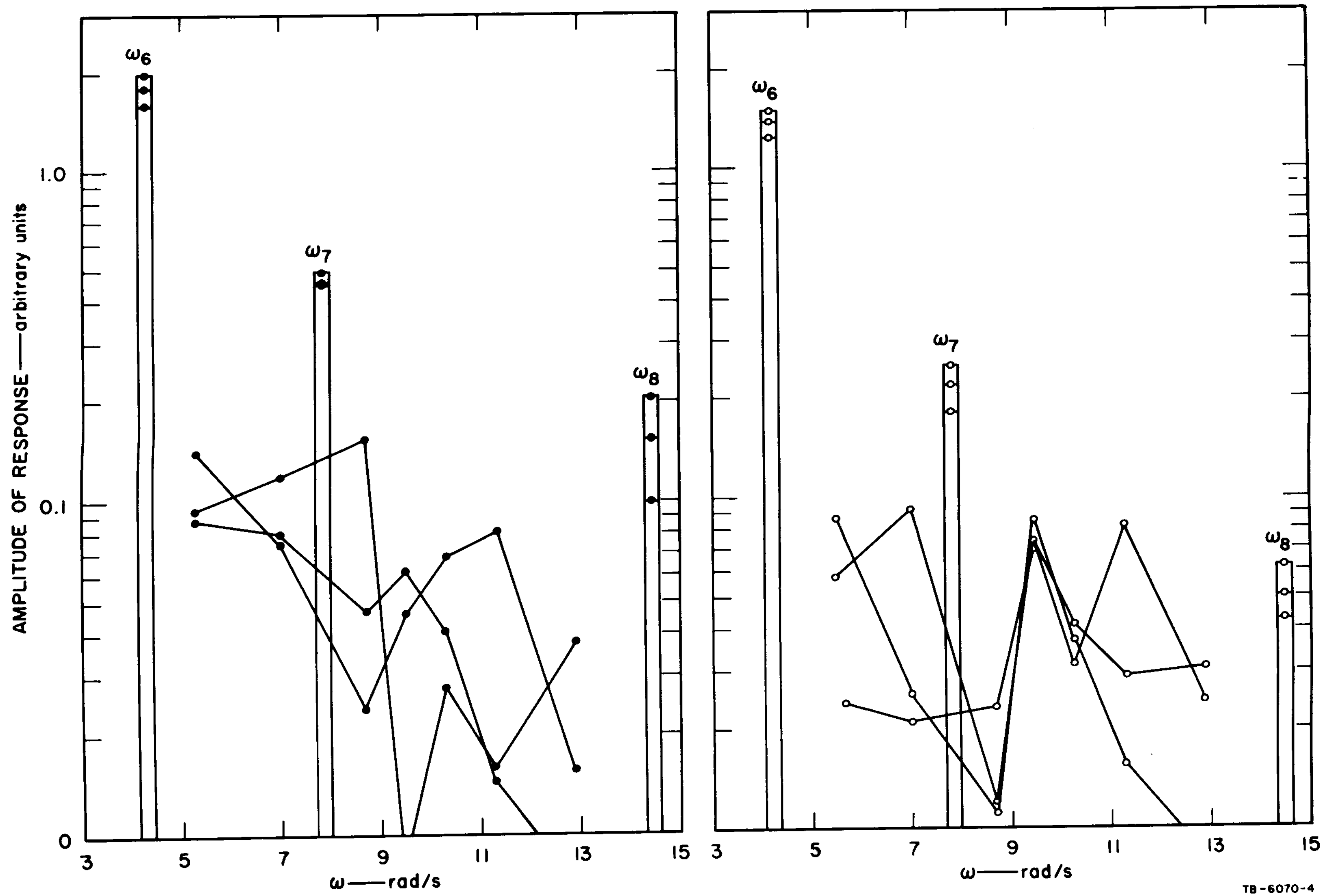


FIG. 15 AMPLITUDE OF RESPONSE AS A FUNCTION OF FREQUENCY FOR SUBJECT 1 — THREE RUNS
(a) Visual Display (b) Tactile Display - Forehead, 200 c/s

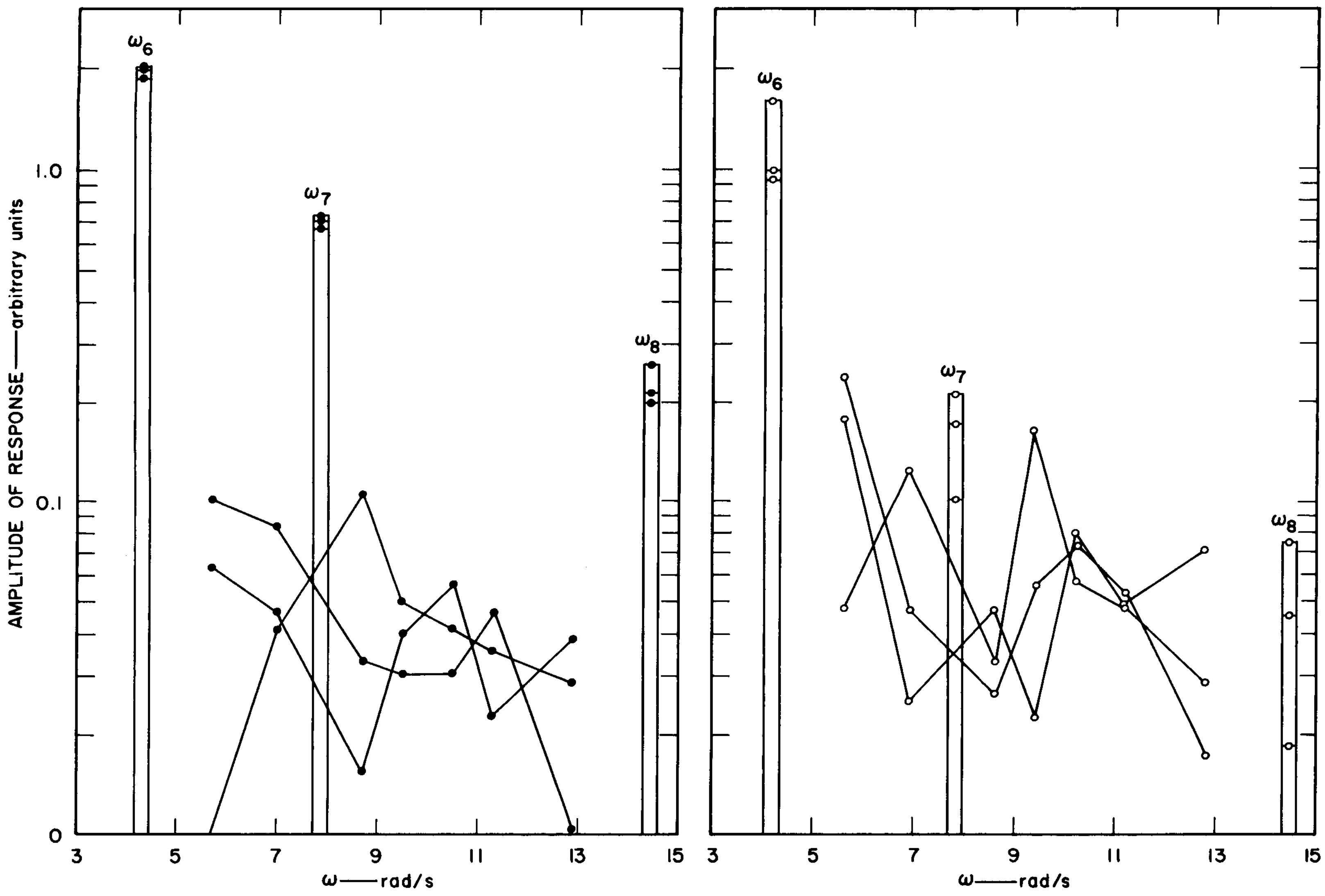


FIG. 16 AMPLITUDE OF RESPONSE AS A FUNCTION OF FREQUENCY FOR SUBJECT 2 — THREE RUNS
(a) Visual Display (b) Tactile Display – Forehead, 200 c/s

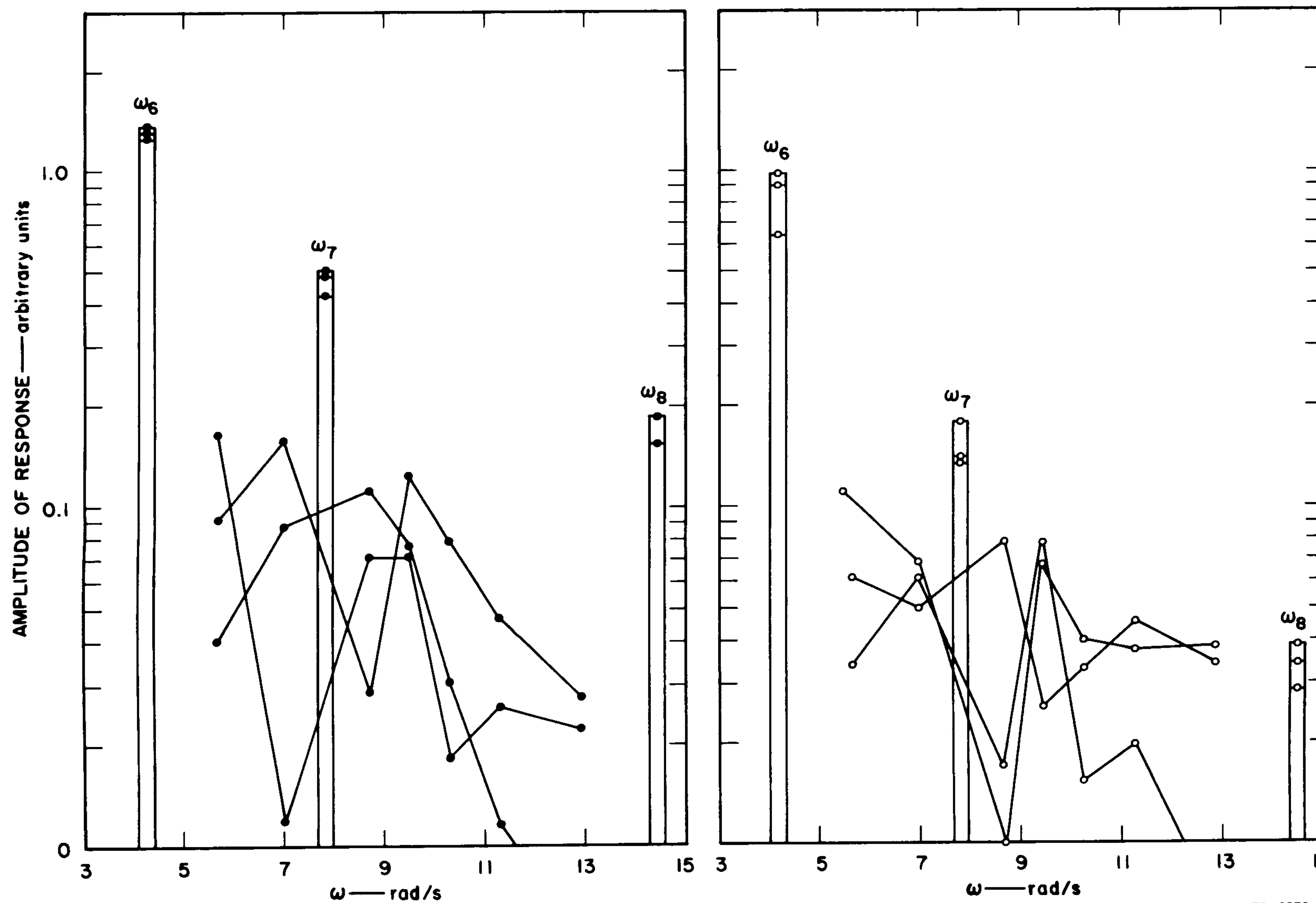


FIG. 17 AMPLITUDE OF RESPONSE AS A FUNCTION OF FREQUENCY FOR SUBJECT 3 — THREE RUNS
(a) Visual Display (b) Tactile Display – Forehead, 200 c/s

While the response power at ω_6, ω_7, and ω_8 with the visual display is consistently greater than that with the tactile display, the remnant power is roughly the same with the two displays.

B. BISENSORY PERFORMANCE ON THE "CRITICAL" TRACKING TASK

Jex, McDonnell, and Phatak (1966) have developed a "critical" tracking task in which a human operator is required to stabilize an increasingly unstable first-order controlled element up to the critical point of loss of control. They show that this critical point of instability depends primarily on the operator's effective time delay while tracking. Their data with this task indicate that the operator's behavior is tightly constrained so that a measure of effective operator delay with small variance is obtained.

To compare sensory effects in this task, we have developed LINC-8 programs and peripheral equipment for performing the "critical" tracking task with visual and tactile displays. Figure 18 shows a block diagram of the autopaced "critical" tracking task developed by Jex, McDonnell, and Phatak. Our initial LINC-8 program attempted to simulate this block diagram as closely as possible, with all blocks except the display and operator being realized by the computer. Our computer program also contains a command generator that produces a sum of eight sinusoids in the range .026 to 2.3 c/s.

The tactile display for this task consisted of a servo-positioned 3/8-inch-diameter spring-loaded wheel that moved along the palmar surface of the hand and index finger as shown in Fig. 19. The subject's task was to manipulate a pencil-type joystick so that the tactile wheel was always at the same anatomical position. The subject wore a blindfold for this display condition. The visual display consisted of merely visually observing the wheel. On some trials both display conditions were used simultaneously, the subject visually observing the wheel moving against his hand.

The frequency characteristics of the servomechanism that positioned the wheel have been reported previously (Bliss, 1966).

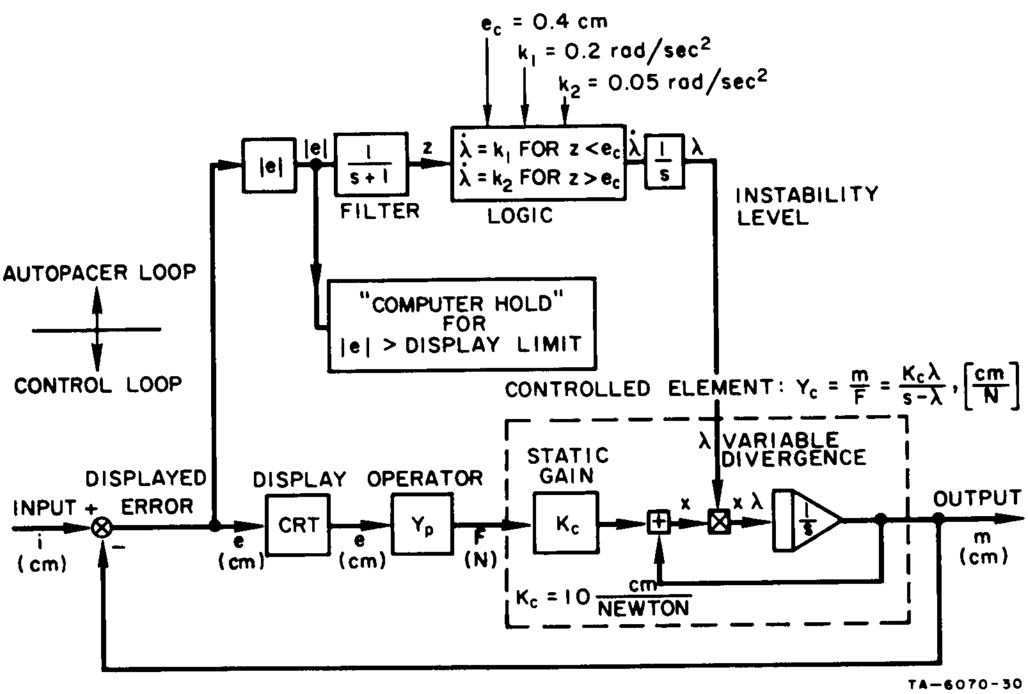


FIG. 18 BLOCK DIAGRAM OF CRITICAL TASK (from Jex, McDonnell, and Phatak, 1966)

FIG. 19 TACTILE DISPLAY FOR "CRITICAL" TRACKING TASK

Figure 20 shows the results obtained with one subject on each display condition over a 3-week period. During this period several difficulties were noticed with the task. The major difficulty was that if the subject failed to respond at all, the LINC-8 system was sufficiently noise-free that the output didn't reach the display limit until very large values of λ were reached. That is, even though the controlled dynamics were unstable, with no input the output always stayed within bounds. (While this problem does not occur with the STI Model MK IV Critical Task Tester because of internal drift and noise in the operational amplifiers, it is important to realize the crucial role of this noise.)

To get around this difficulty, two modifications of the task were tried. In the first, the initial conditions of the controlled dynamics were set to one-half the final condition from the preceding run. This had the effect of giving the subject an initial command step of random size and direction. If the subject made no response, the display limit was reached with a λ of about 2.5, so that the subject was forced to respond to obtain a reasonable score. However, the subject soon learned that early in the trial it was possible to properly zero the controlled dynamics so that subsequently a "no response" strategy would produce an extremely high λ score. Since the subject had to work hard initially to bring the system under control, the result was that the variability was high. Either control was lost in the initial few seconds of the trial or the system was stabilized so that "no response" would produce a high value of λ.

The second modification, made instead of the first modification, was more successful. The command signal was removed from the summing junction ahead of the display and moved to a new summing junction ahead of the controlled dynamics as shown in Fig. 21. This meant that throughout the trial there was always an input to this controlled dynamics and unless the subject responded continuously, the display limit would be reached very quickly.

Figure 20 also shows results obtained after the second modification. Following this modification, the subject's performance improved in all

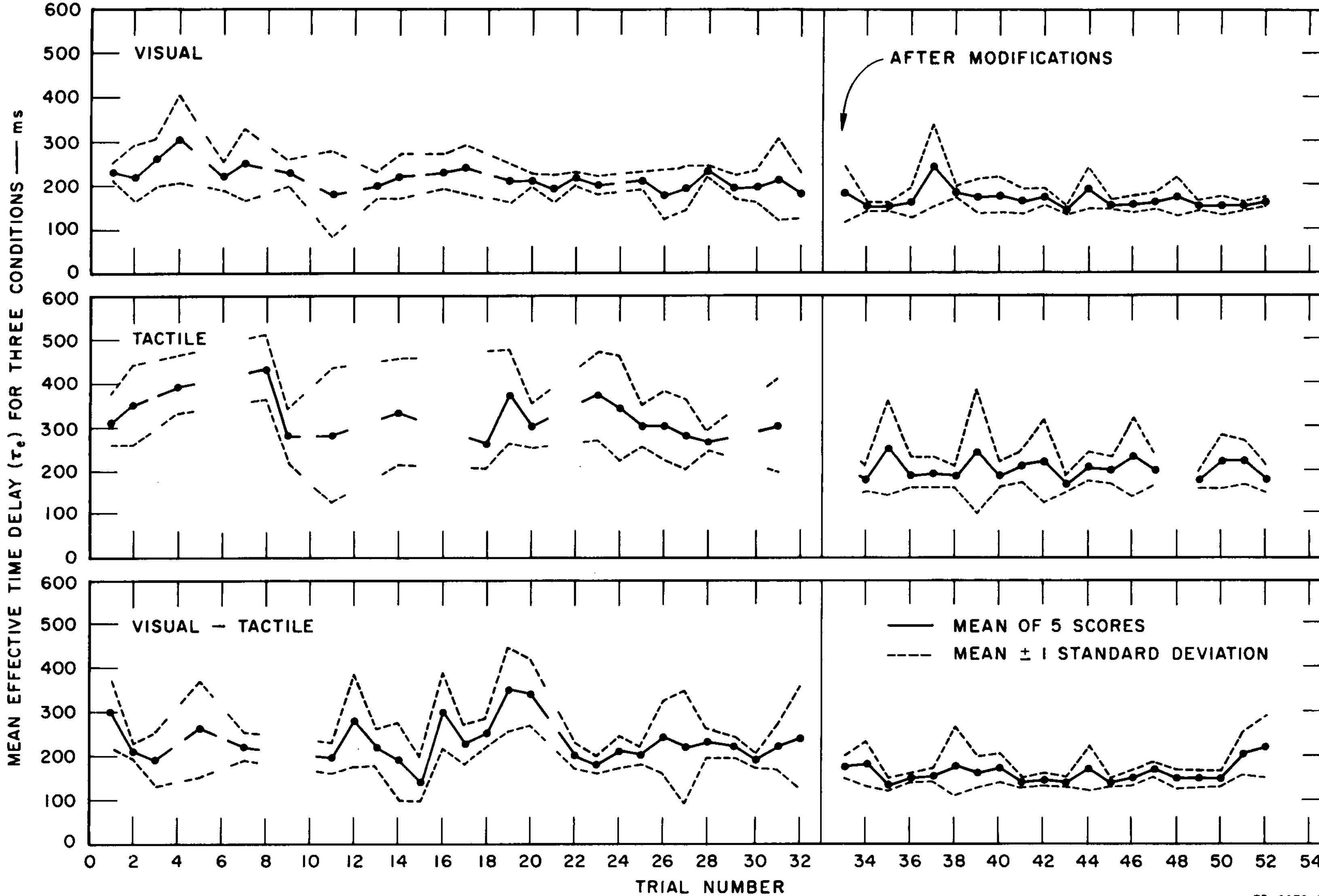


FIG. 20 MEAN EFFECTIVE TIME DELAY OVER TRIALS FOR VISUAL, TACTILE, AND VISUAL-TACTILE CONDITIONS
Each point is an average of five runs that made up a trial. A trial with no plotted data is one in which the subject was unprepared and thus scored unusually low on the first run. All such trials were ignored.

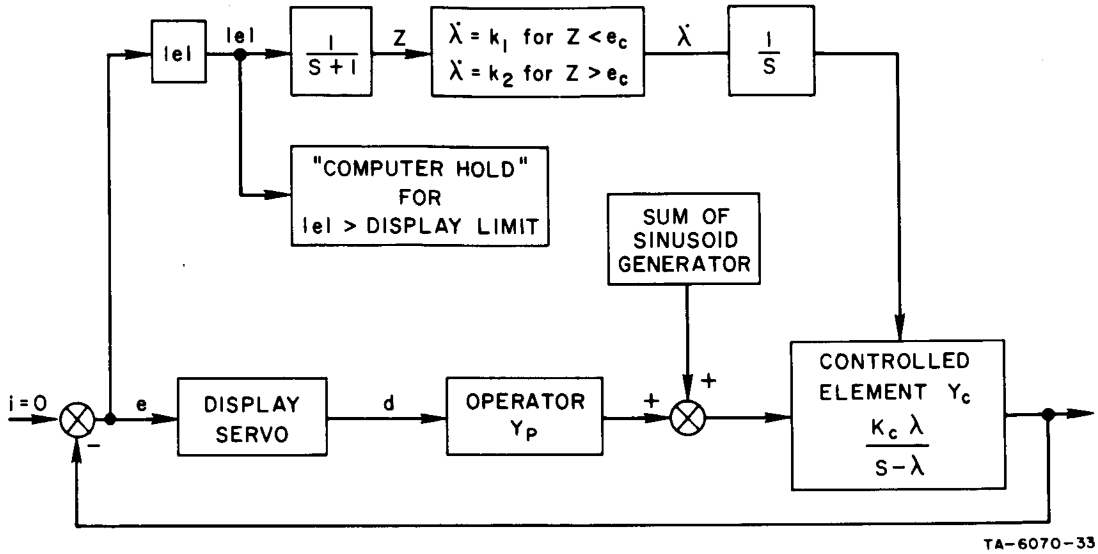


FIG. 21 MODIFIED CRITICAL TRACKING TASK

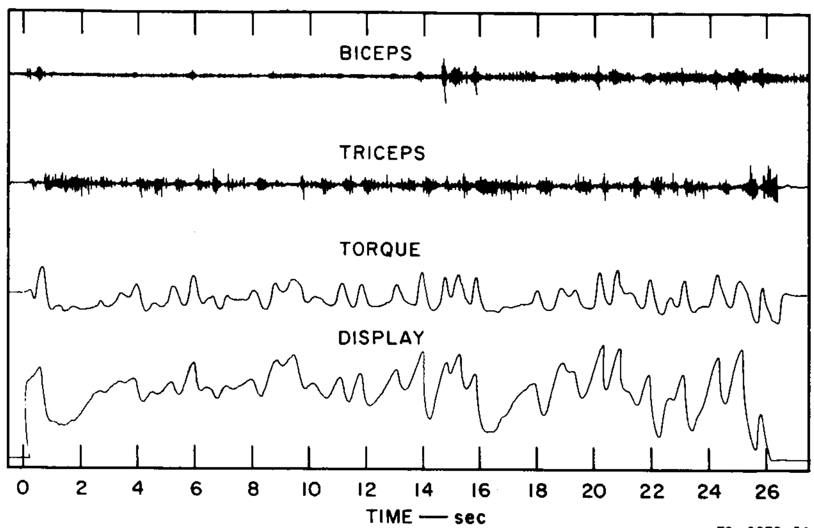
three conditions. Also noticeable was a reduction in the variability of his performance within each condition; however, there was still more variability in the tactile condition than in the visual or visual-tactile conditions. Statistical analyses compared the subject's performance across conditions. Table XII summarizes the data on which the analyses were based. The results showed that there was no significant difference between the performance in the visual and visual-tactile conditions. However, the mean effective time delays in the visual and visual-tactile conditions were clearly lower than in the tactile condition ($p < 0.01$ two tail).

Table XII

MEAN EFFECTIVE TIME DELAY, τ_e(ms), FOR THREE CONDITIONS

Condition	Mean Effective Time Delay (τ_e)	S.D.	No. Trials
Visual	166.05	22.45	20
Tactile	205.78	22.38	18
Visual-Tactile	161.2	22.40	20

In addition, a number of trials were run in which EMG activity was recorded from the biceps and triceps. In these trials the subject's arm was fixed by a splint in a horizontal position with 90^0 flexion about the elbow joint. The response was isometric, and torque about the elbow joint was also recorded. An oscilloscope was used for the display. Figure 22 shows two runs that typify the results. These runs illustrate an increase in tension in both the agonist and antagonist as λ increases, a result predicted by McRuer, Magdaleno, and Moore (1967).



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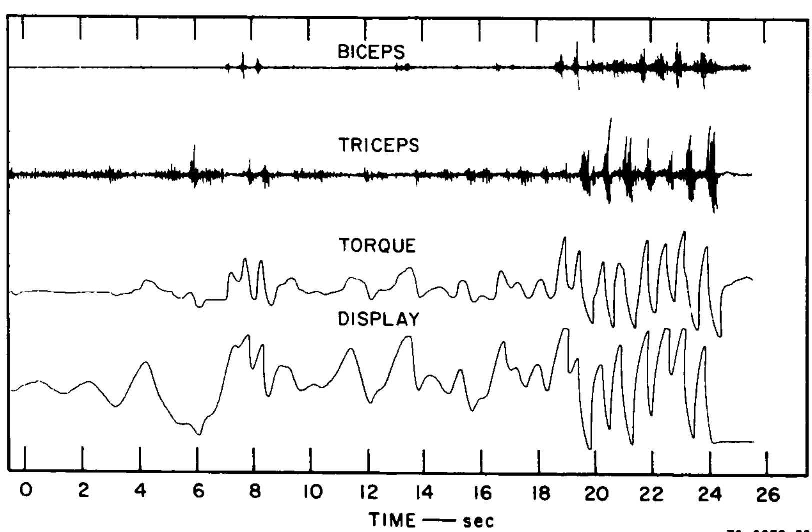
(a)



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(b)

FIG. 22 EMG ACTIVITY RECORDED FROM THE BICEPS AND TRICEPS DURING VISUAL "CRITICAL" TASK TRACKING

IV BISENSORY CHOICE REACTIONS

by S. W. Link

A. GENERAL

This section presents the results of five studies designed to investigate the interaction between the tactile and visual sense modalities. As the title implies, the subject in these experiments is required to attend to information presented through two sensory channels in order to select a response from a fixed response set. The measure of the subject's performance is the time taken to respond to the presented stimuli.

The assumption is made that the ideal subject consists of three interacting mechanisms. First, stimuli are assumed to be elements that traverse an abstract sensory path called a <u>channel</u>. Secondly, channels must converge on the <u>sensory channel monitor</u>. Finally, a response is made by activation of the <u>response mechanism</u>. The structure of these systems has not been investigated. Rather functional characteristics have been exposed to yield insights into the assumptions that can be made about the three systems.

The bisensory experimental paradigm is similar to that of choice reaction time. In fact, if only a single channel is considered, stimuli are mapped onto the response set in a one-to-one fashion, that is, the same manner as in disjunctive choice reaction time. However, when two channels map different stimuli onto the same response set the experiment closely resembles the complication experiment first discussed by Wundt in 1863.

Thus when bisensory stimuli are perceived well within the interval for perceived simultaneity, the fundamental difference between bisensory and unisensory experiments results from the mapping of stimuli onto responses. In the bisensory experiments discussed below, either of two sensory channels can activate any of the possible responses. On a single trial, information transmitted through different sensory channels may

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indicate that only a single response, A_1, is required. Alternatively, the stimulus elements transmitted on one channel may require response A_1, while the other channel carries elements requiring response A_2. The subject's task is simply to respond to the stimulus perceived first.

Intuitively there appears to be a basic distinction between the presentations of conflicting and non-conflicting response information. When both channels indicate response A_1 the reaction time might be less than when one channel requires an A_1 response, while another channel requires A_2. Furthermore it is intuitively expected that the presentation of conflicting response information leads to a response time that is longer than the response time if only a single stimulus indicates a single response. These intuitions are shown by the results reported below to be in error.

There are several reasons for this. The sparse experimental literature on responding to multiple stimuli (e.g., Todd, 1912) indicated that responses to two stimuli are faster than responses to only a single stimulus when stimuli are mapped uniquely onto the response set. Howell and Donaldson (1963) found that responses to intermodality stimuli were generally faster than responses to intramodality stimuli. Buser _et al._ (1963) found that with short delays between two stimuli presented to different sense modalities, a strong facilitation occurred in the latency of the evoked potential recorded at the motor cortex of cats. Finally, Morrell (1967) has also found a facilitation of reaction time when two sense modalities are nearly simultaneously stimulated. Subjects instructed to respond to a light, which was followed at various delays by a sharp click, exhibited reaction times that were a linearly increasing function of the delay of click over a range of 20 to 120 ms. These results confirm the observation that reaction time is reduced when two bisensory stimuli are presented in close temporal proximity to each other.

The focus of this section is largely on the effect of presenting conflicting response information through two different sensory channels. The model describing reaction-time performance under bisensory stimulation rests heavily on ideas first discussed by Falmagne (1964) and later examined by Ollman (1966) and Yellott (1967). First we assume that correct responses to unisensory stimuli form a distribution of correct response times characterized by a linear combination of fast and slow response time distributions. Presumably, in choice reaction time, fast response times are associated with "guesses," and slower times with the "true" reaction time distribution. Secondly, we assume that when two stimuli are simultaneously presented the joint distribution of input times to the sensory channel monitor is the minimum over the distributions for each independent sensory channel. Obviously the mean input time for the minimum is smaller than the mean for either channel independently.

To examine this model we have performed five experiments. The first experiment (simple reaction time) was to determine if there were any significant differences between responding to tactile and visual stimuli. This experiment tests the assumption that if discrimination of the content of the stimulus is ignored, then response times for either visual or tactile stimuli should be roughly equal.

The succeeding experiments were designed to test the notion that responses to bisensory stimulation would be faster than responses to unisensory stimuli.

B. EXPERIMENTS ON BISENSORY CHOICE REACTIONS

1. Apparatus

The experimental apparatus shown in Fig. 23 is the same as that described by Bliss (1966). Neon bulbs mounted on two of the posts corresponding to the positions right and left provided visual stimuli (the forward and backward portions were not used). Inside the joystick, airjets pointing to the right and left provided tactile stimuli. Mounted on top of the joystick case was the visual warning light; an airjet within the joystick and pointing toward the subject was used as a tactile warning signal. An arm rest ensured that the pivotal point of the response was at the wrist.

The experiments were carried out under control of a CDC 8090 computer system, which was used to store stimuli, measure reaction times,

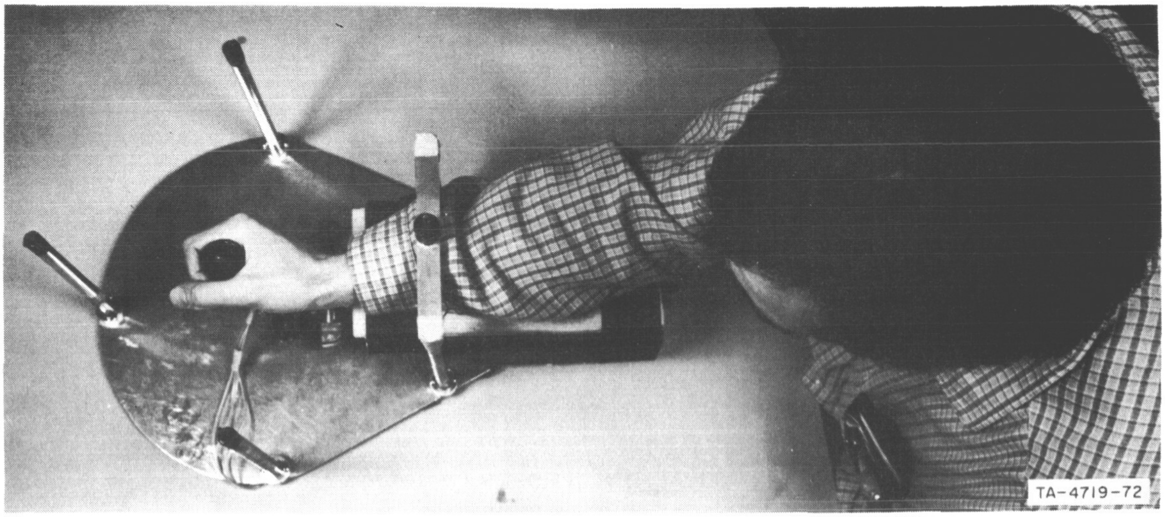

FIG. 23 STIMULUS-RESPONSE APPARATUS FOR REACTION-TIME EXPERIMENT

record responses, and control the sequence in which the stimuli were presented. For each presentation the computer transmitted a word of 12 bits to specially designed external apparatus. The external equipment then simultaneously activated the tactile and visual stimuli.

The tactile stimulator generated bursts of air from a 1.4-mm outlet port under control of a sensitive high-speed electromagnet. The pulse pressure, measured 1/8 inch above the airjet outlet, was about 3 psi, with a rise and fall time of about a millisecond and an overall pulse width of about 2.5 ms. A 200-c/s pulse-repetition rate was used throughout the experiments--i.e., the airjet was turned on and off 10 times during a stimulus lasting 0.05s. The positions of the tactile stimulators with respect to the palmar side of the hand are shown in Fig. 24. Visual stimuli were provided by GE NE2 neon bulbs. These were of low intensity, but to a slightly dark-adapted subject they provided ample indication of the direction in which a response was to be made. All experimental sessions were run in a sparsely illuminated room in which the only light source was external light filtering through a shaded skylight.

Responses were made by moving the joystick either to the left or to the right. Special circuits were designed to detect when movements of the joystick exceeded any of the four boundaries shown in Fig. 25.

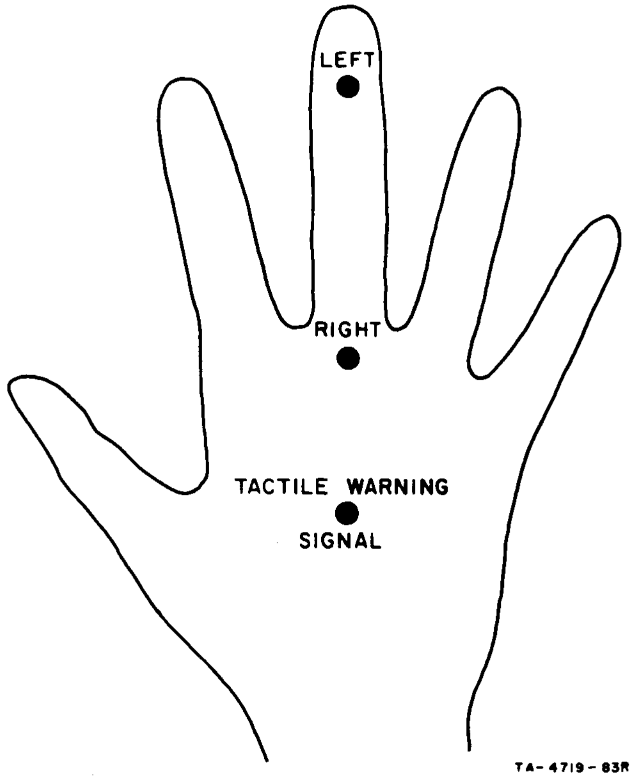

FIG. 24 POSITIONS OF STIMULI ON THE HAND

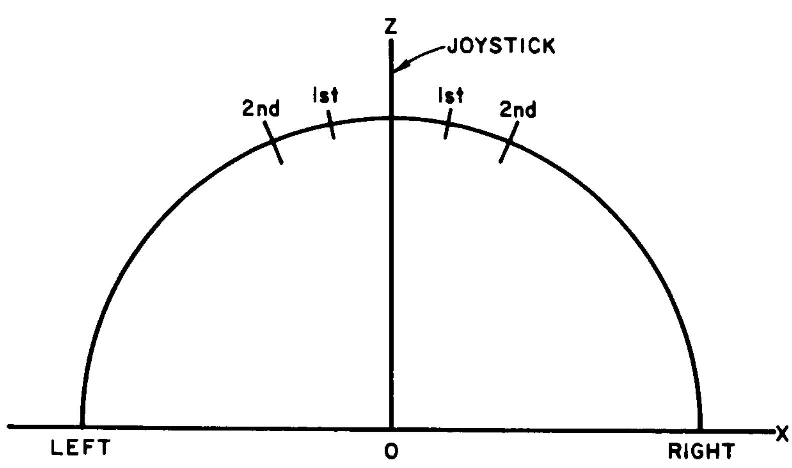

FIG. 25 THRESHOLDS FOR RECORDING RESPONSES (first threshold 11.25°, second threshold 22.5°)

These thresholds were set at about 11^0 and 22^0 from the center position. Whenever a threshold was exceeded, the computer was signaled and the reaction time and the position of the response were recorded. In addition, the z coordinate of the joystick was recorded when a threshold was exceeded. Response times were measured with an accuracy of one-half millisecond.

2. Experimental Procedure

Nine subjects were trained in making responses to four possible stimuli. Five experiments were performed to determine the speed, accuracy, and processing characteristics of the tactile-visual system. As shown in Fig. 26, on each trial the subject was presented with a warning signal 0.5s after returning the joystick to the center position. After another delay of 1.15s, the stimulus was presented. If, during these delays, the subject moved the joystick from the center position, brief pulses were sent to all stimuli. To a slightly dark-adapted subject, this provided a clear indication that the joystick should be repositioned. After repositioning, a new trial began.

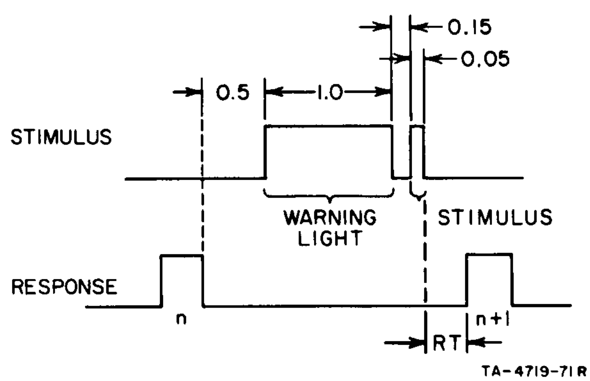

FIG. 26 TIMING ARRANGEMENT FOR REACTION-TIME EXPERIMENTS

Precautions were taken to ensure that the subjects could not simply respond to auditory stimulation created by activating one of the four airjets. On every trial (except rest trials in Experiment 1), three dummy airjets were activated in addition to the stimulus. These jets provided ample masking of auditory cues associated with a tactile stimulus.

As indicated in Fig. 25, there were two positions for stimulation of each of the two sensory modalities. Thus, there were four distinct stimuli but only two different responses. For the sake of brevity, we will refer to the stimuli and responses by using a code of two letters;

the first letter indicates the sensory mode and the second letter the position. Thus "tactile right" becomes TR.

C. EXPERIMENTS

To obtain data concerning the experimental apparatus, a simple reaction-time experiment was run. This served the purpose of providing subjects with extensive training before participating in succeeding experiments. In this experiment, each subject received two sessions of 525 trials. During a single session, one of the four possible stimuli was presented for 21 consecutive trials, followed by a different stimulus presented for 21 consecutive trials, and so on until all four stimuli had been presented. In addition, occasional rest periods were provided by illuminating the warning light in lieu of a stimulus for 21 consecutive trials. Each subject was presented with a random ordering of four stimuli and one rest period, five times, making a total of 525 trials per session.

Experiments 2 through 5 are described by Table XIII, which specifies the parameter values used to obtain the probabilities of presenting a stimulus according to Fig. 27.

Table XIII

STIMULUS SCHEDULES FOR EXPERIMENTS 2 - 5

Experiment	Parameter					Warning Signal
	x	r	a	b	c	
2	0	1/2	1/2	1/2		Visual
3	1/2	1/2	0	0	1/2	Visual
4	1/4	1/2	1/3	1/3	1/2	Visual
5	1/4	1/2	1/3	1/3	1/2	Tactile

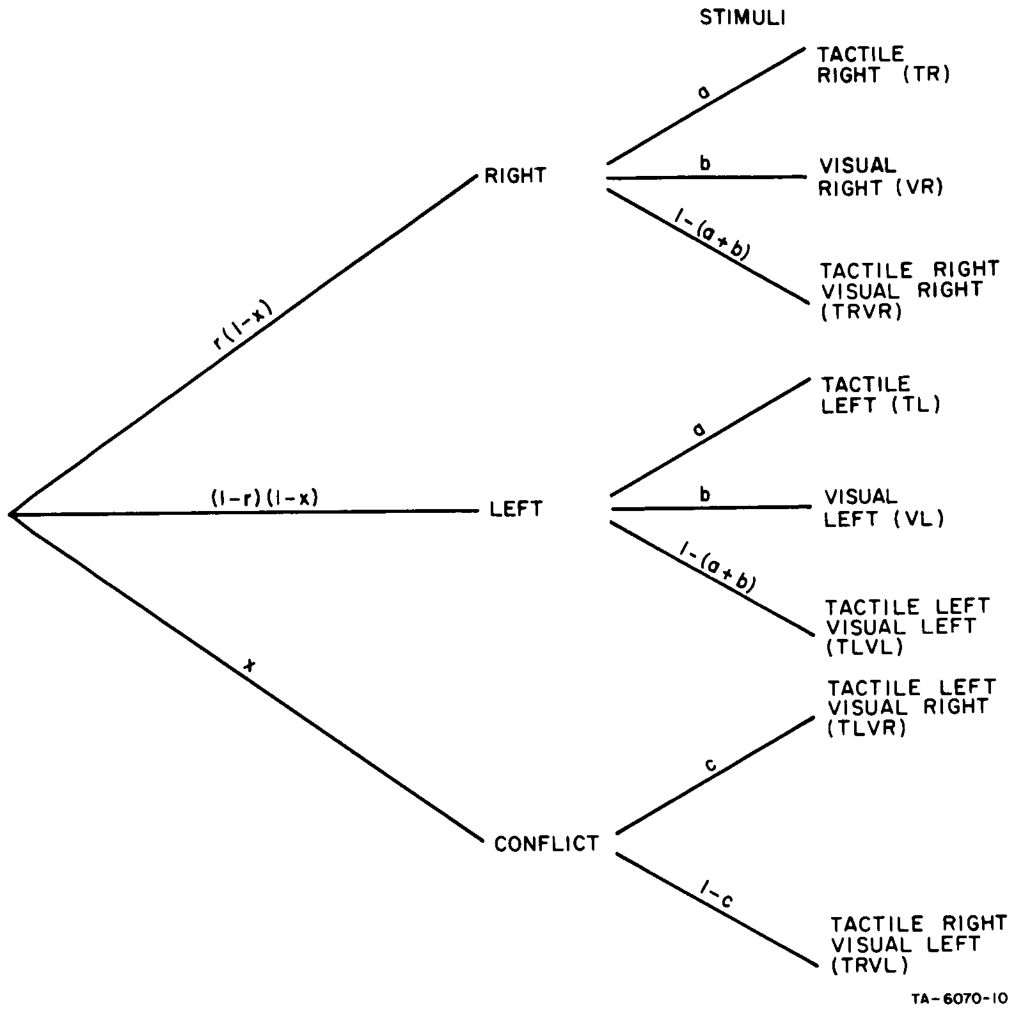

FIG. 27 DESIGN FOR OBTAINING THE PROBABILITY OF PRESENTING A GIVEN STIMULUS

D. RESULTS

Only responses measured at the first of the two response boundaries (Fig. 25) were used in the analysis. The results for each experiment were obtained by averaging the entire group of subjects. In general, the performance characteristics of the subjects are remarkably similar. Error rates were found to be higher in these experiments than in many choice reaction time experiments. Therefore errors and correct responses are presented for each experiment.

1. <u>Experiment 1</u>

To measure simple reaction time each subject was presented a series of 21 consecutive trials of a single stimulus five times. Thus each stimulus (TR, TL, VR, VL) was presented a total of 105 times during the experimental session. For the purpose of analysis the first trial in a block was ignored, leaving 100 trials from which to compute mean reaction times. The results are shown in Table XIV.

Table XIV

MEAN REACTION TIMES AND ERROR PROBABILITIES FOR EXPERIMENT 1

Stimulus	Reaction Time (ms)		Probability of Error
	Correct	Error	
TR	184	234	0.027
TL	190	262	0.067
VR	177	233	0.040
VL	194	224	0.035
T	187	254	0.047
V	186	228	0.038
Total	186	242	0.042

The results from Experiment 1 indicate that responses to the right are slightly faster than responses to the left. Secondly, responses to tactile and visual stimuli appear to be equally rapid. We may conclude that the perception of tactile or visual stimulation results in equal reaction times. This result does not imply that the discriminability of stimulus direction is equivalent in the two modalities. Rather that in a Go or No-Go task the intensities of stimulation are sufficient to ensure equal reaction times.

The error rate in Experiment 1 was approximately 4 percent. For each stimulus the error latencies were substantially longer than correct response times. These errors may be attributed to lack of attention or unfamiliarity with the experimental task. Error rates will be examined more fully in the succeeding experiments.

2. Experiments 2 and 3

In Experiment 2 the stimuli presented in blocks during Experiment 1 were presented in a random order. Each stimulus occurred with probability 0.25 on any trial of the experiment. Thus the experiment was one of disjunctive choice reaction time. Each subject participated in two experimental sessions of 500 trials each.

For Experiment 3 the stimuli presented in Experiment 2 were combined to form doublets that provided conflicting or non-conflicting response information. The set of stimuli was VRTL, VLTR, VRTR, VLTL. Each doublet was presented equally often during a random presentation of 500 trials. Subjects were instructed to respond to the first stimulus perceived.

The results from the last 400 trials of Experiment 2 are shown in Table XV. In this experiment there was a marked increase in the difference between latencies to tactile and visual stimuli. In addition, the error probabilities increased substantially above those observed in Experiment 1. In contrast to Experiment 1 the error latencies are shorter than correct-response reaction times.

Table XV

MEAN REACTION TIMES AND ERROR PROBABILITIES FOR EXPERIMENT 2

Stimulus	Reaction Time (ms)		Probability of Error
	Correct	Error	
TR	326	270	0.218
TL	322	254	0.169
VR	288	310	0.115
VL	298	262	0.078
T	324	263	0.194
V	293	290	0.096
Total	308	272	0.145

These differences are attributable to the increased difficulty of the response task. Not only must the subject perceive the stimulation, but he must also detect the correct direction toward which to make a response.

Table XVI presents the results for the last 400 trials of Experiment 3. Although there are differences in latency of response to each doublet, the response probabilities are quite well behaved. In particular, the probability of a right response given TRVL is 0.308, and the probability of a left response given TLVR is 0.295. Further, there is little if any response bias. For the conflicting doublets the probability of a right response is 0.500, and for the non-conflicting doublets, 0.506.

Table XVI

MEAN REACTION TIMES AND RESPONSE PROBABILITIES FOR EXPERIMENT 3

Stimulus	Reaction Time (ms)		Probability of Left Response
	Left	Right	
TRVL	244	248	0.692
TLVR	231	244	0.295
TRVR	212	244	0.168
TLVL	248	198	0.871
Conflicting	240	245	0.500
Non-Conflicting	241	238	0.506

Experiment 3 was run on the same day and immediately following the completion of the last session of Experiment 2. Assuming that there are no substantial practice effects, we can compare the results for Experiments 2 and 3. The difference in reaction time for correct responses in Experiment 2 versus doublets in Experiment 3 is about 50 ms.

3. Experiment 4

The stimuli presented in Experiments 2 and 3 were combined into a single list of 600 randomly presented stimuli. During a single experimental session the subject, already well practiced in making responses to the stimuli, was presented with the following set of stimuli: TR, VR, TL, VL, TRVL, TLVR, TRVR, and TLVL. Although there are only four distinct stimuli, there are eight different patterns of stimulation. The motivation for this experiment was to obtain data that would be free largely from sequential effects. That is, sequential effects due to repeated presentation of a specific stimulus would be unlikely to have any significant influence on mean reaction times.

To ensure that subjects were well practiced in making responses to the totality of available stimuli, each subject participated in six sessions of 600 trials each. In the analysis of the data the first two sessions were ignored, and only the last 400 trials of the remaining sessions were analyzed. Thus for each subject there are 1600 observations, or a total, for the group, of 14,400 observations. The expected number of presentations per stimulus is 1800 (see Fig. 27 and Table XIII).

The results in Table XVII corroborate the differences between unisensory and bisensory stimulation reported by Bliss (1966). In general, reaction times to bisensory stimulation are faster than reaction times to unisensory stimuli, regardless of the nature of the response information.

4. Experiment 5

Precisely the same experimental procedure was followed in Experiment 5 as in Experiment 4 except for a change in the modality of the warning signal. In previous experiments the warning signal was provided by the illumination of a neon bulb fixed atop the joystick. In this experiment a tactile warning signal was provided by airjet stimulation of the palm (see Fig. 24). Each subject ran in two sessions of 600 trials each. The data reported in Table XVIII are from the last 400 trials of each subject's last session.

The results from this experiment are quite similar to the results for Experiment 4. Except for a diminution of about 25 ms in overall response time to singlet presentations and a comparable reduction for doublets, the results are similar to those obtained in Experiment 4. It is worth noting that the mean reaction times for errors drops by nearly 40 ms.

Table XVII

MEAN REACTION TIMES AND RESPONSE PROBABILITIES FOR EXPERIMENT 4

Stimulus	Reaction Time (ms)		Probability of Error
	Correct	Error	
TR	251	224	0.246
TL	258	216	0.221
VR	244	233	0.075
VL	250	217	0.061
T	254	220	0.234
V	248	226	0.068
Total Unisensory	250	222	0.151
Stimulus	**Reaction Time (ms)**		**Probability of Left Response**
	Left	**Right**	
TRVL	236	238	0.707
TLVR	256	227	0.294
TRVR	192	222	0.090
TLVL	232	186	0.914
Conflict	242	230	0.500
Non-conflict	228	218	0.505

Table XVIII

MEAN REACTION TIMES AND RESPONSE PROBABILITIES FOR EXPERIMENT 5

Stimulus	Reaction Time (ms)		Probability of Error
	Correct	Error	
TR	225	195	0.345
TL	234	189	0.242
VR	220	172	0.114
VL	229	140	0.103
T	230	192	0.293
V	225	154	0.108
Total Unisensory	227	182	0.200
Stimulus	**Reaction Time (ms)**		**Probability of Left Response**
	Left	Right	
TRVL	222	216	0.657
TLVR	210	212	0.328
TRVR	168	208	0.119
TLVL	222	134	0.868
Conflict	218	213	0.495
Non-conflict	215	198	0.491

E. DISCUSSION

The basic model for subject performance under bisensory stimulation assumes that (1) the sensory input channels are independent, (2) subjects respond to the first perceived stimulus, and (3) the time taken to respond consists of an input distribution characteristic of the sensory channel plus a motor time corresponding to the direction of the response.

However, the high error probabilities observed in these experiments suggest that a detection process may also affect performance. We assume that for each sensory channel there is a probability of detecting the direction of a stimulus equal to $P_i (i = T, V)$. If the direction is not detected then the subject guesses, and responds to the right with probability a.

Although the perception of direction is not perfect, we can estimate the probability of detection by simply correcting the observed data for guessing. The possible outcomes for the presentation of stimulus $S_{i,j} (i = T, V\ j = R, L)$ are shown in Fig. 28.

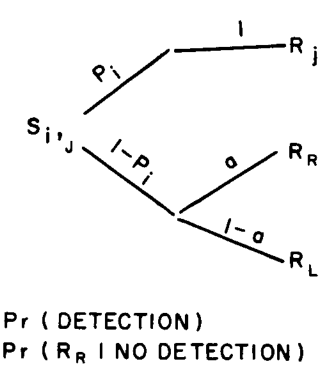

FIG. 28 POSSIBLE OUTCOMES FOR PRESENTATION OF STIMULUS $S_{i,j}$

When all stimuli are presented equally often, we expect a to be 0.5. These assumptions lead to an estimate of p = 1-2 Pr (Error). Estimates may be made independently for each singlet, or an average may be taken over a single sense modality. By averaging over tactile and visual stimuli we obtained estimates of $P_T = 0.53$ and $P_V = 0.86$.

For bisensory doublets we assume that with probability v the subject responds to the visual stimulus. By utilizing the estimates for P_T and P_V we can easily estimate v from one doublet and then predict the probabilities associated with responding left or right to the remaining doublets. Using the data for the TRVL doublet we obtained an estimate of v = 0.68.

The predictions for the probability of a left response to the remaining stimuli are quite close. For TLVR we predict 0.293 and observe 0.295. For TLVL we predict 0.88 and observe 0.91. Similarly we predict the probability of an error TRVR as 0.12 and observe 0.10. These results suggest that rapid error responses may account for the increased speed of bisensory reaction times.

The data from Experiments 2, 3, and 4 show that error latencies are considerably faster than latencies for correct responses. Perhaps a linear combination of reaction times for correct and erroneous responses can account for the observed differences between the bisensory and unisensory stimuli. A simple test of this conjecture can be made. Since all events in the conflicting and non-conflicting presentations have equal probability, average reaction times for these conditions should be equal. However, the mean latency for the conflicting response presentations is 236 ms while the mean for the non-conflict doublets is 273 ms. Since the standard errors are roughly 1.5 ms in either case, we must conclude that the average data cannot be accounted for on the basis of a linear combination of correct and error latencies.

Given the methods of estimation used in Experiment 4, we can assess the effect of the tactile warning signal used in Experiment 5. Estimates of the detection probabilities were found to be $P_T = 0.42$ and $P_V = 0.78$. The estimated probability of responding to the visual stimulus was $v = 0.74$. The low value for P_T corroborates subject's comments that during Experiment 5, continued stimulation of the palm by the warning signal made the perception of tactile stimuli more difficult than in Experiment 4. The site of the TR stimulus was quite close to the site of the tactile warning signal (Fig. 24). This may account for the large difference between error probabilities for TR and TL.

The probability estimates, together with the error latencies, indicate that part of the difference in mean reaction times between Experiments 4 and 5 can be attributed to the numerous fast but erroneous responses occurring in Experiment 5. Another factor contributing to the decrease in reaction time in Experiment 5 may have been the preparation of the subject for the stimulus. Since the tactile warning signal was audible, it is quite possible that the joint effect of a tactile and auditory warning signal produced greater preparedness for the stimulus and thus faster response times.

The results contained in Experiments 2, 3, 4, and 5 have been summarized in Fig. 29. For each experiment the mean reaction times, averaged across right and left responses, for tactile, visual, conflicting, and non-conflicting doublets are shown. The latencies or error responses are indicated by slashes. The spacing of the experiments along the abscissa represents the number of trials to the mean for each experiment. For example, following Experiment 1, there were 1000 trials comprising Experiment 2. The first 600 of these trials were practice, and the last 400 were entered into the data analysis. The 600 practice trials are represented in Fig. 29 as the distance between Experiment 1, our time origin, and the start of the 400 test trials of Experiment 2. If we consider the mean performance to occur midway into the 400 test trials (at trial 200), then the mean reaction time should be plotted at the 200^{th} trial of the test series. Thus, the mean reaction time for Experiment 2 is shown in Fig. 29 at the 800^{th} trial from the origin.

The results are quite consistent in showing that responses to bisensory stimuli are consistently faster than responses to unisensory stimuli. To examine specific models in any detail individual data must be examined. At present, calculations for individual data are in progress.

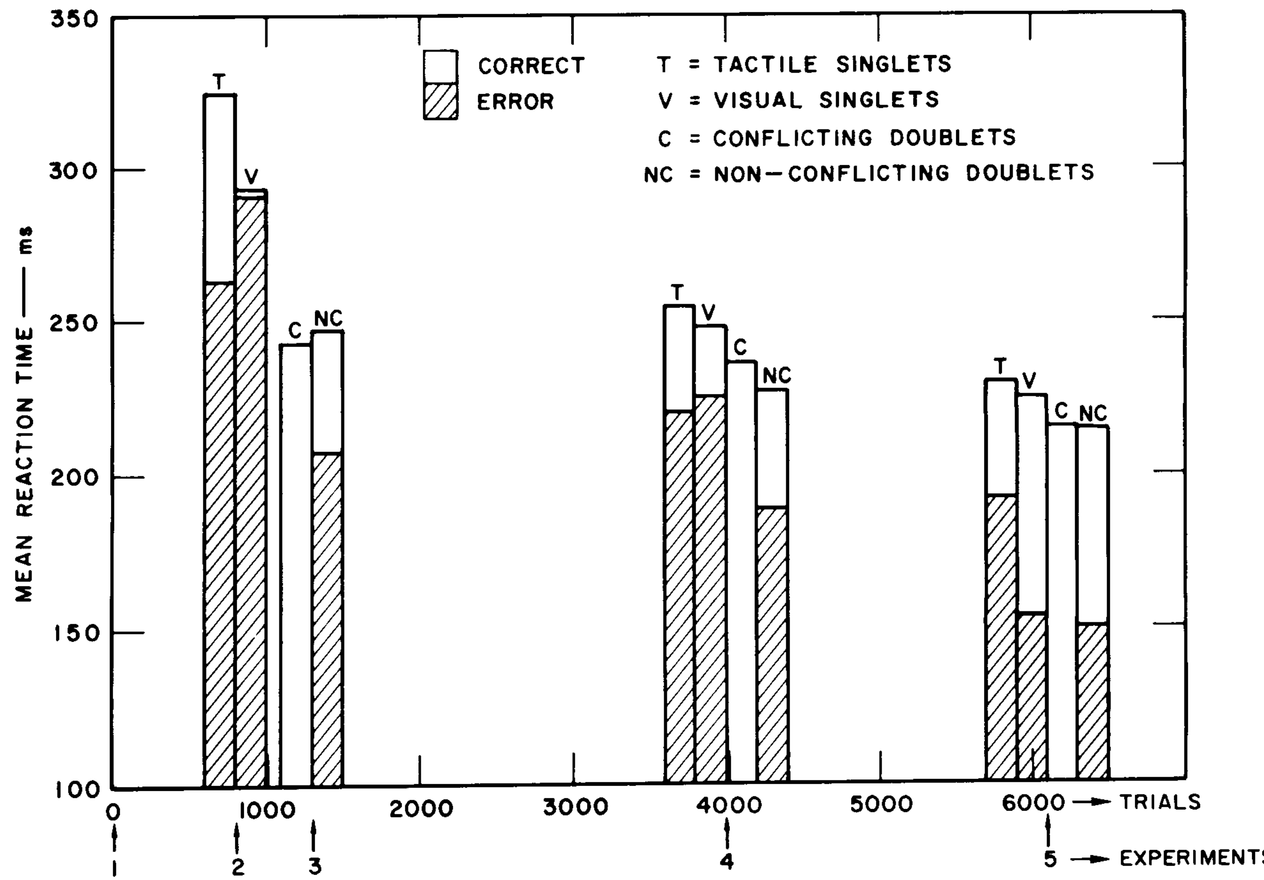

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FIG. 29 MEAN REACTION TIMES, AVERAGED ACROSS RIGHT AND LEFT RESPONSES, FOR EXPERIMENTS 2 THROUGH 5

V CONCLUSIONS

By J. C. Bliss

The results described in this report, combined with our previous results, can be combined to form a rudimentary basis for models of tactile perception and tactile-visual interactions. Major results that any model of tactile perception must be consistent with are:

(1) When the time interval (T_i) between presentation of two brief tactile stimuli is varied, subjects make more pattern identification errors in their first response for values of T_i less than 100 ms (backward masking), and more second-response errors for T_i greater than 200 ms (forward masking). This result suggests a model that operates in discrete temporal epochs.

(2) Tactile pattern perception is enhanced when the pattern is moved over the skin, the optimum rate of a 1-cm-diameter circular motion being about 150 ms per revolution. This result suggests lateral inhibition properties for the tactile channel.

(3) There is a tactile short-term memory that decays approximately exponentially with a time constant of about 1.5 s and can be trained to have a high information capacity. This result suggests a model incorporating rapid parallel input to an eidetic short-term storage.

(4) The number of errors subjects make in trying to report sequentially presented tactile stimuli in correct order decays exponentially, with a time constant of less than a hundred ms, as the interstimulus interval (T_i) is increased. This result specifies a temporal interaction property.

These results suggest a tactile perceptual model patterned after one developed for vision, mainly from the work of Sperling (1963), Estes (1964), and Massa (1964), with supportive evidence from other sources. The model for vision, as described by Massa, has five major operations: rapid parallel signal read-in, eidetic short-term storage, coded read-out, an intermediate memory storage, and an eye-movement feedback control of the operation of the read-in and short-term storage functions. Our data indicate that the tactile channel has characteristics similar to all of these operations except the role of eye movements.

Results that any model for tactile-visual interactions must be consistent with are:

(1) In a task requiring decisions or processing, such as a choice reaction time task or continuous tracking task, the effective time delay of the operator with a tactile display is appreciably longer than that with a visual display.

(2) Mean choice reaction time to tactile and visual stimuli presented simultaneously is significantly faster than that to either stimulus alone.

(3) When simultaneously applied tactile and visual stimuli indicate different responses, the resulting mean reaction time is approximately equal to that when both stimuli indicate the same response.

(4) After training, subjects can track with a contacting tactile display on the hand at a level of performance comparable to that attained with peripheral vision. That is, the phase characteristics are the same for visual and for tactile tracking, but the low-frequency gain is less and the remnant is greater with tactile tracking.

(5) Continuous-command signal tracking performance with both tactile and visual displays is not significantly different from that with the visual display alone.

These results suggest a rudimentary operator model in which the processor input channel is switched, somewhat randomly and somewhat voluntarily, between the tactile and visual modalities. Thus, mean reaction time is shorter with two channels stimulated because the input channel does not need to be switched (which presumably takes time) before the signal can be processed. Two displays are of little advantage with a continuous command because the subject can stay switched to the superior channel most of the time.

These results and model suggest that a tactile display may be particularly useful in a multiple task situation. For example, suppose that an operator must control one axis of a vehicle and also monitor several instruments and his environment. Let us also suppose that he is provided with redundant visual and tactile displays of the error in his control axis. The existence of the tactile display should result in a shorter mean reaction time to sudden changes in tracking error and should free the visual channel somewhat for monitoring the instruments and environment. The same advantages for tactile displays should also occur in multiple-axis tracking tasks. If consistently good performance in one of the axes is crucial, this improvement in performance may be particularly significant.

In addition to these experimental results, the following Appendices describe developments toward more convenient computer control of on-line experiments. It now appears possible and practical to time-share a computer as small as the LINC-8 among several independent activities related to psychological experimentation. Software developments toward this goal are described. With the advent of commercially available integrated circuits, computer interface design and construction are greatly simplified and a particular design for computer control of point stimulators is given. These computer-controlled facilities make possible a rapid and convenient method for real-time analysis of tracking experiments. Finally, a technique for real-time digital computer realization of linear transfer functions is described.

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Appendix A

LUCIFER--A LINC-8 SYSTEM OF UTILITY PROGRAMS FOR PROGRAM GENERATION AND CHECKOUT

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Appendix A

LUCIFER--A LINC-8 SYSTEM OF UTILITY PROGRAMS FOR PROGRAM GENERATION AND CHECKOUT

by M. Wilber

The utility software supplied with the LINC-8 was written for the classic LINC which has a keyboard instead of a teletypewriter as standard equipment. This software, therefore, fails to utilize the potential advantages of two-way communication and hard-copy production that are inherent with the teletypewriter supplied as standard equipment with the LINC-8. In addition, by using the teletypewriter almost exclusively, in preference to the scope and console switches, time sharing is more attractive since several teletypewriters can be connected to the LINC-8 and used simultaneously.

For these reasons, and because we felt the result could significantly increase our ability to generate and modify experiment control programs, we undertook the development of LUCIFER (LINC Unrelenting Console Interception and File Editing Routines). At first LUCIFER was only to consist of the programs (described below) called Iceberg, Editor, and Mung, and they were to peacefully coexist with the LAP4-Guide system supplied with the LINC-8. However, after writing these programs, it became apparent that LUCIFER could produce manuscripts not entirely intelligible to LAP4. Out of the ashes of this work sprang LUCIFER, which incorporates the following programs:

DDT: The purpose of this program is to aid in vanquishing bugs, hence its name (rationalized as Dynamic Debugging Technique). This program permits examination and modification of any memory location, the program counter, or the accumulator. This can be accomplished only through the teletypewriter. DDT also has a facility for control of program execution.

Editor: The program permits editing of a manuscript whose contents are almost entirely unrestricted, but normally consisting of mnemonics, symbolic labels, and comments. After telling the editor the name of a file and specifying a particular line of text within that file, the user can delete or replace that line and open the following or preceding line.

Lister: This is a program to type out a manuscript or a portion of a manuscript.

Iceberg: (There's more to it than meets the eye.) This is a program for manipulating the LUCIFER file directory. It can remove entries from the directory and manufacture new entries. It can change the name or size of the file represented by an entry in the directory.

Assembler: This assembles a program from one or more manuscripts, building the corresponding core image in a standard place on the tape. It is compatible with LAP4 in that a severe restriction of its language is an extremely mild restriction of LAP4's language.

MUNG: This program copies a manuscript into a file, meanwhile packing it and creating a directory for it.

DIRGEN: This program generates a LUCIFER directory to all manuscripts filed by LAP4. This program is useful in the transition from the LAP4 system to the LUCIFER system.

There are several overall concepts on which LUCIFER is based. The first is that of a directory. A directory is a collection of information about the structuring of an entity. Thus GUIDE has a directory to the images of the programs filed under itself; there is a directory giving the name, location, and size of each manuscript, and each manuscript has a directory giving information by which any line of the manuscript may be found easily.

Another overall concept is that of prompting. Each program in the LUCIFER system types out something before expecting a response, and what it types is indicative of the state of the program and thus the desired response. In particular, when a file name is desired, these programs all type an asterisk. When there is no line or location open and the program is waiting for some command particular to itself, it types a dot. When a line or location is open, the last two items typed are the address and the contents.

Still another overall concept is that of similar command structures. Whenever a file name is requested, the special name " Q" (a single blank, followed by a "Q") is the command to quit that level, and whenever a dot is typed for prompting, "Q" is the command to quit that level. Whenever a line or location is open, a carriage return is the command to make the indicated modification, if any, and close the open location.

Furthermore, all input is in one of three modes: arbitrary string with preset maximum size (e.g., file name); possibly a number, followed by a nondigit (cf.,DDT); and a single character (cf., the Editor). In the first mode, input is terminated upon receipt of a carriage return or upon accumulation of more than the preset maximum number of characters; the second is terminated upon receipt of some character other than a digit; and the third is terminated upon receipt of any character. The first two modes also have provision for altering the input before it is terminated. In line mode, the rubout key prints as backslash and functions as a backspace, and in number mode, if more than four digits are typed, only the last four are used, but there is no way to remove the indication that a number has been typed.

A final overall concept of the LUCIFER system is that it should be hard to do any damage to one's files, and especially that most mistakes should be either harmless or harmful to only a limited amount of information. On the other hand, LUCIFER is designed so that for most ways in which information can be destroyed or damaged, the information can be reconstituted with about as much effort as was needed to obliterate it in the first place. The only necessary ingredient is, of course, enough raw knowledge that one know how to resurrect the ruined information. With LUCIFER programs, this knowledge is relatively easy to obtain.

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Appendix B

PROTOCROCK--A STEP TOWARD TIME SHARING ON THE LINC-8

Appendix B

PROTOCROCK: A STEP TOWARD TIME-SHARING ON THE LINC-8

by M. Wilber

We have been working toward a system to time-share the LINC-8 between the conduct of an experiment and the preparation or analysis of data, or the preparation of future experiments. In addition, we are planning to time-share the computer among several experiments, if possible. (The latter is more difficult because of the real-time constraints involved.) Our past experience with the LINC-8 and similar computers in a devoted(non-time-shared) mode has indicated that real-time experiments of the psychophysical variety can easily absorb all available computer time and that during these experiments the computer is loafing most of the time. Therefore, we feel that even a rudimentary form of time-sharing would produce a very significant increment in our output.

Most of the experiments we have planned will fit quite nicely into the time-sharing framework, although we cannot use a perfectly general time-sharing system and still run the experiments. The time-sharing system we are developing will resemble the PDP-6 and PDP-10 systems more closely than any of the other current time-sharing systems, but it will inevitably show signs of implementation on a small computer. In addition, full protection of users from each other will require a slight modification of the computer. Time-sharing is possible because the LINC computer in a LINC-8 system is partly hardware (the LINC subsystem) and partly software (the PDP-8 program named PROGOFOP). The PROGOFOP program is a large enough part of the LINC-8 computer that almost all the time-sharing can be achieved by substituting another PDP-8 program for PROGOFOP.

We have developed a first version of this replacement for PROGOFOP called PROTOCROCK. While time sharing is not yet operational, PROTOCROCK is working well enough to be an adequate substitute for PROGOFOP in the devoted mode. In addition to PROGOFOP capabilities, PROTOCROCK permits LINC program input and output communication between the computer and our own special peripherals. Included in these peripherals are two clocks, a 60-c/s clock and a 1000-c/s clock. The 60-c/s is intended to run all the time, while the 1000-c/s clock is meant to be used only during those portions of experiments in which more accurate timing is required.

Now that PROTOCROCK is working the next step is to commence work on time-sharing itself.

Appendix C

A LINC-8 INTERFACE CONTROL FOR POINT STIMULATORS

Appendix C

A LINC-8 INTERFACE CONTROL FOR POINT STIMULATORS

An electronic interface to a LINC-8 computer, shown in Fig. C-1, has been designed and constructed for control of up to 192 stimulators. Several improvements over our previous system (Bliss and Crane, 1964) have been incorporated in this design. This system consists of a computer interface, a 12-by-16 matrix of storage flip-flops, and stimulator drive circuits. Each point in the storage matrix can activate and modulate an airjet or piezoelectric bimorph tactile stimulator, a light indicator, and (with appropriate drive circuits) unspecified tactile or visual stimulators.

Under program control, the computer can store 12 bits at a time (equivalent to one row) in the storage matrix. These 12 bits come from the computer accumulator and are gated into the row of the matrix specified by a 16-bit ring counter. The ring counter is preset to a "1" state in its first flip-flop and a "0" state in the other 15 flip-flops. The "1" state is stepped to the next flip-flop in the ring after the contents of the accumulator are stored in each row of the storage matrix. The entire 16 rows can be filled with an arbitrary pattern in less than 110 μs. This system is sufficiently flexible that the same hardware can be used in a wide variety of experiments by merely changing computer programs.

The interface system enables the programmer, by means of three basic PDP-8 IOT instructions, to write and erase in the storage matrix. The IOT commands used are:

Code	Function
6471	Reset all the flip-flops in the storage matrix.
6472	Reset the ring counter so that the first flip-flop is in the "1" state and all others are in the "0" state.
6474	Write the accumulator into the storage-matrix row indicated by the ring counter; step the ring counter to the next position; and clear the accumulator.

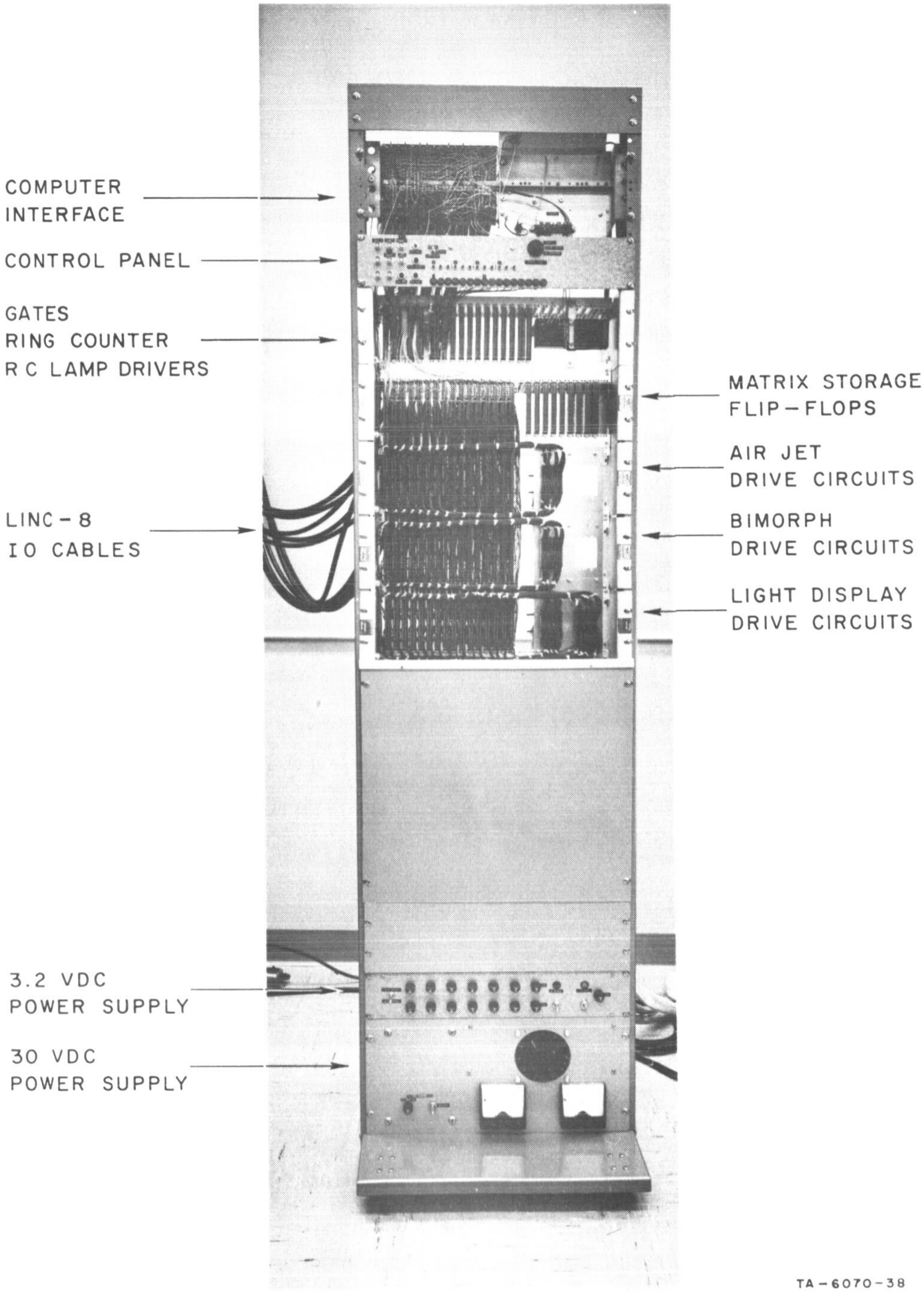

FIG. C-1 LINC-8 INTERFACE CONTROL FOR POINT TACTILE STIMULATORS

These codes can be used in combination. For example, 6473 resets both the storage matrix and the ring counter, while 6477 resets the storage matrix and ring counter, writes the accumulator into the first row of the matrix, steps the ring counter to the second row, and clears the accumulator.

Although this set of commands is not completely general, since any row of the storage matrix cannot be randomly addressed, our experience has indicated that this command set is adequate for psychophysical experiments because of the high speed of the LINC-8.

To illustrate how this system can be used, the following programming example is offered:

Problem: Present a stimulus pattern on the first N rows of the matrix. It is assumed that the address of the first row of the stimulus pattern (minus one) is stored in location 10 and that the other rows follow in order. Minus N is initially stored in location 7.

Location	Program	Timing (μs)	Comment
20	6473	3.75	Resets the storage matrix and ring counter.
21	cla	1.5	Clears the accumulator.
22	→ tad i 10	4.5	Loads the accumulator with one row of the stimulus pattern.
23	6474	3.75	Writes the accumulator into one row of the storage matrix and steps the ring counter.
24	isz 7	3.0	Increments the contents of location 7 and skips the next instruction if the contents of 7 are zero.
25	jmp 22 hlt	1.5	Gets the next row.

The DEC FLIP-CHIP specification for this interface is shown in Fig. C-2. This interface also controls the modulation of the stimulators (typically 200 c/s for airjets and 250 c/s for bimorphs) by modulating the storage matrix flip-flop output, which controls the stimulator driver. In order to avoid split pulses and synchronize the modulation with the

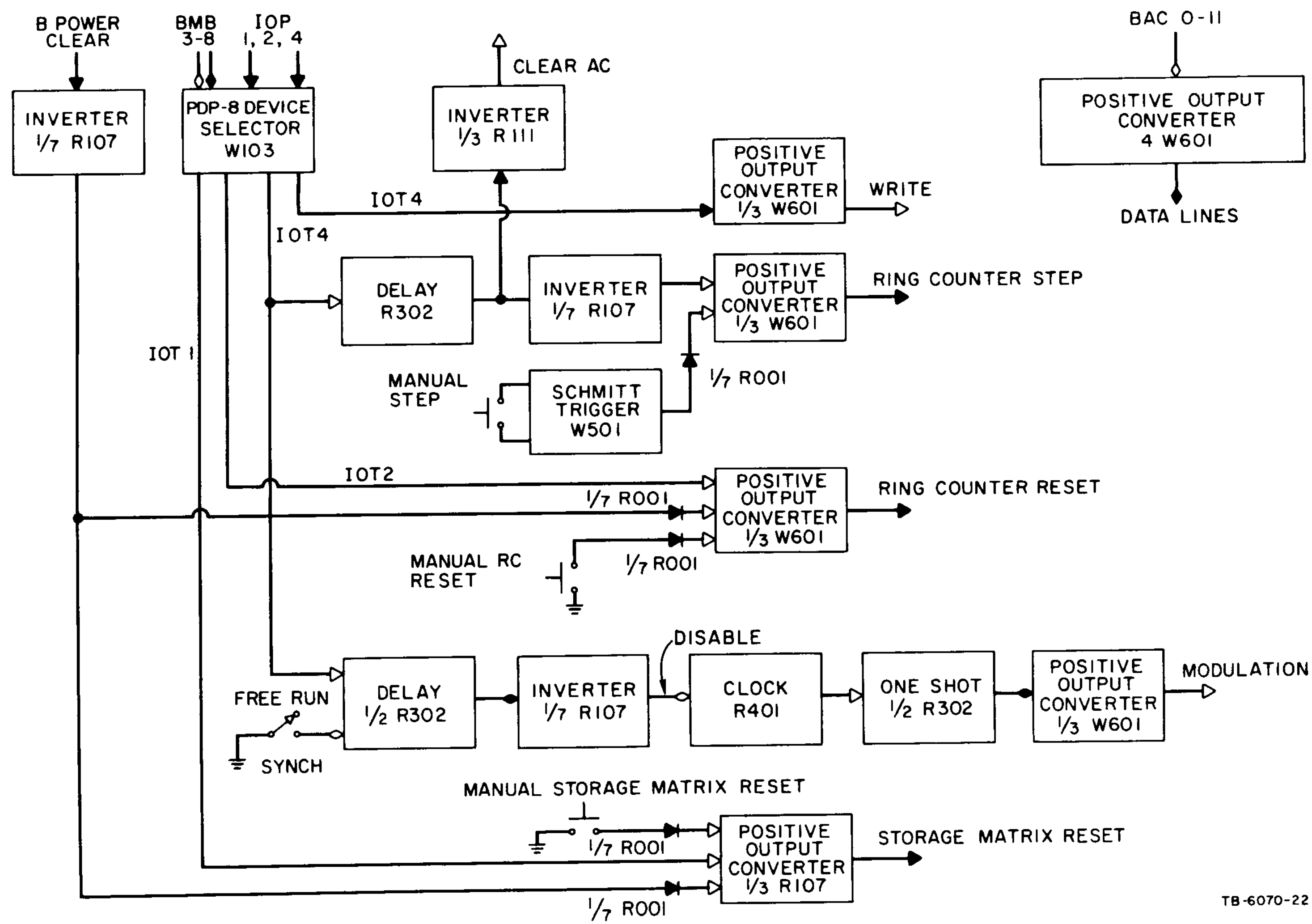

FIG. C-2 STIMULATOR CONTROL INTERFACE

computer output, provision is made for disabling the modulation clock while the computer is writing in the storage matrix.

The storage matrix and ring counter consist of Fairchild integrated circuits. These are shown in Figs. C-3(a), (b), and (c). A teletype keyboard is used with this system to allow the experimenter to type responses of the subjects into the computer. Figure C-4 is a block diagram of the keyboard interface.

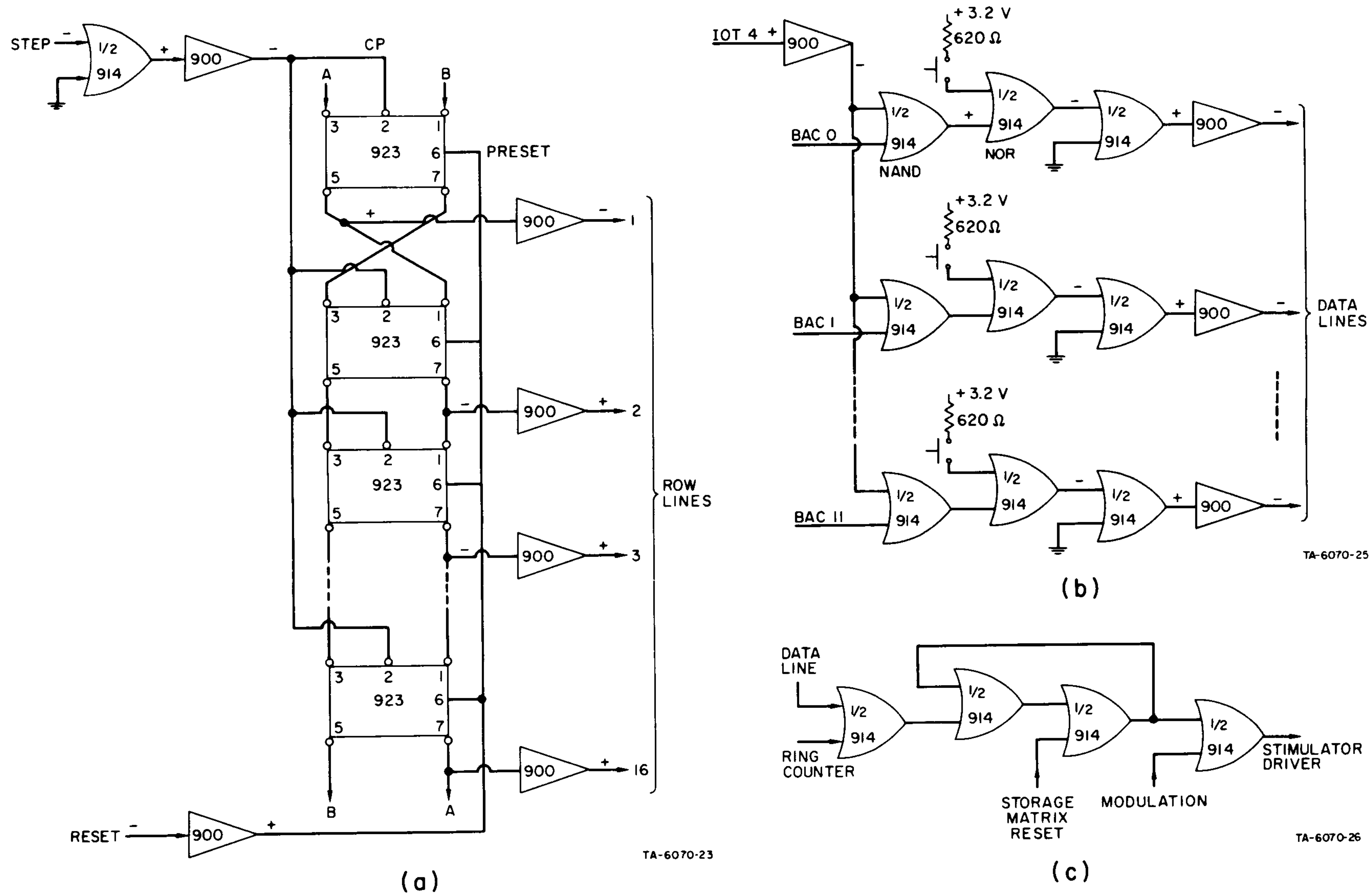

FIG. C-3 (a) RING COUNTER (b) DATA-LINE GATES (c) CIRCUIT FOR EACH STORAGE MATRIX POINT

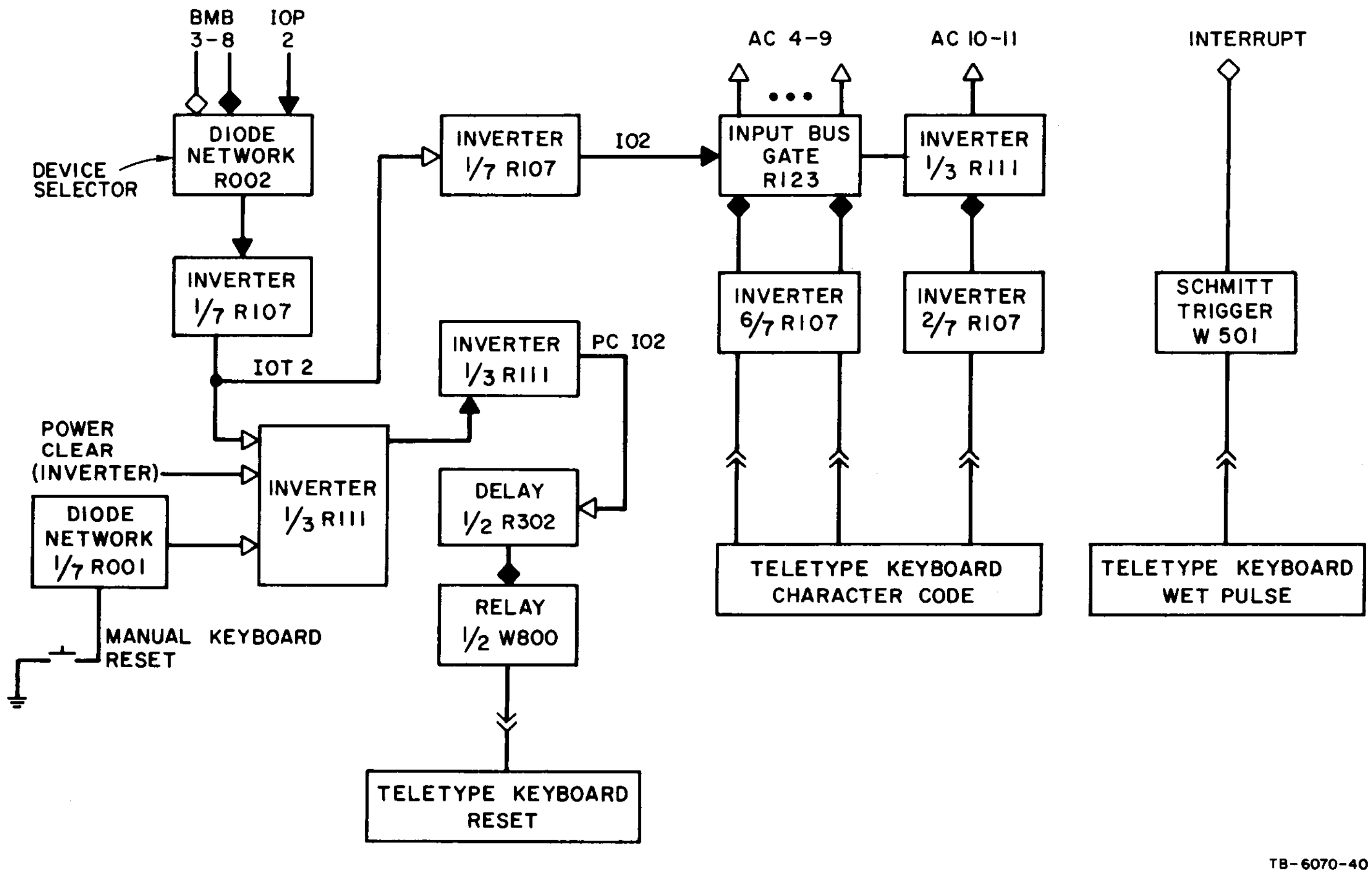

FIG. C-4 TELETYPE KEYBOARD INTERFACE

Appendix D

AN ON-LINE DIGITAL COMPUTER SYSTEM FOR TRACKING RESEARCH

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Appendix D

AN ON-LINE DIGITAL COMPUTER SYSTEM FOR TRACKING RESEARCH

by J. C. Bliss

Previously we reported a convenient method for obtaining human operator describing functions with an on-line digital computer system (Bliss, 1966). In this system a digital computer (CDC 8090) simulated the command generator and determined the subject's response or error spectra in real time. The Bode plots, or amplitude and phase measurements of the response or error as a function of frequency, were available to the experimenter immediately after a tracking run (usually 4 minutes).

During this year, similar programs for the LINC-8, but incorporating several major improvements over our previous system, were planned. The writing and debugging of the first of these programs, that of the "critical" tracking task (Jex, McDonnell, and Phatak, 1966) have been completed. Planned programs yet to be completed involve determination of the subject's open-loop describing function, response spectra, and error spectra--all analyzed at an increased number of frequency values on a single trial. We also expect to be able to switch between the "critical" tracking task mode and the describing function analysis mode under program control, making it possible to study the adaptation process as the controlled element pole diverges.

A block diagram for this type of experiment is shown in Fig. D-1. All parts of the system, except the display, subject, and manipulator, consist of the LINC-8 and software. In the describing function analysis mode, the LINC-8 cyclically generates a value for the display via the D/A channel, inputs a response value via the A/D channel, and updates the sums corresponding to the components of a Fourier analysis of two signals at up to 20 values of frequency. Each of these cycles of the program is arbitrarily set to 16-2/3 ms (our basic clock rate), so that the display appears continuous to the subject. At the end of an

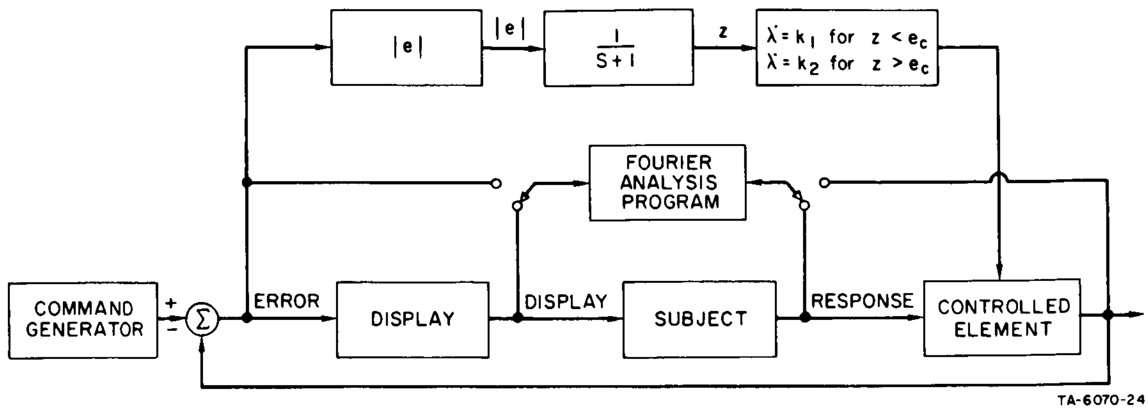

FIG. D-1 ON-LINE COMPUTER SYSTEM FOR TRACKING RESEARCH (All blocks except the Display and Subject consist of the Linc-8 computer and software.)

adjustable time, the experiment trial is terminated, and the required floating point calculations are performed and outputted.

The command generator program contains a table of 15 values representing a quarter cycle of a sinusoid. The program uses this table to generate a composite signal, consisting of a sum of sinusoids of arbitrary amplitude and phase. Thus,

$$c(t_k) = \sum_{i}^{N} c_i \sin(\omega_i t_k + \varphi_i) \tag{D-1}$$

where $c(t_k)$ is the value of the command during program cycle t_k; c_i is the amplitude, φ_i the phase, and ω_i the frequency of the i^{th} sinusoid. Up to 10 frequencies can be accommodated by the command generator program, and the subsequent analysis is performed at these, plus 10 additional frequencies.

In the analysis programs, the input signals are multiplied by each of a number of sine and cosine components, consisting of the frequencies generated by the command generator plus up to 10 additional frequencies.

The two input signals may be either the error or display signals and the response signal from the manipulator. Cumulative sums of the results of these multiplications are updated each program cycle. Thus, if the input signal is $r(t_k)$ and the controlled element dynamics are a pure gain, then the sums a_j and b_j are formed as follows:

$$a_j = \sum_{k=0}^{T} c_j \sin(\omega_j t_k) r(t_k)$$

$$b_j = \sum_{k=0}^{T} c_j \cos(\omega_j t_k) r(t_k) \quad . \qquad \text{(D-2)}$$

The controlled element dynamics are also simulated in the LINC-8, using the principles of digital filtering (Mantey, 1966; Kuo and Kaiser, 1966). In Appendix E the difference equations for several types of controlled elements are derived.

The floating point program takes the sums generated during the experimental trial by the on-line analysis program and computes the amplitudes x_j and phases φ_j of each of the up to 20 frequency components for the two desired spectra, according to the following equations:

$$x_j = \frac{2}{T}\sqrt{a_j^2 + b_j^2}$$

$$\varphi_j = \tan^{-1} \frac{a_j}{b_j} \quad . \qquad \text{(D-3)}$$

The two signals analyzed can be either the error signal or display signal, and either the response signal or the controlled element output. The amplitude components of these two signals are divided and their corresponding phases subtracted to obtain an open-loop describing function. The correlation coefficient between the response and the corresponding linear system is also determined. The results of all these calculations are then typed out on the on-line teletypewriter.

In the "critical" tracking task mode, the computer takes the absolute value of the error signal, filters it with a first-order lag, and adjusts the rate of divergence of the controlled element pole according to whether the filtered absolute error signal is above or below a threshold. The experiment is terminated when the absolute error signal exceeds the limits of the display. The final value of λ, the position of the controlled element pole, is then typed out. The effective time delay of the subject is approximately $1/\lambda$.

Section III of the main text describes our first experiment with the "critical" tracking task. As it continues to evolve, we plan to use this system for tracking research to extend our previous investigation of subject performance with visual and/or tactile displays.

Appendix E

REAL-TIME DIGITAL COMPUTER REALIZATION OF LINEAR TRANSFER FUNCTIONS

Appendix E

REAL-TIME DIGITAL COMPUTER REALIZATION OF LINEAR TRANSFER FUNCTIONS

by J. C. Bliss

A digital computer can conveniently realize the filter and controlled element transfer functions used in tracking experiments. The basic procedures for design of these digital filters are derived from z-transform theory and are discussed by Mantey (1966) and Kuo and Kaiser (1966).

It is useful to make certain "predistortions" in the desired continuous transfer function in order to improve the resulting discrete approximation to the continuous system. To understand this "predistortion" step, recall that when a signal is sampled, the resulting spectrum is obtained by convolving a periodic impulse train with the original spectrum. If the spectrum of the original signal has finite bandwidth--for example, negligible energy outside some low-frequency region f_o--then if the sampling frequency is greater than $2f_o$, the resulting spectrum is a train of nonoverlapping replicas of the original spectrum. Since these individual spectral pulses do not overlap, the spectrum of the sampled signal contains no less information about the original signal than does the original spectrum, and the original signal is recoverable from the sampled signal with an ideal low-pass filter. However, in situations in which the signal does not have a finite bandwidth, information is lost and distortion occurs. To ensure that this does not happen, a finite bandwidth filter, to limit the bandwidth of the incoming signal, is incorporated in the design. Ideally, this "predistortion" filter should have a gain of 1 over the band of interest and a gain of 0 elsewhere. However, these frequency characteristics are not realizable in real time. After considering several functions for this "predistortion" filter, including Butterworth, Tschebyscheff, zero-order hold, first-order hold, and a combination of zero-order and first-order hold, the zero-order hold function was chosen because it is a good approximation to the ideal filter, it results in a filter with a step response that is exactly correct at the sampling instants, and it is relatively simple to realize.

Thus, the steps in determining a difference equation suitable for digital computer programming, approximating a continuous transfer function, are:

(1) Multiply the desired continuous transfer function by the transfer function for a zero-order hold.

Example: Let $H(s) = K/(s - a)$ be the desired continuous transfer function. The transfer function for a zero-order hold is $(1 - e^{-sT}/s)$. Then,

$$H_1(s) = \left(\frac{K}{s - a}\right)\left(\frac{1 - e^{-sT}}{s}\right) \quad . \tag{E-1}$$

(2) Make a partial fraction expansion of this product:

$$H_1(s) = \left(1 - e^{-sT}\right)\left[\frac{K/a}{s - a} - \frac{K/a}{s}\right] \quad . \tag{E-2}$$

(3) Convert to z-transforms using a table (Mantey, 1966) or the following transform pairs:

$$\begin{aligned} 1/s &\rightarrow \frac{1}{1 - z^{-1}} \\ \frac{1}{s + a} &\rightarrow \frac{1}{1 - e^{-aT}z^{-1}} \quad . \end{aligned} \tag{E-3}$$

Thus,

$$H_1(z) = \left(1 - z^{-1}\right)\left[\frac{K/a}{1 - e^{aT}z^{-1}} - \frac{K/a}{1 - z^{-1}}\right] \quad . \tag{E-4}$$

(4) Invert the z-transform to obtain the desired difference equation,

$$H_1(z) = \frac{Y(z)}{X(z)} = \frac{K/a\ z^{-1}\left(e^{aT} - 1\right)}{1 - e^{aT}z^{-1}}$$

$$y(nT) = (K/a)x[(n - 1)T]\left(e^{aT} - 1\right) + e^{aT}y[(n - 1)T] \qquad \text{(E-5)}$$

where x is the input and y is the output of the filter.

<u>Check</u>: The resulting difference equation should give exactly the same output to a step-function input as the corresponding continuous transfer function. That is, if

$$x(nT) = 1 \quad \text{for} \quad n = 0, 1, 2, \ldots$$
$$= 0 \quad \text{elsewhere,}$$

then from Eq. (E-5),

$$y(0) = 0$$
$$y(T) = K/a\left(e^{aT} - 1\right)$$
$$y(2T) = K/a\left(e^{2aT} - 1\right)$$
$$y(3T) = K/a\left(e^{3aT} - 1\right)$$
$$\vdots \qquad\qquad \vdots$$

Table E-1 gives difference equations for several continuous transfer functions.

Table E-1

DIFFERENCE EQUATIONS FOR SEVERAL LINEAR TRANSFER FUNCTIONS

H(s)	Difference Equation
K/s	$y(nT) = KTx[(n-1)T] + y[(n-1)T]$
$\frac{K}{s-a}$	$y(nT) = \frac{K}{a} x[(n-1)T] \left(e^{aT} - 1\right) + e^{aT} y[(n-1)T]$
$\frac{K}{s^2}$	$y(nT) = \frac{KT^2}{2} \{x[(n-1)T] + x[(n-2)T]\} + 2y[(n-1)T] - y[(n-2)T]$
$\frac{K}{s(s-a)}$	$y(nT) = \frac{K}{a^2} \left\{\left(e^{aT} - aT - 1\right) x[(n-1)T] + \left[1 + e^{aT}(aT-1)\right] x[(n-2)T]\right\}$ $+ \left(e^{aT} + 1\right) y[(n-1)T] - e^{aT} y[(n-2)T]$

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Stanford Research Institute 333 Ravenswood Avenue Menlo Park, California	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

TACTUAL PERCEPTION: EXPERIMENTS AND MODELS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report Covering the period 24 May 1966 to 24 May 1967

5. AUTHOR(S) *(First name, middle initial, last name)*

James C. Bliss

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1967	116	32

8a. CONTRACT OR GRANT NO. Contract NAS2-3649 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Final Report SRI Project 6070 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY National Aeronautics and Space Administration Ames Research Center Moffett Field, Calif.

13. ABSTRACT

Experiments in tactile perception, tactile and visual tracking behavior, and tactile and visual choice reaction time are described. Results from an experiment on tactile perception of sequentially presented point stimuli indicate that content errors (responses that are incorrect regardless of what order they are in) are constant as the interstimulus interval is increased up to 200 ms, and that sequence errors (errors caused only by responding in an incorrect order) decrease exponentially with interstimulus interval. The total error can be expressed as a linear sum of a constant, representing the content error, and a decaying exponential function of interstimulus interval (with a time constant of less than 100 ms), representing the sequential error.

In the tracking experiments comparisons were made between tracking performance when an airjet stimulator moved horizontally across the forehead and when it moved along the palmar side of the hand and index finger. Performance appeared to be about equal in these two cases. A comparison of performance with a contacting tactile stimulus and a visual display revealed essentially the same phase characteristics for both displays, but less gain and more remnant power with the tactile display.

Results from "critical" tracking with both visual and tactile displays indicated a greater effective time delay with the tactile display and no significant difference between tracking with the visual display only and tracking with both the visual and tactile displays used simultaneously.

In the reaction-time experiments subjects could receive either tactile or visual stimuli, or both simultaneously, on any one trial. In a simple reaction-time experiment in which only one response was required, the tactile and visual reaction times were approximately equal. However, in the two-choice version of the experiment, response times were appreciably longer, and the probability of an error was greater with the tactile stimuli than with the visual stimuli. When both tactile and visual stimuli were presented simultaneously, significantly shorter reaction times were obtained than with either stimulus alone. These results are consistent with a model which assumes that the sensory input channels are independent of each other and that subjects tend to respond to the first perceived stimulus.

Five Appendices describe developments on new techniques and facilities for conducting a wide variety of experiments on tactile perception, which range from presentation of multiple point stimuli to analyses of describing functions in tracking experiments. The key item in these facilities is a LINC-8 computer, which will control, in a time-shared mode, the presentation of the stimuli, and record and analyze the responses.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Tactile perception						
Psychophysics						
Short-term memory						
Span of attention						
Displays						
Reaction time						
Manual control						
Display movement						
Vision						
On-line computer						

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