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CHARACTERISTICS OF THE TACTILE INFORMATION CHANNEL

by J. C. Bliss, J. W. Hill, and B. M. Wilber

Prepared by
STANFORD RESEARCH INSTITUTE
Menlo Park, Calif.
for Ames Research Center

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By J. C. Bliss, J. W. Hill, and B. M. Wilber

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ABSTRACT

Experiments with multiple-point tactile and visual stimulus fields are described. A number of the experiments involved a brief presentation of between 2- and 12-point stimuli randomly distributed in a 3 by 8 matrix. The subject's task was to specify the location of each point stimulated in the entire matrix (whole report) or in the subset of the matrix indicated by a marker (partial report). In some of these latter experiments all stimulators were activated after the point stimuli, forming an "erasure" field which interfered with the perception of the stimuli. Analogous visual and tactile experiments were performed. These experiments indicated the existence of a tactile sensory register (i.e., a very short term memory of relatively unprocessed information) with greater capacity than the span of immediate memory. The number of tactile points perceived increased with the logarithm of stimulus duration over the range 1 to 500 ms. The frequency of modulation of the tactile stimulators had no significant effect. No evidence for a visual sensory register was found, and several explanations for this are discussed. The experiments with the erasure post-field indicated that information is transferred in parallel, rather than sequentially, to higher centers. A model for both visual and tactile information processing is proposed.

In another series of experiments the point stimuli were presented sequentially rather than simultaneously. The results indicated a strong dependence of the number of positions perceived in the correct spatial location (independent of temporal order) on the Stimulus Onset Interval (SOI), with a minimum occurring with SOI values in the range of 50 to

100 ms. Backward masking is examined as a possible explanation for this effect and ruled out. These results also rule out a push-down-store model, but not a first-in-first-out model.

In another line of experimentation, the compensatory tracking paradigm is applied to a psychophysical study of two neurologically distinguishable tactile systems. In this study two-point tactile discrimination is tested as a function of vibration frequency of the stimulators by requiring the subject to continuously balance the intensity of two vibrators. In a preliminary test slightly better performance was obtained at 300 Hz than at 10 Hz.

In addition, advances in on-line computer control of experiments are described. Included is a description of a computer program for compensatory tracking and a program for time-sharing on a LINC-8 computer.

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I INTRODUCTION

For the past hundred years tactile displays have been suggested for many purposes, including sensory feedback for remote manipulation and prosthetic limbs, sensory aids for the deaf and the blind, control and navigational displays for astronauts and aviators, and "feelies." However, very few of these suggestions have been developed to the point of common usage.

Many difficulties confront the designer of tactile displays. There are few commercially available tactile stimulators, and special designs are not always straightforward. Little has been known about optimum stimulus parameters and about the characteristics and capabilities of the tactile channel. Thus the engineering of tactile displays has been relatively undeveloped, and the psychology of the tactile sense has been little understood.

For the past few years the Bioinformation Systems Group at the Stanford Research Institute has been trying to contribute to the improvement of this situation. If one considers the enormous number of different combinations of stimulus conditions that could possibly be used in a tactile display, then the empirical approach of comparing performance with every possible combination seems hopeless. Therefore, we have taken the approach of trying to develop models to describe tactile information processing characteristics in a general way. We expect these models to serve as a guide to predicting conditions for optimum information transfer and to reveal the causes of certain limitations. We feel that this approach has been very fruitful in terms of increasing our basic understanding of the tactile channel and in terms of providing a foundation for the design of useful tactile displays.

This report, covering one year of research, mainly extends our previous research. In previous years we developed tactile stimulators suitable for use in closely packed arrays, developed on-line computer control of experiments with these stimulator arrays, and studied human information acquisition capabilities from tactile and visual displays.

During the period covered by this report, two patent disclosures were made on new types of valves for airjet stimulators,* three technical papers were submitted for publication in scientific journals (Hill and Bliss, 1968a and 1968b; Wilber, 1967), and additional results are presented in this report.

The beginning of a tactile information processing model was proposed in Bliss et al. (1966). In this model, tactile memory is divided into three components: a sensory register, a short-term store, and a long term store.

The results described in this report and in our recent papers support and further extend this model. The spatial and temporal characteristics of the tactile sensory register are described in Hill and Bliss (1968a). An investigation of the temporal resolution of the tactile channel is described in Hill and Bliss (1968b). In addition, the effects of stimulus duration are described in Sec. IV of this report, and the effects of stimulus frequency are described in Secs. V and XI. By comparing performances of directly analogous visual and tactile perception tasks, a new model for both channels is introduced in Sec. V. These results also indicate the nature of the scanning process between the sensory registers and the common short-term store. Sequentially presented stimuli are further investigated in Secs. VIII

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* Patent disclosure "Diaphram Operated Air Jet" by John W. Hill, July 29, 1968. Patent disclosure "Biomorph Operated Air Jet" by John W. Hill, July 29, 1968.

and IX, and relations between these results and reaction time results are pointed out. The techniques described in Secs. X and XI suggest a convenient and effective tactile display for tracking tasks.

Throughout this report it should be evident that experiments of this complexity, with this precision of control and accuracy of data collection, and the extensiveness of the data analysis, would not have been possible, especially in the span of one year, without the use of on-line computer control. We have maintained a continuing research effort in the field of on-line experiment control in order to extend these techniques both in our laboratory and in general. Wilber (1967) described a first step in the development of software for this purpose. Further developments leading to a demonstrable time-sharing system for experiment control are described in Sec. XII.

II MEASUREMENT OF TACTILE EVOKED POTENTIALS

One of our goals for this project was to decide on the appropriateness of evoked-potential experiments for further development of tactile perception models. Related to this, Mr. Arthur F. Lange began an Electrical Engineer's thesis on tactile evoked potentials at Stanford University last spring under the direction of Dr. James Bliss. This thesis was completed during the report period, and a portion of the abstract of the thesis is quoted below:

> "Experiments were performed in which average evoked cortical potentials resulting from vibratory stimuli on the finger were recorded from an array of ten electrodes. Only late components were detectable and no localization was found over the sensory projection area. A correlation technique for measuring recovery functions with paired stimuli is developed and experimental results are given.
>
> Peripheral nerve recordings from the ulnar nerve with electrical and vibratory stimuli on the finger were attempted with identifiable responses only being obtained with the electrical stimuli. A dispersion explanation is given for failing to detect responses to vibratory stimuli."

In the peripheral nerve recordings a valiant effort was made to obtain signals with vibratory (airjet) stimuli. Simultaneous millisecond airjet pulses from six of our stimulators were directed at the finger pad. Two hundred recordings from the nerve were averaged together with no observable response, even though recordings taken from the same subject at the same time with electrical stimuli gave clear responses. This result discourages an attempt to relate peripheral nerve recordings with mechanical stimuli.

The other result, that of detecting only late components from cortical electrodes with vibratory stimuli, is also discouraging from the viewpoint of relating mechanical stimulus parameters to neural events. Up until at least a few years ago, it was generally thought that the late components reflected general cortical responses, such as from the reticular formation, and were not directly related to stimulus parameters.

However, two rays of hope appear on the horizon that may change the picture with respect to narrowing the gap between the psychophysics and neurophysiology of this system by evoked-potential studies. The first is that we have found a way to produce 100-μs airjet pulses,* which should alleviate the dispersion problem with the millisecond pulses. The second is that several workers in the field are challenging the notion that the late components of the cortical potential are only indirectly related to stimulus parameters (e.g., Fhurstofer, 1966; Allison, 1968).

Therefore, based on these considerations, it was decided by SRI and NASA personnel not to pursue evoked-potential studies further for the time being. Our interest in this area may be renewed later, when the meaning of the early and late components becomes clearer.

---

* Patent disclosure, "Diaphram Operated Air Jet," by John W. Hill, July 29, 1968.

III PERCEPTION OF VERY BRIEF MULTIPLE-POINT STIMULI

A. Introduction

Previous tactile perception experiments, described by Bliss et al. (1966), were carried out to compare tactile perception with visual perception. These experiments suggested the existence of a tactile sensory register that (1) is capable of storing information for a few seconds, (2) varies considerably in size for different subjects, and (3) has a capacity limited by spatial confusions. Following a thorough analysis of the previous data by Hill (1967), combined with subjects' comments and an experiment with a longer intertrial duration (4 seconds), an improved version of the tactile perception experiment was run. This new experiment included the following modifications:

(1) The stimulus presentation time was reduced from 100 ms to 1 ms. (This means there was only a single pulse from the airjets, which normally pulsate at 200 Hz.)

(2) The finger positions were relabeled so that each of the three rows used the letters 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 sensitivity in reporting positions in the bottom row (because of their less familiar letter labels), all three rows were identically labeled.

(3) Reinforcement (which consisted of presenting the original stimulus both visually and tactually after the subject had responded) during testing was eliminated. 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.

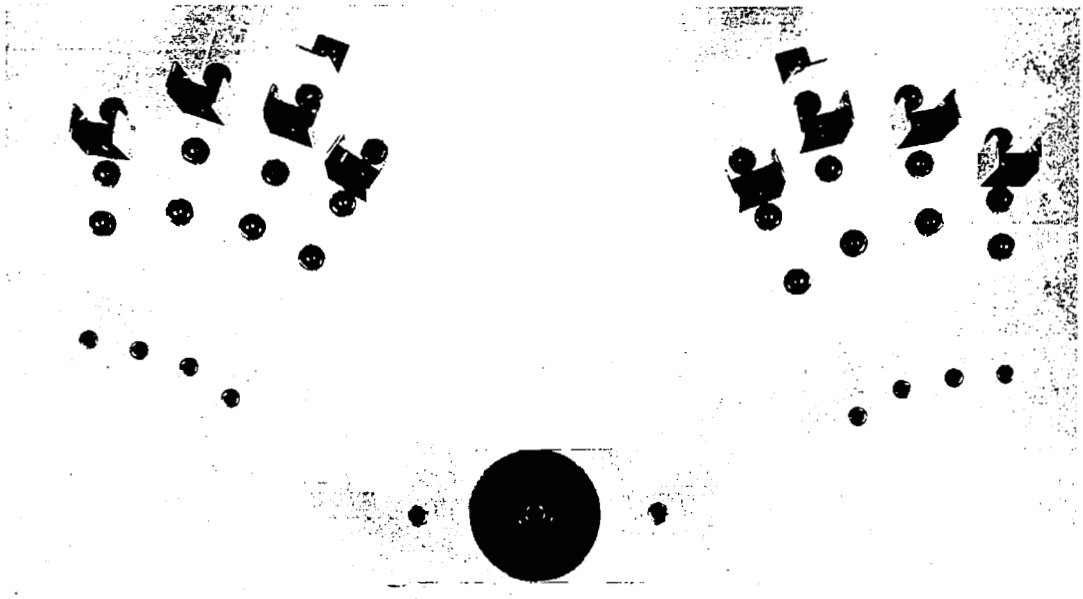
(4) The intertrial duration was increased from 2 to 4 seconds. Allison (1962) has shown that 4 seconds is adequate for full recovery of all components of the evoked response occurring within 300 ms of nerve and finger stimulation.

(5) The experiment was lengthened (52 days instead of 22). Hill (1967) has suggested that the wide range of subject performance can be explained by a learning hypothesis. Other authors have noted the presence of slow tactile learning (e.g., Krohn, 1893; Mukheriee, 1933; Diespecker, 1967; Howell, 1956; Viereck, 1967), but have not isolated the variable on which it depends. This experiment, containing four replications of each experimental condition, allowed several measures of learning to be made in addition to furnishing more stable data.

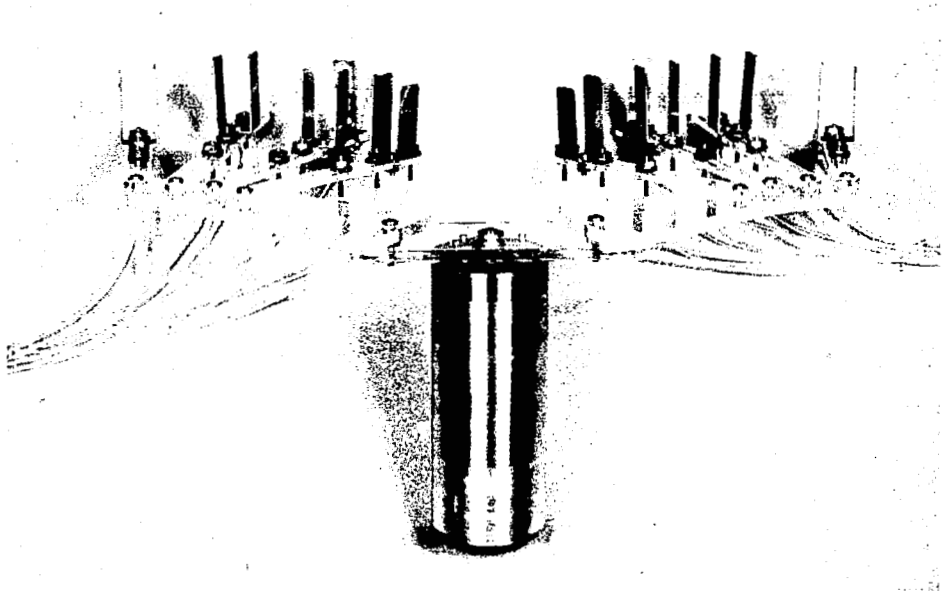
B. Method

1. Apparatus

The experiment was carried out under control of a LINC-8 computer system, which was used to store stimulus patterns and the sequence in which the patterns were to be presented (Bliss, 1967, Appendices A, B, C). This system was designed for use with up to 192 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 over extended periods without fatigue. Each subject has 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.



(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

Each jet of air was formed by a 0.031-inch outlet nozzle under control of a high-speed electromagnetic valve. The air-pressure pulses, measured 1/8 inch directly above the airjet outlet, have a peak pressure amplitude of about 1 lbf/in^2. The time course of pressure waveform is shown in Fig. 2. In all of the experiments (except one using stimulus

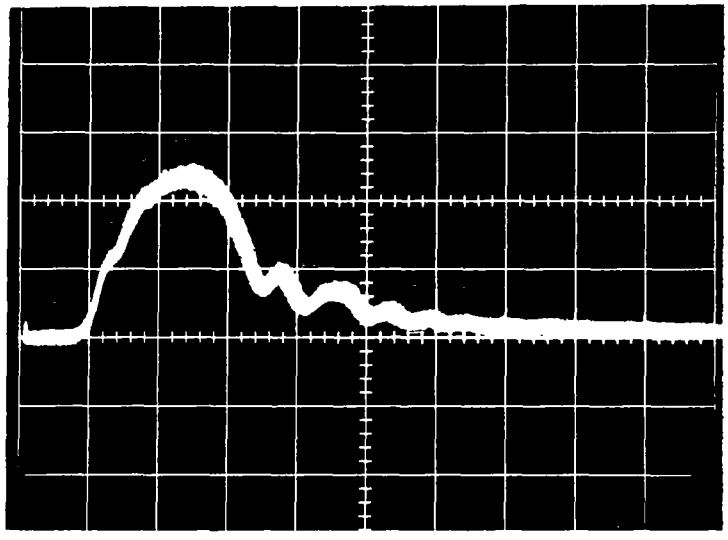

FIG. 2 FIVE SUPERIMPOSED AIR PRESSURE WAVEFORMS.
The time scale is 0.5 ms per division.

patterns of longer duration) the airjets produced one pressure pulse. Thus, the selected stimulators were simultaneously turned on once to produce the stimulus patterns. In an additional variable duration experiment, the stimulators selected for a given pattern were simultaneously turned on and off 2, 5, or 10 times at a 200 Hz rate. 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

Two college students served as paid subjects. Subject RR was a male college freshman and EM a female college junior. Neither of the subjects had ever participated in an experiment of this nature.

3. Procedure

Each subject was tested in two or three 15- to 30-minute sessions per day, with a 5- to 20-minute rest between sessions. The training and testing schedule is shown in Table I. The number of total presentations for each value of n during training was chosen so that subjects spent three sessions on each value of n. For whole report testing, the number of total presentations for each value of n was chosen to allow the variance for the mean number correct per n-value to remain constant across all values of n. (Specifically, the number of total presentations was set so that the probability that the mean number correct per value of n would exceed the true mean by more than 0.4 stimulus positions was ≤ 0.1.) For each value of n, the number of presentations at each interjoint position was equal.

In all portions of the experiment, each subject has before him at all times a replica (Fig. 3) of the alpha-numeric response alphabet. On any one trial, n stimulation points were chosen (by the computer) out of the possible 24 interjoint locations. In any one session the number of positions simultaneously stimulated, n, was constant and known by the subject. The subjects orally reported the locations perceived, using the alphabetic labels shown in Fig. 3.

The subjects were asked to report the stimulated positions in alphabetical order, giving the number of the row (in numerical order 1, 2, or 3) followed by a string of letters (A through H) corresponding to the stimulated positions of the row. These responses were typed

Table I

TRAINING AND TESTING SCHEDULE

Training Series

Day	1		2		3		4		5		6		7		8		9		10	
n	1	1	2	2	2	4	4	4	6	6	6	8	8	8	10	10	10	12	12	12
No. Trials	72	72	144	144	144	96	96	96	88	88	88	90	90	90	50	50	50	47	47	47

First Whole Report Test Series

Day	11			12		13		14		15		
n	2	6	10	10	10	12	12	12	12	8	8	4
No. Trials	36	96	50	50	56	47	47	47	47	90	36	66

First Partial Report Test Series (n=12)

Day	16*		17		18		19		20		21		22	
Marker Delay	none	none	-.75	-.75	0.0	0.0	0.3	0.3	0.8	0.8	2.0	2.0	0.1	0.1
No. Trials	66	66	66	66	66	66	66	66	66	66	66	66	66	66

Second Whole Report Test Series

Day	23			24		25		26		27		
n	2	6	10	10	10	12	12	12	12	8	8	4
No. Trials	36	96	50	50	56	47	47	47	47	90	36	66

Second Partial Report Test Series (n=12)

Day	28		29		30		31		32		33		34*	
Marker Delay	-.75	-.75	0.0	0.0	0.3	0.3	0.8	0.8	2.0	2.0	0.1	0.1	none	none
No. Trials	66	66	66	66	66	66	66	66	66	66	66	66	66	66

First Partials with Erasure Series (n=12)

Day	35		36		37		38		39		40	
Marker Delay	-.75	-.75	0.0	0.0	0.3	0.3	0.8	0.8	2.0	2.0	0.1	0.1
No. Trials	66	66	66	66	66	66	66	66	66	66	66	66

Second Partials with Erasure Series (n=12)

Day	41		42		43		44		45		46	
Marker Delay	-.75	-.75	0.0	0.0	0.3	0.3	0.8	0.8	2.0	2.0	0.1	0.1
No. Trials	66	66	66	66	66	66	66	66	66	66	66	66

*Whole report from patterns used in the partial report series.

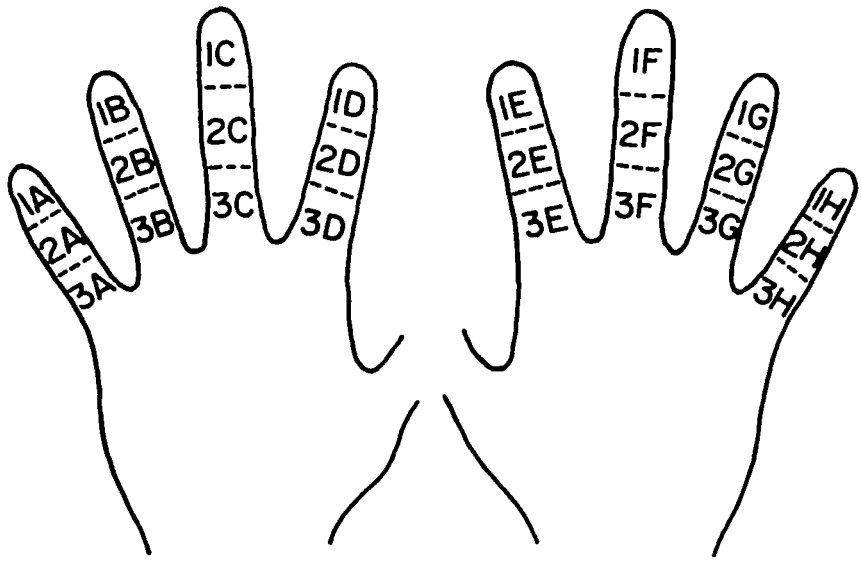

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FIG. 3 FINGER LABELING FOR TWO HANDS

into the control computer by the experimenter. There was no fixed time within which a subject was forced to respond.

In the training series the subjects were required to report all of the stimulated locations row by row in alphabetical order. A typical response with n = 10 would be 1ACH2BCDH3ABC. If a subject reported fewer than n locations, he was asked to continue reporting and to guess when necessary. If he reported more than n locations, only the first n were recorded.

As soon as the experimenter finished typing the last response, a reinforcement was automatically initiated by the computer. Reinforcement consisted of a repeat of the stimulus, presented both tactually and on a visual display box. Reinforcement duration ranged from 1-1 1/6 seconds for n = 1, to 3 seconds for n = 12, increasing linearly by 1/6 second whenever n was increased by one. The reinforcement was followed by a 4-second pause and then the next stimulus.

The whole report procedure was the same as the training procedure, except that there was no reinforcement. The experimenter's typing of the last response initiated a 4-second pause, followed by the next stimulus.

In the partial report series, subjects were informed by a marker as to the row from which their response should come. The eight topmost interjoint positions (1A-1H) were considered the top row, positions labeled (2A-2H) were considered the middle row, and (3A-3H) were considered the bottom row. The marker onset occurred either 0.75 seconds before or 0, 0.1, 0.3, 0.8, or 2.0 seconds following stimulus termination. The marker was one of three lights (top, middle, or bottom) on the visual display box, lasting 250 ms. The subject's response to a partial report trial was a number (1, 2, or 3), corresponding to the marker, followed by four letters, corresponding to the stimulated positions of the row (e.g., 3ACDF). Each marker position occurred an equal number of times in each session. Marker position order was random and varied from session to session. During all partial report sessions, the total number of stimulation points was 12, with 4 points in each row.

In the partial report experiment with erasure, the erasure consisted of simultaneous activation of all 24 airjet stimulators for a period of 60 ms, beginning 600 ms after the presentation of the stimulus pattern.

The variable-duration procedure was the same as the whole report procedure. The added parameter in the duration series was the number of 2.5 ms airjet pressure pulses. Either 2, 5, or 10 pulses were used. The schedule for the duration series is given in Table II. Since this experiment was conceived after the main schedule (Table I) had been planned and begun, variable duration sessions were run as the third

session of the day after the two scheduled sessions of Table I had been run. These additional sessions were run from the 34th to the 39th day of testing.

Table II

DURATION SERIES

Test	1	2	3	4	5	6
n	4	10	10	4	4	10
No. Air Pulses	5	2	10	2	10	5
No. Trials	66	50	50	88	66	56

C. Whole Report Results

The data of the training series and both first and second whole report series were corrected for guessing using Model II, described by Hill and Bliss (1968a). This model assumes that subjects perceive a given number of positions from the tactile patterns and guess at the remaining unperceived positions. The results of this correction, which are shown in Figs. 4(a) and 4(b), are discussed below.

(1) The functional relationship between the number of positions presented and the number perceived is essentially constant. This finding is different from that of the previous experiment (Hill and Bliss, 1968a) in which the subjects' performance increased linearly with n. In that experiment, performance increased by 1.9 positions in going from n = 2 to n = 12; in this experiment the increase was only 0.3 position.

(2) The improvement in subjects' performance during the first month of the experiment was small (20 to 30 percent). Learning was not as evident as in the previous experiment, as indicated by the amount of hysteresis of the whole report data.

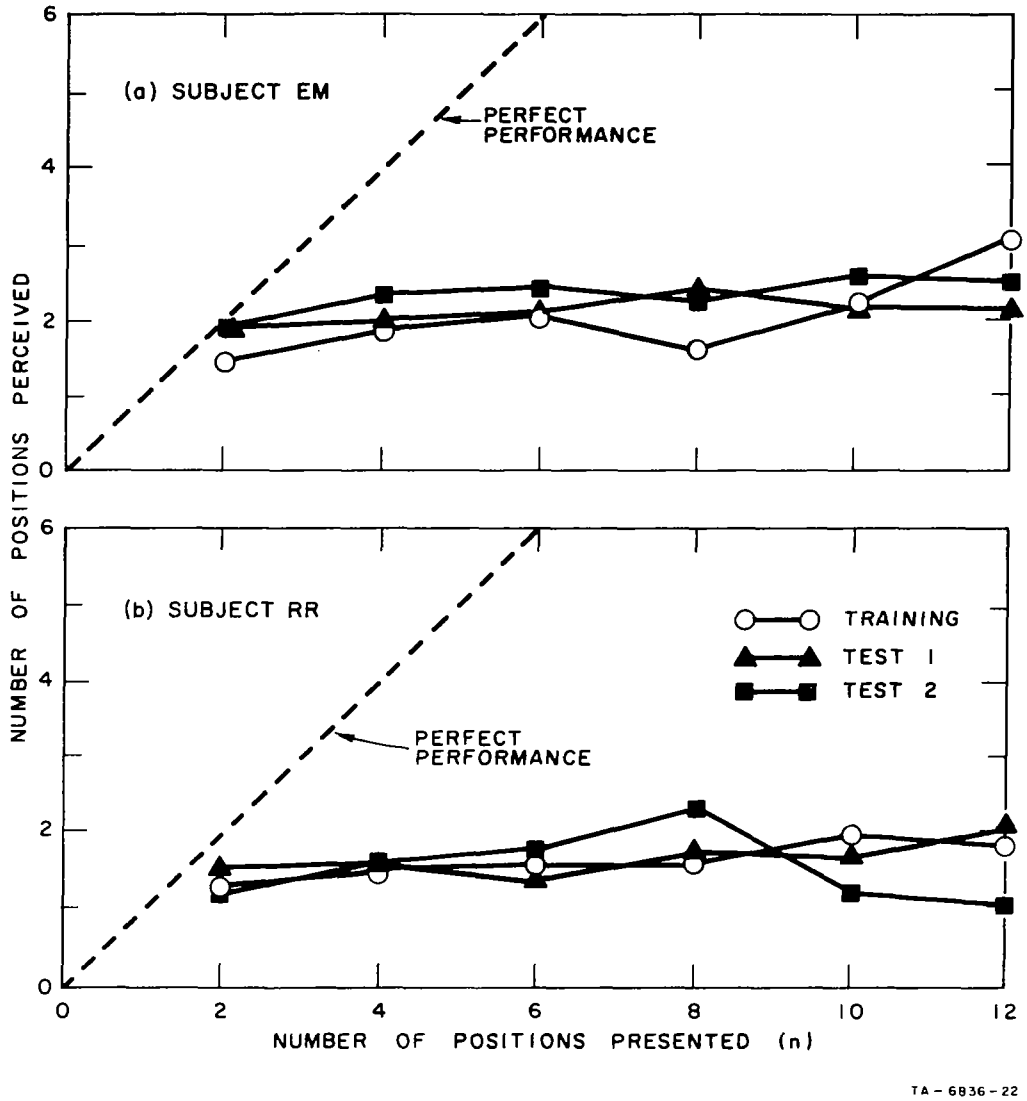

FIG. 4 WHOLE REPORT PERFORMANCE CURVES

A direct comparison between the two subjects in this experiment and those of the previous experiment is shown in Fig. 5. In Fig. 5 the data of the first whole report series of both subjects EM and RR are compared to the whole report data of the previous experiments (Hill and Bliss, 1968a), which were obtained from four subjects with the same amount of training experience.

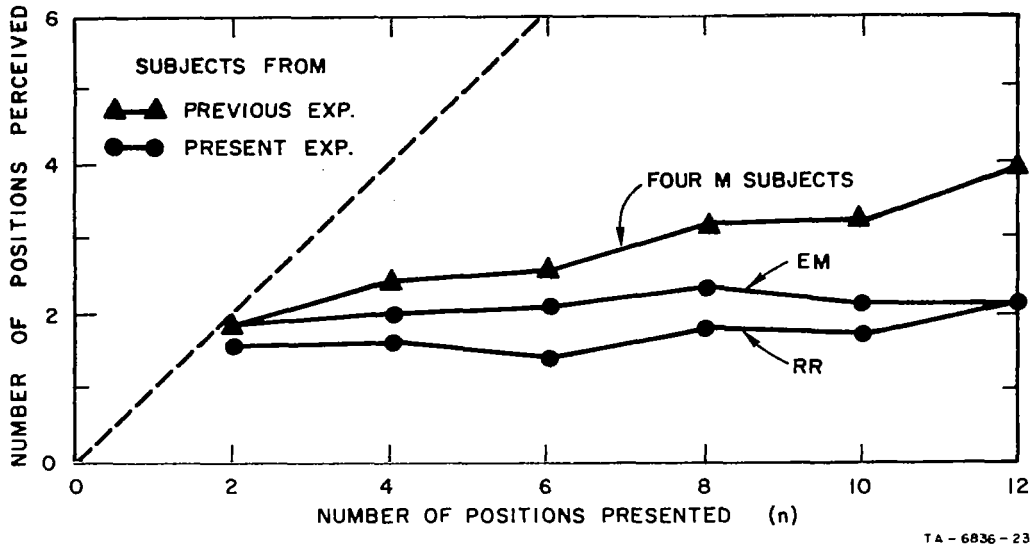

FIG. 5 COMPARISON OF WHOLE REPORT PERFORMANCE OF SIMILARLY TRAINED SUBJECTS IN TWO EXPERIMENTS, USING THE SAME GUESSING CORRECTION

An analysis of the subjects' ability to localize the positions of the whole report patterns was made using the basic method described by Hill and Bliss, (1968a). The measure for this analysis is the spread correlation coefficient (SC). The magnitude of the SC, calculated using stimuli at a given position in the patterns and adjacent responses to the right (say), is the fraction of stimulus positions reported by the subject a distance of one unit right of where they should be reported. SC values have been computed for adjacent left, right, proximal, and distal locations as well as the central (or correct) location using the data of the first whole report series. These SC values are shown in Figs. 6(a) and 6(b).

Figures 6(a) and (b) show that with increasing pattern density (n), both subjects localize fewer positions correctly, and localize proportionally more positions in adjacent locations (left, right, proximal, and distal). Several features of the data are listed below:

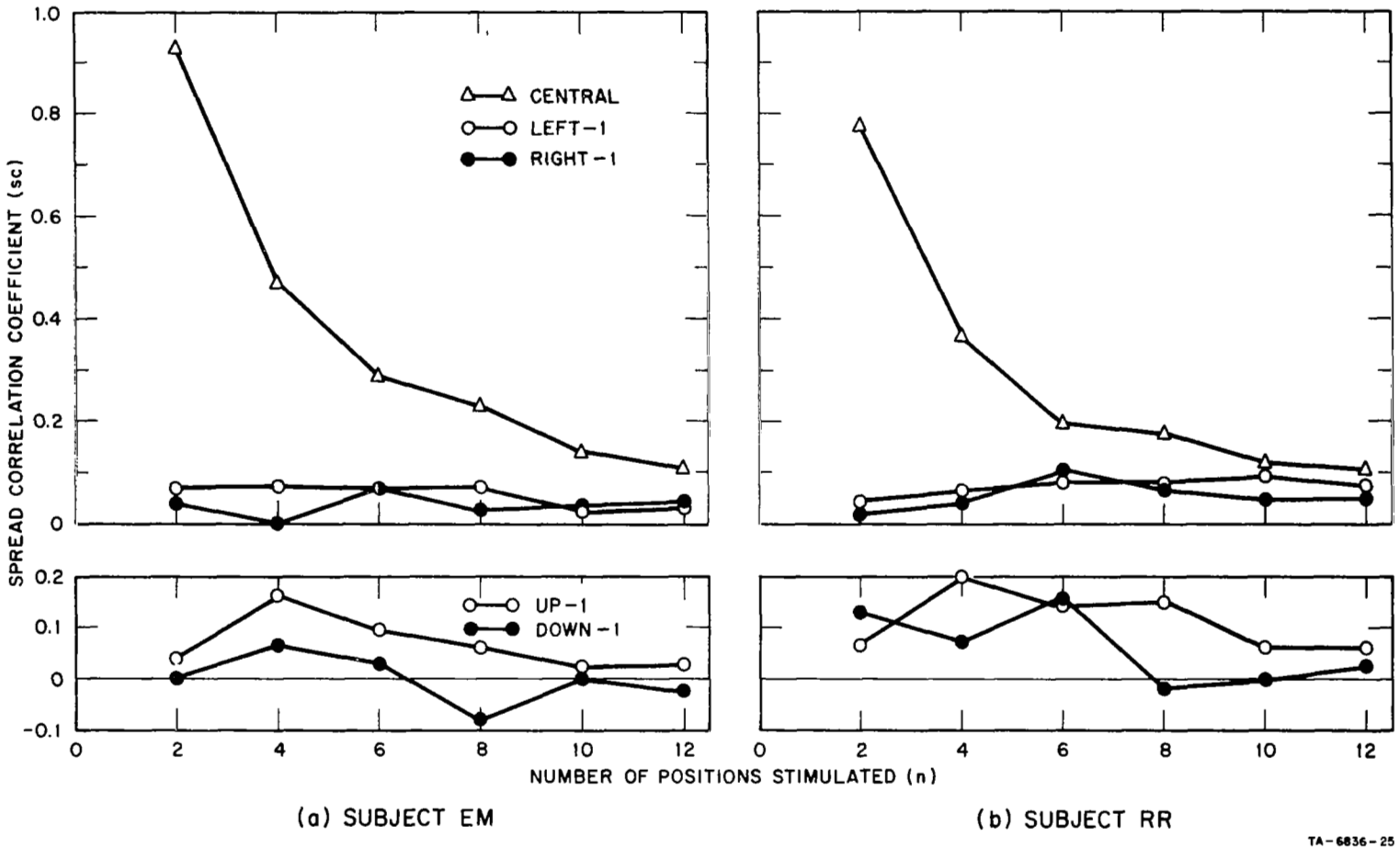

FIG. 6 SPECIAL CORRELATION COEFFICIENT COMPUTED FROM THE FIRST WHOLE REPORT SERIES

(1) A comparison of the left and right confusion of both subjects reveals no clear predominance of left over right confusions.

(2) A comparison of distal and proximal confusion shows that the subjects apparently made more distally directed that proximally directed confusions.

(3) A comparison of left and right confusion with proximal and distal confusions shows that the subjects made more errors within fingers than between fingers.

The basic difference between these results and those of the previous experiment is the third feature. In the previous experiment, subjects made the same proportion of left-right confusions as proximal-distal confusions. It appears that the shorter stimulus patterns of this experiment caused more confusions within fingers than did the previous experiment.

Central spread correlation coefficients for each of the 24 phalanx locations were also computed. The SC values averaged over finger and phalanx for both subjects are shown in Figs. 7 and 8. These figures show the fraction of positions correctly reported on each finger or phalanx row with n = 4, 8, and 12. The accuracy on the three rows of phalanges dropped off from the distal to the proximal positions. This drop is attributable to the sequence in which the subjects reported the stimulus positions; distal row first, then middle row, and then proximal row. The accuracy on the eight fingers apparently does not follow a lawful relationship. Accuracy did not always drop off from left to right with the reporting sequence, but was different with different individuals. For subject EM, the ring and little fingers were the more accurate, while for subject RR these fingers were the least accurate.

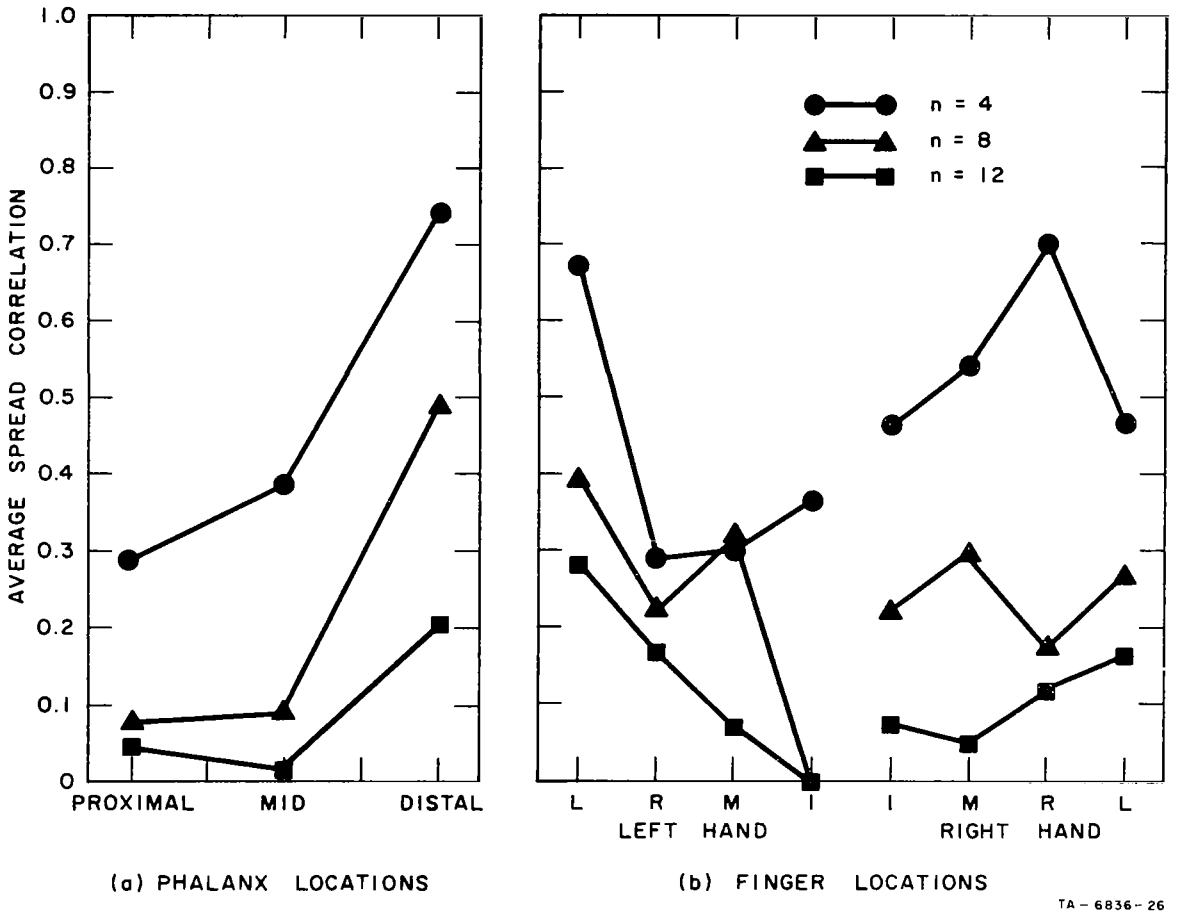

FIG. 7 AVERAGE FINGER AND PHALANX ACCURACY OF SUBJECT EM

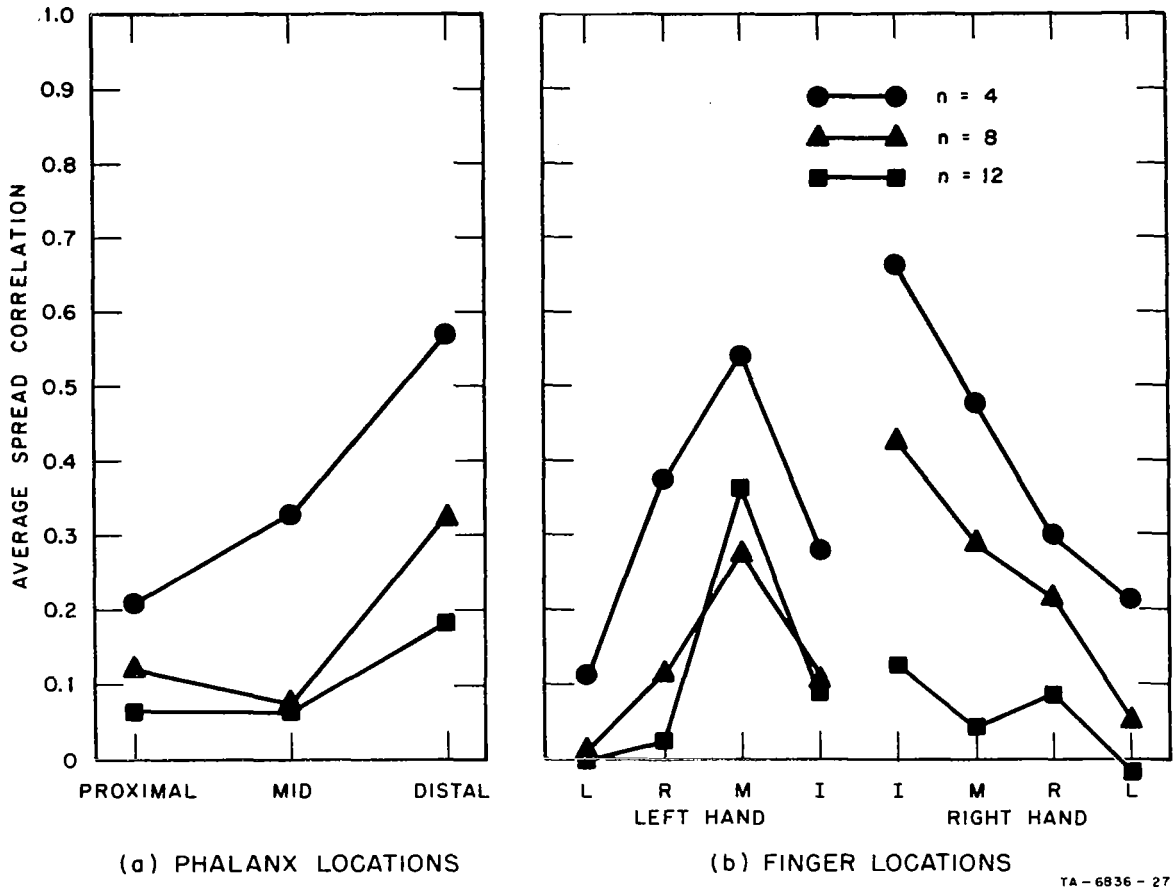

FIG. 8 AVERAGE FINGER AND PHALANX ACCURACY OF SUBJECT RR

D. Partial Report Results

The data of the partial report experiment were corrected for guessing, using Model II, described by Hill and Bliss (1968a). This model assumes that subjects perceive a given number of positions from the tactile patterns and guess at the remaining unperceived positions. The partial report results of subjects EM and RR computed using this correction are shown in Figs. 9 and 10. The results of subject EM are from both first and second partial report series, but those of subject RR are from the first series only. Since the only complete data from this experiment were from subject EM, this subject's data were further analyzed to investigate the effects of the other experimental variables.

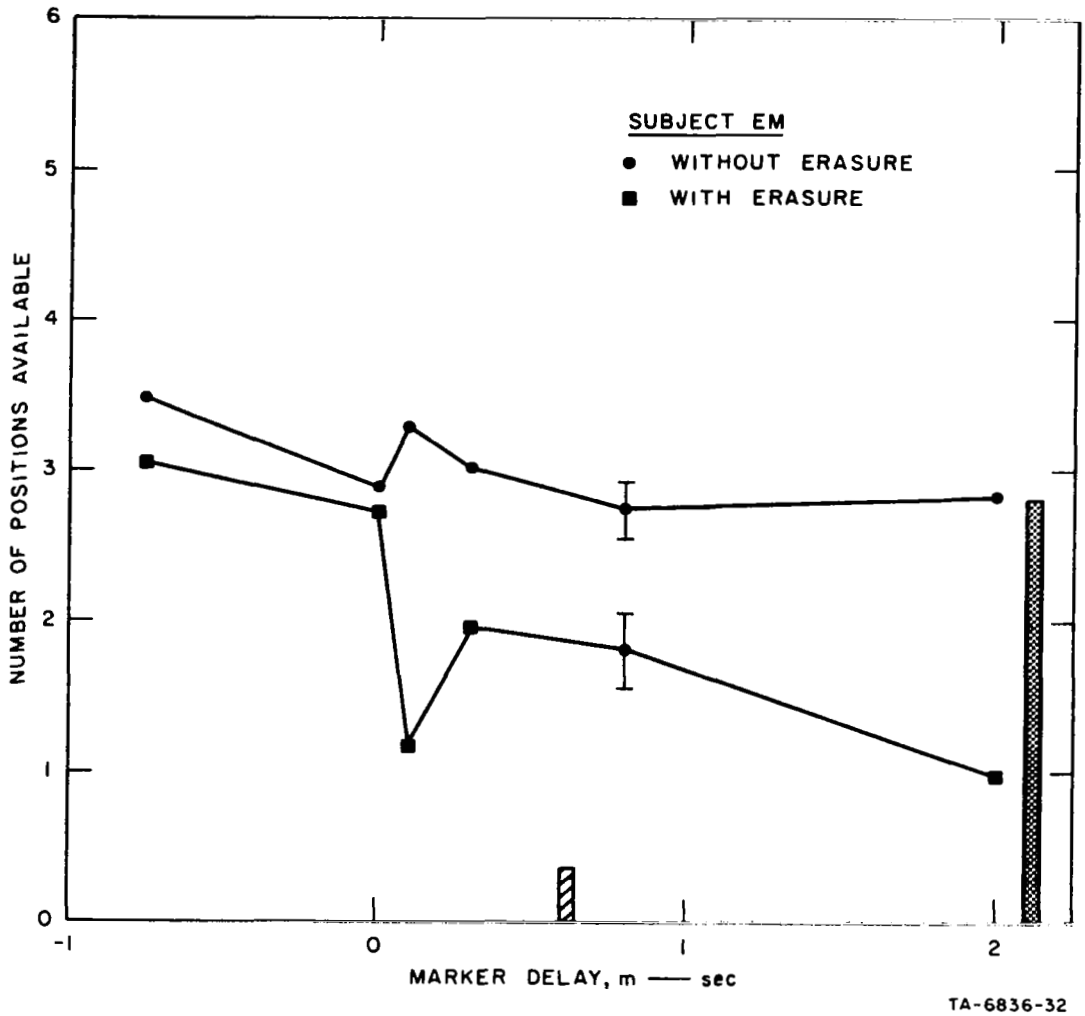

FIG. 9 PARTIAL REPORT PERFORMANCE AS A FUNCTION OF MARKER DELAY

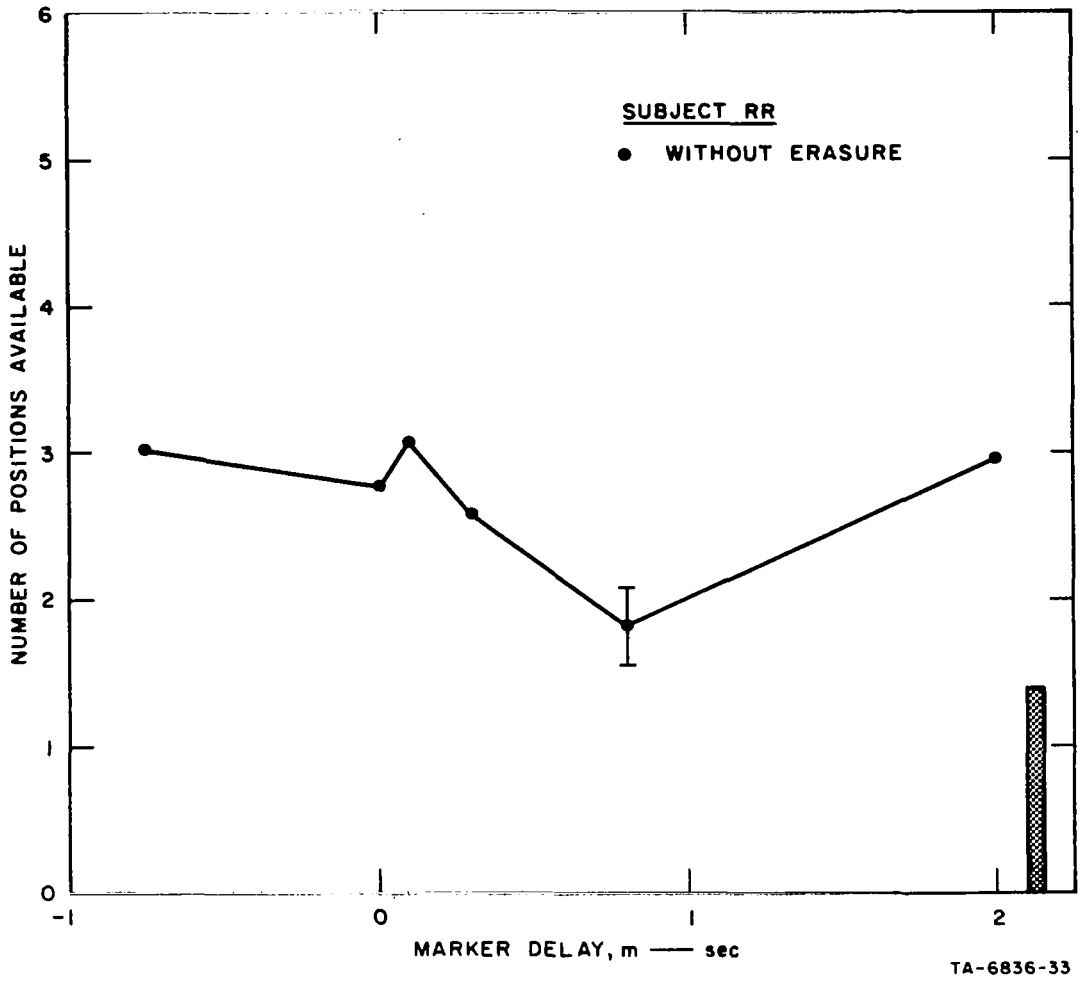

FIG. 10 PARTIAL REPORT PERFORMANCE AS A FUNCTION OF MARKER DELAY

Tables III and IV give two analyses of variance considering effects of marker delay (6 values), phalanx row from which the report was given (3 values, proximal, middle, and distal), and series (2 values, first and second) on the number of positions available in the partial report and partial report with erasure. An analysis of variance was also made on the partial report (first series only) of subject RR. This analysis, though not shown, yielded essentially the same results as those of Table III.

Table III

ANALYSIS OF VARIANCE OF THE NUMBER OF POSITIONS PERCEIVED IN THE PARTIAL REPORT BY SUBJECT EM

Source	df	Mean Square	F Ratio	Sig.
Series (S)	1	0.2167	1.75	--
Marker (M)	5	0.1155		
Phalanx Row (P)	2	8.7126	70.5	$p < 0.001$
S X M	5	0.1793	1.45	--
S X P	2	0.3269	2.64	--
M X P	10	0.1480	1.19	--
S X M X P	10	0.1101		
Experimental Error	36	0.1235		

Table IV

ANALYSIS OF VARIANCE OF THE NUMBER OF POSITIONS PERCEIVED IN THE PARTIAL REPORT WITH ERASURE BY SUBJECT EM

Source	df	Mean Square	F Ratio	Sig.
Series (S)	1	0.0196		
Marker (M)	5	0.8166	3.18	$p < 0.02$
Phalanx Row (P)	2	2.0747	8.08	$p < 0.005$
S X M	5	0.4319	1.72	
S X P	2	0.2954	1.15	
M X P	10	0.5996	2.33	$p < 0.05$
S X M X P	10	0.5798	2.26	$p < 0.05$
Experimental Error	36	0.2566		

The partial report analysis of Table III shows that marker delay did not influence the results. Thus for the duration of the brief stimulus there is no evidence for a tactile sensory register.

A comparison of the partial report experiment with and without erasure is given in Fig. 9. With the presence of the tactile erasure field, occurring 600 ms after the stimulus, there was a marked reduction in the number of stimulus positions available ($p < 0.001$, using a t-test). Thus, the erasure field strongly reduced the subject's ability to report the patterns. The analysis of Table IV shows that with the erasure field, marker delay influenced the results ($p < 0.01$). Figure 9 shows that there is a stronger interference effect with positive marker delays than with zero, and negative marker delays. Table IV also shows that the interaction between marker delay and phalanx row is significant ($p < 0.05$). The data for this interaction are plotted in Fig. 11. The figure shows that the dip in partial report performance with the 0.1-s marker is due to the reporting accuracy of the finger tips alone falling to zero. The figure also shows that while proximal and distal phalanx locations were the ones more accurately reported with negative marker delay, all phalanx locations were equally well reported at the longer delays.

Analysis of Tables III and IV also shows that there were very significant differences in reporting accuracy on the different phalanx rows. The data are plotted to show phalanx row accuracy in Fig. 12. The main result is that the reporting accuracy of the middle row was considerably less than that of the other rows. This is in agreement with the previous experiment (Bliss et al., 1966) where a different reporting alphabet was used on every row. In this experiment the same alphabet (the letters A to H) was used for every row, and the results prove conclusively that the subjects were less able to localize middle phalanx locations than either proximal or distal locations.

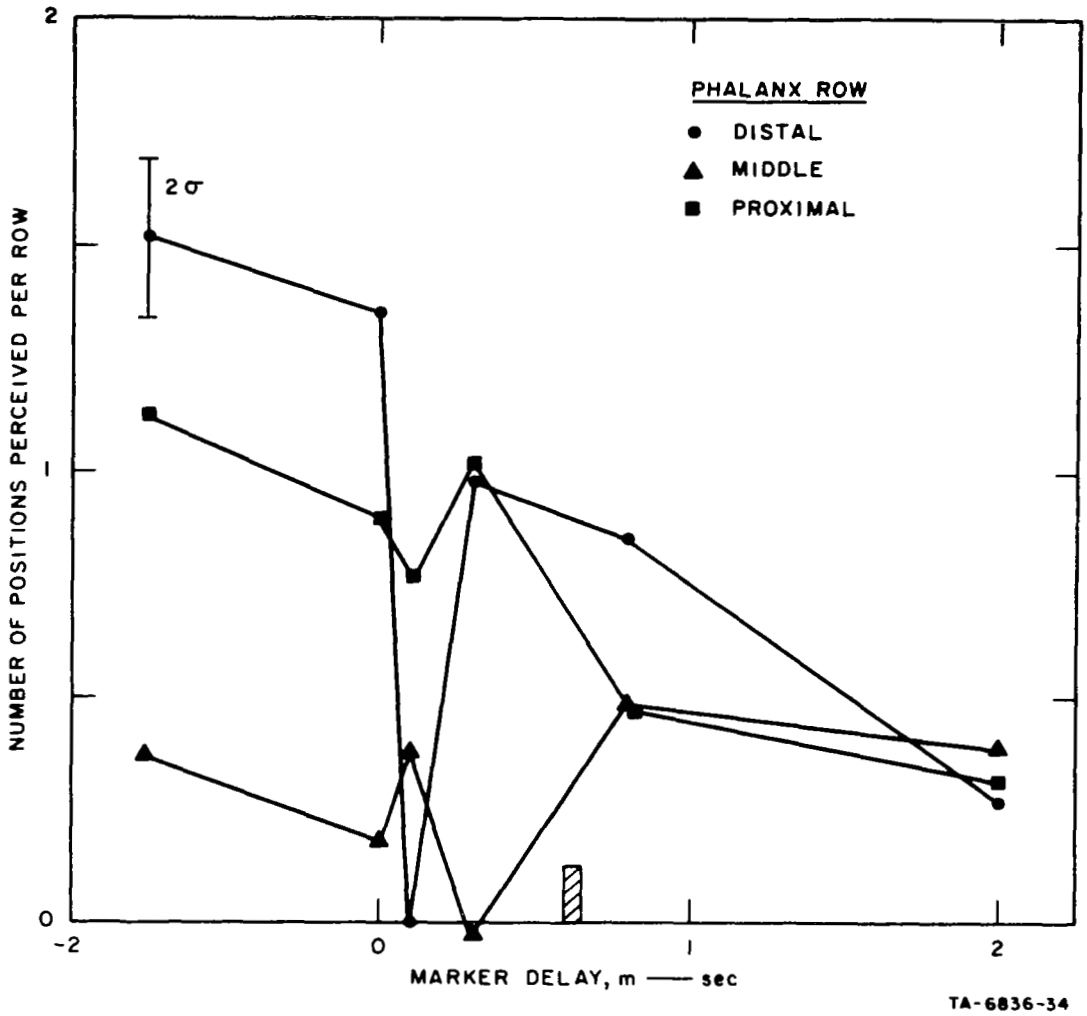

FIG. 11 PARTIAL REPORT OF SUBJECT EM BY ROWS

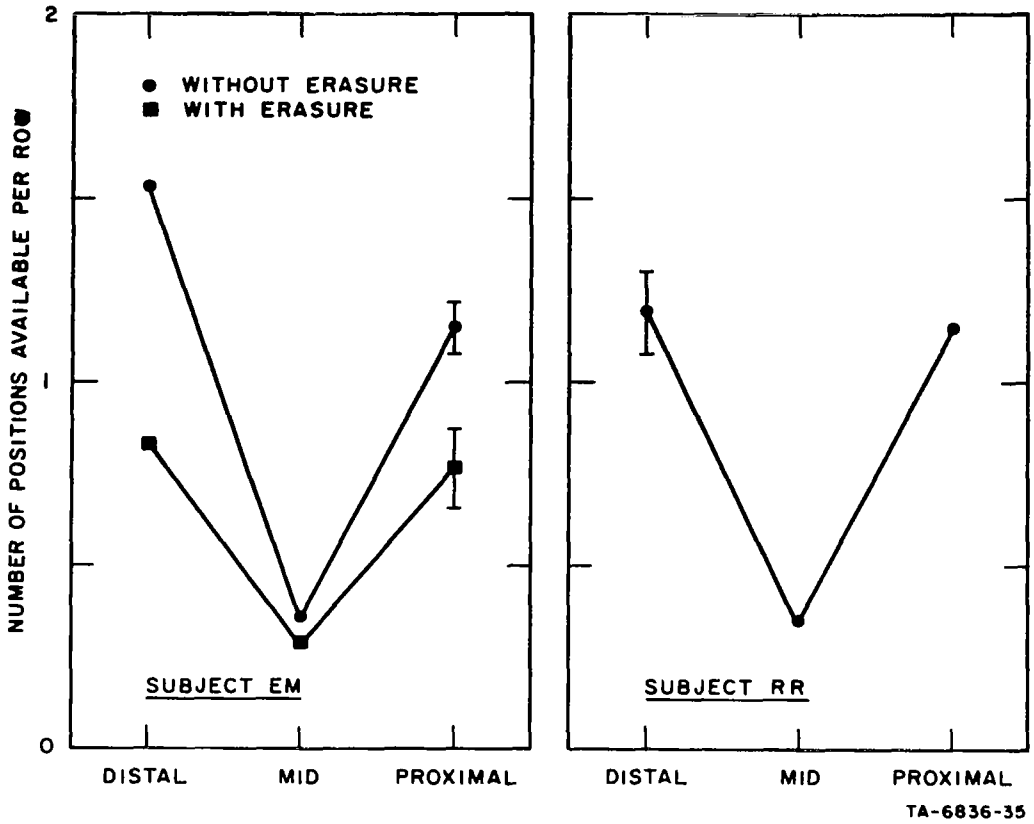

FIG. 12 AVERAGE PARTIAL REPORT PERFORMANCE ON THE THREE PHALANX ROWS

In the analysis of the previous n-tuple experiment (Hill and Bliss, 1968a) a slow tactile learning process was noticed. The present experiment was designed to allow several measures of tactile learning. There were two replications of the whole report experiment spaced 11 days apart, two replications of the partial report experiment spaced 10 days apart, and two replications of the partial report experiment with erasure spaced 5 days apart. The effect of learning in the partial report experiment is tested in Tables III and IV by the Test Series term. The similar analysis for the whole report is given in Table V. Since none of these three tests for learning was significant, we must assume that little or no learning occurred with the brief stimuli used in this experiment.

Table V

ANALYSIS OF VARIANCE OF NUMBER OF POSITIONS PERCEIVED IN THE WHOLE REPORT

Source	df	Mean Square	F Ratio	Sig.
Stimuli (n)	5	0.1195	3.81	--
n X Subjects	5	0.0314		
Series (S)	1	0.0084	--	
S X Subjects	1	0.2185		
n X S	5	0.0638	--	
n X S X Subjects	5	0.1148		

One explanation of the low middle phalanx accuracy shown in Fig. 12 is offered by tactile masking, another by facilitation. In the analysis of the previous n-tuple experiment (Hill and Bliss, 1968a) a test for tactile masking was developed. This test considered the reporting accuracy on a typical middle phalanx location when it was surrounded by no neighboring stimuli, one stimulus, etc., to all four nearest neighboring stimuli. If masking describes the results, then the reporting accuracy would be less with the larger number of surrounding stimulus locations. The statistical test for this masking hypothesis is a t-test. When accuracy increases with the number of surrounding locations (facilitation), the sign of t is positive; when it decreases (masking), the sign is negative. Table VI gives the results of this test applied to the middle phalanx accuracy measured using the spread correlation coefficient (Hill and Bliss, 1968a, Appendix B). The table shows that none of the results supports tactile masking, and one result (partial report with erasure) supports tactile facilitation. These results are in agreement with those of the previous experiment, indicating that neither the duration of the brief stimulus nor the presence of the erasure field introduces tactile masking.

Table VI

t-TESTS FOR THE MASKING HYPOTHESIS

Condition	df	t	Sig.
Whole Report, n = 12 Subject EM	14	+0.32	--
Whole Report, n = 12 Subject RR	14	-0.87	--
Partial Report Subject EM	14	-1.40	--
Partial Report/Erasure Subject EM	14	+2.18	$p < 0.025$

The partial report spread correlations (SC) are shown in Fig. 13. The meaning and computation of these correlations are discussed in detail by Hill and Bliss (1968a). They measure the ability of subjects in localizing the position of the tactile patterns. These correlations are estimates of the fraction of positions correctly reported (zero separation), fraction of positions reported one unit to the right (1-right separation), etc. An analysis of variance of the SC showed that no significant variation of the SC occurred with different values of marker delay. The analysis also showed that the SC for different separations were significantly different ($p < 0.001$). The partial report spread correlations of subject EM are shown in Fig. 13 with solid dots and those of the previous four subjects (M1, M2, M3, and M4) are shown with open dots. The five percent, two sided t-test is also given in the figure for comparison of pairs of data points. Figure 13 shows clearly that with the brief (1-ms) stimuli EM perceived fewer locations and made proportionally more localization errors than the previous subjects. The shape of the curves shows that subject EM made relatively few left-right errors and that the main source of her errors was localization within a finger. There seems to be no noticeable effect of the erasure presentation on the form of the localization curves other than an overall

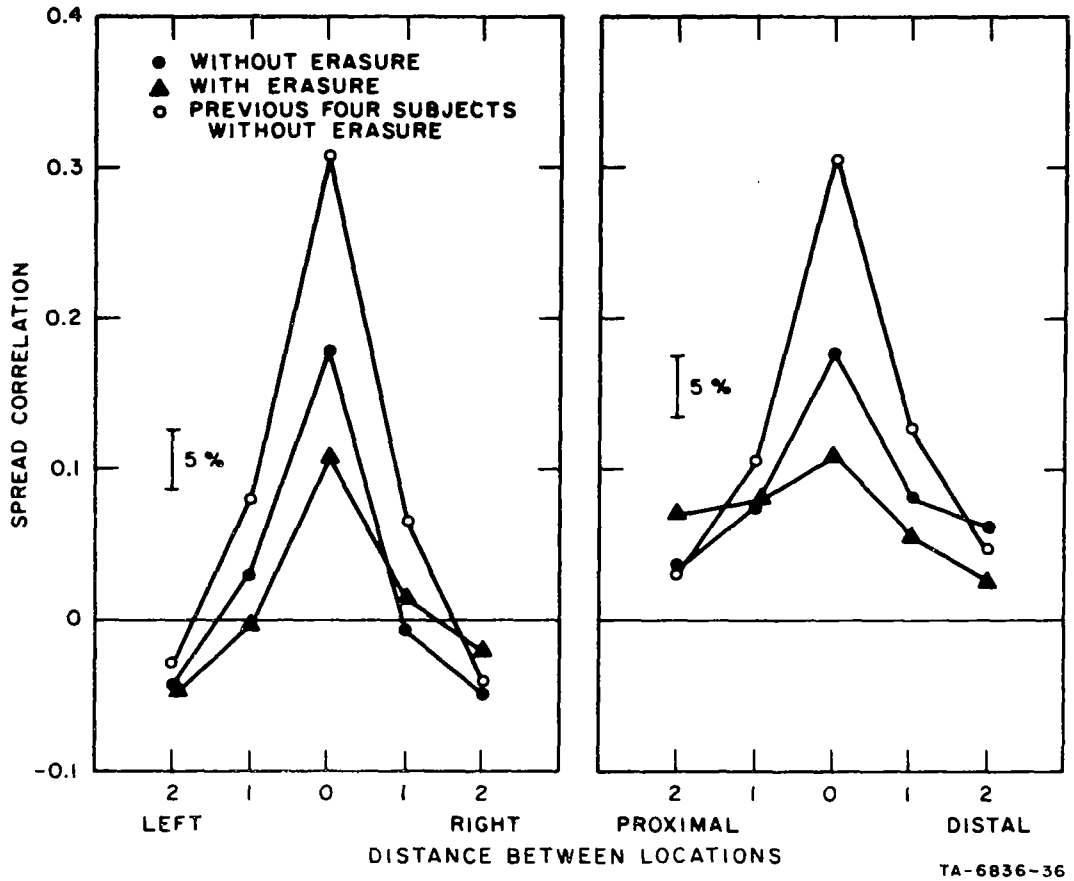

FIG. 13 PARTIAL REPORT SPREAD CORRELATION OF SUBJECT EM COMPARED WITH THOSE OF THE PREVIOUS EXPERIMENT

reduction in height. It thus appears that the erasure presentation only decreased the number of positions perceived and did not affect the ability of subject EM to localize the tactile stimuli.

E. Results of Preliminary Stimulus Duration Experiment

Using a commercial time-sharing computer to compute the guessing corrections shortly after subjects finished their experimental sessions, it was noted early in the experiment that subjects were not performing as well as in the previous experiment. Since the shortened duration of the stimulus patterns was one of the main differences between the two experiments, we decided to explore the effect of the stimulus duration

by modifying the whole report program on the LINC-8 control computer to present the stimulus patterns with various intermediate durations. These additional sessions were run shortly after the second whole report series as a third, nonproprietary, session of the day, so as not to interfere with the schedule of the experiment given in Table I. The variable-duration series consisted of stimulus patterns having either 4 or 10 stimulus positions presented with 2, 5, or 10 pressure pulses, as described in the procedure outline.

In addition to the results of subject EM, the fragmentary results of subject RR are shown in Fig. 14. Data points from the second whole report series (having but one pressure pulse) are the left-most points of the figure, and data from the four M subjects of the previous experiment (taken with 20 pressure pulses) are shown on the right. Without complete results from both subjects, it is not possible to perform an analysis determining the effect of stimulus duration on performance, because the error variance cannot be computed, and the data of Fig. 14 suggest no clear relation between whole report performance and stimulus duration. In Sec. IV a more comprehensive experiment with several subjects using stimulus durations in the range from 1 ms to 500 ms is reported.

F. Discussion

This experiment showed that information-processing models describing very brief (1-ms) tactile patterns and the previous 100-ms patterns are different in character. The main differences are:

(1) With very brief patterns the total number of positions perceived was constant (between 1.5 and 2 positions) independent of the number presented (n), while with the 100-ms patterns the number of positions perceived increased linearly (from 1.8 to 4.0 positions) as n increased from 2 to 12.

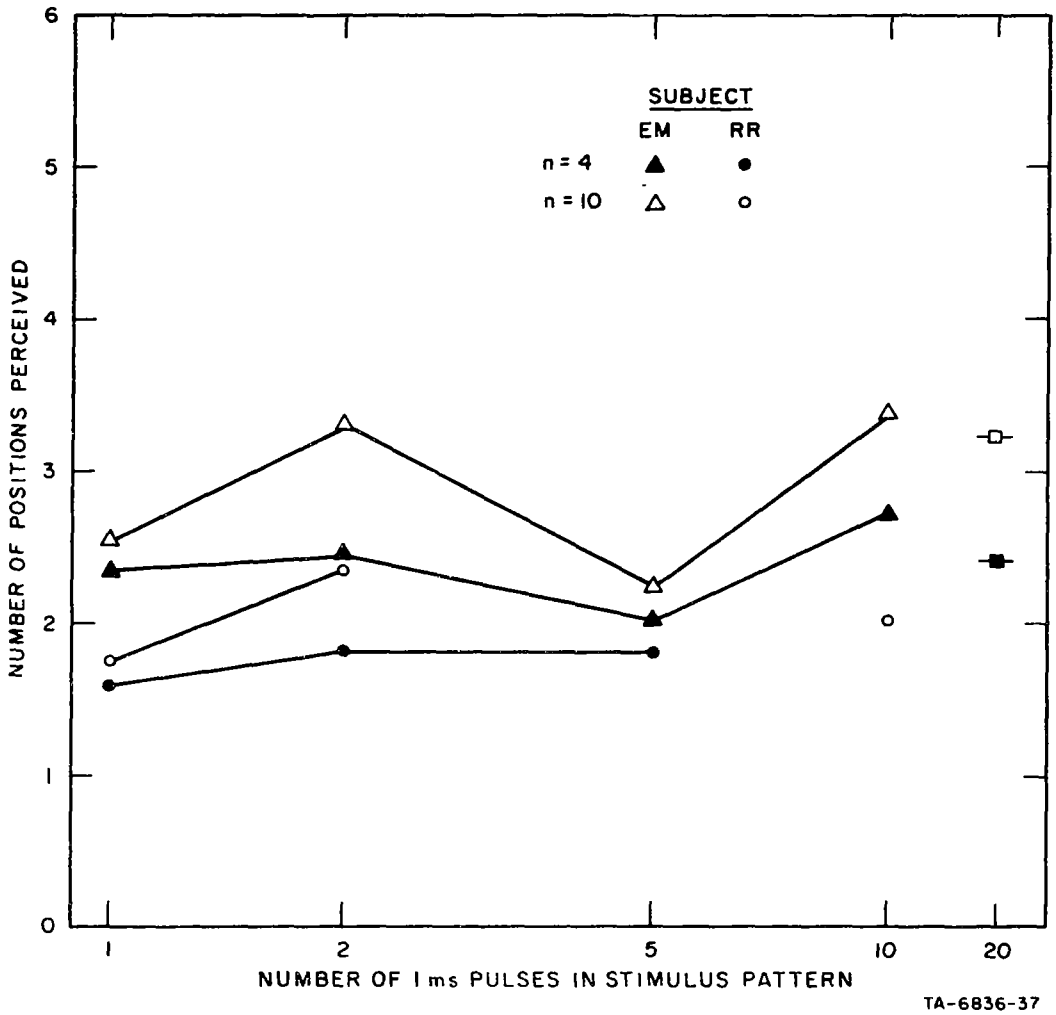

FIG. 14 SUBJECT PERFORMANCE WITH THE NUMBER OF 1-ms PULSES IN TACTILE PRESENTATION OF WHOLE REPORT PATTERNS

(2) With very brief patterns there was no evidence for the tactile sensory register measured and studied in the previous experiment.

This experiment also showed that a field of tactile stimuli, applied simultaneously on all 24 phalanx locations 0.6 second after the stimulus pattern is presented, significantly reduces the number of positions available. Because of this property, this field may be referred to as an erasure field. In this erasure field experiment

there is a significant dip in subject performance with the 100-ms marker delay. This may be the same type of "masking" effect observed in visual perception experiments by Averbach and Corrill (1961) and Mayzner, Tresselt, and Helfer (1967).

The reporting alphabet of this experiment was the same for each row of phalanges. Thus the very poor reporting accuracy on the middle phalanges cannot be attributed to the reporting alphabet as in the previous experiment. A hypothesis designed to show the presence of tactile masking failed to explain this strong effect, and we must assume that tactile masking is not responsible. Even with very brief stimuli a spreading model can explain this low middle-phalanx accuracy. The spread correlation analyses showed that, in both the whole and partial report experiments, relatively poor localization within a finger accounted for the low performance on all three rows. Considerably fewer errors were made between fingers.

IV THE INFLUENCE OF STIMULUS DURATION ON TACTILE PATTERN PERCEPTION

A. Introduction

In Sec. III, we reported results indicating that the information available is much less with a 1-ms stimulus duration than with a 100-ms stimulus duration. These results also indicated that the functional relationship between memory capacity and number of stimuli presented is different for the 1-ms duration patterns and the 100-ms patterns. In addition, our previous results indicated that training has an appreciable long-term influence on subject performance in these tasks (Hill and Bliss, 1968a).

Stimulus duration and amount of training are important variables that must be handled by any model of tactile information processing. Sperling (1960) has shown that visual perception of letter patterns is practically insensitive to stimulus duration over the range 15 to 500 ms. The experiment described below uses whole report and partial report procedures to measure the effects of stimulus duration and training on the capacity of the tactile sensory register and the short-term store. A Greco-Latin square experimental design was used. The whole report experiment estimates the linearly separable effects of stimulus duration, learning by the subjects, and number of stimuli presented on the number of positions perceived from tactile patterns. The partial report design estimates the effects of stimulus duration and learning on the number of positions available in the partial report.

B. Method

1. Apparatus

The array of airjet tactile stimulators and their use in these experiments are described in Sec. III. The same jets independently stimulated the same 24 interjoint regions of the hand. Both the whole and partial report computer programs gated on n of the 24 airjets for a given length of time. The times were chosen so that the 150 Hz clock turned the airjets on and off 1, 2, 5, 10, 20, 40, or 80 times. Thus, the selected stimulators were simultaneously turned on and off a given number of times at a 150-Hz rate to produce the stimulus patterns. An oscilloscope photograph showing the shape of the pressure pulses used in this experiment is shown in Fig. 2.

2. Subjects

Three college students served as paid subjects. Subject EB was a male college sophomore, JI a female college freshman, and MS a male graduate student. Subject EB has never participated in an experiment of this nature, but both subject JI and MS had two weeks' practice on a similar visual perception experiment.

3. Procedure

Each subject participated in the experiments for approximately a one-hour period each day. During this period he was paced through part of his sequential test schedule. Since the sessions of the test schedule varied from 10 to 25 minutes each, and a 5-to-10-minute rest period was allowed between sessions, a variable number (from 2 to 4) of sessions were completed each day. The whole and partial report testing schedules used are shown in Tables VII and VIII. No training was undertaken in these experiments, since the experimental design allowed subject learning to be isolated from the other parts of the experiment, and separately measured.

Table VII

WHOLE REPORT TESTING SCHEDULE

Session	-1-	-2-	-3-	-4-	-5-	-6-
n	4	10	8	2	6	12
Stimulus pulses	40	20	80	5	2	10
# Trials	24	36	24	24	24	72
Session	-7-	-8-	-9-	-10-	-11-	-12-
n	8	2	6	12	4	10
Stimulus pulses	20	80	5	2	10	40
# Trials	24	24	24	72	24	36
Session	-13-	-14-	-15-	-16-	-17-	-18-
n	6	12	4	10	8	2
Stimulus pulses	80	5	2	10	40	20
# Trials	24	72	24	36	24	24
Session	-19-	-20-	-21-	-22-	-23-	-24-
n	10	8	2	6	12	4
Stimulus pulses	2	10	40	20	80	5
# Trials	36	24	24	24	72	24
Session	-25-	-26-	-27-	-28-	-29-	-30-
n	2	6	12	4	10	8
Stimulus pulses	10	40	20	80	5	2
# Trials	24	24	72	24	36	24
Session	-31-	-32-	-33-	-34-	-35-	-36-
n	12	4	10	8	2	6
Stimulus pulses	40	20	80	5	2	10
# Trials	72	24	36	24	24	24

Table VIII

PARTIAL REPORT TESTING SCHEDULE

Session	-1-	-4-	-7-	-10-	-13-
# Stimulus pulses	40	80	5	2	1
Session	-2-	-5-	-8-	-11-	-14-
# Stimulus pulses	5	10	80	10	1
Session	-3-	-6-	-9-	-12-	
# Stimulus pulses	20	2	20	40	

For whole report testing, the number of presentations for each value of n was chosen to allow the variance of the mean number of positions perceived to be less than or equal to a constant ($\sigma \leq .61$), under the constraint that the duration of the experiment be two weeks. For partial report testing with n = 12, 132 presentations for each value of stimulus duration were chosen to allow the variance of the number of positions available to be a constant ($\sigma = .78$), under the constraint that the duration of the experiment be one week. During each session an equal number of presentations were made at all interjoint positions.

In both portions of the experiment, each subject had before him at all times a replica (Fig. 3) of the alphanumeric response alphabet. On any one trial, n stimulation sites were chosen (by the computer) out of the possible 24 interjoint locations. In any one session the number of positions simultaneously stimulated, n, was constant and known by the subjects. The duration (equivalently, the number of pulses in the stimulus) was also constant, but unknown by the subjects.

In the whole report experiment the subjects were asked to report all the stimulated positions row by row, from left to right. The reporting scheme and the timing of stimulus presentations are exactly the same as the training series described in Sec. III.

In the partial report experiment the subjects were informed by a visual marker, beginning immediately upon termination of the stimulus, of which row to report. Again, the complete description of the stimulus-marker timing and the subjects' reporting scheme is the same as the partial report series described in Sec. III.

C. Whole Report Results

The whole report results were corrected for guessing with Model II described by Hill and Bliss (1968a) to obtain the number of positions perceived. The number of positions perceived by each subject on each session was given an analysis of variance, the summary of which is given in Table IX. The table shows that all three of the experimental variables significantly affect the subjects' scores. In addition, there is insufficient evidence to show that the subjects' scores do not depend linearly on each of the three variables.

The main results of the experiment are given in Figs. 15, 16, and 17. Figure 15 gives the number of positions perceived as a function of n, averaged over all six values of stimulus duration and all six sessions. This figure shows that the individual differences observed in this type of experiment were (1) variations in overall performance level and (2) variations in upward slope.

Figure 16 shows the linear increase in performance in relation to the logarithm of the stimulus duration (note logarithmic scale on the ordinate). The relatively slow increase in performance over a wide range of stimulus duration (i.e., 30 percent increase with a 40 to 1 change in stimulus duration) suggests that the onset of the pressure

Table IX

SUMMARY OF ANALYSIS OF VARIANCE OF THE NUMBER OF POSITIONS PERCEIVED IN THE WHOLE REPORT

Source	df	Mean Square	F	Sig.
Subjects	5	8.216		
Stimulus Duration (D)	5			
Linear	1	6.976	52.1	$p < 0.001$
Remainder	4	.043	--	
Subjects × D	10	.133		
n	5			
Linear	1	28.554	25.2	$p < 0.001$
Remainder	4	1.836	1.62	
Subjects × n	10	1.133		
D × n	20	.326	1.08	
Subjects × D × n	40	.301		
Learning (L)	5			
Linear	1	2.069	7.12	$p < 0.025$
Remainder	4	.006	--	
Subjects × L	10	.292		

pulses transmits the most information and that little additional information is transmitted by the later pulses of the stimulus.

This result may be made more quantative by fitting the number of positions perceived, P, of Fig. 16 with the equation

$$P = A + \alpha \ln D \quad , \tag{1}$$

where A is the number of positions perceived by a subject with one pulse, α is the slope of the curves, and D is the number of pressure pulses at the 150-Hz rate. For the three subjects, Eq. (1) becomes

$$P = 2.2 + 0.26 \ln D \quad . \tag{2}$$

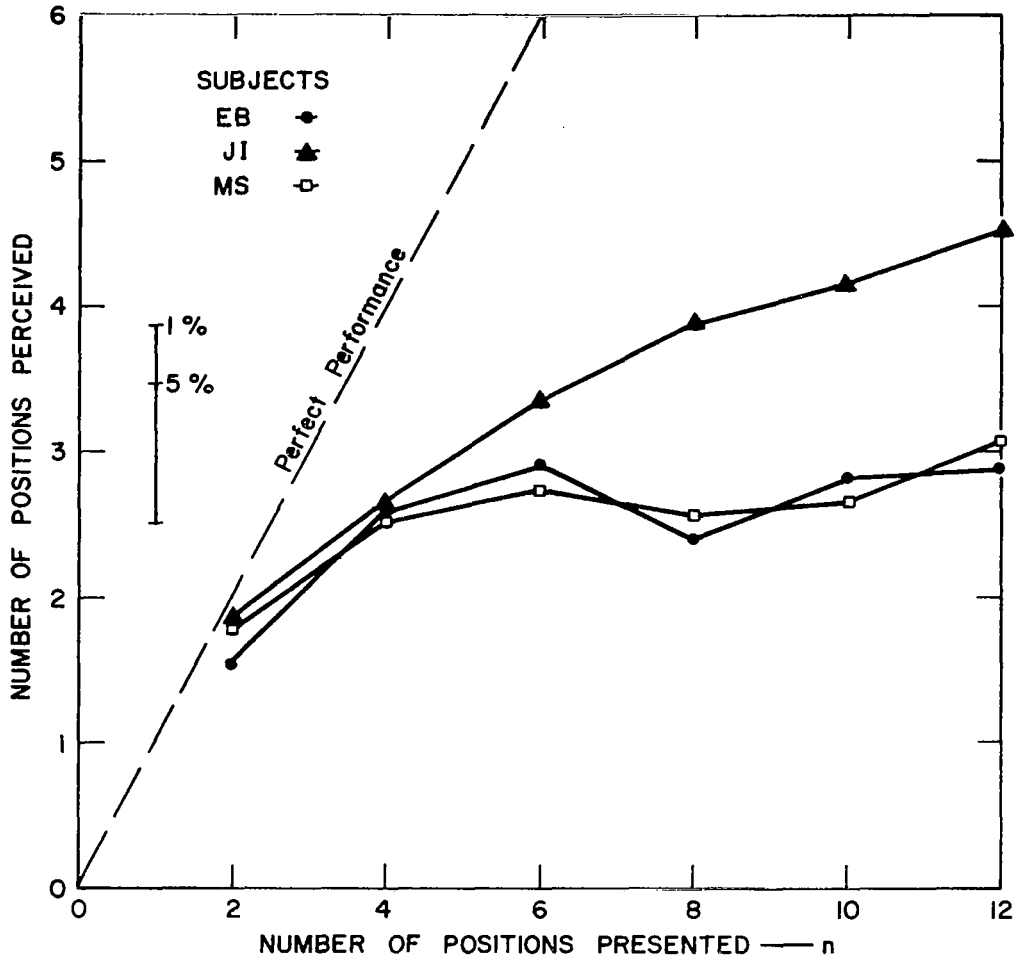

FIG. 15 WHOLE REPORT PERFORMANCE FOR THREE SUBJECTS VERSUS n

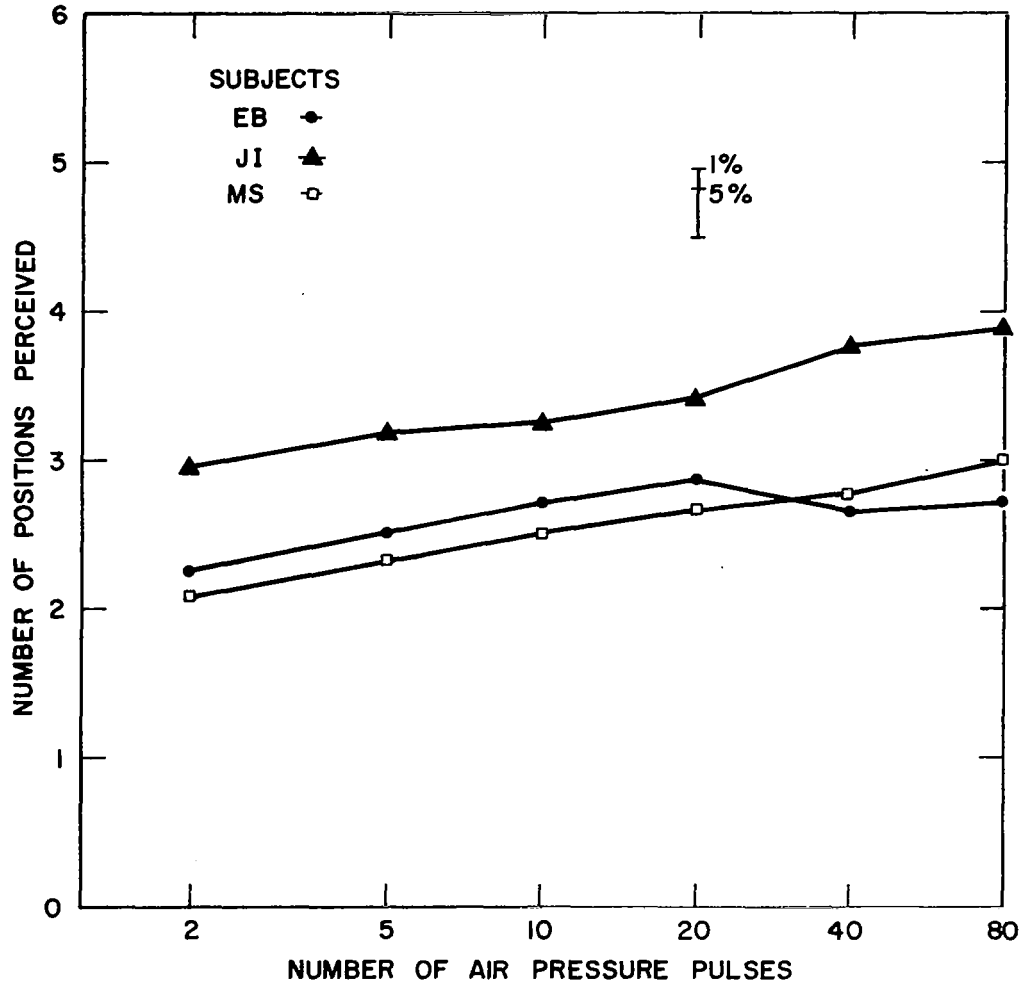

FIG. 16 WHOLE REPORT PERFORMANCE VERSUS STIMULUS DURATION

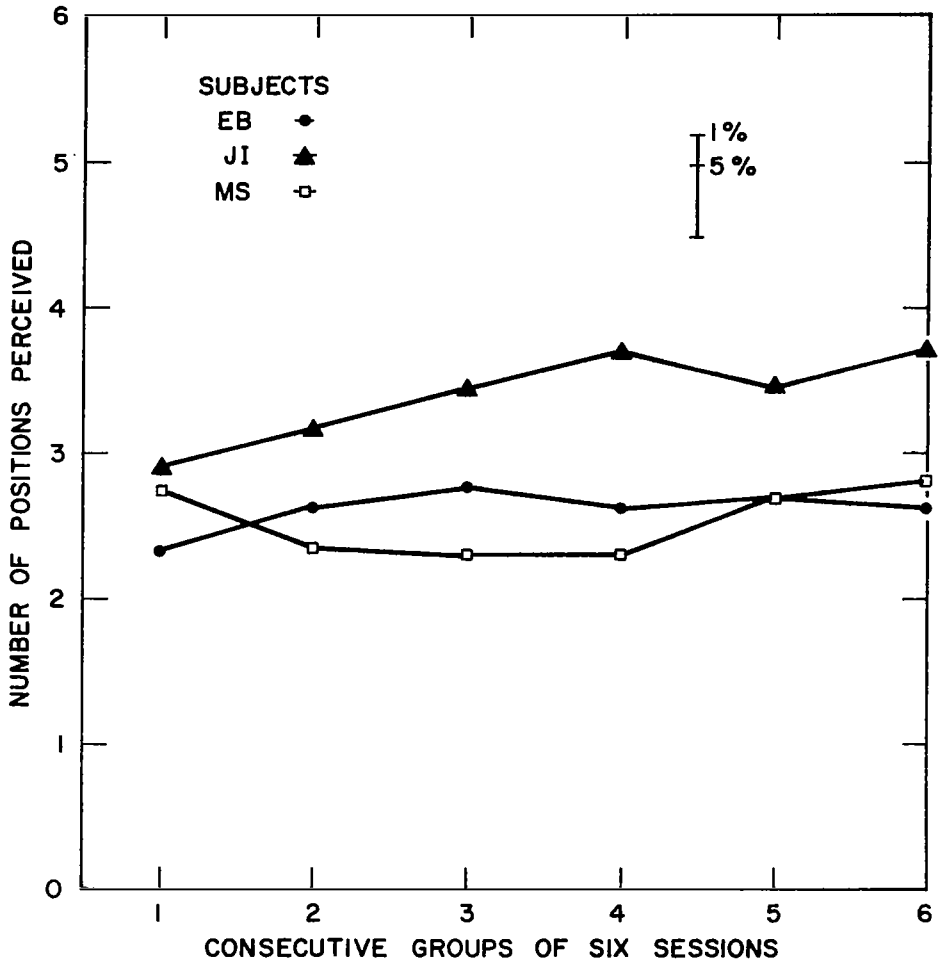

FIG. 17 WHOLE REPORT PERFORMANCE DURING SIX BALANCED SESSIONS OF THE EXPERIMENT

Using Eq. (2) to form a difference equation, the increment in P for each additional pulse is

$$\Delta P = 0.26 \ln \frac{D + 1}{D} \approx \frac{0.26}{D + 1/2} \tag{3}$$

The effect of learning during the 2-1/2-week period over which the experiment was run is shown in Fig. 17. The Greco-Latin square experimental design allowed each consecutive group of six sessions to contain one session with each value of n and one session with each value of stimulus duration. Thus, each consecutive group is independent of the other experimental variables. The linear increase in performance with time is small but significant (see Table IX). Over the 2-1/2-week testing period, the average subject performance increased by 0.4 position. These results favor model P_1 (linear model) over model P_2 (percentage model) described by Hill and Bliss (1968a). The increase in performance in this experiment was 0.04 position per test day, and the increase predicted by model P_1, 0.066 position per test day. There is evidence that learning on these experiments is dependent on stimulus duration. For example, in experiments with 1-ms pulses (Sec. III) practically no learning was observed for two subjects. The interaction between learning and stimulus duration cannot be tested with this experimental design.

Figure 18 shows the whole report characteristics averaged over all three subjects with stimulus duration as a parameter. Only four values of stimulus duration have been shown to simplify the presentation. This family of curves explains the differences in both the amount and the functional relation of the information conveyed by 1-ms and 100-ms tactile patterns noted in Sec. III. Both the overall number of positions perceived and the slope of the curves increase with stimulus duration. Figure 18 suggests that stimulus duration affects perception of patterns with a large number of stimuli (n) more than those with a

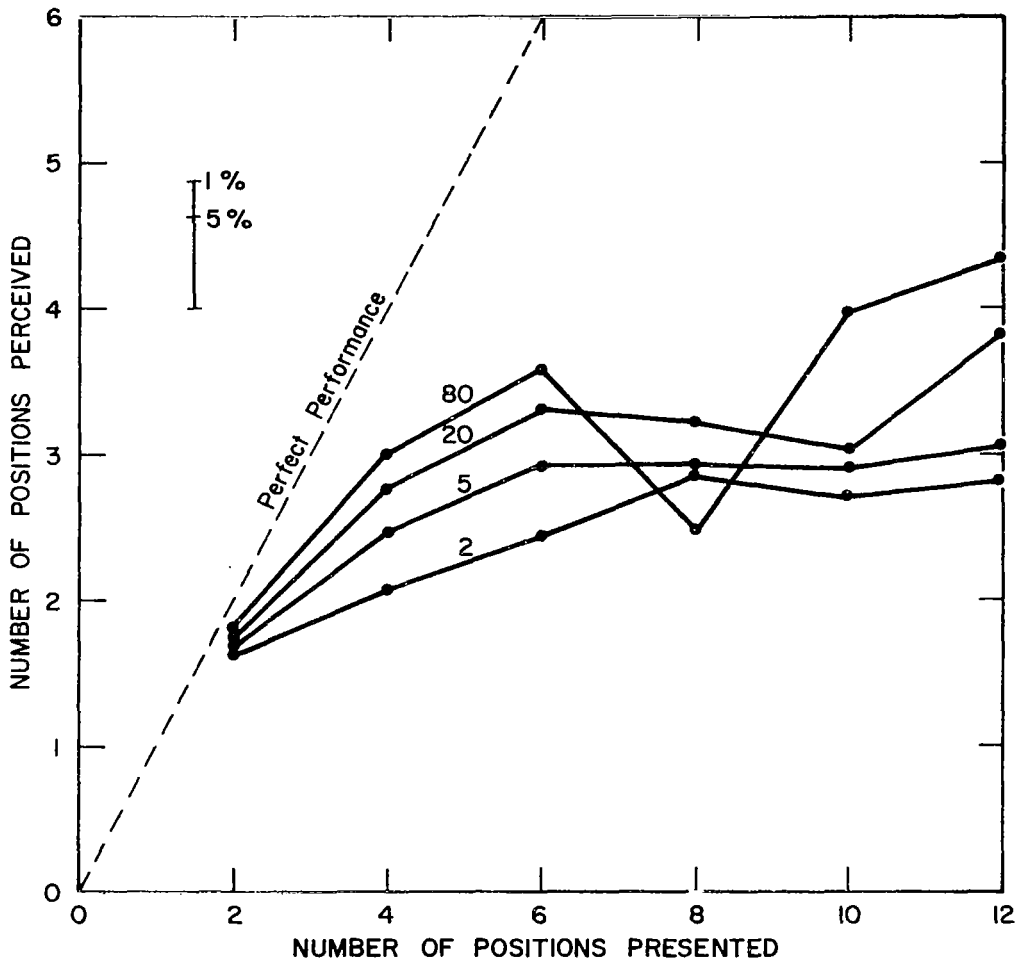

FIG. 18 FAMILY OF CURVES SHOWING RELATION OF WHOLE REPORT PERFORMANCE TO STIMULUS DURATION. The numbers on the curves are the number of pulses in the stimulus patterns.

low number. However, Table IX shows that there is not enough experimental evidence to support this conclusion.

The analysis of variance performed on the data gives a least squares fit of the following equation

$$P = S_i + D_j + N_k + L_l + \epsilon \quad , \tag{4}$$

where S, D, N, and L refer, respectively, to the effects of subjects, stimulus duration, n, and the learning periods. The last term ϵ, is a normally distributed random variable with a mean of zero. Since Table IX shows that the results only depend linearly on the parameters of the experiment, Eq. (4) may be simplified to

$$P_a = S_i + \alpha \log D + \beta n + \gamma t + \epsilon \quad , \tag{5}$$

where α, β, and γ are constants reflecting the slopes of the experimental variables. Another possible model is suggested by Fig. 18.

$$P_b = S_i + \alpha n \left(1 + \beta \log D\right) + \gamma t + \epsilon \quad , \tag{6}$$

where both the height <u>and</u> slope of the curves increase with stimulus duration.

Models like Eqs. (5) and (6) can be fitted to the data by multiple linear regression, and the corresponding residual variance can be used to decide on the validity of the models.

D. Partial Report Results

The results of the partial report were corrected for guessing with the same model used in the whole report experiment. The accuracy for each response from each phalanx row for each subject and session was given an analysis of variance to determine the significance of the experimental variables. The analysis given in Table X shows that only two variables, stimulus duration and phalanx row, significantly affect

Table X

SUMMARY OF ANALYSIS OF VARIANCE OF THE RESPONSE ACCURACY IN THE PARTIAL REPORT

Source	df	Mean Square	F	Sign.
Subjects	2	1.714		
Stimulus Duration (D)	6			
Linear	1	.612	7.65	$p < 0.025$
Remainder	5	.029	--	
Subjects × D	12	.080		
Repeats (R)	1	.008	--	
Subjects × R	2	.062		
Phalanx Row (P)	2			
Linear	1	.272	--	
Quadratic	1	3.494	11.9	$p < 0.05$
Subjects × P	4	.320		
D × R	6	.041	--	
Subjects × D × R	12	.049		
D × P	12	.041	1.24	
Subjects × D × P	24	.033		
R × P	2	.048	1.23	
Subjects × R × P	4	.039		

the subjects' scores. There is not enough evidence to show that learning, measured over a two-day span in this experiment, is significant.

The number of positions available in the partial report is shown in Fig. 19 for the three subjects. There appear to be intrinsic differences in the effect of the different stimulus durations on the three subjects. For both subjects JI and MS, the number of positions available

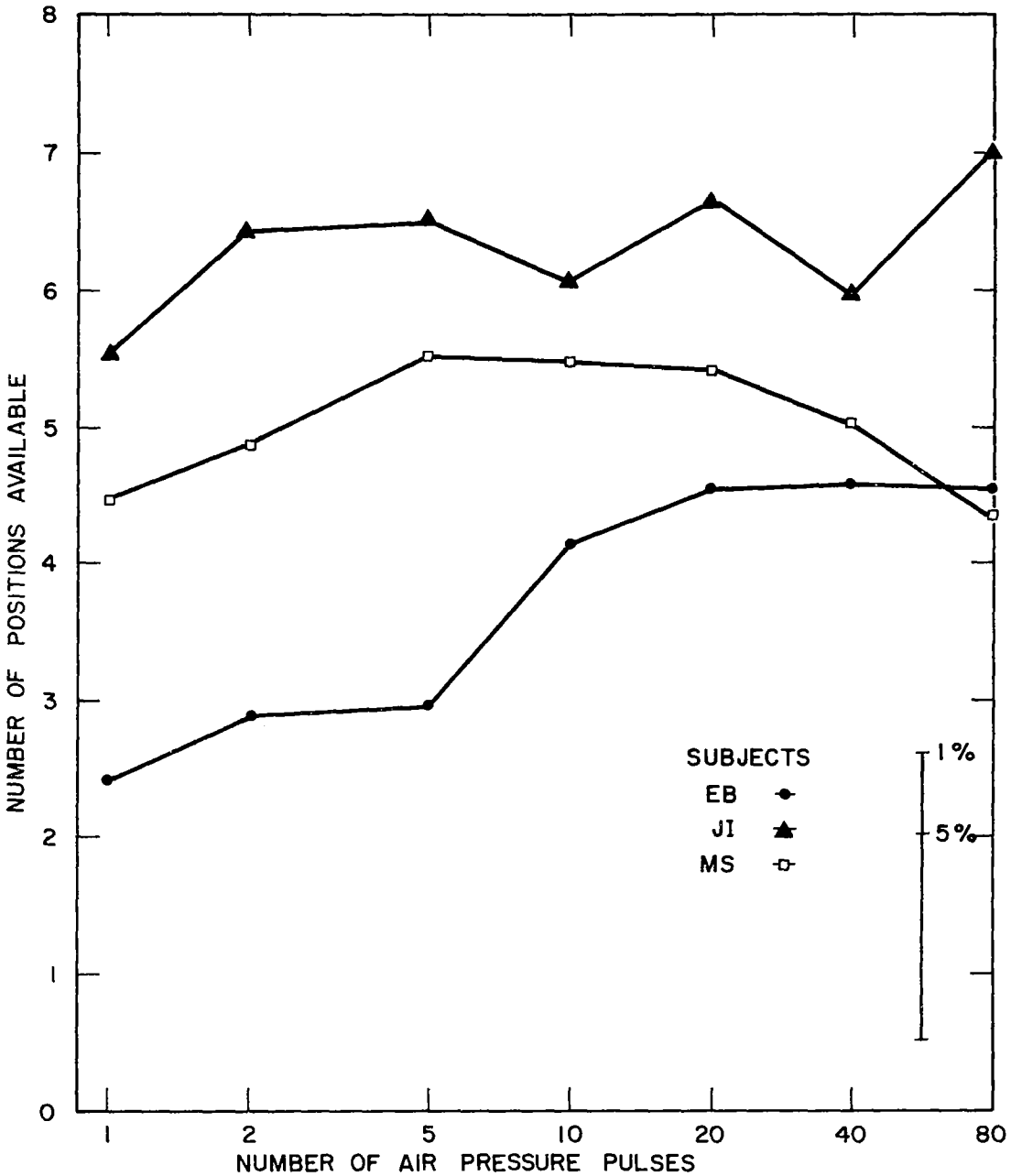

FIG. 19 PARTIAL REPORT PERFORMANCE VERSUS STIMULUS DURATION WITH $n = 12$

was relatively constant with stimulus duration, while for subject EB the number increased with stimulus duration. These differences may be due to statistical fluctuations of the data.

The different reporting accuracies on each phalanx are shown in Fig. 20. The low reporting accuracy on the middle row (significant, $p < 0.05$) has been accounted for before and is part of the basis of the "stimulus spreading" model described by Hill and Bliss (1968a).

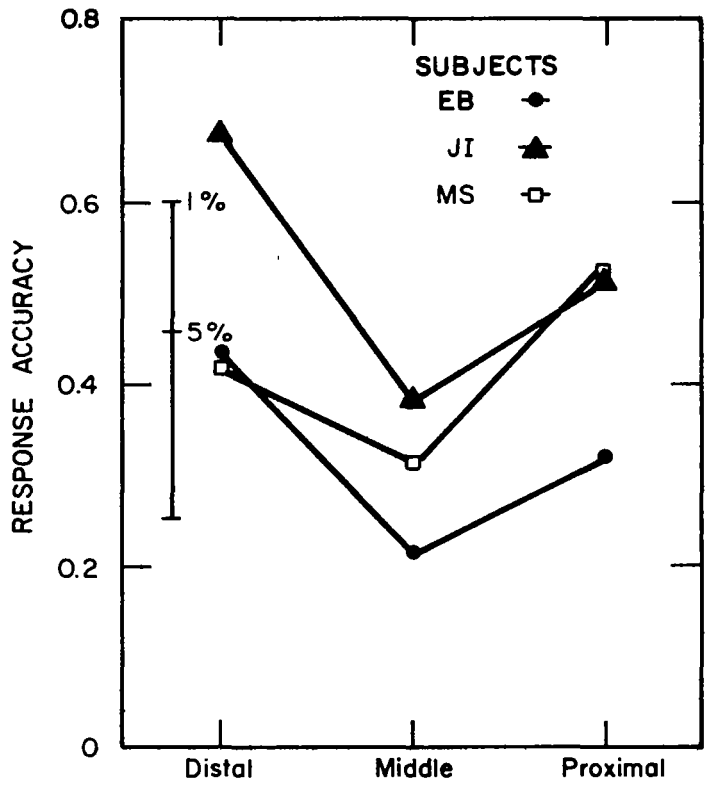

FIG. 20 THE RESPONSE ACCURACY ON EACH PHALANX ROW AVERAGED OVER STIMULUS DURATION AND REPETITIONS

An interesting feature of the data broken into phalanx rows is shown in Fig. 21. The middle row is more strongly affected by stimulus duration than either the distal or proximal row ($p < 0.05$). Thus, the upward trend in partial report performance with stimulus duration is due largely to increased performance on the middle phalanges.

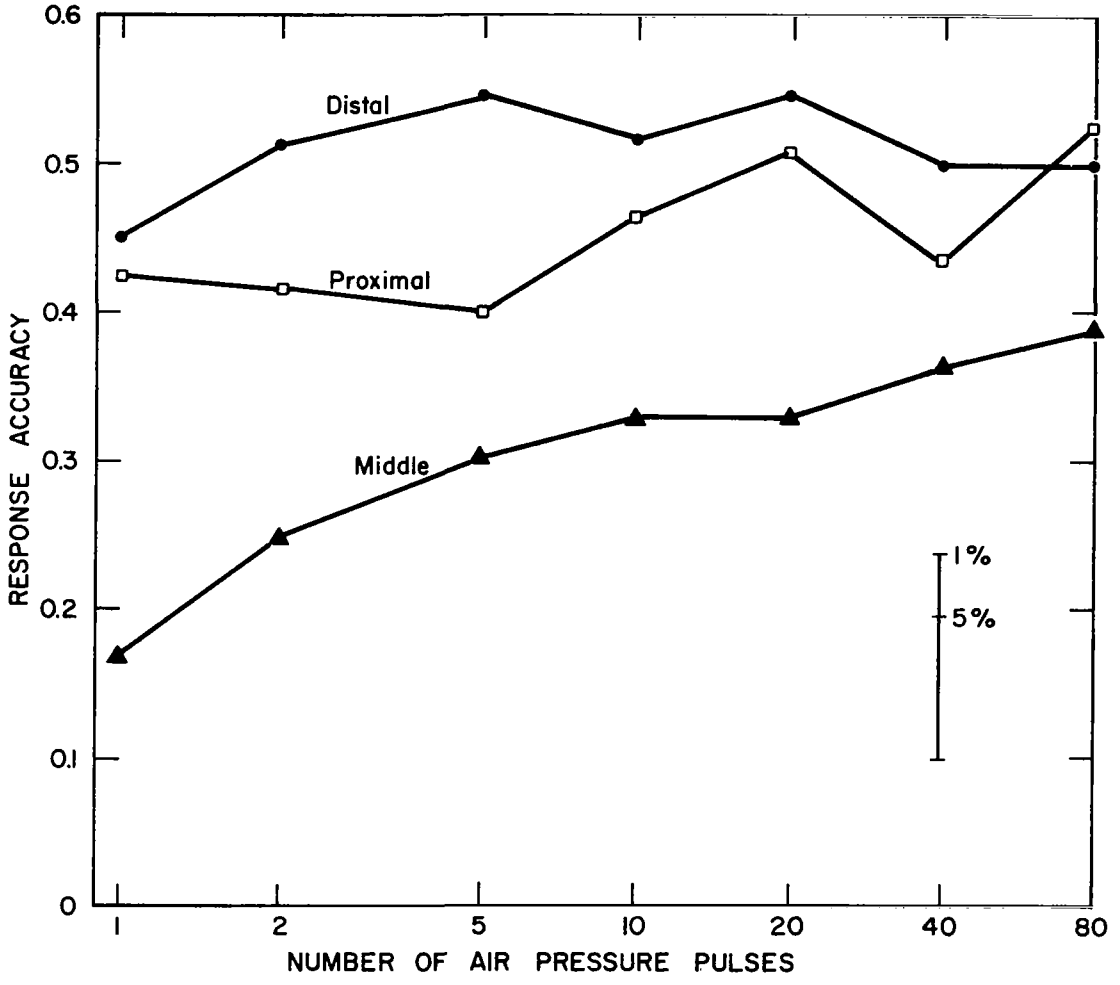

FIG. 21 THE AVERAGE PARTIAL REPORT PERFORMANCE OF THREE SUBJECTS ON EACH PHALANX ROW

E. Discussion

Both whole and partial reports for n = 12 patterns for all three subjects as a function of stimulus duration are shown in Fig. 22. The capacity of the tactile short-term store (STS) is represented by the whole report curves, and the capacity of the tactile sensory register by the partial report curves. Regarding individual subjects, there appear to be two types of results. For subjects JI and MS, the difference between sensory register capacity and STS seems to decrease with stimulus duration, while for subject EB, this difference seems to increase with stimulus duration. These differing results may represent individual differences or statistical fluctuations in the data. Assuming thay they represent statistical fluctuations of the data, the average scores of all three subjects are also shown in Fig. 22. The average scores suggest that both whole report and partial report performances increase linearly with the logarithm of the stimulus duration. The capacity of the average sensory register is always about 1.5 to 2 positions greater than that of the STS. The slopes of both average curves in Fig. 22 are about the same: an additional 0.3 position is perceived for every doubling of stimulus duration. Here most of the information entering both the sensory register and STS is conveyed by the first stimulus pulse, and little additional information is conveyed by the later pulses.

Results from similar experiments conducted previously are shown along with the three-subject average of Fig. 22. The square data points (Hill and Bliss, 1968a) represent the results of four subjects with a 100-ms stimulus duration. The triangular points (Sec. III) are the average scores of two subjects with one brief (1 ms) stimulus pulse. Considering the relative differences between individual subjects' overall scores, the data of all three experiments are in fair agreement. The data of this experiment include durations used in both of these other experiments and describe the character of pattern perception for intermediate and longer durations as well.

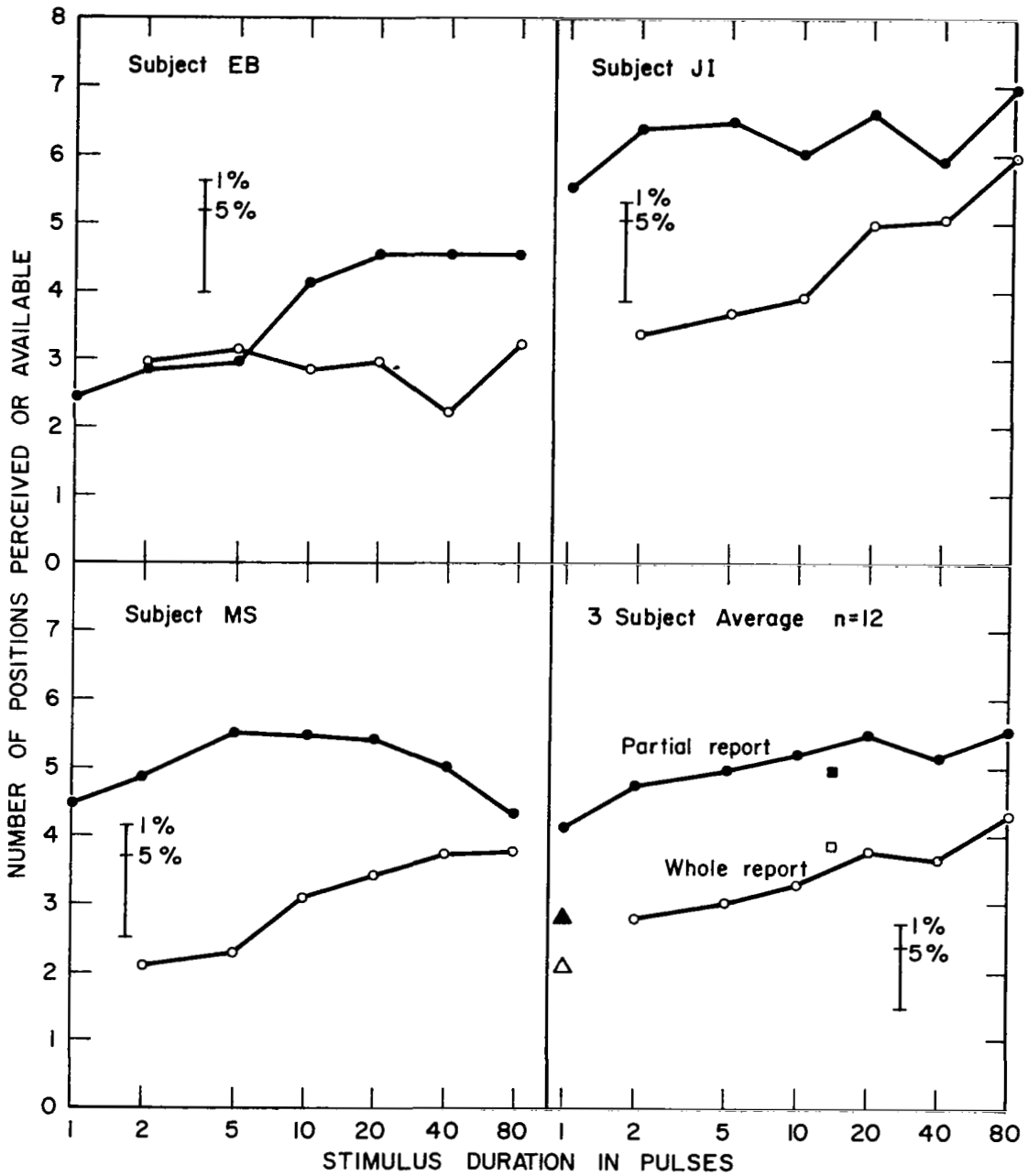

FIG. 22 COMPARISON OF WHOLE AND PARTIAL REPORTS WITH n = 12 FOR THE THREE SUBJECTS IN THE EXPERIMENT. T-tests for comparing whole and partial report data points are given.

V EFFECT OF AIRJET FREQUENCY ON TACTILE PATTERN PERCEPTION

A. Introduction

Considerable evidence has been accumulated that shows that tactile sensibility to mechanical stimulation is mediated by several types of receptors and two different tactile systems. A survey of these different systems and their frequency response is discussed in Sec. XI. The higher frequency system has a peak response at about 200 to 300 Hz, while the low frequency system peaks at about 30 to 60 Hz.

Previous experiments on tactile perception in this laboratory were carried out at 150 to 200 Hz. These frequencies were chosen for mechanical reasons and because the higher sensitivity to the high frequencies makes the stimulus appear more intense. The airjets operated at these frequencies were possibly stimulating the high frequency, not the high resolution system, and thus the psychophysical results obtained could be due to one tactile system only. This experiment was designed to investigate any differences in the perception of tactile dot patterns in a controlled experiment when the frequency of the airjet stimulator is either zero Hz (a single 0.5 s pressure pulse from the airjets), 40 Hz, or 100 Hz.

B. Method

1. Apparatus

The array of tactile stimulators and their use in this experiment are as described in Sec. III. These stimulators were operated under computer control as described in that section. During a given session either 6 or 12 of the airjet stimulators were turned on for a period of

512 ms by the LINC-8 computer. When on, the airjets were gated on and off at one of two frequencies, 40 Hz and 100 Hz, or were left on for the whole 512 ms period (referred to as the zero Hz condition). The duty cycle for the 40 Hz and 100 Hz frequencies was 50 percent; thus the stimulators produced air pressure square waves. The tank pressure for this experiment was higher than in the previous tactile experiments, being 9 lbf/in^2 instead of 6 lbf/in^2.

2. Subjects

Three college students served as paid subjects in this experiment. Subject EB was a male college sophomore, subject JI a female college freshman, and subject MS a male graduate student. All three of the subjects had from two to three months' intermittent practice on similar visual and tactile experiments.

3. Procedure

The program used to run this experiment is the same as that used in the whole report series described in Sec. III. The stimulus timing and reporting alphabet were exactly as described in that section and will not be repeated here. The two controlled variables in this experiment were the frequency with which the stimulus patterns were turned on and off (either 0 Hz, 40 Hz, or 100 Hz) and the number of stimulators, n , simultaneously activated (n = 6 or 12).

The schedule for the experiment is given in Table XI. Each subject was tested on six sessions, each with separate values of frequency and n in a balanced 3 X 2 factorial design.

Table XI

VARIABLE FREQUENCY TESTING SCHEDULE

Session	-1-	-3-	-5-
n	6	12	6
Frequency	100 Hz	100 Hz	40 Hz
Session	-2-	-4-	-6-
n	12	6	12
Frequency	40 Hz	340 Hz	340 Hz

C. Results

The number of positions correctly reported in each of the six sessions was corrected for guessing with Model II described by Hill and Bliss (1968a). The resulting number of positions perceived is given in Fig. 23. The figure shows that there are relatively minor changes in performance at a given value of n with different frequencies. No further analysis was carried out, because average changes in performance for the three subjects, to be significant, must be at least 0.5 position for $n = 6$ and 1.0 position for $n = 12$. No changes of these magnitudes are observed.

One conclusion that can be drawn from these results is that the information of the patterns is entirely conveyed by the dc portions of the air pressure stimuli. In this case, only the very low frequency system of tactile neurons responding to step indentations of the skin (Mountcastle, et al., 1967) may be responsible for the pattern perception measured in the experiment. Another possibility is that all three stimulus frequencies used in the experiment had enough energy to stimulate the high resolution tactile system ("dermal ridge receptors," Mountcastle, et al., 1967). In this case, the high resolution system

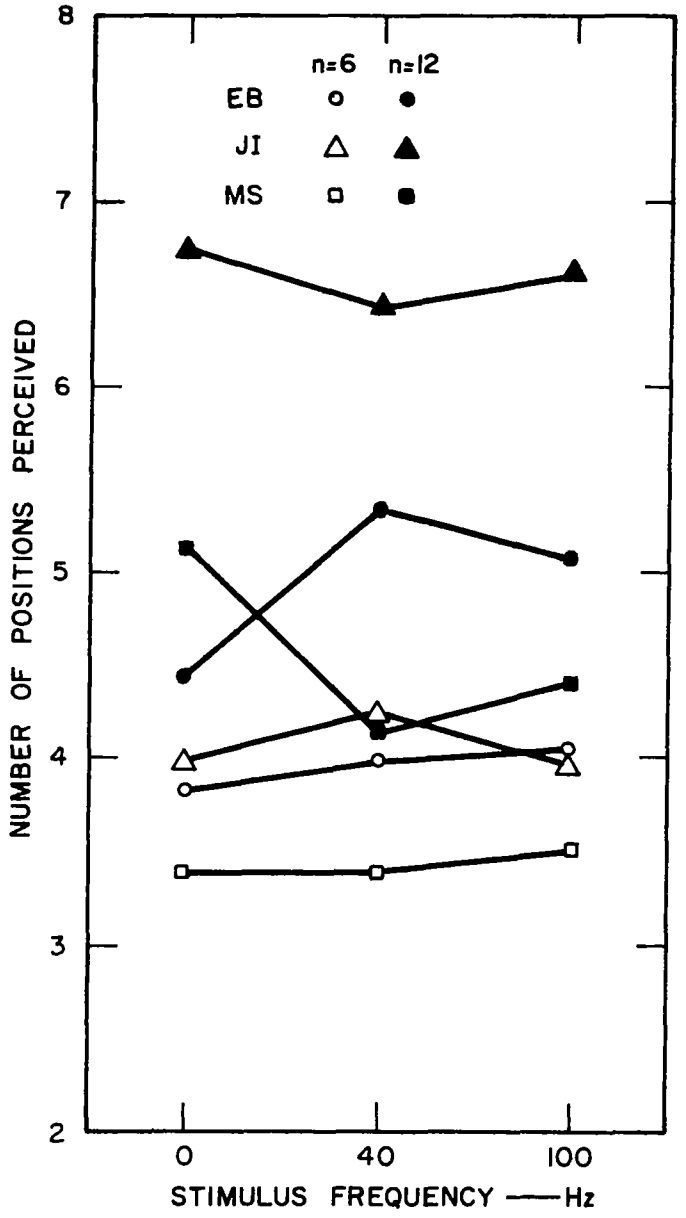

FIG. 23 WHOLE REPORT PERFORMANCE AS A FUNCTION OF STIMULUS FREQUENCY

could be conveying the information. Still another explanation is that the transients in the stimuli could be briefly stimulating any or all three of the systems.

Similar negative results were obtained by Gilson (1968) in an experiment measuring the abilities of subjects to discriminate between pairs of tactile patterns at three frequencies, 60, 300, and 500 Hz. He found no significant differences in his comparison measure. (The 200 ms vibratory stimuli used in his experiments could also be transiently stimulating any or all three of the tactile systems.)

VI PRELIMINARY EXPERIMENT FOR COMPARING VISUAL AND TACTILE PATTERN PERCEPTION

A. Introduction

An important aspect of our tactile experiments has been their relation to somewhat analogous visual experiments performed by other investigators. However, the visual experiments have primarily been performed with stimulus patterns consisting of arrays of alphabetic letters, while in our tactile experiments, we have used point stimuli at locations with alphabetic labels. To establish the relation between the visual and tactile experiments more firmly, it was important to perform a visual experiment as similar as possible to our tactile experiments.

The experiment described below is a preliminary experiment to determine stimulus conditions most appropriate for the tactile-visual comparison. Some surprising results were found that led to the further experiments described in Sec. VII.

B. Method

1. Apparatus

The array of lights used in the experiment was part of a 12 X 12 array of NE-2H neon lamps mounted on 7/16 inch centers. This array is driven by the same LINC-8 interface as were the airjet arrays used in the previous experiments. A 3 X 9 rectangular array of lamps was visible to the subjects through a cardboard mask. This white mask divided the array into two 3 X 4 fields on a black background, separated by a 3 X 1 field on a white background. The front view of the light box as seen by the subjects is shown in Fig. 24. The bulbs in the two 3 X 4 fields were labeled with

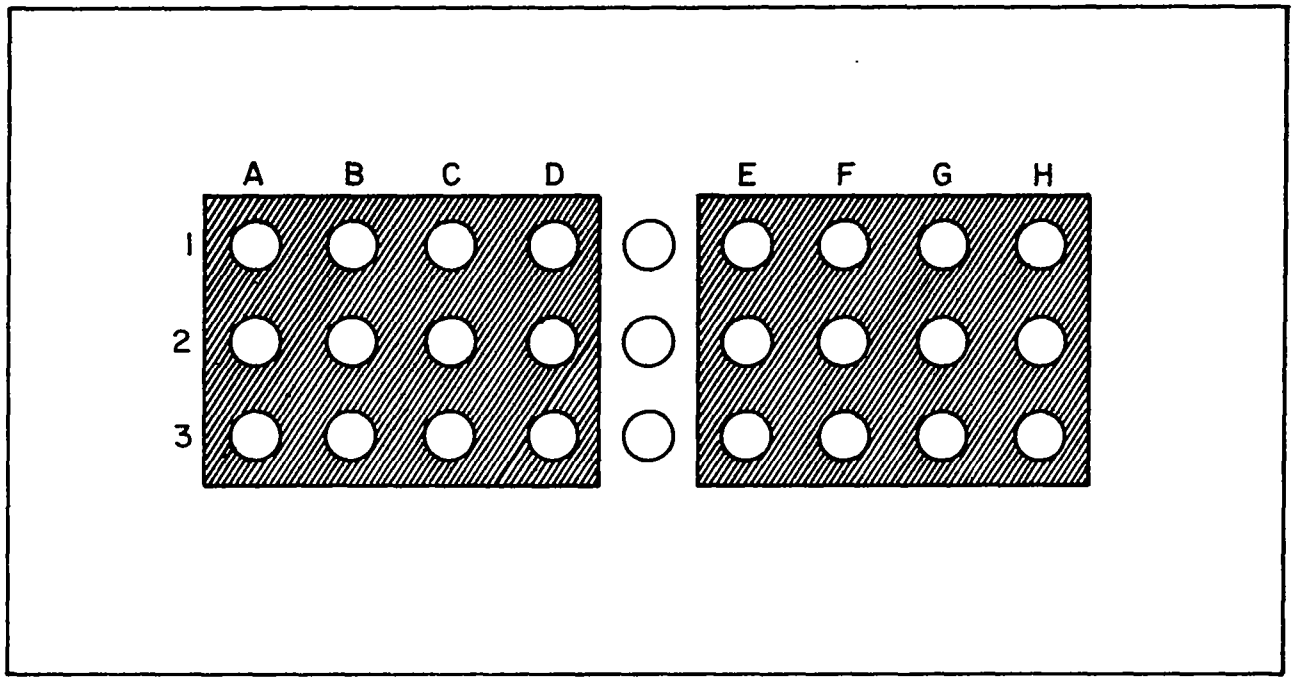

FIG. 24 FRONT VIEW OF LIGHT BOX USED IN THE EXPERIMENT. The middle column contains the marker lamps.

the same alphanumeric reporting alphabet used in the tactile perception experiments described in Sec. III.

Four physical parameters were varied in both the whole and partial report pattern perception experiments. These were background brightness, lamp brightness, display angle, and stimulus duration. The brightness of the white cardboard mask was either 46 fL or 0.08 fL. These conditions, referred to as "room bright" or "room dark" in the experimental design, were obtained by turning on or off the fluorescent lamps in the experiment room. The brightness of the neon lamps was either 700 fL or 40 fL, and was obtained by passing either 6 mA or 0.8 mA through the lamps. The 24 neon lamps used in the experiment were selected from a larger group for fast firing characteristics. All lamps fired within 0.1 ms of the striking voltage onset. The four display angles used in the experiment refer to the angular width of the display as viewed by the subject. The angles, 2°, 4°, 8°, and 16°, were obtained by placing the same display 114", 57", 29", or 14" from the subjects' eyes.

To obtain the four stimulus durations, the control computer gated on the lamp drivers for 1, 8, 64, or 512 ms. The lamp drivers, synchronized with the onset of the computer gate, fired the lamps at a 340 Hz rate with 1.0 ms pulses. The resultant number of light pulses produced by the 1, 8, 64, and 512 ms gates were 1, 3, 22, and 174, respectively. The 340 Hz frequency is considerably higher than the visual flicker fusion rate, and, when on, the stimulus patterns appeared as steady illumination.

2. Subjects

Three college students served as paid subjects. Subject EB was a male college sophomore, subject JI a female college freshman, and MS a male graduate student. Subjects JI and MS had no previous experience on experiments of this nature, but subject EB had two months' intermittent practice on similar tactile perception experiments.

3. Procedure

Each subject participated in the experiments for approximately a one-hour period each day. During this period he was paced through the next part of his sequential test schedule. Since the sessions of the test schedule varied from 10 to 15 minutes each, and a 5 to 10 minute rest period was allowed between sessions, a variable number (from 3 to 4) of sessions were completed each day.

The whole and partial report testing schedules used are shown in Tables XII and XIII. Both schedules are a random 4 X 4 Greco-Latin square design and allow the effects of four variables to be independently measured. In each design, stimulus duration is one variable, display angle is another, and the two variables, background brightness and lamp brightness, are confounded to make the third. The whole report design uses four values of n (n = 4, 6, 8, and 10) as the fourth variable. The

Table XII

DESIGN OF WHOLE REPORT PRELIMINARY EXPERIMENT

Session	-1-	-2-	-3-	-4-
Lamps-room	D-B	B-B	D-B	B-D
n-presentations	6-24	6-24	8-24	4-24
Display angle	4°	8°	16°	8°
Stimulus duration	8	512	1	1
Session	-5-	-6-	-7-	-8-
Lamps-room	D-B	B-D	D-D	B-B
n-presentations	6-24	10-36	8-24	8-24
Display angle	16°	2°	8°	2°
Stimulus duration	64	8	8	64
Session	-9-	-10-	-11-	-12-
Lamps-room	B-B	D-B	B-D	D-D
n-presentations	10-36	10-36	8-36	4-36
Display angle	4°	8°	4°	4°
Stimulus duration	1	64	512	64
Session	-13-	-14-	-15-	-16-
Lamps-room	D-D	D-D	B-B	D-B
n-presentations	6-24	10-36	4-24	4-24
Display angle	2°	16°	16°	2°
Stimulus duration	1	512	8	512

Table XIII

DESIGN OF THE PARTIAL REPORT PRELIMINARY EXPERIMENT

Session	-1-	-2-	-3-	-4-
Lamps-room	B-D	B-B	D-D	D-B
Display angle	8°	16°	4°	2°
Stimulus duration	1	8	64	512
Session	-5-	-6-	-7-	-8-
Lamps-room	B-B	B-D	D-B	D-D
Display angle	2°	4°	8°	16°
Stimulus duration	512	64	8	1
Session	-9-	-10-	-11-	-12-
Lamps-room	B-B	B-D	D-D	D-B
Display angle	2°	4°	8°	16°
Stimulus duration	64	512	8	1
Session	-13-	-14-	-15-	-16-
Lamps-room	B-B	B-D	D-D	D-B
Display angle	4°	2°	16°	8°
Stimulus duration	1	8	512	64

partial report design uses four repetitions of the experiment (to measure learning) as the fourth variable. In addition, since partial report performance is measured in terms of the accuracy of each report on each of the three possible rows, there are two additional extrinsic factorial variables in this design. Both whole and partial report designs have three subjects as their final (random) variable. In the whole report experiment, performance as a function of six variables is investigated; in the partial report experiment, eight variables are considered.

For whole report testing, the number of presentations at each session was chosen to allow the variance of the mean number of positions perceived to be less than or equal to a constant ($\sigma \leq 0.61$), under the constraint that the duration of the experiment be one week. For partial report testing with $n = 12$, 66 presentations for each session were chosen to allow the variance of the number of positions available to be a constant ($\sigma = 1.10$), under the constraint that the duration of the experiment be one week. During each session an equal number of presentations were made at all lamp locations.

In all portions of the experiment, the subjects were asked to fixate on the center lamp of the marker column. On any one trial, n lamps were chosen (by the computer) out of the 24 possible lamps. In any one session the number of lamps simultaneously lighted, n, was constant and known by the subjects. All of the other experimental variables were constant during a session, and all of the other variables except duration were known by the subjects.

In the whole report experiment, the subjects were asked to report all the stimulated positions row by row, from left to right. The reporting scheme and timing of stimulus presentations are exactly the same as the training series described in Sec. III.

In the partial report experiment, the subjects were informed by a visual marker, beginning immediately upon termination of the stimulus, of which row to report. Again, the complete description of the stimulus-marker timing and the subjects' reporting scheme is the same as the partial report series described in Sec. III.

C. Whole Report Results

The number of positions correctly reported by the subjects at each session was corrected for guessing by Model II described by Hill and Bliss (1968a) to obtain the number of positions perceived. The number of positions perceived was subjected to analysis of variance to determine the significant effects of the five controlled variables. The analysis of variance summary is given in Table XIV. The table shows that display angle, duration, and n significantly influenced the subjects' scores, while neither lamp brightness, nor background brightness, nor their interaction influenced the scores.

Visual whole report performance as a function of n is shown in Fig. 25. The curves are somewhat steeper and the overall values somewhat higher than the equivalent tactile results of the same three subjects, shown previously in Fig. 15. The shape of the results closely resembles the results from tactile dot pattern perception reported in previous experiments (Bliss, Crane, Mansfield, and Townsend, 1966; and Hill and Bliss, 1968a). The results are in disagreement with many letter perception experiments reported in the literature (Sperling, 1960; and 1963; Averbach and Coriell, 1961; Estes and Taylor, 1964; and others). With visual arrays of letters, these authors found that the number of letters perceived leveled off at a constant number as the number of letters presented was increased past 4 or 6. The previously reported results lead to the concept of a fixed-capacity short-term store information processing model to explain visual perception. The results of this visual perception experiment using dot patterns--instead of letters--indicate that the previously accepted information processing model is not as general as was supposed and indeed does not explain this upward sloping dot pattern curve.

Change in performance related to stimulus duration is given in Fig. 26. Only the linear increase with duration is significant ($p < 0.005$).

Table XIV

SUMMARY OF ANALYSIS OF VARIANCE OF THE NUMBER OF POSITIONS PERCEIVED IN THE VISUAL WHOLE REPORT

Source	df	Mean Square	F	Sign
Subjects	2	2.412		
Display Angle (A)	3			
Linear	1	14.920	64.1	$p < 0.001$
Quadratic	1	6.020	25.9	$p < 0.005$
Cubic	1	.214	--	
Subjects × A	6	.233		
Duration (D)	3			
Linear	1	5.346	31.6	$p < 0.005$
Remainder	2	.005	--	
Subjects × D	6	.169		
n	3			
Linear	1	24.716	22.4	$p < 0.005$
Remainder	2	.550	--	
Subjects × n	6	1.102		
Lamp Brightness (LB)	1	.388	1.22	
Subjects × LB	2	.318		
Background Brightness (BB)	1	2.813	6.87	
Subjects × BB	2	.409		
LB × BB	1	.952	2.46	
Subjects × LB × BB	2	.387		

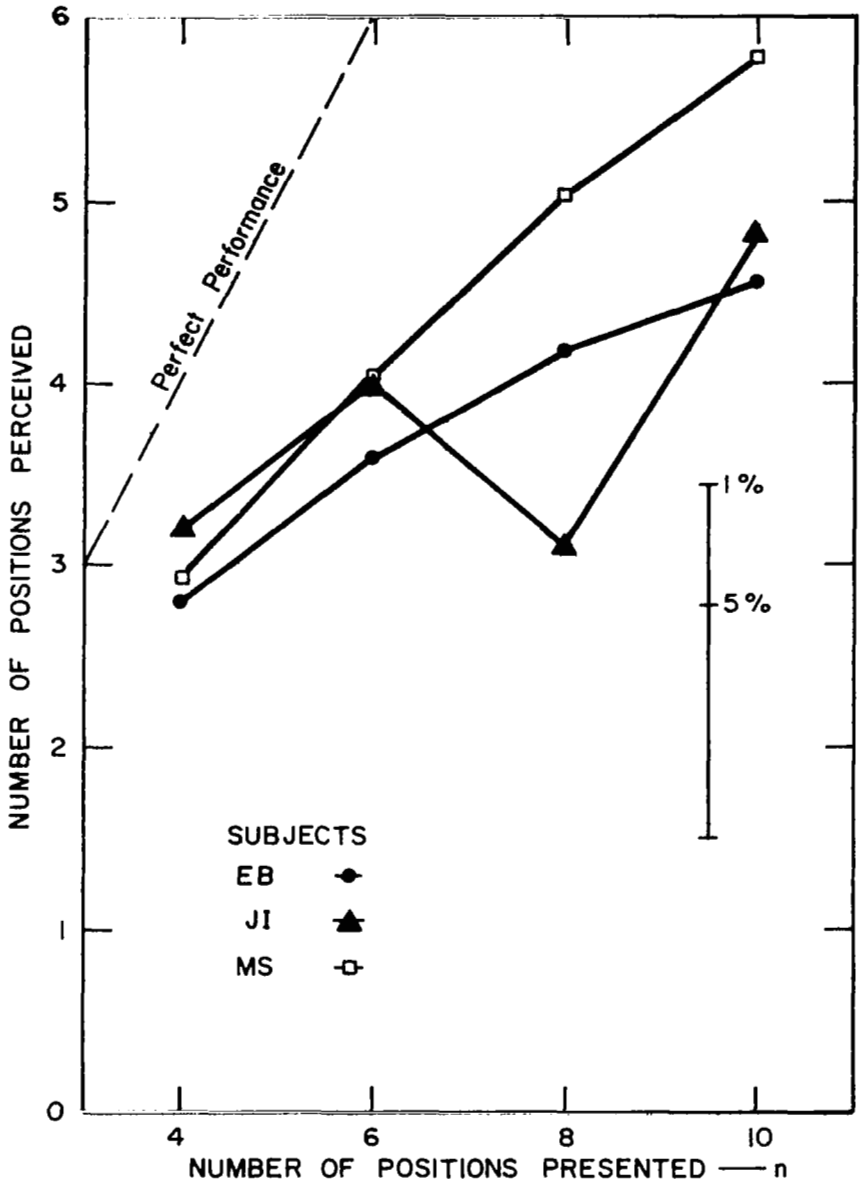

FIG. 25 VISUAL WHOLE REPORT PERFORMANCE AS A FUNCTION OF n

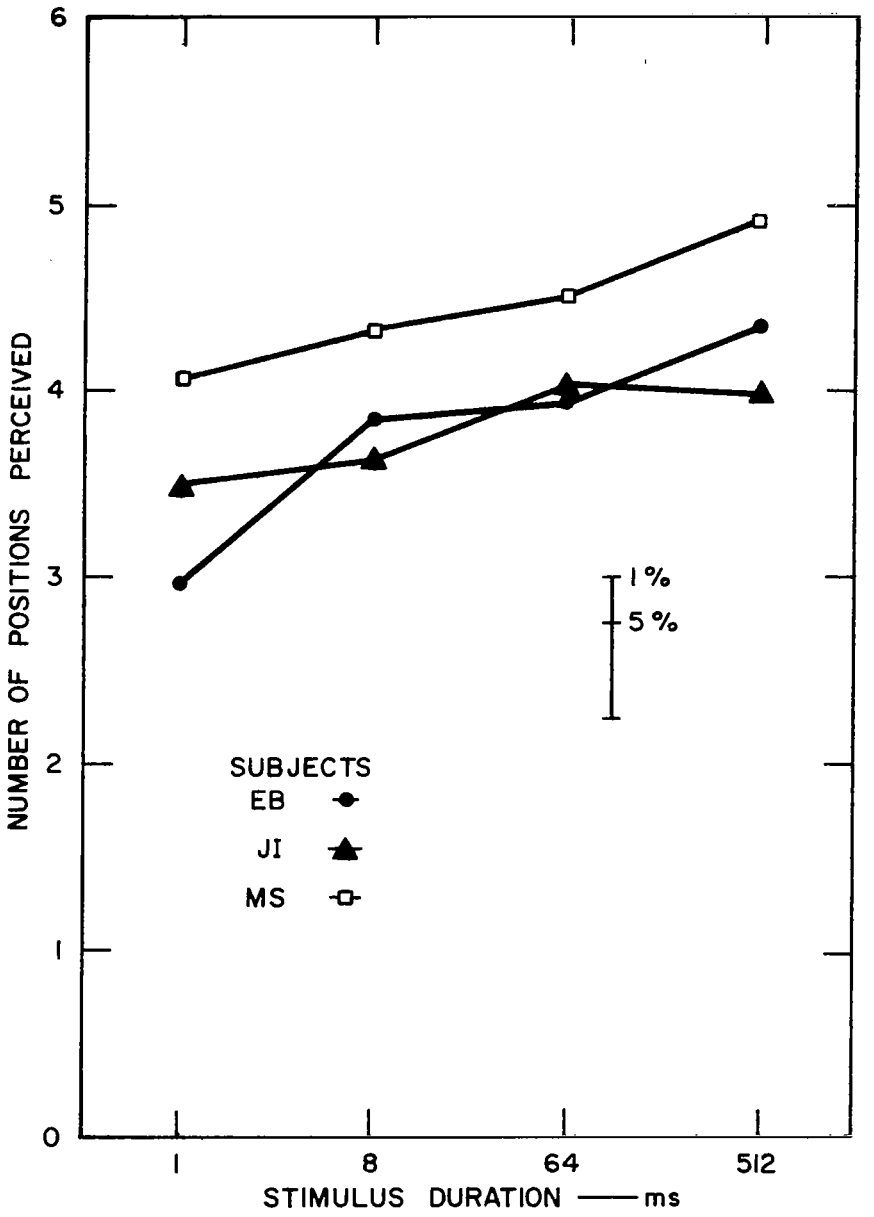

FIG. 26 VISUAL WHOLE REPORT PERFORMANCE AS A FUNCTION OF STIMULUS DURATION

However, the total change is small, being about 25-30 percent for an increase in stimulus duration of 500 to 1. This result is similar to the tactile result, where performance is proportional to the logarithm of the stimulus duration.

Whole report performance related to display angle is given in Fig. 27. Here both the linear ($p < 0.001$) and quadratic ($p < 0.005$) terms are significant. The results indicate that the closer the display is to the subjects (or equivalently, the farther separated the stimulus points on the retina), the better the accuracy. Performance over the smallest three angles is fairly constant, being about 3.5 positions perceived. The equivalent whole report tactile performance level for the same three subjects over the same ranges of stimulus duration and the same range of n is 2.8 positions perceived. Thus, the visual results with 2 and 4 degree display angles are only slightly higher than the tactile results.

The influence of both room and lamp brightness is shown in Fig. 28. Neither of these two variables nor their interaction significantly affected the results. From Fig. 28 it appears that a 20-fold increase in lamp brightness may cause a small increase in performance, and a 500-fold decrease in background illumination may cause a small (12 percent) increase in performance. Both of these brightness effects on performance are very small, and it appears that characteristics of the visual span of immediate memory are very independent of overall brightness and contrast.

D. Partial Report Results

The number of positions available on each row for each subject and each session was determined from the number of positions correctly reported using Model II described by Hill and Bliss (1968a). The number of positions available was given an analysis of variance to determine the extent to which the six experimental variables influenced the results.

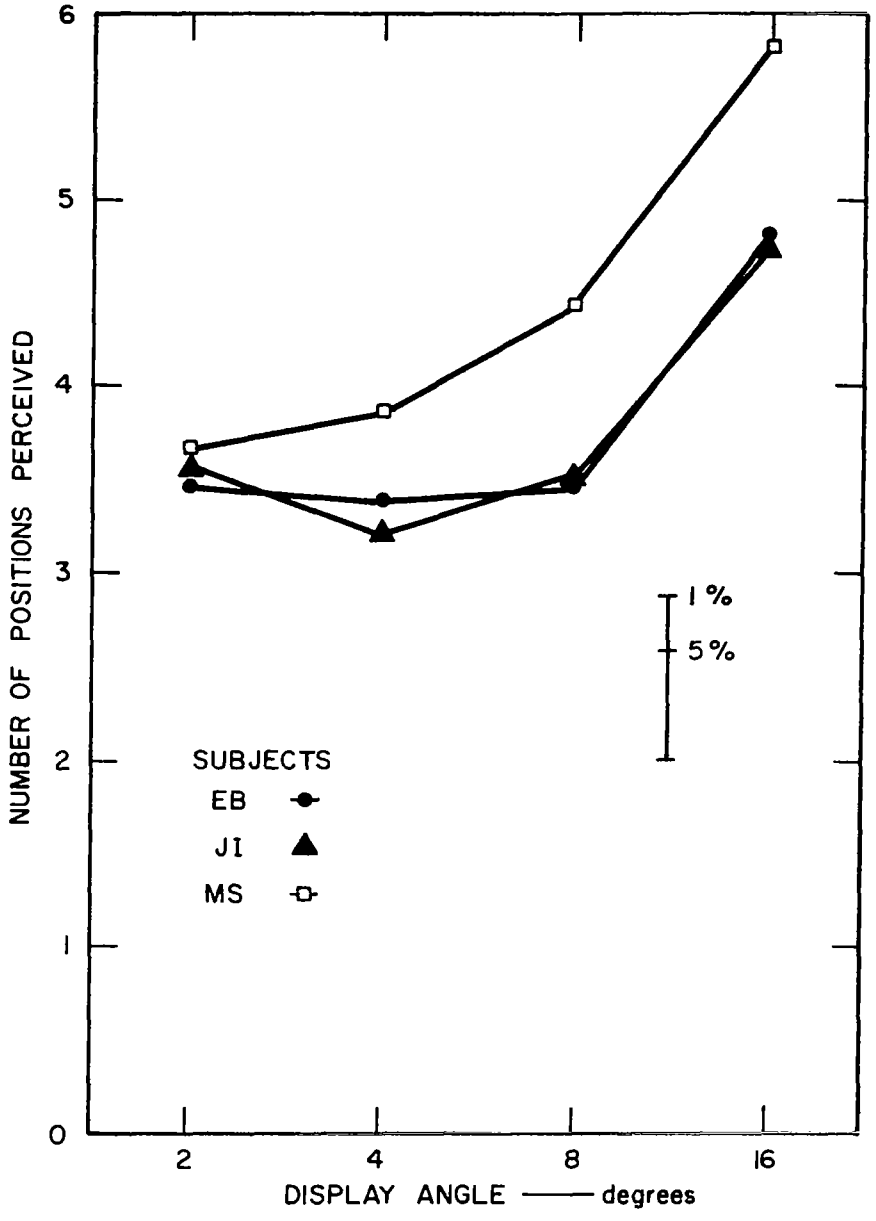

FIG. 27 VISUAL WHOLE REPORT PERFORMANCE AS A FUNCTION OF DISPLAY ANGLE

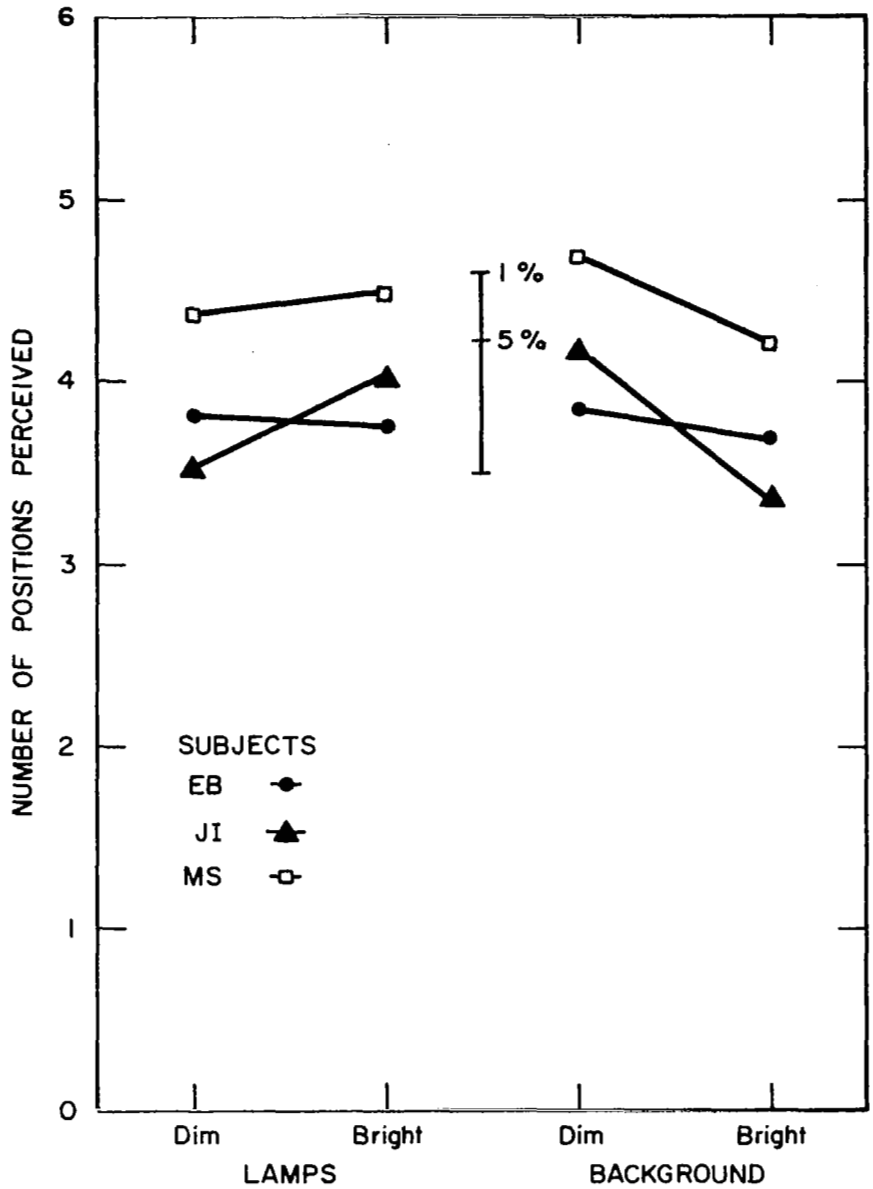

FIG. 28 VISUAL WHOLE REPORT PERFORMANCE AS A FUNCTION OF LAMP AND BACKGROUND BRIGHTNESS

Table XV

SUMMARY OF ANALYSIS OF VARIANCE OF THE NUMBER OF POSITIONS AVAILABLE IN THE PARTIAL REPORT

Source	df	Mean Square	F	Sign
Subjects	2	4.38		
Display Angle (A)	3	1.510	--	
Subjects × A	6	1.713		
Duration (D)	3			
Linear	1	113.175	75.3	$p < 0.001$
Remainder	2	7.030	4.66	
Subjects × D	6	1.509		
Learning (L)	3			
Linear	1	3.185	2.79	
Remainder	2	.843	--	
Subjects × L	6	1.778		
Lamp Brightness (LB)	1	2.249	11.2	
Subjects × EB	2	.202		
Background Brightness(BB)	1	11.030	4.74	
Subjects × BB	2	2.336		
LB × BB	1	5.747	6.92	
Subjects × LB × BB	2	.831		
Report Row (R)	2			
Linear	1	.439	--	
Quadratic	1	2.477	5.61	
Subject × R	4	.441		

The analysis summarized in Table XV shows that of all the variables, there is only evidence to show that one (stimulus duration) is influential.

The effect of stimulus duration on partial report accuracy is shown in Fig. 29. The number of positions available increases strongly with stimulus duration, being more than twice as large with 512 ms duration as with 1 ms. This is a larger increase than observed either in the tactile or whole report visual experiments. With the three briefest durations (1, 8, and 64 ms) there is insufficient time for the eye to refixate on the pattern, and these changes in duration should be equivalent to brightness change that should have little effect. With the longest duration (512 ms) there is time for the eye to fixate on more than one portion of the pattern, possibly enhancing performance in this case. However, why the visual partial report increases so much with the 512 ms exposure, and the whole report with the same long exposure does not, remains unexplained.

The effect of display angle on partial report performance is shown in Fig. 30. Although this variable does not significantly affect the results, it appears that there might be individual differences. Subject EB's and JI's performances are constant with display angle, while subject MS's performance drops 30 percent with the 8 to 1 increase in display angle.

The change in performance as a function of time in the partial report experiment is shown in Fig. 31. Though the change was not significant, the scores of all three subjects increased 20 percent over the week of testing. It appears that learning on the visual perception experiment may not be as great as that on tactile perception experiments. However, this one test cannot be considered conclusive. If the same slow learning process is observed on the visual as well as the tactile experiments, then we must assume that learning is a very central association process. If, on the other hand, the learning is only associated with the tactile experiment, then we must assume that it is a parameter of the relatively unused tactile system.

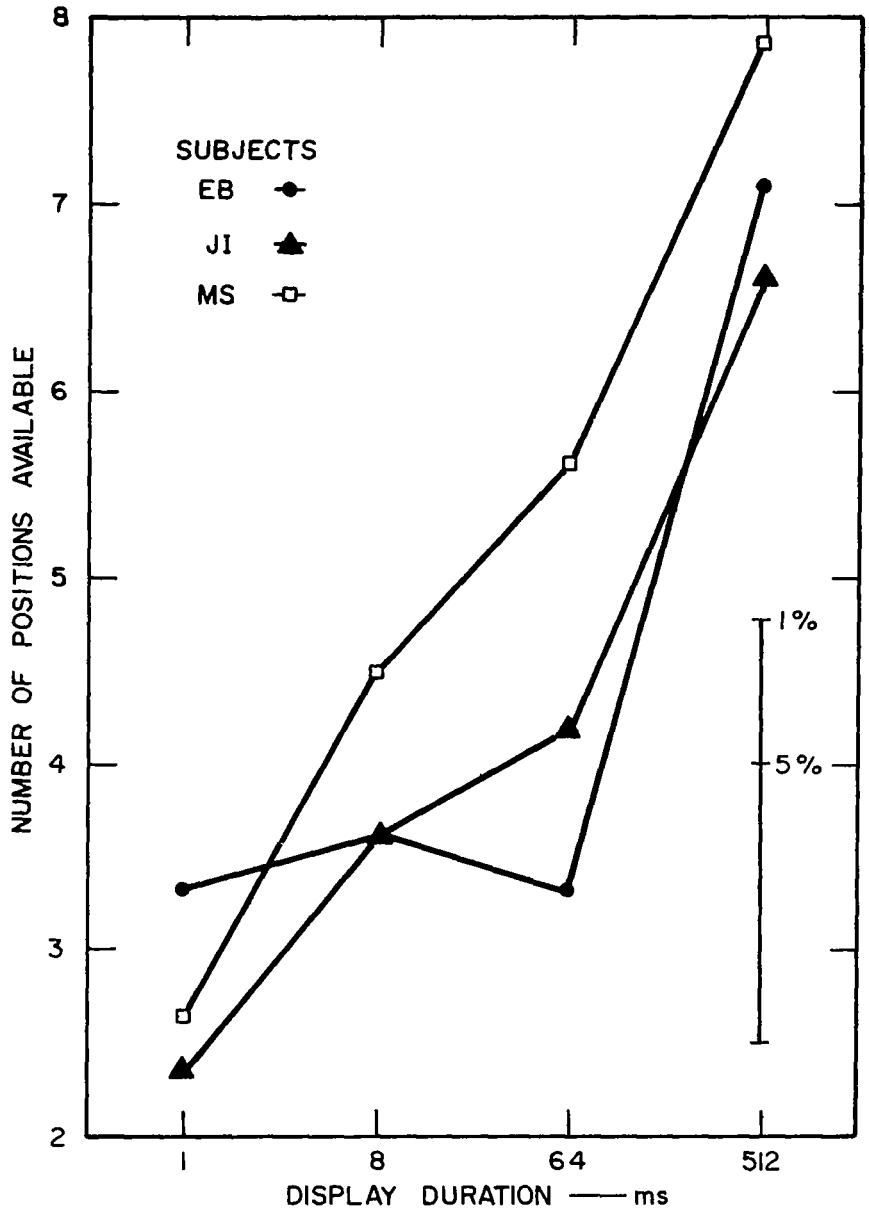

FIG. 29 VISUAL PARTIAL REPORT PERFORMANCE AS A FUNCTION OF DISPLAY DURATION

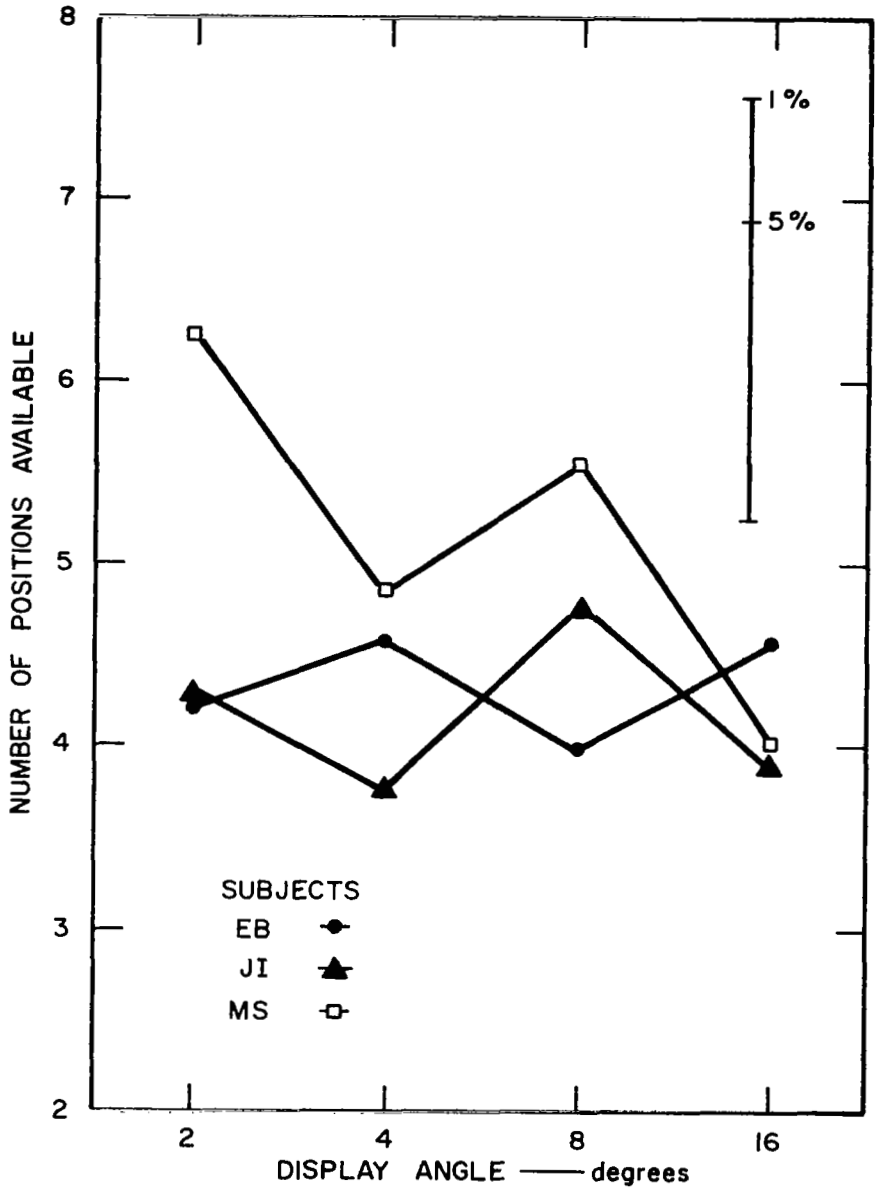

FIG. 30 PARTIAL REPORT PERFORMANCE AS A FUNCTION OF DISPLAY ANGLES

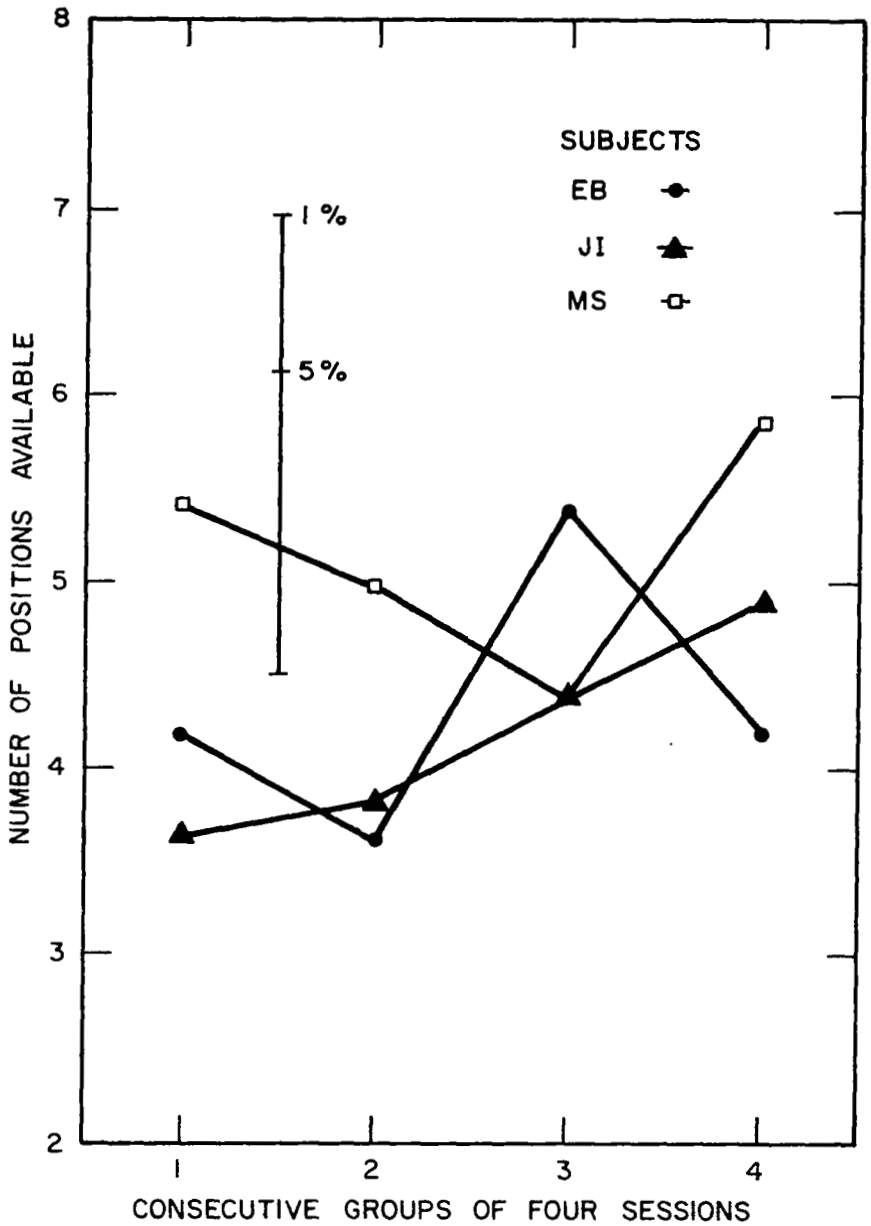

FIG. 31 PARTIAL REPORT PERFORMANCE AS A FUNCTION OF TIME IN THE EXPERIMENT

The effects of both lamp and background brightness are given in Fig. 32. Neither of these two variables shows enough change to be statistically significant. A 20-fold increase in lamp brightness causes a slight decrease in performance, while the 500-fold change in background brightness causes a 25 percent decrease in performance.

The change in performance over the three reporting rows is shown in Fig. 33. Here the reports from the middle row are the most accurate, and the top and bottom rows the least. This finding, though not significant, is probably a consequence of asking the subjects to fixate on the center row of the display. This greater middle row accuracy, common to all three subjects, is the opposite of their tactile partial report data, in which all three of them had lower accuracy on the middle row. When more visual dot pattern data is available, models such as the stimulus spreading model and masking model can be tested against the visual data to better understand the underlying mechanisms and to compare them with tactile mechanisms.

E. Discussion

The average display angle scores of all three subjects in both the visual whole and partial report exploratory experiments are shown in Fig. 34 for comparison. The scores represent averages over three variables (stimulus duration, lamp brightness, and background brightness). In addition, the whole report scores are averaged over n (n = 4, 6, 8, and 10). The figure shows that the whole report performance of the subjects increases with display angle, while the partial report performance does not. This first finding contradicts the expected outcome of the experiment. With the 2° display angle the entire display is presented on the fovea of the retina while in the 16° case, at most a couple of the center lamps are presented on the fovea and the rest are presented on the lower resolution periphery of the retina. From the point of view of spatial resolution,

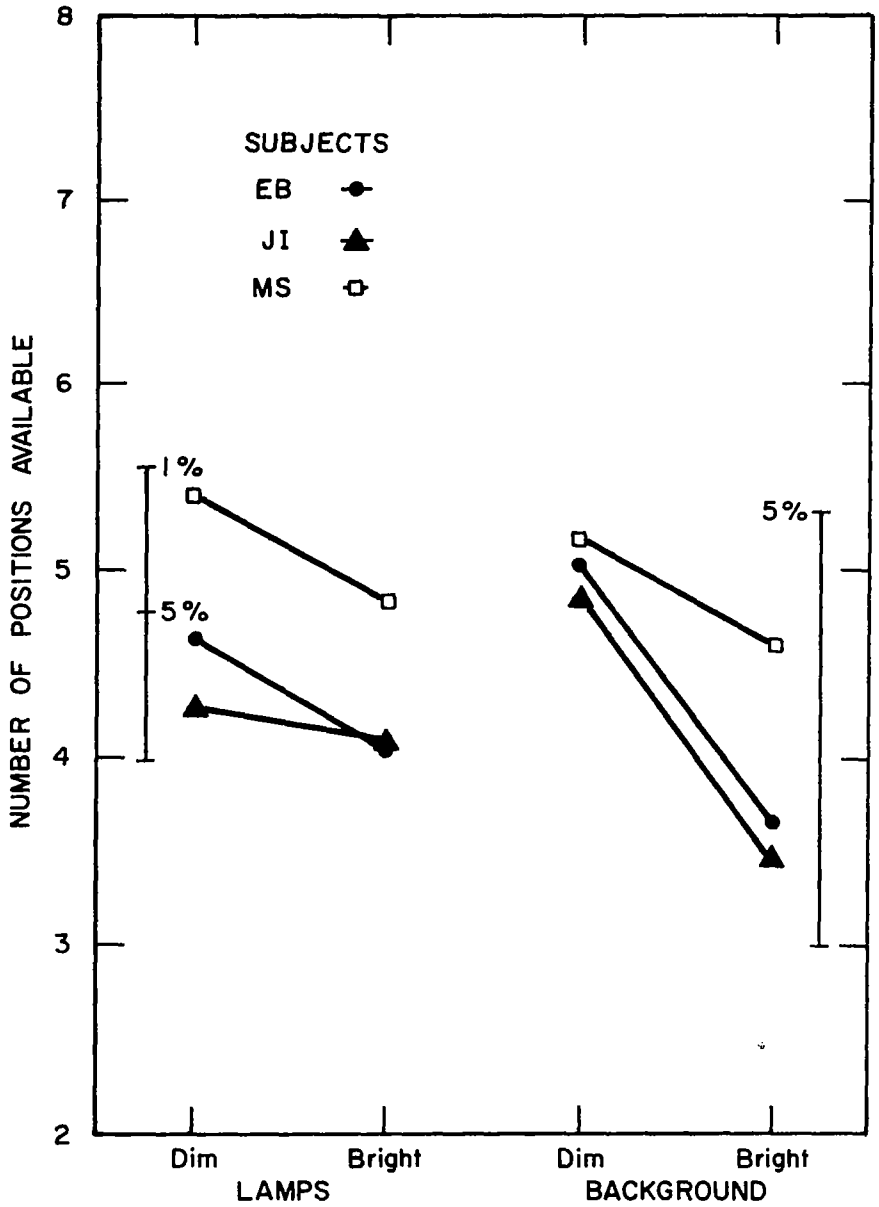

FIG. 32 PARTIAL REPORT PERFORMANCE AS A FUNCTION OF LAMP AND BACKGROUND BRIGHTNESS

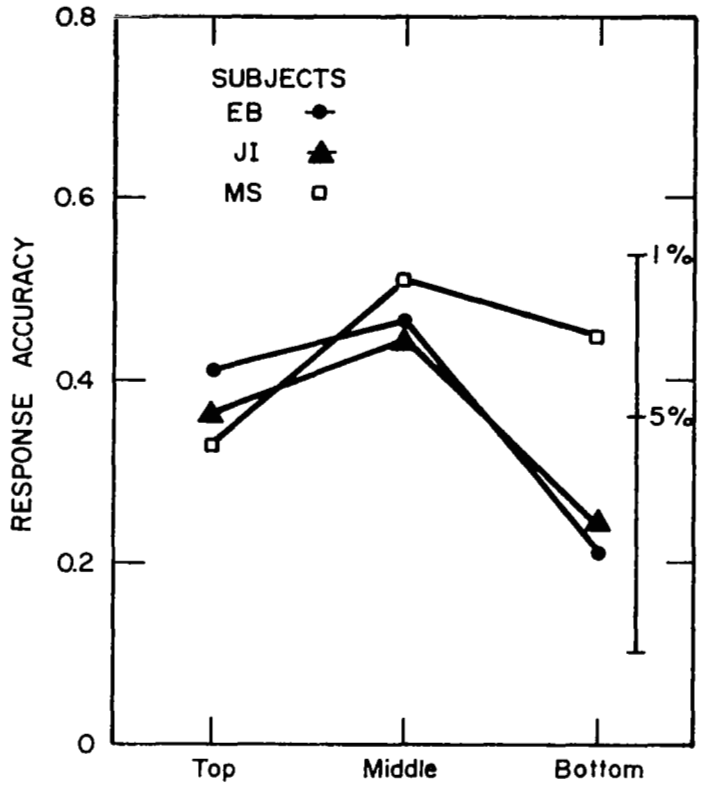

FIG. 33 AVERAGE RESPONSE ACCURACY ON EACH OF THE THREE LAMP ROWS IN THE PARTIAL REPORT

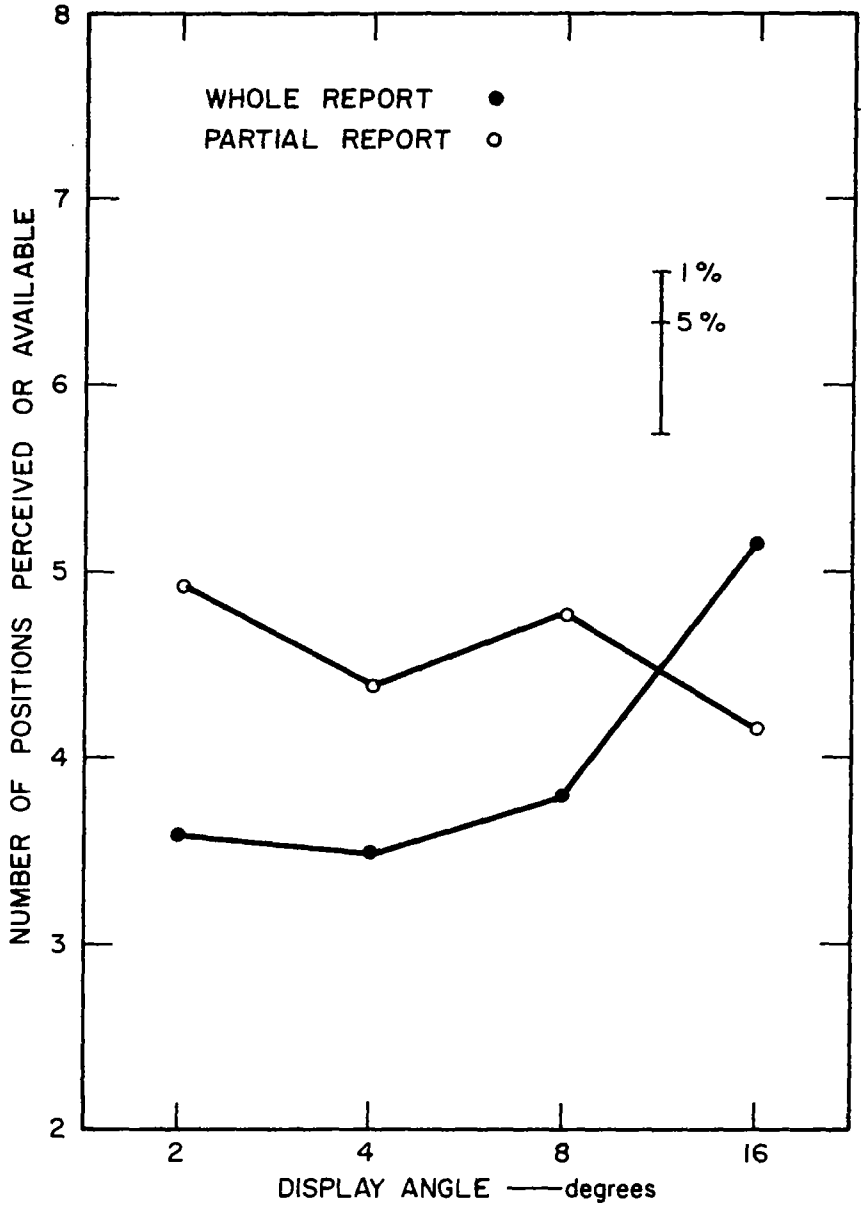

FIG. 34 COMPARISON OF THE VISUAL WHOLE AND PARTIAL REPORT PERFORMANCE AS A FUNCTION OF DISPLAY ANGLE FOR THE THREE SUBJECTS AVERAGED SCORES. The t-tests are shown for comparing whole with partial report scores.

the presentation on the fovea would be expected to yield higher reporting accuracy than that on the periphery, for both whole and partial report.

The total change in performance with display angle was relatively small, however, being only 1.5 positions (or 40 percent) at most and resulting from a relatively large change of eight to one in display angle. This relative independence suggests a central limitation on the information processing model rather than a peripheral (or retinal) one. In other words, the resolution on the retina is evidently great enough to pass on the information for all values of display angle, and the central decision making process that decides which lamps in the spatial array were on is the limiting factor. These results suggest that, since the smallest change in performance with display angle occurs at the small angles, the 2° display (or foveal display) should be used in future experiments. This small display has the added advantage that the results of these dot pattern experiments may be compared with the body of visual data in the literature, which was largely collected using 2° to 3° foveal displays.

The average whole and partial report scores in relation to stimulus duration for the three subjects participating in the experiment are shown in Fig. 35. These scores are averaged over the other three experimental variables of the experiment (display angle, lamp brightness, and background brightness) in both whole and partial reports. Both curves increase slowly with stimulus duration up to the 64 ms point; with the 512 ms stimulus presentation the partial report performance increases 70 percent, while whole report performance does not increase significantly. The expected change in performance with stimulus duration would be a small increase in performance up to 100 or 200 ms, and then an increase of approximately 2 to 1 at this point. The reason for the abrupt increase after 200 ms may be that the eye can refixate in this time interval and

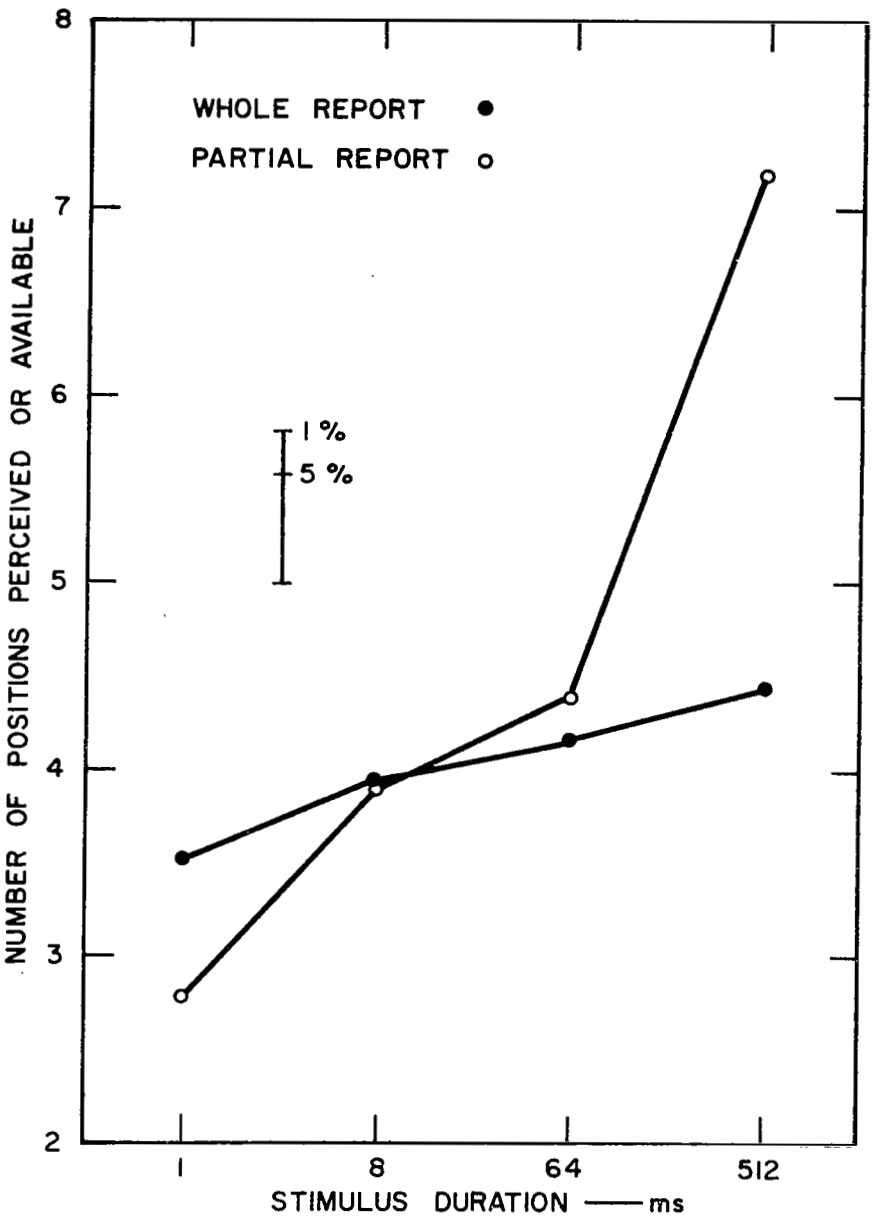

FIG. 35 COMPARISON OF THE WHOLE AND PARTIAL REPORT DATA AS A FUNCTION OF STIMULUS DURATION FROM THE THREE SUBJECTS AVERAGED SCORES. The t-tests are shown for comparing whole and partial report scores.

scan a different portion of the display pattern. The reason for the increase in performance up to the 200 ms point may be that in this range the eye does not move appreciably, and changes in stimulus duration appear as changes in intensity. The unexplained part of the data is that the whole report performance at 512 ms duration did not increase abruptly, as the partial report performance did.

In future experiments, stimulus durations less than 100 ms should be used, in order to insure that the eye does not move appreciably during the stimulus presentation. With brief presentations, the positions of the patterns depend only on internal processing, not on the additional uncontrolled variable, eye movement. Visual and tactile experiments would then be more comparable, since the tactile displays used do not move over the skin.

The influence of the two brightness parameters on the whole and partial report scores can be compared in Fig. 28 and 32. Neither lamp brightness nor display brightness significantly influenced the results.

A 20-fold increase in lamp brightness slightly increased whole report performance and slightly decreased partial report performance (ca. 10 percent change in each case) so that these changes may be presumed random. A 500-fold increase in background illumination caused small (ca. 10 to 20 percent) decreases in each case, and we might assume that a small influence exists. Both of these brightness changes had such a small effect, however, that it appears that neither brightness nor contrast is an important part of the information processing models derived from these experiments. Evidently, as long as the patterns are clearly visible, the limitations on pattern perception do not depend on stimulus brightness.

A comparison of both whole and partial report data is given as a function of n in Fig. 36. Both whole and partial report data are averaged over the same four variables (stimulus duration, display angle, lamp brightness, and room brightness). The remarkable feature shown in Fig. 36 is the lack of a sensory register (or equivalently, a short-term memory) by the subjects in this experiment. Evidence for a sensory register is shown by the partial report scores with a given number of stimuli (n) being higher than the partial report scores with the same value of n. Although both of these tests were not made with the same value of n, linear extrapolations of the whole report performance to n = 12 allows a first-order comparison of both tests at this point. If this extrapolation is carried out, it can be seen in Fig. 22 that the partial report scores for all three subjects are actually less than the whole report scores, indicating the absence of a visual sensory register for these dot patterns.

Another difference between these results and those previously reported using patterns of letters (instead of dots) is that an upward sloping, not saturating model describes the results. This discrepancy between results with visual dot and letter patterns indicates that the previous letter information processing models are not as general as thought and that an additional stage in the model may be necessary. The missing stage may be the "object locator" in the model discussed by Shaw (1968). Here the first stage of the visual information processing model is a locator making only the binary decisions, "is there an object here or not?"

Another interesting point is raised by the absence of a visual sensory register for dot patterns. Previously, tactile dot pattern data had compared favorably with visual letter pattern data in that both

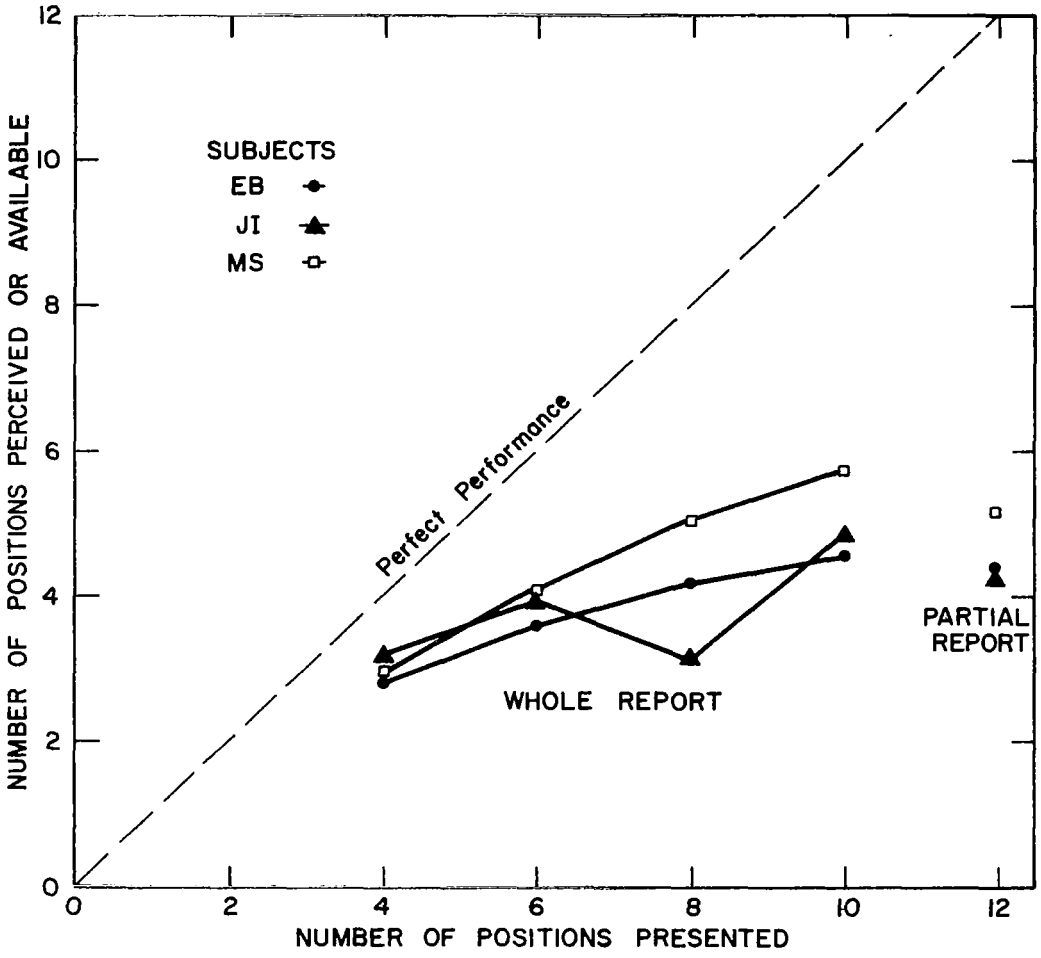

FIG. 36 COMPARISON OF THE VISUAL WHOLE AND PARTIAL REPORT EXPERIMENTS

showed evidence for a sensory register. However, if visual dot and tactile dot pattern data are compared, there appear to be fundamental differences. The differences may be traceable to the differences in the neural mechanism involved in processing the patterns. The differences may be accounted for by assuming that in vision there is one more element in the information processing chain than there is in the tactile chain.

VII A COMPARISON OF VISUAL AND TACTILE MEMORY MODEL PARAMETERS

A. Introduction

Previous tactile dot pattern perception experiments carried out in this laboratory (Bliss, Crane, Mansfield, and Townsend, 1966; Hill and Bliss, 1968a) were modeled after the visual short-term memory experiments of Sperling (1960), Averbach and Corrill (1961), Estes and Taylor (1964), and others. These tactile experiments led to a model for multiple tactile perception consisting of a sensory register capable of storing tactile information for a 1-2 second interval and a short term store of a more limited capacity which reads information out of the sensory register, and retains it for a 10- to 30-second interval. The two-stage form of the resulting tactile model is the same as that of the previous visual model, however, the time constants, capacities, and some other details are different.

The purposes of the experiments described in this section were two-fold. First, because of the success of the two-stage information processing model in describing tactile dot pattern perception, these experiments were designed to further extend the model by studying the effect of a tactile erasure stimulus on tactile pattern perception. Secondly, because of the difficulties involved in drawing conclusions from not completely analogous tactile and visual experiments, these experiments were designed to provide comparable data for these two modalities.

A more thorough understanding of the visual information processing model has been obtained using various erasure or interference stimuli to try to erase the contents of the visual sensory register (Averbach and

Sperling, 1961; Sperling, 1963, 1967; and others). The erasure experiments allow measurement of overall visual short term store scanning rates and can determine whether this scanning is serial or parallel. In order to further investigate the tactile information processing model with regard to scan rate and scan mode, experiments with tactile erasure stimuli were carried out. The paradigm used in the experiments was basically that of the partial report experiment described in Sec. II. The sequence of the erasure experiment was as follows: First, the tactile patterns are presented to the subjects by activating 12 of the 24 airjet stimulators for a 100-ms interval. Then, following a variable time delay (up to 2.0 s) called the marker delay, all 24 of the airjets are activated to present the erasure stimulus. The subjects' task was to report the activated airjets in the row designated by a marker lamp that was activated simultaneously with the erasure stimulus.

One example of a difference between tactile dot patterns results and visual letter results is the upward sloping tactile model versus the saturating visual model for the short term store. Another difference is the ratio between the sensory register and short term store capacities in the two modalities. With visual letter stimuli the ratio is greater than 3:1, while with tactile dot stimuli the ratio is 3:2. Are these differences due to the modality of presentation or to the different stimulus materials used in the experiments? In order to eliminate some of the ambiguities in comparing these tactile and visual experiments, the following visual dot pattern experiments were carried out.

B. Method

1. Apparatus

The visual dot patterns stimuli were produced with the light box described in Sec. VI. Here 24 neon lamps in the same 3 × 8 spatial

arrangement replaced the airjet stimulators. The visual stimulus conditions (display brightness, contrast, angular size, duration, etc.) for this analogous experiment were determined from the preliminary experiment of Sec. VI. The particular conditions were chosen to afford the best comparison between previous tactile and previous visual experiments as discussed in that section. The visual dot pattern experiment was run without erasure to determine the sensory register and short term store capacities for the visual information processing model and with erasure to determine the erasure's effect on the sensory register, the scan rate of the short term store, and the mode of the short term store (serial or parallel). Both visual and tactile experiments were designed to be as similar as possible. The same reporting alphabet, same spatial arrangement of stimulators, same stimulus materials, same stimulus timing, and same subjects were used in both experiments.

The light box for the visual part of the experiment is described in Sec. VI. In this experiment the NE-2H lamps were replaced with NE-2 neon lamps because of their better temporal firing characteristics. Twelve of the 24 lamps were simultaneously gated on for 100 ms to produce the stimulus patterns. The visual display box was placed 114 inches from the subject and subtended a visual angle of 2 degrees at the subject's eye. The average brightness of the white cardboard mask was 46 fL, and that of the lamps 140 fL.

The array of tactile airjet stimulators and their use in this experiment is as described in Sec. III. The same airjets simultaneously stimulated 12 of the 24 interjoint regions of the hand. The jets were gated on and off for a 100-ms interval to produce the 1-ms air pressure pulses shown in Fig. 2 at a 150 Hz rate.

2. Subjects

Two college students served as paid subjects. Subject EB was a male college sophomore and subject MS was a male graduate student. Both subjects had at least two months' intermittent practice on similar tactile and visual perception experiments using the same types of stimulus materials and the same response alphabet.

3. Procedure

The testing schedule used, in both the tactile and visual parts of the experiment is given in Table XVI. The testing schedule is a factorial design with six balanced marker delays, two balanced replications, and two balanced erasure conditions. In addition two whole report sessions are included in the design to measure the subjects' span of apprehension. In both the tactile and visual experiments, 66 presentations for each session were chosen to allow the variance of the number of positions available to be a constant ($\sigma = 1.10$ positions), under the constraint that the duration of each experiment be 10 days.

Each subject participated in the experiments for approximately a one-hour period each day. During this period he was paced through the next part of his sequential test schedule. Since the sessions of the test schedule varied from 10 to 15 minutes each, and a 5- to 10-minute rest period was allowed between sessions, a variable number (from 3 to 4) of sessions were completed each day. Both subjects completed the tactile portions of the experiment first and then the visual portion.

On any one trial, 12 stimuli (four airjets or four lamps per row) were chosen (by the computer) out of the 3×8 arrays. The subjects were asked to report only the four stimuli in the row specified by the marker lamp using the response alphavet shown in Fig. 3. A more complete description of the subjects' reporting scheme used in both visual and

Table XVI

PARTIAL REPORT DESIGN

Session	Marker	Erasure	Session	Marker	Erasure
1	-0.75	Without	14	-0.75	With
2	0.0	Without	15	0.0	With
3	0.1	Without	16	0.1	With
4	0.3	Without	17	0.3	With
5	0.8	Without	18	0.8	With
6	2.0	Without	19	2.0	With
7	Whole Report		20	Whole Report	
8	2.0	With	21	2.0	Without
9	0.8	With	22	0.8	Without
10	0.3	With	23	0.3	Without
11	0.1	With	24	0.1	Without
12	0.0	With	25	0.0	Without
13	-0.75	With	26	-0.75	Without

tactile parts of this experiment is described in Sec. III. In a given session the 250-ms duration marker lamp came on a fixed time called the marker delay (either -0.75, 0.0, 0.1, 0.3, 0.8, or 2.0 s) after the termination of the stimuli. In the erasure condition, all 24 of the stimuli were simultaneously turned on with the marker lamp.

C. Results

The responses made by the subjects on each tactile and visual session were corrected for guessing with Model II described by Hill and Bliss (1968a) to obtain the accuracy of the four reports in each of the three rows. The reporting accuracies for each modality (tactile and visual) and each erasure condition were given an analysis of variance

to determine the significant dependencies on the three controlled variables. The analysis of variance summaries are given in Tables XVII and XVIII. The tables show that marker delay significantly influenced reporting accuracy in all four cases. With the tactile stimuli, marker delay was the only significant variable; however, with visual stimuli, several additional variables and interactions are significant.

The results of each subject on each modality are shown in Fig. 37. The number of positions available was computed from the reporting accuracy using the method described by Sperling (1960). Figure 37 indicates that both subjects' scores were similarly affected by marker delay and erasure in each of the four different cases. The results of both subjects were averaged together as shown in Fig. 38.

The tactile results without erasure shown in Fig. 38 are very similar to those obtained in a previous experiment from three sighted subjects and one late blind subject (Hill and Bliss, 1968a). Figure 38 shows that the tactile Sensory Registor capacity or number of positions available with zero marker delay is 5.0 positions (versus 4.9 positions measured previously), the tactile short term store capacity or number of positions perceived in the whole report is 3.4 positions (vs. 3.3 positions), and the time constant of the decaying tactile sensory register capacity is about 1.0 s. (vs. 1.3 s). Thus, the tactile partial report results of the two subjects reported here further substantiate the tactile information processing model described by Hill and Bliss (1968a).

The additional feature investigated in this experiment is the tactile erasure stimulus coincident with the marker. As is shown in Fig. 38, when the marker and erasure preceded the stimulus by 0.75 s, partial report performance was reduced by 1.2 positions (significant, $p < 0.05$) indicating that the tactile system had not yet recovered from the tactile erasure stimulus when the pattern stimulus arrived. This finding

Table XVII

SUMMARY OF ANALYSIS OF VARIANCE OF THE REPORTING ACCURACY IN THE TACTILE PARTIAL REPORT

Source	df	Without Erasure			With Erasure		
		Mean Square	F	Significance	Mean Square	F	Significance
Marker Delay-(M)	5	.225	10.2	$p < .025$	.647	6.05	$p < .05$
Subjects X M	5	.022			.107		
Response Row (RR)	2						
Linear	1	.127	-		.020	-	
Quadratic	1	1.090	1.72		.201	-	
Subjects X (RR)	2	.632			.494		
Report (R)	3	.040	-		.052	1.53	
Subjects X R	3	.056			.034		
M X RR	10	.049	1.36		.114	1.05	
Subjects X M X RR	10	.036			.109		
M X R	15	.023	1.04		.038	2.11	
Subjects X M X R	15	.022			.018		
R X RR	6	.091	3.04		.023	-	
Subjects X R X RR	6	.030			.045		

Table XVIII

SUMMARY OF ANALYSIS OF VARIANCE OF THE REPORTING ACCURACY IN THE VISUAL PARTIAL REPORT

Source	df	Without Erasure			With Erasure		
		Mean Square	F	Significance	Mean Square	F	Significance
Marker Delay-(M)	5	.700	7.61	$p < .025$	3.530	48.4	$p < .001$
Subjects X M	5	.092			.073		
Response Row (RR)	2						
Linear	1	1.425	39.6	$p < .025$	1.519	1.52	
Quadratic	1	.688	19.1	$p < .05$	.494	-	
Subjects < (RR)	2	.036			1.000		
Report (R)	3	.398	2.54		.834	41.5	$p < .01$
Subjects X R	3	.157			.020		
M X RR	10	.126	6.29	$p < .005$	.107	-	
Subjects X M X RR	10	.020			.189		
M X RR	15	.045	2.50	$p < .05$	.045	-	
Subjects X M X R	15	.018			.052		
R X RR	6	.084	13.9	$p < .005$	.017	1.06	
Subjects X R X RR	6	.006			.016		

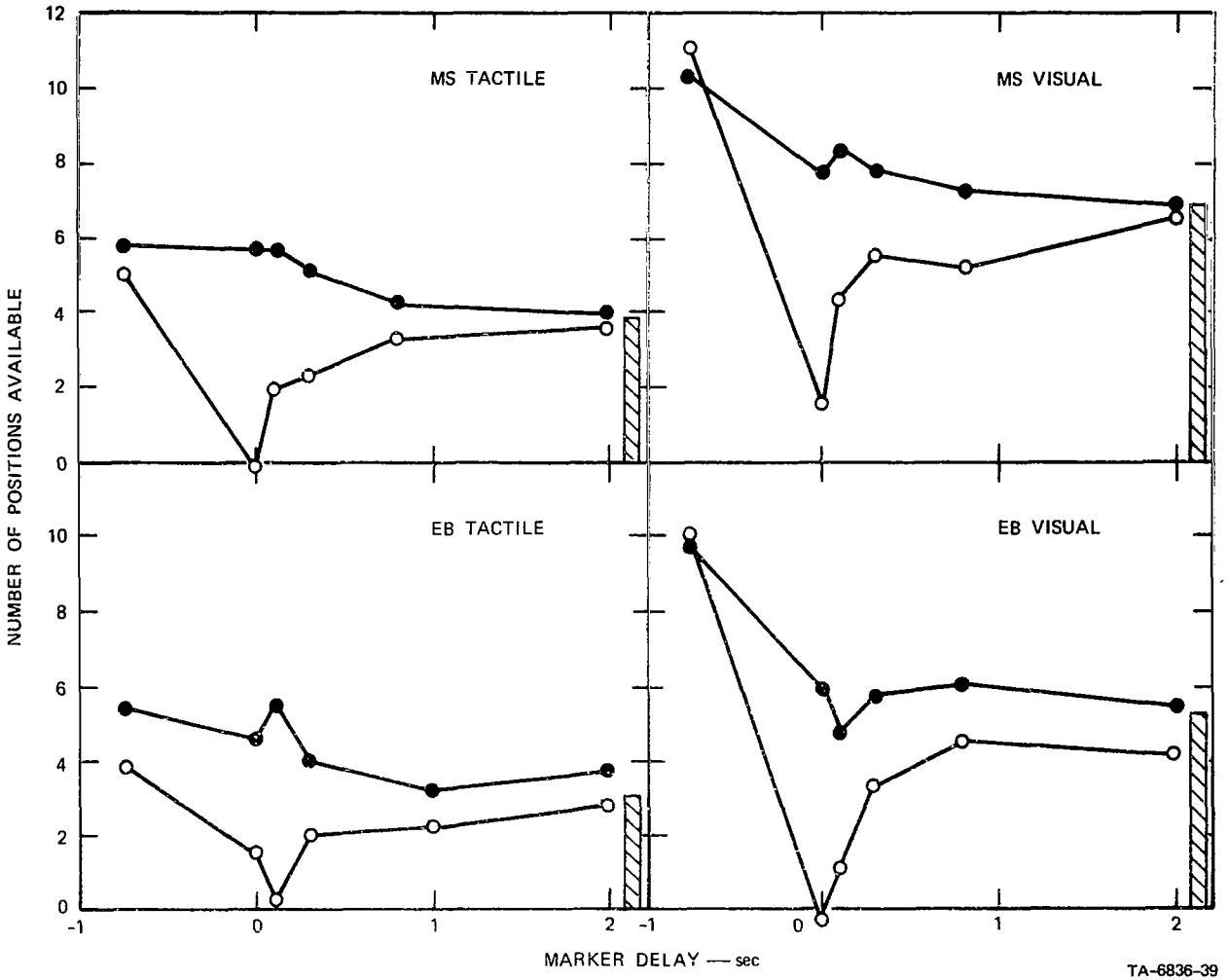

FIG. 37 RESULTS OF THE TWO SUBJECTS ON THE TWO PARTS OF THE PARTIAL REPORT EXPERIMENT

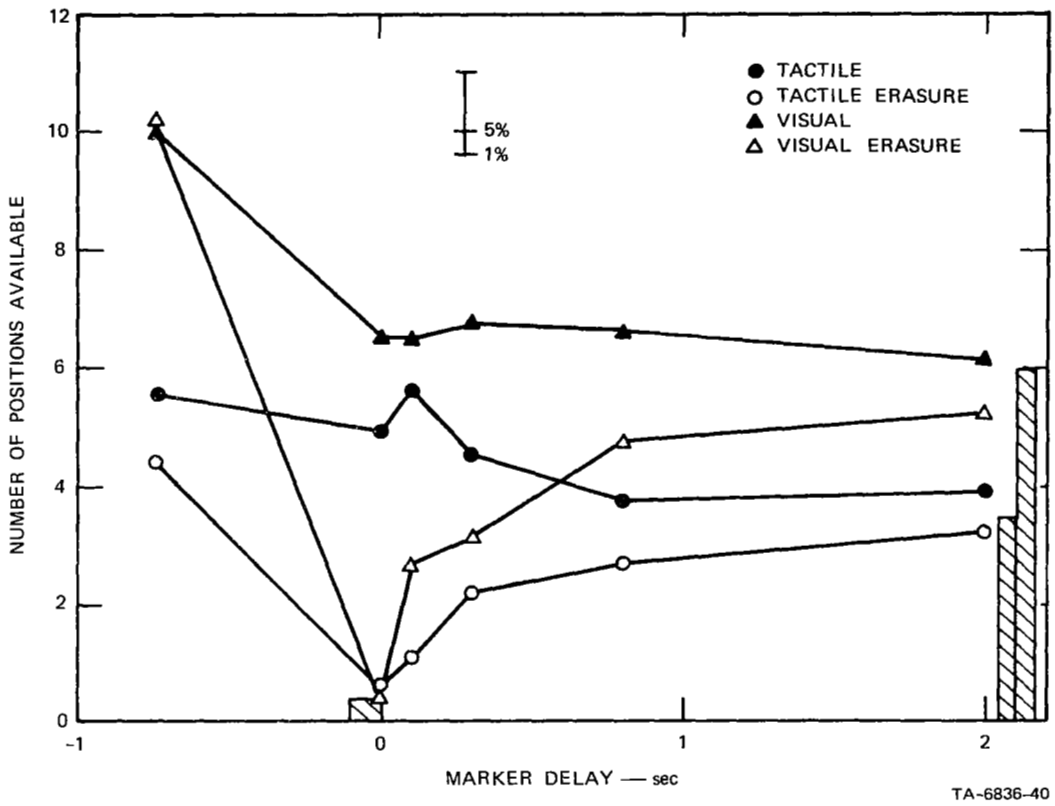

FIG. 38 AVERAGE PARTIAL REPORT RESULTS OF TWO SUBJECTS WITH BOTH MODALITIES AND ERASURE CONDITIONS

is in agreement with that of Bliss, Crane, Mansfield, and Townsend (1966, Table 2), which showed that recovery is not yet complete two seconds after a tactile reinforcement pattern. Their tactile reinforcement may be considered to be an erasure stimulus, since it was a random pattern not related to the stimulus pattern. When the erasure stimulus occurs immediately after the pattern stimulus ends (zero marker delay in Fig. 38) the number of positions available is practically reduced to zero. Increases in marker delay enable more and more of the tactile patterns to be correctly reported.

The results of the visual partial report are also shown in Fig. 38. One obvious difference between visual and tactile partial reports is the difference in magnitude between them: visual scores are as much as twice as high as tactile scores. The surprising feature of the visual partial report is the lack of a visual sensory register for these dot patterns! The partial report with zero marker delay (6.5 positions) is not significantly higher than the whole report from the same patterns (5.9 positions). The visual results of Sperling (1960, Fig. 7) obtained with arrays of 12 letters showed that, with zero marker delay, subjects had many more letters available than they did in their whole reports (11 versus 4.7 letters). This difference between visual letter and dot patterns perception experiments indicates that there may be some fundamental differences between the type of human information processing involved in the two cases.

The addition of an erasure stimulus affected visual performance somewhat differently than the tactile performance. With the marker preceding the stimulus pattern (-0.75 s marker delay), the number of positions available was the same with or without the erasure stimulus, indicating that for dot pattern recognition, the visual system has completely recovered in this time interval. As discussed previously, the tactile system is not fully recovered two seconds after a tactile

erasure stimulus. These different results suggest that either the visual system has a different recovery dynamics for the erasure or initial condition reset mechanism than the tactile system, or that tactile afterimages are much longer than visual afterimages. With a marker delay of zero, the erasure stimulus effectively reduces the subjects' reports to zero as in the tactile case. Increasing long marker delays allow more and more positions to be reported in both visual and tactile experiments.

To determine whether the scanning mechanisms used by the subjects in these experiments are serial or parallel, the subjects' reporting accuracy in the erasure condition is plotted against marker delay in Fig. 39. Here the accuracy of each response (first through fourth) is seen to increase along similar curves in both the tactile and visual conditions. Following the argument given by Sperling (1967), equal initial slopes describe a parallel scan model and higher first than last response slopes describe a serial scan model. A brief explanation for this expected difference is as follows: Assuming that the erasure stimulus erases the sensory register contents, the display is only available to the subject for a brief, well-defined interval. As this interval is made longer, a serial scanner will transfer more and more positions, and the first responses will become more accurate before the later ones; a parallel scanner will transfer positions irrespectively of location, and the accuracy at each location will grow similarly with the stimulus interval. Following this argument, the results of Fig. 39 suggest a parallel scanner model for both tactile and visual dot pattern perception. The hypothesis that there is no difference between the time course of the four responses in Fig. 39 is tested by the Marker $\times$ Response Row interaction of tables XVII and XVIII. Neither interaction was significant, and we must assume that there is insufficient evidence to show that the curves are different (i.e., insufficient evidence for a serial model).

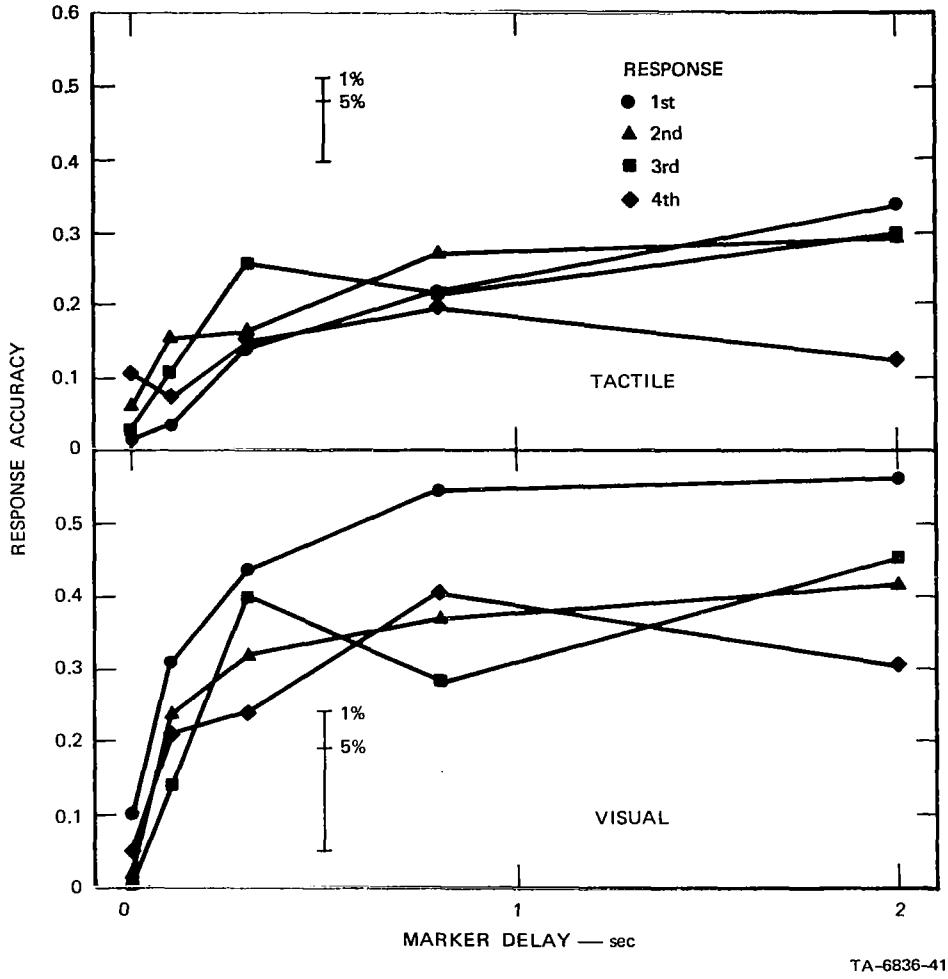

FIG. 39 ACCURACY OF EACH SERIAL RESPONSE AS A FUNCTION OF MARKER DELAY FOR TWO SUBJECTS

D. Discussion

The most surprising result of the partial report experiment is the lack of evidence for a visual sensory register. There are several possible explanations, however, for the missing sensory register. Since letter recognition is not involved in this experiment, perhaps the visual sensory register is associated with the letter recognition process, i.e. that a single letter recognizer is not scanned across the fading retinal afterimage, but that the scanning process operates on the fading outputs of a parallel bank of pattern recognizers. Another explanation is that there is a two-stage scanner consisting of an object locator capable of making only binary decisions and a pattern recognizer (Shaw, 1968). Again, if the short term memory were associated with the pattern recognizer, this model would reconcile the visual letter and dot pattern results. Still another, perhaps more fundamental, difference between our visual dot pattern experiment and previous letter experiments is that the marker information in our experiment was conveyed by the same visual display and not by a separate modality. The lack of a measurable sensory register in this case could be due to the interference of the marker with the dot display.

These alternative explanations suggest simple modifications of the visual dot pattern experiments that might reconcile the outcome of these experiments with previous letter experiments. A measurement of the number of positions available with zero marker delay using three tones to denote the response rows would replicate Sperling's (1960) original conditions more exactly. A similar measurement made attaching letters to the front of our lamps could show whether visual short term memory was dependent on the alphabetic character shapes rather than location alone.

It is important to determine whether the differing tactile-visual data are due to the absence of a visual sensory register for these dot patterns or are due to the marker modality used in the experiment. The difference between tactile and visual data is important from the point of understanding the tactile information processing chain. We had previously assumed that a tactile sensory register with certain well-defined spatial and temporal properties (Hill and Bliss, 1968a) could account for the observed results; however, in the visual case, where considerable evidence for a sensory register has already been shown, the analogous dot pattern experiments do not seem to support a sensory register model. If the visual data are not simply due to marker modality as previously discussed, then further experiments and modeling attempts should be carried out to explain the source of the tactile sensory register.

An important question to be answered by the two erasure experiments is how the erasure stimulus actually affects the visual and tactile sensory inputs. One hypothesis, the erasure hypothesis, assumes that subsequently presented information can supplant current information. This hypothesis has been fostered by Sperling (1963), Averbach and Corrill (1961), and Fehrer and Raab (1962). Another hypothesis, the temporal summation hypothesis, assumes that subsequently presented information summates with current sensory information. Ericksen and Hoffman (1963), Ericksen and Collins (1964, 1965) give evidence to support the later hypothesis. The summation hypothesis predicts that the interference caused by an erasure stimulus will be symmetrical in time (i.e. the same reduction in performance will occur whether the erasure stimulus appears a given time before or after the pattern stimulus), while the erasure hypothesis predicts little or no interference when the erasure stimulus precedes the pattern stimulus (pattern supplants erasure) but significant interference in the reverse order (erasure supplants pattern).

The data of Fig. 38 suggest that different hypotheses may explain the results of the two different modalities. Here a comparison of temporal interference symmetry can be made by comparing the erasure scores with +0.8 s and -0.75 s marker delays. The results in the tactile case appear symmetrical, suggesting the summation hypothesis, since the erasure stimulus at -0.75 s reduces performance by 22 percent and at +0.8 s reduces performance about the same amount (27 percent). The visual results are definitely unsymmetrical, suggesting the erasure hypothesis, since the -0.75 second erasure stimulus does not affect performance, while the +0.8 second erasure reduces performance by 28 percent.

Carrying the visual erasure hypothesis further, the initial slope of the visual erasure curves of Fig. 38 with positive marker delay measure the overall input rate. This follows from the idea that the erasure supplants the current information, making it available for input only for a definite period of time. The visual rate measured this way is 50 ms/position. Although the tactile data may not support the erasure hypothesis, the slope of the equivalent tactile data is only 200 ms/position, indicating that if a separate tactile scanner were involved, it is considerably slower than the visual one. The accuracy of both of these estimated slopes is about ±50 percent because of the uncertainty in the data points of Fig. 38.

Carrying the tactile summation hypothesis further, the upward sloping tactile erasure curves of Fig. 38 measure the decay of the tactile afterimage. Arbitrarily fitting this curve with an exponential function (assuming an exponential decay) gives a time constant of 0.6 second. Interestingly enough, when the visual data is fitted with the same exponential curve, the resultant time constant is also 0.6 second!

The tolerance on both time constants is about ±100 ms. This tactile-visual similarity suggests that there may be a feature common to the tactile and visual information processing chains.

E. A Proposed Visual-Tactile Information Processing Model

If it is assumed that the visual sensory register exists, but was not properly measured in this experiment, it is possible to explain all of the experimental data with one model having two sensory input channels, and a common spatial-position to letter translator (see Fig. 40). This model combines the sensory register of the temporal

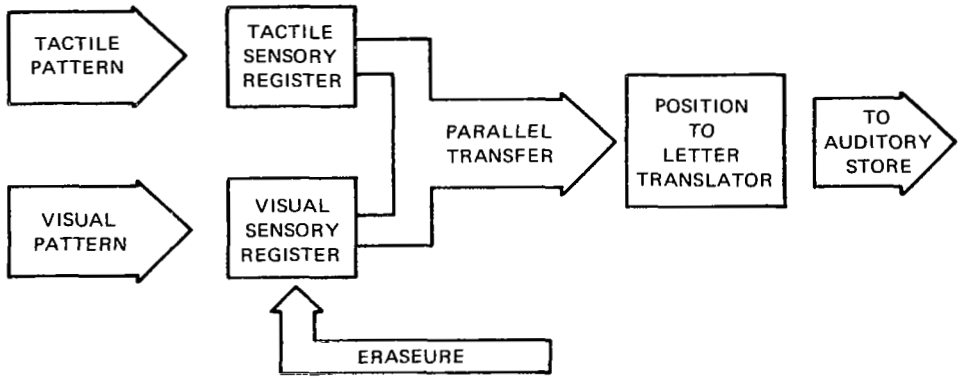

FIG. 40 MODEL FOR VISUAL-TACTILE PATTERN PROCESSOR

summation model with the scanner (or translator) of the erasure model. The basic idea is that the parallel translator differentiates stimulated from nonstimulated positions on the basis of intensity at a maximum overall rate (the equivalent scanning rate), and that the erasure stimulus presented in these experiments summates with the sensory register contents to render the stimulus positions undifferentiable. In this model the partial report experiment without the erasure stimulus measures the persistence and capacity of the sensory registers, and the

partial report experiment with erasure measures the speed and capacity of the translator. The model requires the following assumptions:

(1) Both tactile and visual sensory registers can be described spatially by a spread model (Hill and Bliss, 1968a) and can be described temporally by a persistence (decaying afterimage) of a given time constant.

(2) Both sensory registers are described by the temporal summation hypothesis.

(3) The visual sensory register either has a time constant short with respect to 0.75 second or else has an erasure input that is internally activated.

(4) A parallel, limited capacity, position to letter translator that can store only 60 percent of positions in the patterns available to it and has an overall processing rate described by a 0.6 second time constant.

Assumption (1) explains the differing capacities with negative marker delay (visual, 10.0 positions available; tactile, 5.6 positions). The spreading model attributes this less than perfect performance to the jumbling of the input pattern, not its attenuation. This spreading model is substantiated in similar tactile dot pattern perception experiments (Hill and Bliss, 1968a) but has not yet been tested against the visual dot pattern data.

Assumption (3) is necessary to explain the recovery of the visual input from the erasure stimulus at -0.75 second marker delay. At this marker delay, partial report scores with and without erasure are the same. One explanation is that the subject can voluntarily remove the effect of the erasure stimulus by voluntarily blinking or refixating his eyes in the 0.75-second interval. Another explanation is that the visual afterimage decays fast enough so that the stimulus pattern is readily visible superimposed on the attenuated erasure stimulus 0.75 s

later. This second hypothesis can be tested later when the experiment is replicated with another marker modality allowing the sensory register time constant to be measured.

The processor of the model is the position to letter translator (assumption 4) that accepts the filtered patterns of the sensory registers and decides on an intensity basis which positions were stimulated. The intensity input (assumption 2) at any time is determined by the persistence (assumed to be an integrator with a given time constant) of each modality. Without the erasure stimulus, the sensory register information dies out with the given time constant. With the erasure stimulus, the sensory register contents at any time is a linear sum of the stimulus pattern and erasure pattern weighted by the persistence time constant. In the erasure stimulus case with zero marker delay, subject performance is zero, indicating that the resultant intensity difference between a 350 and a 250 ms exposure is not detectable. It follows that with any positive marker delay the different intensities after the occurrence of the erasure stimulus are also not detectable, because the stimulus intensity will be lower than when originally presented. In this erasure stimulus case, the translator can only process the sensory register information from the time the stimulus pattern begins to the time the erasure stimulus begins. The data of Fig. 38 indicate that both tactile and visual erasure curves increase with a 0.6-second time constant with positive marker delays. Also both curves reach a maximum of 60 percent (58 percent for visual, 61 percent for tactile) of their respective maximum sensory register capacities (measured at -0.75 second marker delay) indicating that the maximum capacity of the translator is 7.2 positions and that the initial input rate is 600 ms/7.2 position, or 83 ms/position in this case.

The predicted dot pattern, partial and whole report performance of this model with positive and negative marker delays is shown in Fig. 41. The time constant of the decaying sensory register is denoted by τ_1, and that of the translator by τ_2. The model presented here tries to incorporate the results of the previous tactile dot pattern data, and previously reported visual data, together with the data of the experiment into a single information processing block. The form of the model can be tested with further dot pattern experiments.

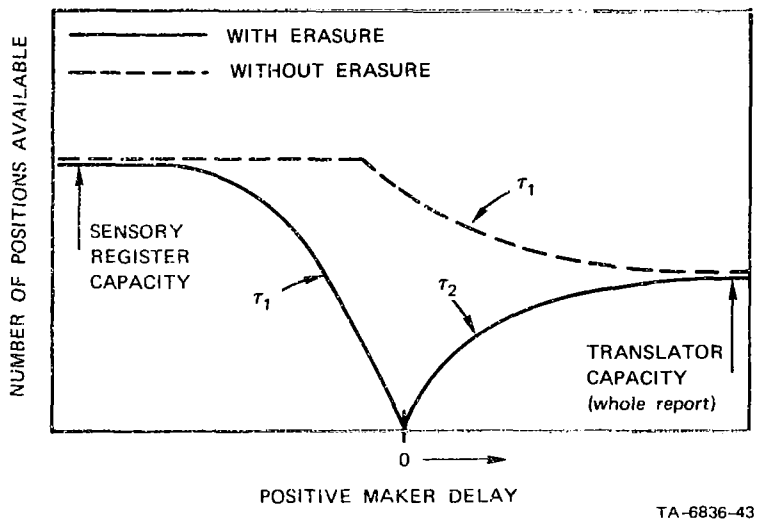

FIG. 41 HYPOTHETICAL RESULTS OF A SHORT-TERM-MEMORY EXPERIMENT

VIII FURTHER ANALYSIS OF SEQUENTIALLY PRESENTED POINT STIMULATION DATA

A. Introduction

Hirsh and Sherrick (1961) described a series of perceived order experiments on the tactile as well as on visual and auditory senses. Their results show that all three modalities have equal abilities to differentiate between two temporal stimuli. They hypothesize that there is a central temporal decision maker common to these three sense modalities. More recent experiments by Babkoff and Sutton (1963) (auditory), and Robinson (1967) (visual), show that the site of stimulation and intensity cues influence the temporal limen. In particular, separate stimuli presented to separate eyes or ears (dichoptic or dichotic) are perceived with greater temporal accuracy than are stimuli presented to only one sense organ or sensory surface. The above authors do not give data to disprove Hirsh and Sherrick's (1961) concept of a constant temporal limen when the two stimuli are presented on the same sensory surface.

Gescheider (1965, 1966) conducted experiments to determine the interstimulus interval where two tactile point stimuli appeared as two successive taps rather than one. He found that this "simultaneous vs successive" limen varied from 1 ms with closely spaced stimuli on a finger to 11 ms for stimuli on separate hands. Gescheider's measure is not the same as the temporal limen, because stimuli that are separated sufficiently in time to be recognized as two rather than one event (were there one or two?) cannot be ordered in time (which came first?) until the time interval is considerably increased.

In a previous experiment (Hill and Bliss, 1968b) the perception of two and three sequentially presented point stimuli on the hands is described. In this sequential experiment n (n = 2 or 3) brief (10 ms)

jets of air are sequentially presented to any of the 24 interjoint regions of the fingers (thumbs excluded). The subjects' task was to report the region stimulated in the order stimulated. One of the interesting results of the sequential experiment was that the sequential error was very uniform for different subjects and may represent a basic limit on human temporal resolution with tactile inputs following Hirsh and Sherrick's (1961) speculation.

B. Analysis

In order to further investigate human temporal resolution between different body locations, the data of the sequential experiment with two stimuli (n = 2) were broken down to make two additional analyses. The first analysis compares temporal resolution when both stimuli were on one hand to that when the stimuli were on separate hands. This analysis tests whether one hand has better temporal resolving power than two. The second analysis compares temporal resolution when both stimuli are on the same hand but occur on the same finger, neighboring fingers, etc., up to and including fingers on the extreme sides of the hand. This analysis tests whether resolution depends on finger spacing.

The measure for temporal resolution for both of these analyses is the sequential error fraction. The sequential error fraction is the fraction of reversed stimulus pairs (i.e. if the stimulus order was AB and the response was BA). When the stimuli are presented with a sufficiently small interstimulus interval (i.e. the interval from the termination of the first stimulus to the onset of the second), subjects can only guess at the correct order and their sequential error fraction is 0.5 for n = 2. When the stimuli are presented with a sufficiently long interstimulus interval, subjects always report in the right order and the sequential error fraction is zero. The temporal limen is the intermediate point where the sequential error fraction is 0.25.

To make the analysis as unambiguous as possible and more independent of the localization part of the experiment than the previous sequential error analysis, only the correctly reported patterns were considered. Each of the locations of a stimulus pattern had to be correctly reported for the stimulus pattern to be included in this analysis. This accuracy restriction eliminated about 30 percent of the patterns from the sequential analysis. Because of this restriction, however, no guessing correction had to be applied to these patterns.

The data for the one hand vs two hand analysis are shown in Fig. 42, and analyzed with an analysis of variance in Table XIX. Figure 42 shows little difference between the two conditions. In the analysis of variance of Table XIX the Hands × Interstimulus Interval ($H \times T_i$) tests the hypothesis that the temporal limen is the same for one hand as for two. Since this hypothesis is acceptable, we assume that there is insufficient data to show any differences in the limen.

Table XIX

ANALYSIS OF VARIANCE OF SEQUENCE ERROR FRACTION
FOR 5 SUBJECTS WITH n = 2

Source	df	Mean Square	F Ratio	P
Hands (H)	1	0.00106	2.11	
Series (S)	1	0.00005	--	
T_i	4	0.02115	419	0.001
$H \times S$	1	0.00002	--	
$H \times T_i$	4	0.00131	2.60	
$S \times T_i$	4	0.00143	2.87	
$H \times S \times T_i$	4	0.00050		

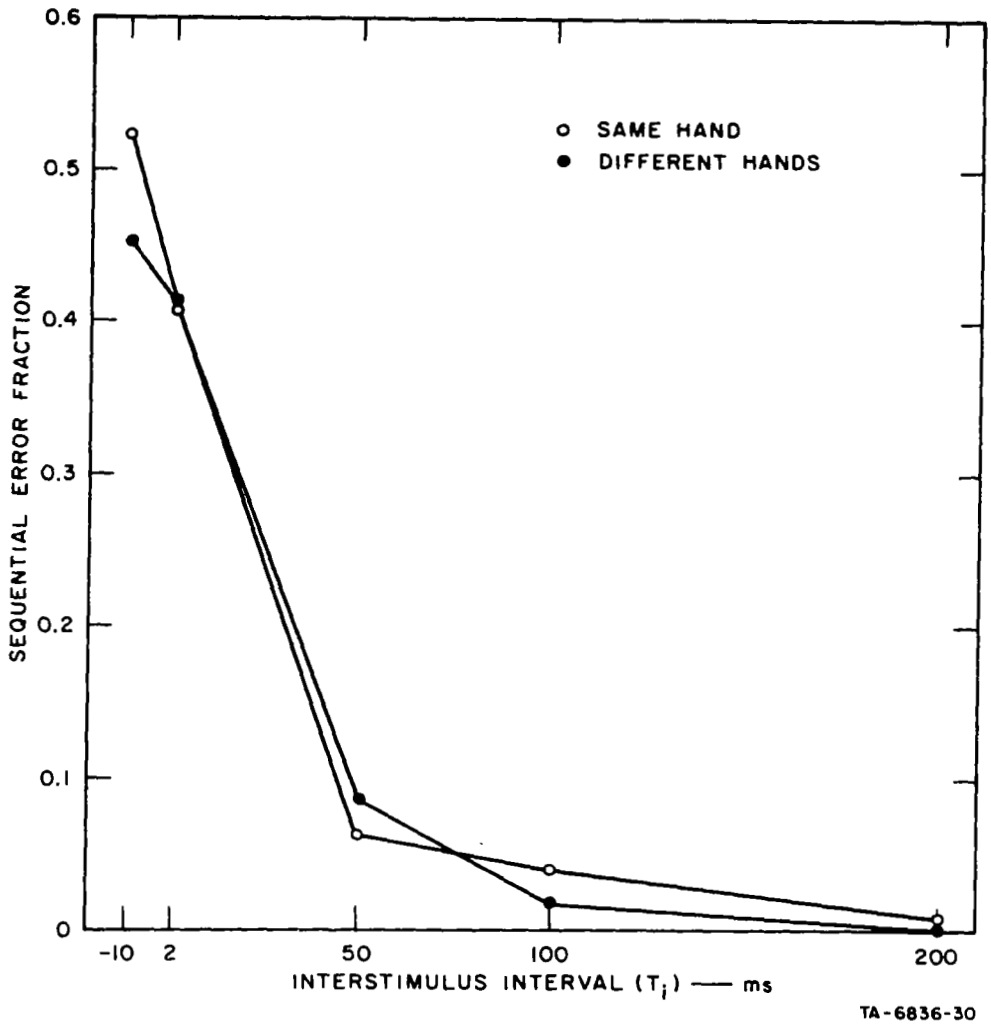

FIG. 42 COMPARISON OF SEQUENTIAL ERROR WHEN STIMULI APPEAR ON THE SAME OR ON DIFFERENT HANDS

The data for the finger-spacing analysis are given in Fig. 43 and are analyzed with an analysis of variance in Table XX. Figure 43 shows that there was a decrease in sequential error with finger spacing at T_i = 2 ms, suggesting that the temporal limen was less for more closely spaced tactile stimuli. In Table XX the Finger Spacing × Interstimulus Interval (F × T_i) tests the hypothesis that the temporal limen is the same for all finger spacings. Since the hypothesis is not rejected, we assume that there is insufficient evidence to show any differences in limen with finger spacing.

However, the data of Fig. 43 suggest that temporal limen may decrease with decreased stimulus spacing, thus further exploration may be warranted. In the first place, the Interstimulus Intervals chosen for the experiment are not the most appropriate for measuring this temporal limen. The data of Figs. 42 and 43 show that the tactile temporal limen is about 30 ms. To most effectively measure this limen, values of T_i between 10 and 40 ms should be used. In the second place, if better temporal resolution results from closer stimulator spacings, smaller tactile displays may be more effective for communicating timing information to human operators.

Table XX

ANALYSIS OF VARIANCE OF SEQUENTIAL ERROR FRACTION FOR 5 SUBJECTS WITH TWO STIMULI ON THE SAME HAND

Source	df	Mean Square	F Ratio	P
Series (S)	1	0.00380	--	
Finger Spacing (F)	3	0.00332	--	
T_i	4	0.50650	47	0.001
S × F	3	0.02225	2.08	
S × T_i	4	0.00181	--	
F × T_i	12	0.01315	1.22	
S × F × T_i	12	0.01695		

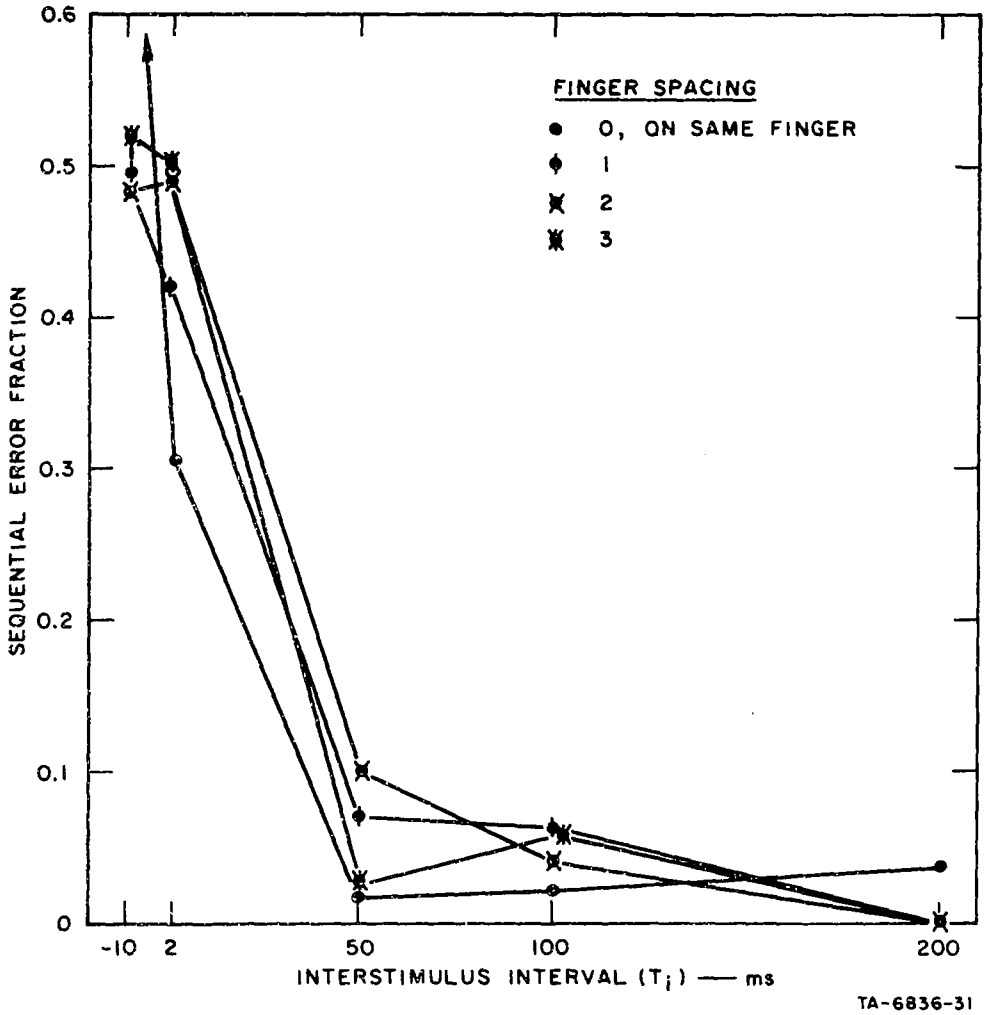

FIG. 43 COMPARISON OF SEQUENTIAL ERROR ON ONE HAND WITH DIFFERENT STIMULUS SPACINGS

IX THE PERCEPTION OF SEQUENTIALLY PRESENTED VISUAL AND TACTILE PATTERNS WITH FOUR AND SIX STIMULI

A. Introduction

A previous experiment (Hill and Bliss, 1968b) with two and three sequentially presented tactile stimuli showed that subjects' ability to localize the stimuli did not depend on the stimulus onset interval (SOI), but that their ability to temporally order the stimuli depended strongly on SOI. Furthermore, the simple normal distribution model for temporal order did not hold in the three-stimulus case, but a model with a constant information uptake rate could explain the results. In order to obtain additional sequential data that would be more demanding of the theory and models suggested by the two- and three-stimuli cases, similar experiments with four and six sequentially presented stimuli were carried out.

In a paper on temporal resolution in three different modalities, Hirsh and Sherrick (1961) presented data to show that, with two stimuli, auditory, visual, and tactile temporal resolutions are the same. The failure of their simple temporal resolution model to describe the tactile three-stimulus case leads to questions about the temporal equivalence of the modalities when more than two stimuli are sequentially presented. To further compare tactile and visual temporal resolutions with a larger number of stimuli, the same four and six stimulus experiments were conducted with the analogous visual display described in Sec. VI.

B. Method

1. Apparatus

The array of tactile airjet stimulators used in this experiment is described in Sec. III. The same airjets sequentially stimulated n (n = 4 or n = 6) interjoint regions of the hands. When activated, each jet produced the pressure pulses shown in Fig. 44. The duration of each pulse was about 7 ms, and the peak pulse pressure about 1 $\ell bf/in^2$. A typical skin deflection waveform resulting from the pressure pulses is shown in Fig. 45. The maximum skin deflection in Fig. 45 is about 100 μ.

The visual display box used in the visual part of the experiment is described in Sec. VI. A given number of the lamps were sequentially gated on for a 5 ms period to produce the stimulus patterns. The bulbs all fired within 25 μs of the gate onset and were extinguished within 25 μs after the gate offset. The light box was placed 114 inches in front of the subject's eyes and subtended a visual angle of 2 degrees at this distance. The brightness of the white cardboard mask was 46 fL and of the bulbs, when on, was 420 fL.

2. Subjects

Two college students served as paid subjects. Subject EB was a male college sophomore and subject MS was a male graduate student. Both subjects had at least two months' intermittent practice on similar tactile and visual perception experiments using the same types of stimulus materials and the same alphanumeric response alphabet.

3. Procedure

Each subject participated in the experiments for approximately a one-hour period each day. During this period he was paced through the next part of his sequential test schedule. Since the sessions of the test schedule varied from 10 to 15 minutes each, and a 5- to 10-minute

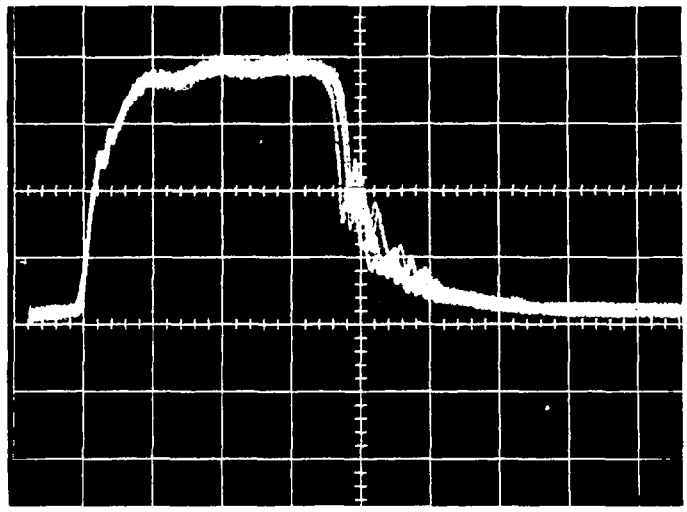

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FIG. 44 FIVE SUPERIMPOSED AIR PRESSURE PULSES

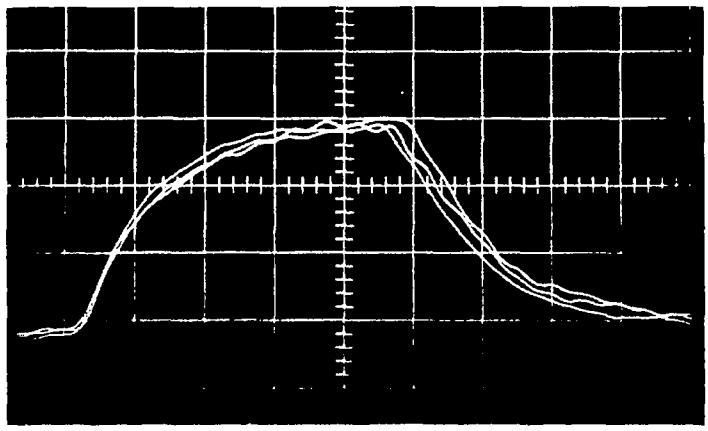

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FIG. 45 THREE SUPERIMPOSED SKIN DEFLECTION WAVEFORMS

rest period was allowed between sessions, a variable number (from 3 to 4) of sessions were completed each day.

The testing schedule for both parts of the experiment is given in Table XXI. Both subjects completed the tactile version of the experiment first and then the visual version. The testing schedule is a factorial design with six stimulus onset intervals in random order, two balanced values of n, and two balanced replications. In both the tactile and visual versions of the experiment, the sessions with n = 4 consisted of 36 stimulus presentation, and those with n = 6 consisted of 48.

Table XXI

TESTING SCHEDULES FOR BOTH TACTILE AND VISUAL SEQUENTIAL EXPERIMENTS

Session	SOI	n	Session	SOI	n
1	100	4	13	100	6
2	0	4	14	200	6
3	200	4	15	0	6
4	25	4	16	50	6
5	50	4	17	10	6
6	10	4	18	25	6
7	0	6	19	50	4
8	25	6	20	100	4
9	100	6	21	200	4
10	50	6	22	10	4
11	200	6	23	25	4
12	10	6	24	0	4

These numbers were chosen to allow the variance of the number of positions perceived to be a constant (σ = 0.23 positions), under the constraint that the duration of each experiment be 10 days. The location of the positions stimulated on each trial was random within the constraint that each position was stimulated the same number of times per session.

On any one trial, n stimulus positions were chosen by the control computer out of the 3 X 8 arrays. The stimulus positions were assigned a random order (by the computer) and gated on sequentially with a given stimulus onset interval. (The SOI is the time interval between the onset of the first and second pulse, second and third pulse, etc.) In a given session the SOI was either 0 (simultaneous presentation) 10, 25, 50, 100, or 200 ms. In any one session n was constant and known by the subjects, and the SOI was constant but unknown. The subjects were asked to report the positions stimulated in the order that they were stimulated, using the alphanumeric reporting alphabet described in Sec. III. A typical verbal response with n = 4 would be 2H3A1B1C. The responses were typed into the control computer by the experimenter. After a response was typed in, the next stimulus pattern was presented after a 4-second time delay.

C. Results

Subjects in this experiment could make two different types of errors: errors in identifying the spatial location and errors in identifying the temporal order of the stimuli. Several statistical measures were previously derived to account for these spatial and temporal errors (Hill and Bliss, 1968b); they will not be repeated here in detail. Two of these measures used in the analysis of this experiment are:

(1) Content Positions--The number of positions perceived in the correct spatial location, independent of sequence.

(2) Content and Sequence Positions--The number of positions perceived in the correct temporal location and in the correct spatial location.

An analysis of variance was performed on the Content Positions and on the Content and Sequence Positions to determine the significant influences of both SOI and n for the two input modalities. The results of these analyses are shown in Tables XXII and XXIII. The data on which the analyses are based are shown in Fig. 46. The same data averaged over the two subjects are shown in Figs. 47 and 48.

The most striking result of this experiment is the strong dependence of the number of Content Positions perceived by the subjects and SOI. With n = 6 the number of Content Positions perceived reaches a minimum at a 50 ms SOI. With n = 4 the drop with increasing SOI is not as large but it is still significant. The number of Content Positions perceived with both tactile and visual stimuli depends linearly and quadratically on SOI (see Table XVII). This result is different from that obtained by Hill and Bliss (1968b) using basically the same experimental paradigm with n = 2 and 3 instead of n = 4 and 6. The previous findings showed that the subjects' ability to localize the positions of the stimulus patterns did not depend on SOI. Apparently, with a greater number of stimuli, there is some masking or other interaction that reduces stimulus localizability or detectability. The number of content positions perceived in both of these experiments are shown in Fig. 49 for comparison. The overall performance levels of Fig. 49 are not meaningful, since different subjects participated in the two experiments; however, the changes in performance level with SOI are.

The number of Content Positions perceived with visual and tactile stimuli changes differently with increasing SOI. Figures 47 and 48 show that even though the number of Content Positions perceived visually is higher than that perceived tactually with SOI = 0, visual performance drops more sharply with SOI. With a SOI of 50 ms, visual performance has

Table XXII

SUMMARY OF ANALYSIS OF VARIANCE OF THE CONTENT POSITIONS PERCEIVED

Source	df	Tactile Stimuli			Visual Stimuli		
		Mean Sq.	F	Significance	Mean Sq.	F	Significance
SOI	5						
Linear	1	0.737	15.7	$p < 0.025$	6.727	62.8	$p < 0.001$
Quadratic	1	0.851	18.1	$p < 0.01$	2.596	21.4	$p < 0.01$
Remainder	3	0.026	--		0.298	2.78	
Subjects X SOI	5	0.047			0.107		
n	1	0.0102	6.71		0.267	--	
Subjects X n	1	0.0018			0.378		
SOI X n	5	0.053	--		0.490	15.3	$p < 0.005$
Subjects X SOI X n	5	0.096			0.032		

Table XXIII

ANALYSIS OF VARIANCE OF THE CONTENT AND SEQUENCE POSITIONS PERCEIVED

Source	df	Tactile Stimuli			Visual Stimuli		
		Mean sq.	F	Significance	Mean Sq.	F	Significance
SOI	5						
Linear	1	4.692	65.6	$p < 0.001$	8.903	153.7	$p < 0.001$
Quadratic	1	0.490	6.71	$p < 0.05$	0.003	--	
Remainder	3	0.044	--		0.098	1.69	
Subjects X SOI	5	0.073			0.058		
n	1	1.380	55.2		3.323	615	
Subjects X n	1	0.025			0.0054		
SOI X n	5	0.015	--		0.205	5.70	
Subjects X SOI X n	5	0.016			0.036		$p < 0.05$

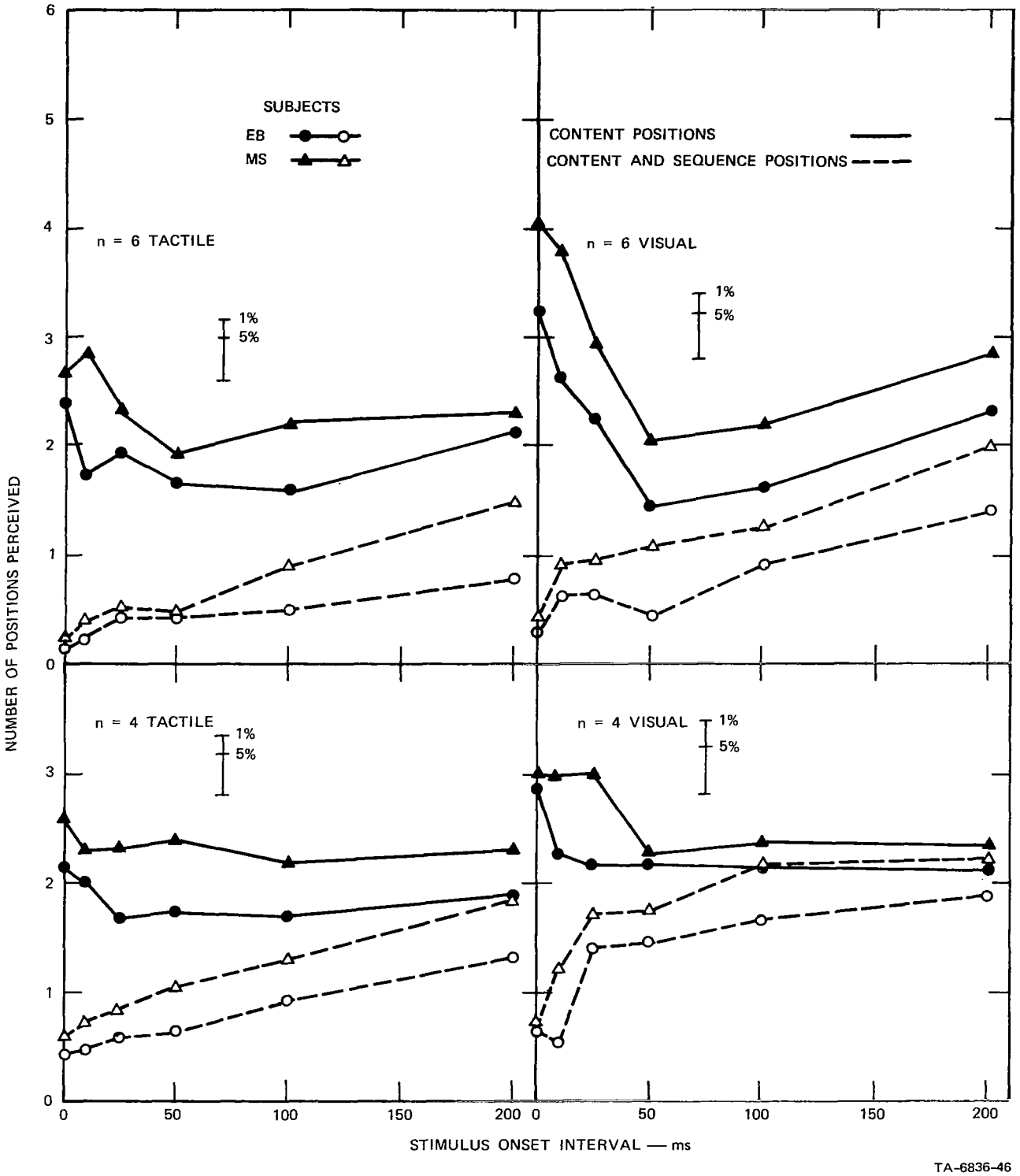

FIG. 46 THE NUMBER OF CONTENT AND SEQUENCE POSITIONS PERCEIVED BY EACH SUBJECT

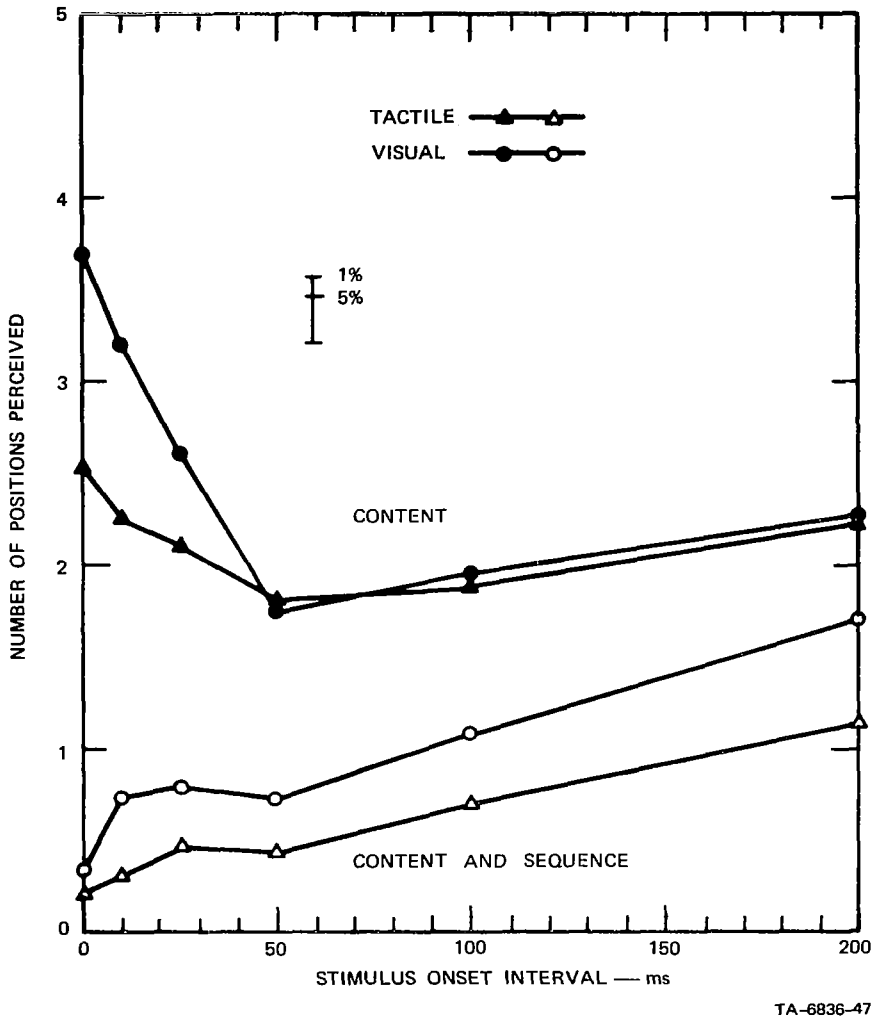

FIG. 47 AVERAGED SEQUENTIAL DATA FROM TWO SUBJECTS WITH n = 6

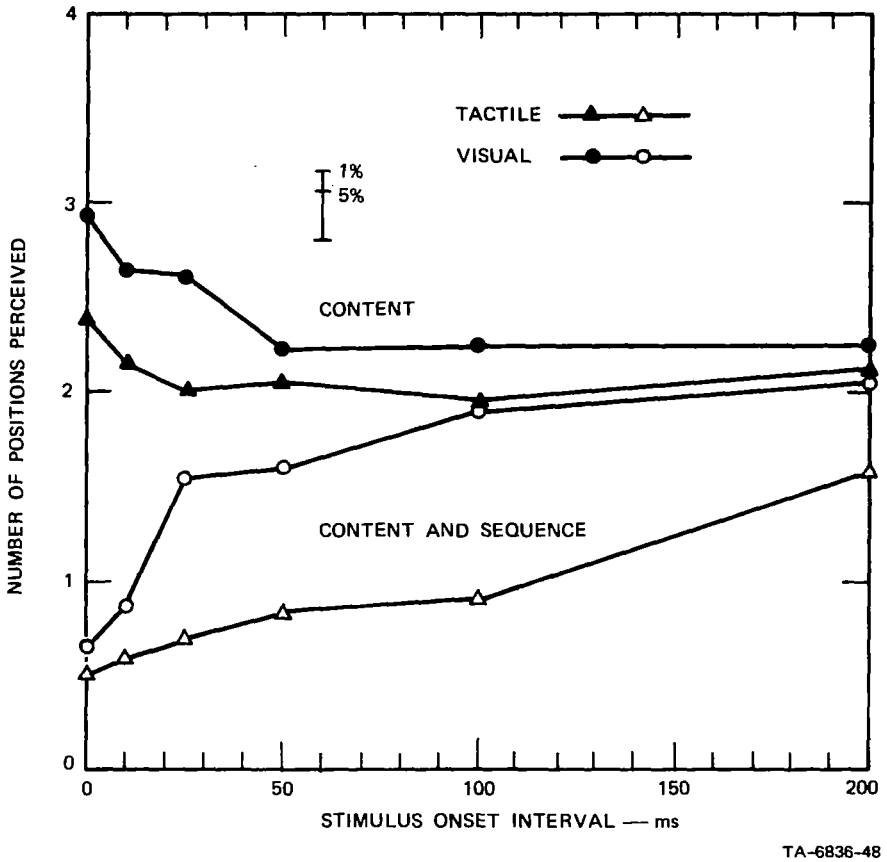

FIG. 48 AVERAGED SEQUENTIAL DATA FOR TWO SUBJECTS WITH WITH n = 4

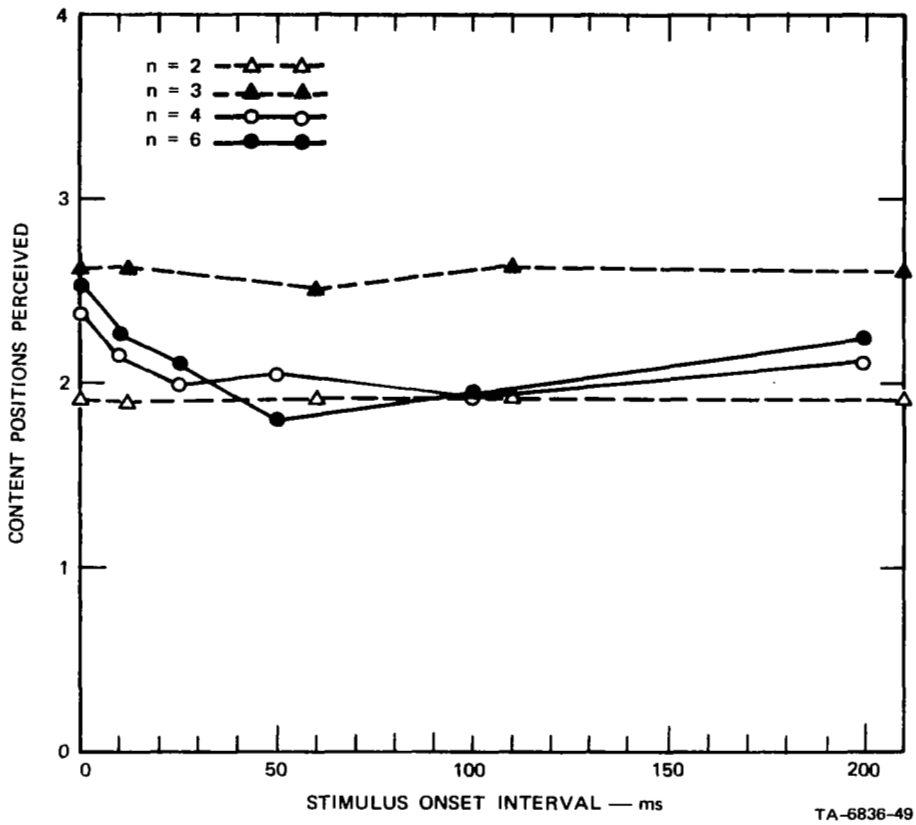

FIG. 49 COMBINED TACTILE RESULTS OF PRESENT EXPERIMENT AND THOSE OF HILL AND BLISS (1968b)

practically dropped to the tactile performance level. With even greater SOI values, both tactile and visual performance levels are nearly the same.

In the previous experiment (Hill and Bliss, 1968b) the number of Content and Sequence Positions perceived was a meaningful measure of the subjects' ability to correctly order the stimuli, because the number of Content Positions perceived did not change with SOI. In the present experiment the number of Content Positions perceived is not constant with SOI, and the number of Content and Sequence Positions perceived is not as meaningful. A more meaningful measure of temporal accuracy is obtained by calling the number of Content Positions perceived at each SOI value 100 percent and measuring the Content and Sequence Positions perceived as a percentage between zero and 100 percent. This quantity, called Sequence Accuracy, is the percentage of perceived positions that were reported in the correct temporal order.

The sequence accuracy for both visual and tactile parts of the experiment are shown in Fig. 50. Both visual sequence accuracy curves are considerably higher than the tactile curves with the same SOI, indicating that visual temporal resolution is better than tactile. A longer SOI is necessary for the tactile sequence accuracy curves to reach the same limit as the visual curves. Figure 50 shows that the visual time scale is about three times faster than the tactile with n = 4 and four times faster with n = 6. The difference in accuracy evidently grows with n, because with two stimuli Hirsh and Sherrick (1961) show that both visual and tactile temporal limens are 20 ms. The results of the previous tactile experiment (Hill and Bliss, 1968b) conducted with two and three stimuli are shown in Fig. 51, together with the tactile results of this experiment. The n = 2 and n = 3 results were described with exponential curves with time constants of 26 and 68 ms. The trend toward longer time

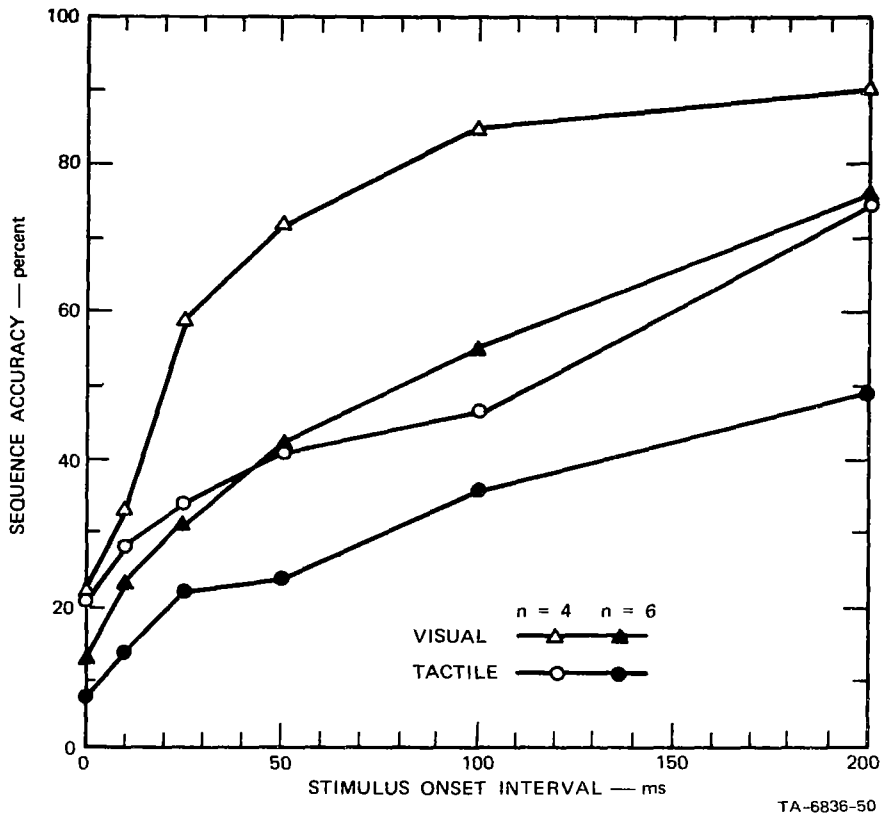

FIG. 50 SEQUENCE ACCURACY FOR BOTH MODALITIES

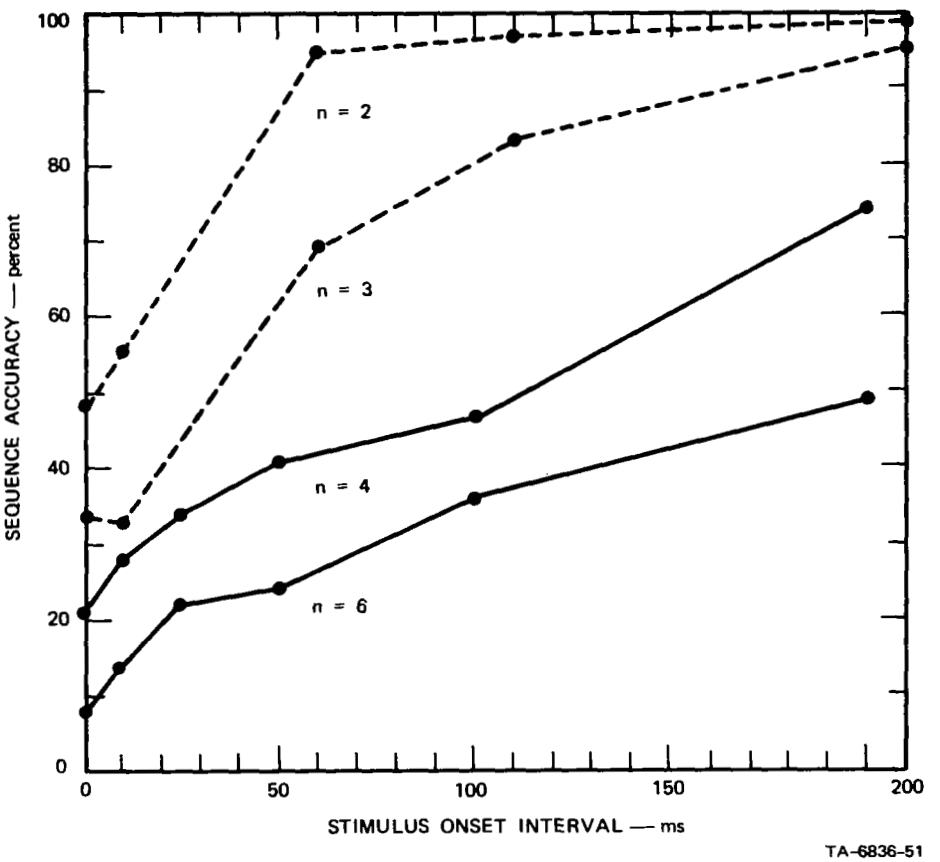

FIG. 51 SEQUENCE ACCURACY OBTAINED FROM HILL AND BLISS (1968b) FOR n = 2 AND n = 3

constants is substantiated in this experiment as the n = 4 and n = 6 time constants are 320 ms and 500 ms, respectively.

D. Tests for Masking

One unexplained result of this experiment is the dip in Content Positions perceived for both modalities with 50 to 100 ms SOI values. The dip is not significant with two and three stimuli, but becomes more pronounced with four, and is very significant with six. These results may be similar to those of Mayzner, Tresselt, and Cohen (1966) and Mayzner, Tresselt, and Helfer (1967), who found that in sequentially presented visual letter strings, letters presented 100 ms after letters previously presented in the same spatial area supplanted the previous letters, causing them not to be seen. Averbach and Corriell (1961), using a surrounding ring to denote a letter selected for recall, found similar backward masking induced by the ring, which was maximum when the ring was presented 100 ms after the letter. With simple geometrical patterns, Fehrer and Raab (1962) found that backward masking was very significant and had a maximum effect with a time interval of 75 ms.

In order to see whether forward or backward masking accounted for the drop in visual and tactile localization accuracy at the 50- and 100-ms SOI's noted previously, an additional analysis of the data was made. The stimulus patterns with each SOI were searched (by a computer) for all cases where any pair of stimuli of a trial appeared in neighboring columns of the arrays (either columns of lamps in the visual part or fingers in the tactile part). The frequency with which the second stimulus of the pair was reported was tabulated as a function of the time delay (called positive stimulus interval in Fig. 52) between the pair to measure any forward masking. Similarly, the frequency with which the first stimulus was reported as a function of the time delay (negative

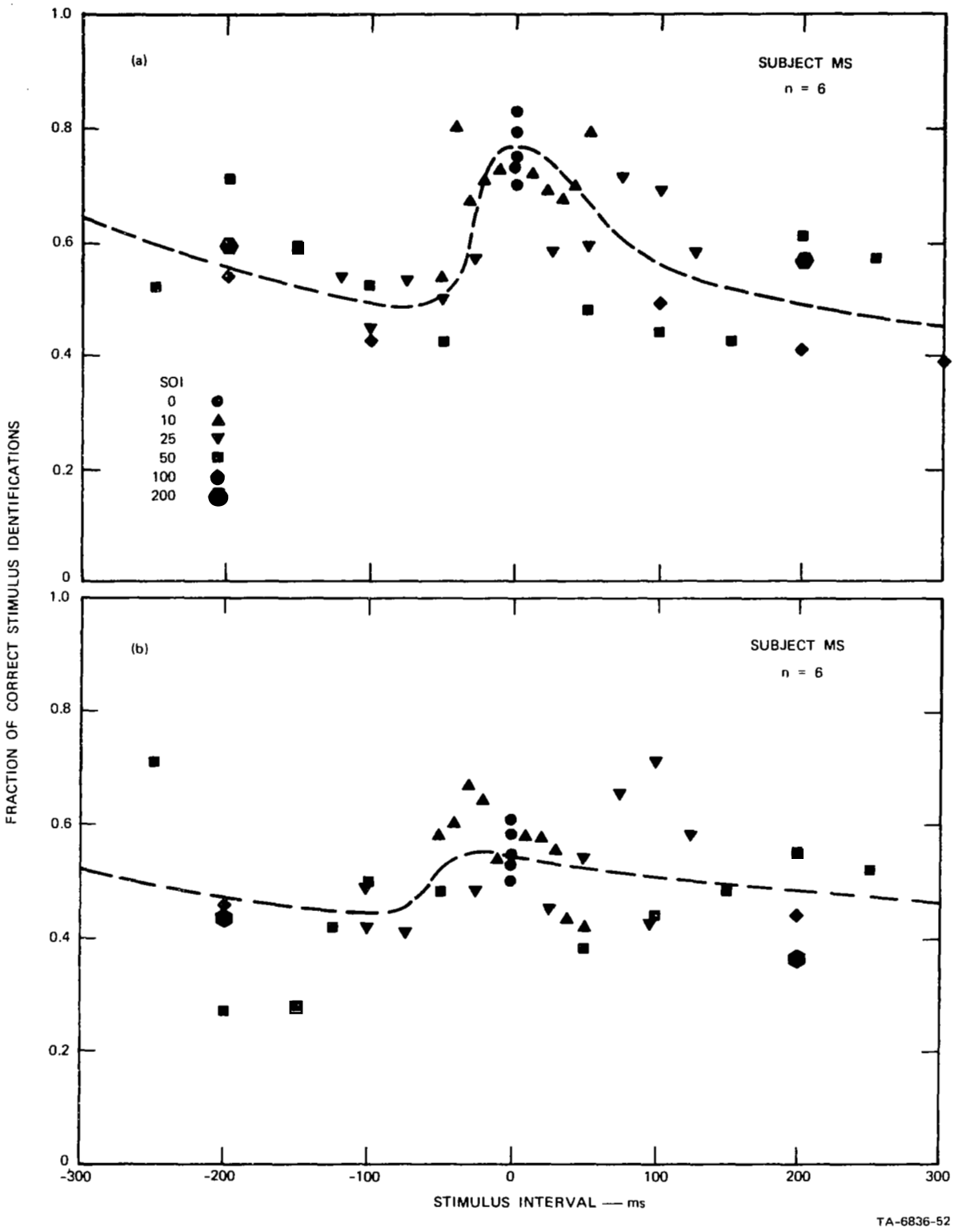

FIG. 52(a) STIMULUS REPORTING ACCURACY VERSUS STIMULUS INTERVAL FOR VISUAL STIMULI IN NEIGHBORING COLUMNS

(b) STIMULUS REPORTING ACCURACY VERSUS STIMULUS INTERVAL FOR TACTILE STIMULI ON NEIGHBORING FINGERS

stimulus interval) was tabulated to measure any backward masking. The results of the analysis for the one subject on which it was carried out are shown in Fig. 52a and 52b. The curves in each figure are hand-drawn smooth curves through the average heights of the data points.

There is some backward masking around 100-ms stimulus intervals, as evidenced by the generally lower fraction of correct stimulus identifications in the -50 to -125 ms stimulus interval range of Fig. 52. The magnitude of this decrease is only about 25 percent, however. If we accept this dip as backward masking, we must also accept that the similar but slower drop in stimulus identifications with positive stimulus intervals represents forward masking. If backward masking were to account for the 50 percent drop in the Content Positions perceived in Fig. 47 with n = 6, then the data points between -50 and -100 ms in Fig. 52a would have to drop to almost zero. Thus backward masking does not account for all of the content data, but may account for some of it.

In order to further confirm whether evidence for some backward masking is given by the data, still another analysis was made. The sequential data with SOI = 0 and 50 ms were used to compute the frequency with which the first and second stimulus of each successive pair of stimuli was reported. In this case, the reporting accuracy was tabulated versus stimulus spacing in columns. The results are shown in Fig. 53. If only spatially dependent masking accounted for the dip in Content Position perceived shown in Fig. 47, then with large stimulus spacing, the 50 ms results of Fig. 53 should be the same as the simultaneous (0 ms) results with the same spacing; and with small stimulus spacing the 50 ms results should be close to zero. In conclusion, we must say that if either forward or backward masking is present in this experiment, it is not a large effect and does not depend on stimulus spacing.

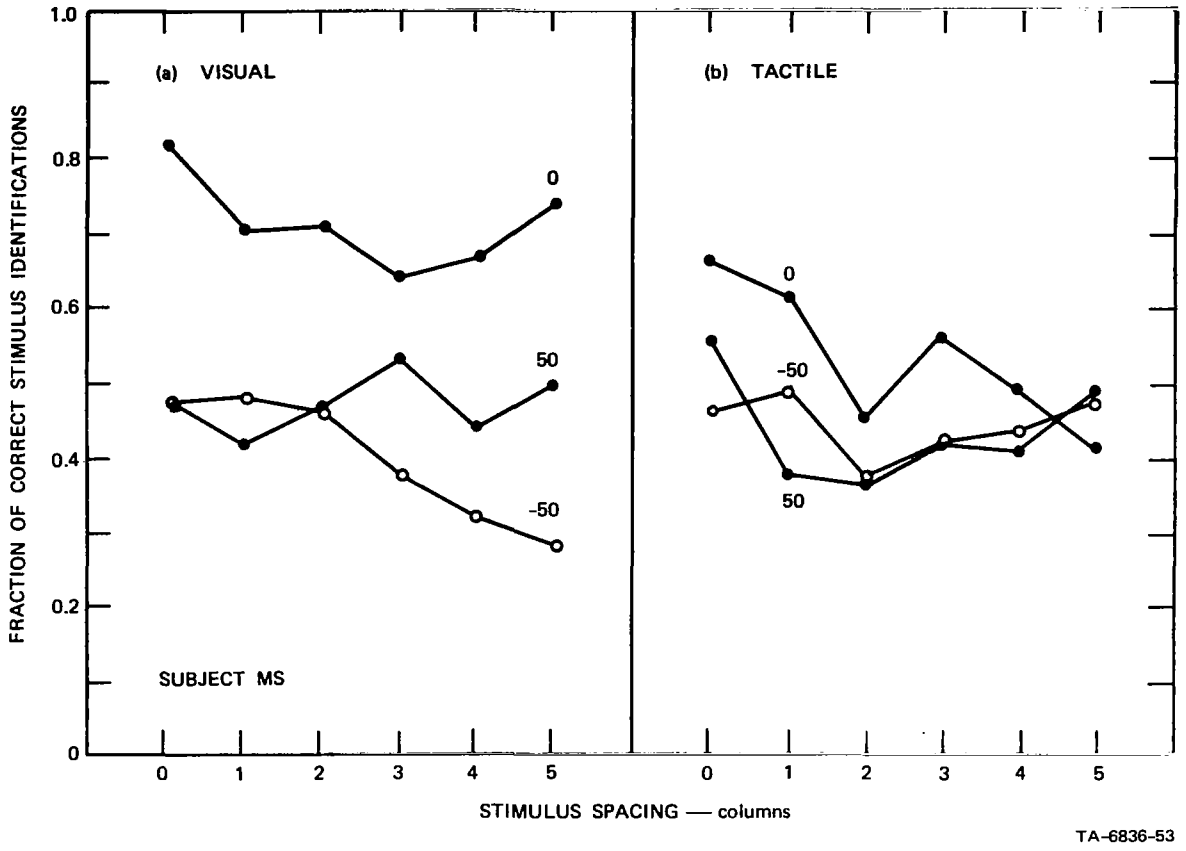

FIG. 53 STIMULUS REPORTING ACCURACY AS A FUNCTION OF STIMULUS SEPARATION FROM SOI = 0 AND 50 ms DATA WITH n = 6

E. Discussion

To provide further data for distinguishing between different models for sequential stimulus perception, the reporting accuracies for each stimulus in the stimulus sequence were calculated. These data at a given stimulus sequence position (for example, the first stimulus of a trial occurs in stimulus sequence position number one) indicate the fraction of the time that the stimulus was perceived. The fraction of stimuli perceived are the guessing-corrected p_i of Model II described by Hill and Bliss (1968a). Here the index i is the stimulus sequence position.

If a form of backward masking influenced the data (later stimuli reducing the accuracy of earlier stimuli), then the 50- and 100-ms curves should be upward sloping, with higher scores on later stimulus sequence positions. This is not the case; indeed, these curves are downward sloping. These results also rule out a push-down-store model, but not a first-in-first-out model. For SOI values up to 100 ms, the curves of Fig. 54 decrease fairly uniformly, indicating that the stimulus sequence position is not important in this range. With SOI of 100 and 200 ms, the first stimuli become more accurately reported at the expense of the last few stimuli in the sequence.

Further detailed analysis of this sequential data should be accompanied by further experimentation. For example, before considering detailed models encompassing both this and previous data, the reason for the drop in localization accuracy with SOI of 50 to 100 ms should be further tested. If the drop were due to subjects paying less attention to the location of stimuli simply because temporally ordering the stimuli was more difficult at these onset intervals, a sequential experiment requiring subjects only to locate, not to order, the stimuli would show if the onset interval dependent results were due to the stimuli or to the experimental procedure. This data might be accounted for by a constant information model. A computation of the content and the sequence information transmitted would show whether the subjects in this experiment were trading spatial for temporal information in their task.

The results of the visual and tactile experiments show that with a larger number of stimuli, visual temporal resolution is much better than tactile. These sequential results seem to tie in with those of

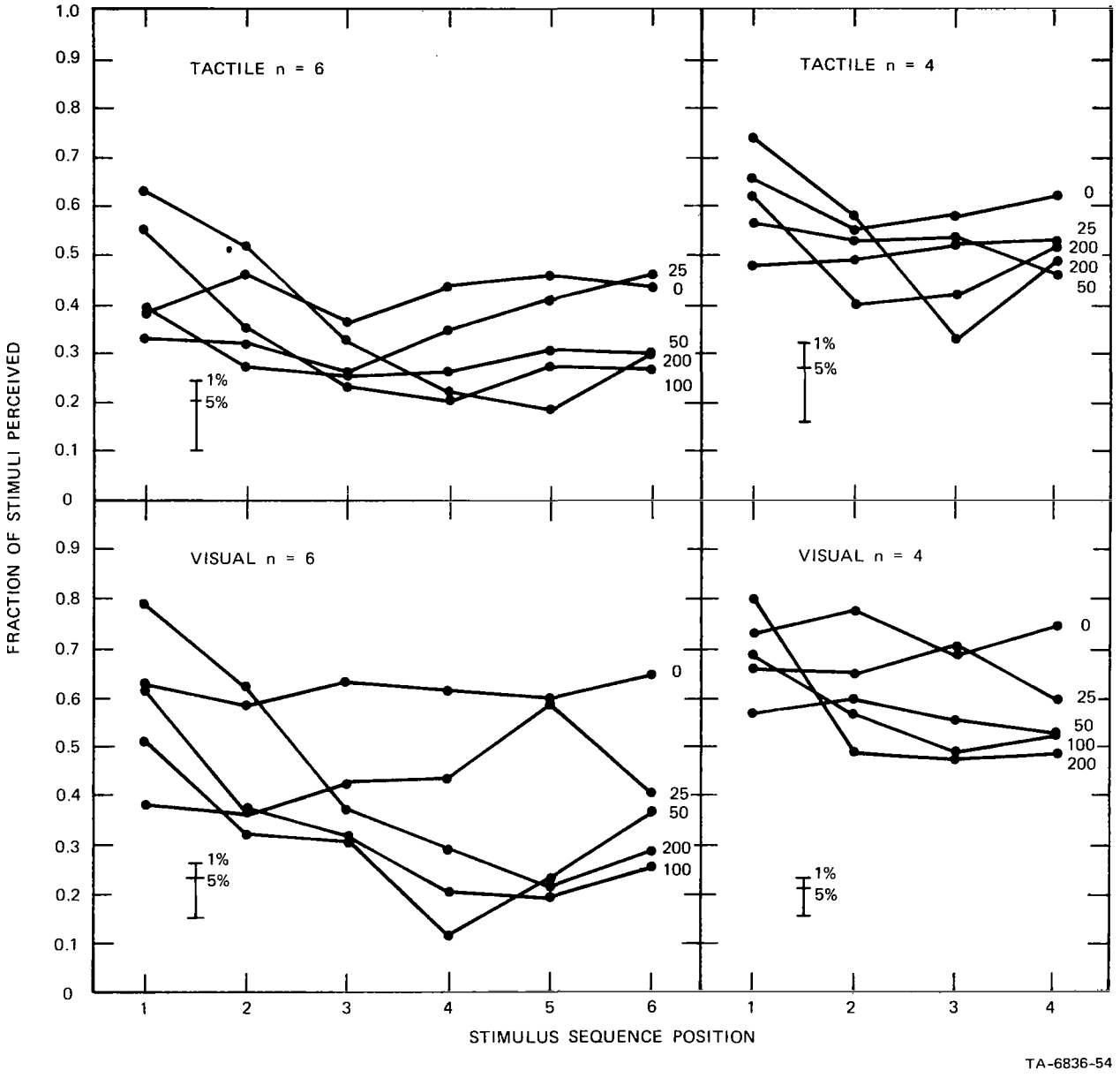

FIG. 54 FRACTION OF STIMULI PERCEIVED VERSUS SEQUENCE POSITION AVERAGED OVER BOTH SUBJECTS

reaction time experiments that show that with one stimulus both visual and tactile simple reaction time are the same, but that with several stimuli, visual choice reaction times are shorter than tactile (Bliss, 1966, Fig. 45). Both the sequential and choice reaction time results may be a consequence of using the same tactile and visual decision-making mechanisms.

X A COMPUTER PROGRAM FOR ON-LINE COMPENSATORY TRACKING

In order to help investigate the perceptual and motor characteristics of a human operator, we have developed a computer program to run compensatory tracking experiments in either of two modes. In one case, the task is the so-called critical task (Jex, McDonnel, and Phatak, 1966), in which the controlled element is unstable and becomes increasingly unstable through the course of the trial. When the operator finally loses control, an instability parameter (which in this case is the inverse of the operator's "effective delay time") is typed out. In the other mode, the length of a trial is predetermined, and at the end of a trial Fourier sums are typed out. Another program on another computer reads these sums and calculates the operator's open loop Bode plot.

The generated command signal is the sum of 10 sinusoids (not harmonically related) with a flat spectrum extending from 0.02 to 2 Hz, and the Fourier sums are taken at those frequencies and at zero frequency. Since the timing is precisely identical for the command and analysis, the program yields an accurate measure of the operator's transfer function at the command frequencies. In order to eliminate any round off errors, the sums are 10 digits wide, with no internal rounding. Of this, about 3 figures are significant. The tracking program goes through its main loop of updating the command signal and all the sums at a rate of 60 Hz, which is much higher than the highest frequency of interest.

The Fourier sums are kept for any 2 of the signals: operator's response, controlled element position, and error (the difference between the command and the controlled element). In addition, if a display system with nontrivial dynamics makes available a signal corresponding to

the displayed error, all other hardware and software links exist to make this signal the source of one of the two sets of Fourier sums.

Figure 55 shows a functional block diagram of the tracking task. All blocks except the display and the operator are realized within the tracking program. There are two modes in which the experiment is run: critical and Fourier. In the Fourier mode there are three sets of controlled element dynamics: unstable [with transfer function $\lambda/(s - \lambda)$], integrating (1/s), and straight (1). The sequencing functions not shown on the diagram are as follows. In the critical mode, 5 trials are run without intervention, and λ is preset to a constant initial value at the beginning of each trial. In the Fourier mode, trials are run singly, and each consists of a warm-up period of about 10 seconds, followed by a period of about 4-1/2 minutes during which the Fourier sums are taken. The frequency of a command or analysis component is specified as the number of cycles of that component during the 4-1/2-minute data-taking portion of the experiment, so it is guaranteed that the analysis interval is an integral number of cycles for each component.

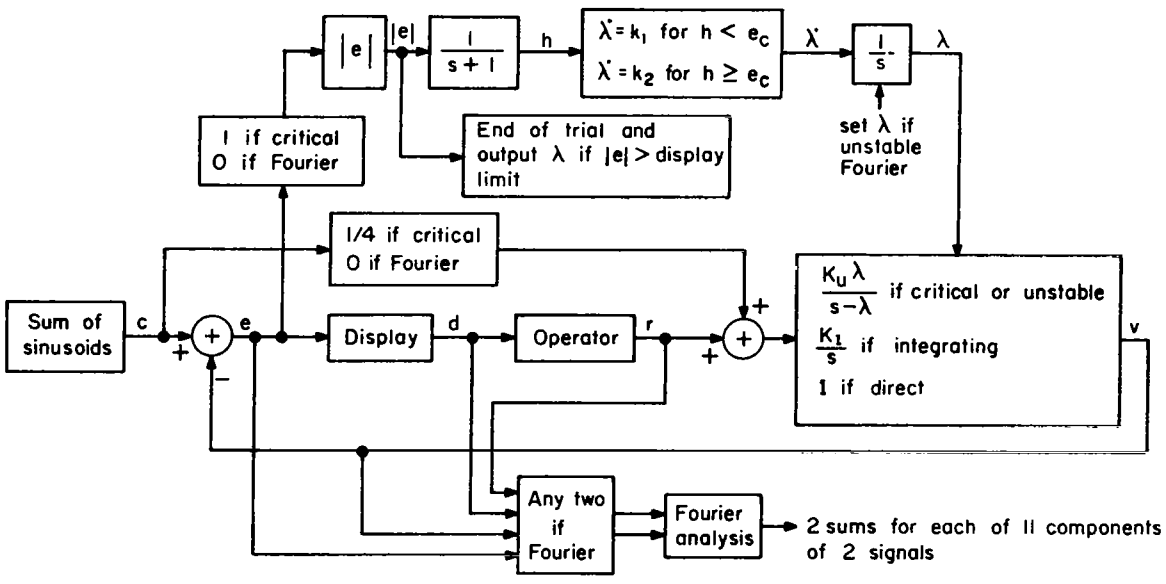

FIG. 55 BLOCK DIAGRAM OF THE GENERAL PURPOSE TRACKING PROGRAM

XI DESIGN OF A TACTILE TRACKING TASK TO MEASURE SPATIAL RESOLUTION

A. Introduction

Considerable evidence suggesting that tactile sensibility to mechanical stimulation is mediated by two different neurological systems has been accumulated by numerous independent investigators in neurophysiology and psychophysics. These findings suggest a model for taction that has important implications both to the development of tactile communication systems and to research aimed at the further understanding of sensory systems. This model will be described first, together with some supporting evidence. Then a tactile tracking task will be described to investigate certain aspects of this model.

The model consists of two separate subsystems. One subsystem, which we have named the high resolution system, exhibits good spatial discrimination but has a relatively high threshold to touch. The second subsystem is a low spatial resolution system and has a lower threshold to touch. An initial basis for this model is suggested by the results of Mountcastle, et al. (1967), who found in glabrous skin of man and monkey evidence for two different peripheral neural systems responsible for the sensation of flutter or vibration. One system of receptors was more sensitive at low frequencies and had better spatial resolution than the other system. Thus, of the myelinated afferents innervating the hand, Mountcastle describes three types that might signal oscillatory movement of the skin surface. Two of these types innervate the dermal ridges, one of which responds to a step indentation of the skin surface with a high-frequency discharge that declines within 100 to 200 ms to a more or less steady rate. The other of these dermal ridge receptors can account for human touch sensitivity in the

range of 2 to 40 Hz, and no other afferents innervating the skin of the hand have been discovered that could do so. These dermal ridge receptors are thought to produce sensations localized to the skin at the site stimulated. In our model we would associate these receptors with the high-resolution subsystem.

The third mechanoreceptor, which innervates the hand and is thought to play a role in the sense of vibration, lies in deep tissue, is extremely sensitive at optimal frequencies of 150 to 250 cps, and is thought to terminate peripherally in Pacinian corpuscles. These receptors are thought to produce sensations, described as vibratory hum deep within the hand, which spread so that accurate localization is impossible. Thus we associate the Pacinian corpuscles with the low-resolution subsystem. Figure 56 schematically represents Mountcastle's results.

Lindblom (1965) and Lindblom and Lund (1966) also studied the tactile receptors in glabrous skin of monkeys and similarly found two types of sensory units. One group had intracutaneously located receptors and small circumscribed receptive fields. The other group is supplied by subcutaneously located receptors with extremely low threshold and has large receptive fields with diffuse borders. The results of these experiments complement the steady-state results of Mountcastle, et al. (1967), in that responses to transient displacements of the skin are studied.

Considering higher levels of neural function, Mountcastle also discusses the somatic system in terms of two subsystems. One of these neural systems, called the lemniscal system, comprises first-order afferents from the periphery, which project via the dorsal columns upon relay nuclei of the dorsal column nuclei, and thence upon cells of the ventrobasal nuclear complex of the thalamus, and from there upon cells of the post-central gyrus of the cortex. This system, Mountcastle

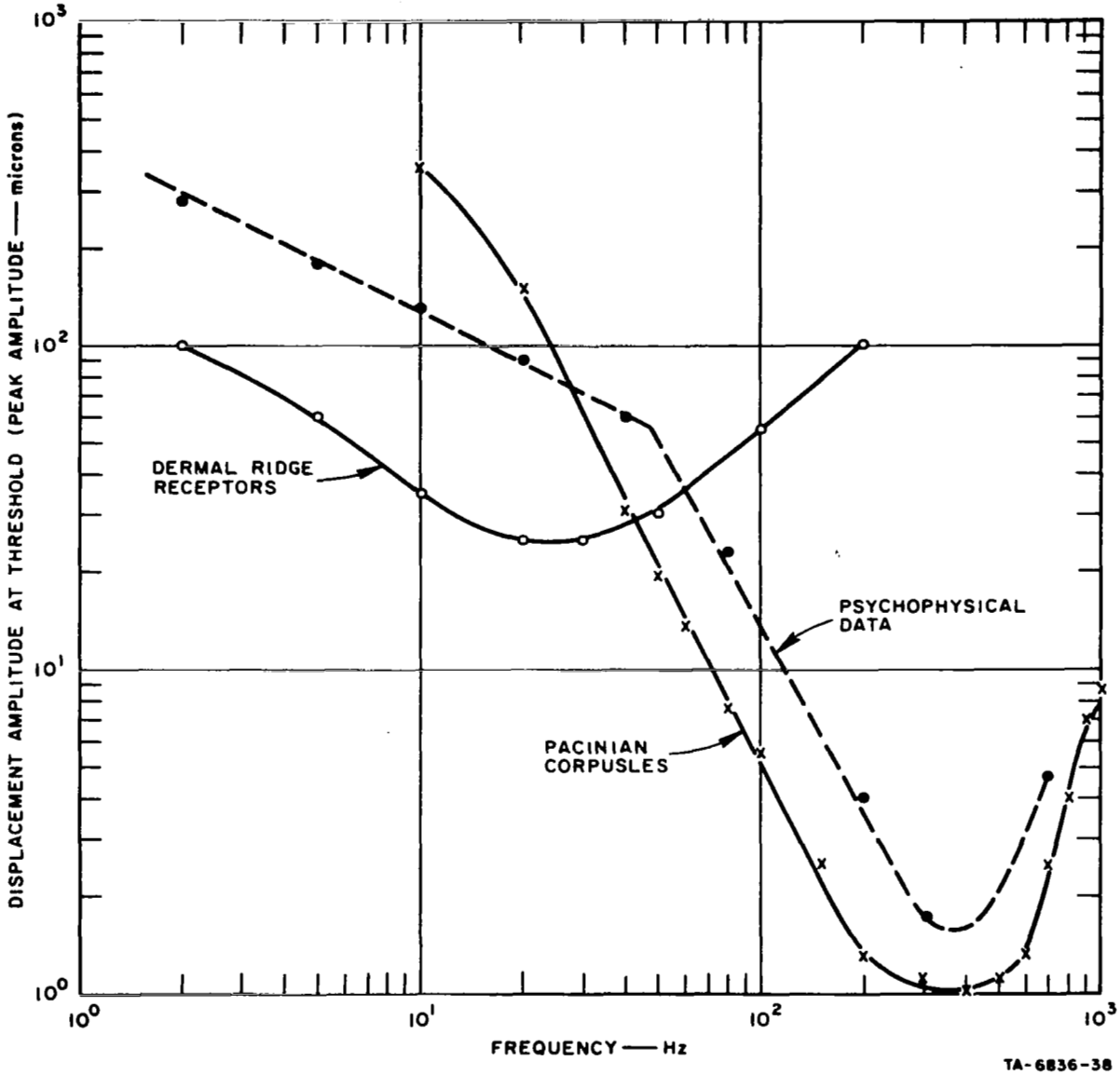

FIG. 56 COMPARISON BETWEEN NEUROPHYSIOLOGICAL AND PSYCHOPHYSICAL THRESHOLD DATA

states, "... is designed to serve the discriminative forms of somatic sensibility and certain of its properties endow it with an exquisite and precise capacity to present to higher levels of the brain neural transforms concerning the position, form or contour, and change with time of the peripheral stimulus."

The second system, called the spinothalamic system, becomes anatomically separate at the level of dorsal root entry, where there is a massive offshoot, impinging upon polysynaptic mechanisms of the dorsal horns at the segmental level and serving reflex functions of many sorts, thus yielding another great ascending pathway, the anterolateral columns. Regarding this system, Mountcastle states:

> "The spinothalamic system, on the other hand, seems to be concerned with much more general aspects of sensation and to transmit information concerning the quantitative nature of peripheral events, rather than place, pattern, or temporal cadence. The very widespread projection of some components of the ascending systems of the anterolateral columns of the spinal cord upon the reticular formations of medulla and midbrain, and upon the intraminar nuclei of the thalamus, predicts its prepotent role in arousal and in what might loosely be called the vegatative functions."

Other supporting evidence for this model comes from psychophysical and evolved potential experiments. Verrillo (1963, 1965)--who studied psychophysical vibrotactile thresholds as a function of contactor area, frequency of stimulation, and stimulus duration--concluded that the response to mechanical displacement of the skin must be mediated by more than one receptor system because of the types of threshold response curves that he found. In his experiments he considered frequencies between 25 and 640 Hz, areas of contactors of 0.05 to 5 cm^2, and stimulus durations to 2 seconds. He found that with low frequencies and small contactors, the absolute threshold for vibration seems to be independent

of frequency and stimulus duration, whereas the threshold seems to be dependent upon frequency, contact area, and stimulus duration for higher values of these parameters. He states that, although direct evidence is lacking, two sets of receptors is a logical conclusion from the results he has determined.

Fruhstorfer (1967), who used various amplitudes of vibratory pulses, showed that the stimulus amplitude was related to the average cortical evoked potential. He measured the area under the average evoked-potential waveform (corresponding to the later components of Allison, 1962), and found a power law relationship between the area of the waveform and the amplitude of the stimulus. The power law relationship that he found is not continuous, however. For low intensities he states that the exponent is 0.1, and for higher intensities the exponent is about 0.5. He goes on to say that (ibid., p. 49) this discontinuity seems to imply two sets of receptors with different thresholds. He suggests that the information transmitted by these two receptor sets is of different significance to the cortical units whose activity he measured.

B. A Tactile Tracking Experiment

In previous measurement of tactile spatial resolution (Boring, 1942, Chap. 13; Kotovsky and Bliss, 1963; Verrick, 1967) and tactile temporal resolution (Efron, 1961; Hirsh and Sherrick, 1961; Gescheider, 1966; Bliss, 1966, Chap. II and III) deliberate care was not taken to separately stimulate the two possible tactile subsystems. These experiments utilized either brief pulsed stimuli or vibratory stimuli that make and break contact with the skin. Both of these methods, however, generate both high- and low-frequency components and can thus stimulate the high- as well as the low-resolution system.

The tracking paradigm described here allows information to be presented to the skin in a narrow bandwidth (0 to 2 Hz) that may be centered

at frequencies from 0 to 500 Hz. Varying the intensity and center frequency of the stimulator can selectively force the tactile information to be mediated by one tactile system or the other, thereby enabling the spatial and temporal properties of each system to be measured.

The stimulators for this experiment are a pair of electromechanical transducers that apply precisely controlled displacement waveforms to the skin. The design for these stimulators is shown in Fig. 57. Both stimulators are in contact with the skin, and a mechanical-to-electrical transducer enables the resultant skin displacement to be measured.

The sensation from two separate stimulators on the skin can be either two sensation points or one point whose perceived location

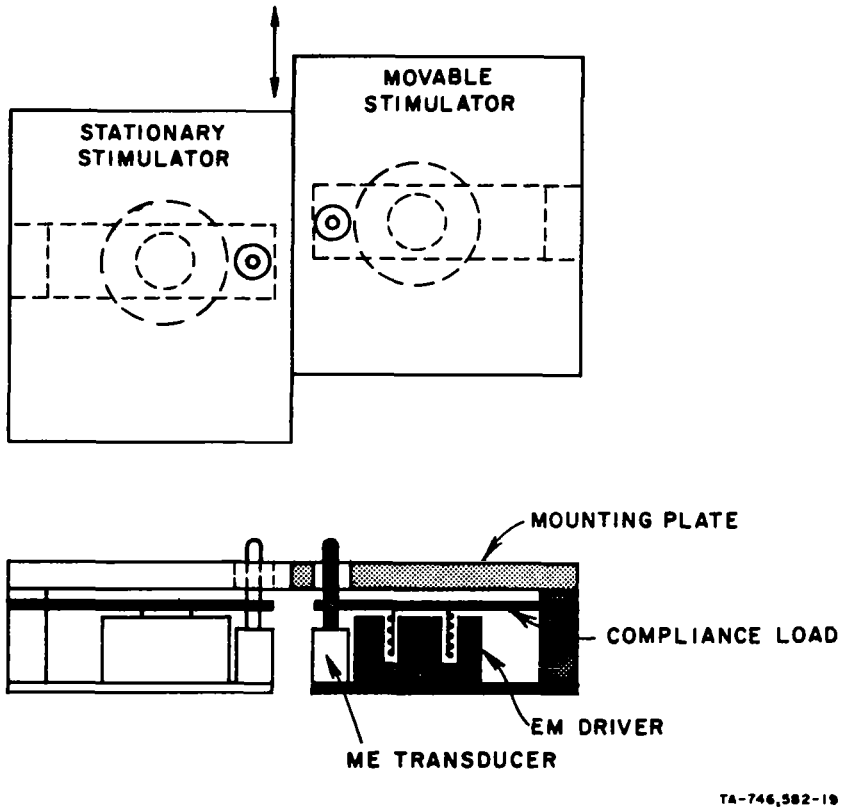

FIG. 57 DESIGN OF THE TACTILE STIMULATORS FOR TRACKING EXPERIMENT

depends on the relative intensities of the two stimulators, the perceived location being nearer the more intense stimulator (von Bekesy, 1957; Kotovsky and Bliss, 1963). Regardless of which way the two stimuli are perceived, the subject's task would be to adjust the two stimulators to equal intensity using a control stick (or alternatively, to center the apparent location of the stimulus midway between the two stimulators). For training purposes reinforcement could be given the subject by turning on a light whenever the error is zero. The control loop for this task is shown in Fig. 58. (Some controlled dynamics may be introduced in the loop to constrain performance and reduce variability.) A

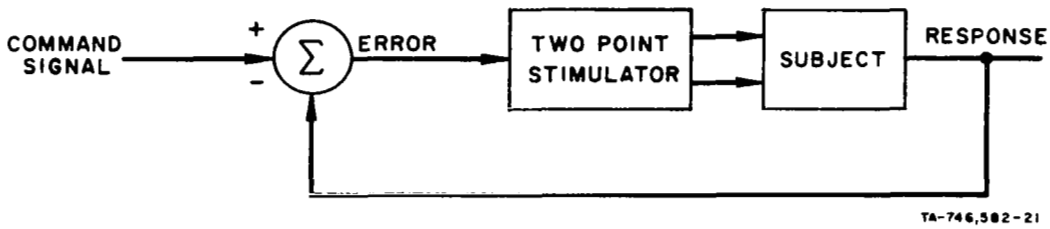

FIG. 58 TRACKING EXPERIMENT TO TEST TACTILE SPATIAL RESOLUTION

command signal composed of frequencies from 0.05 to 2 Hz will cause a shift in the relative intensities at the two stimulator positions (the sum of the intensities is always constant). The subject moves a control stick to counteract this command signal, trying to keep the intensities equal or trying to position the stimulus at the central location.

The spatial resolution of the tactile system can be measured as a function of stimulator frequency and intensity by measuring some signal property, such as the power in the error signal, as a function of the stimulator separation. When the stimulators are closer than the two-point limen, the subject does not get any tracking information and the error signal power is greatest. When the stimulators are further apart, and distinguishable, the subject will be able to track the error signal

and the error power will be minimum. These hypothetical changes are illustrated in Fig. 59(a) along with the data usually obtained using the yes-no method of measuring the limen [Fig. 59(b)]. From the point of view that the limen is the spacing at which the two stimuli are distinguishable 50 percent of the time, both methods should yield the same limens. A check comparison of the two methods should be made to determine what differences, if any, exist between these two methods.

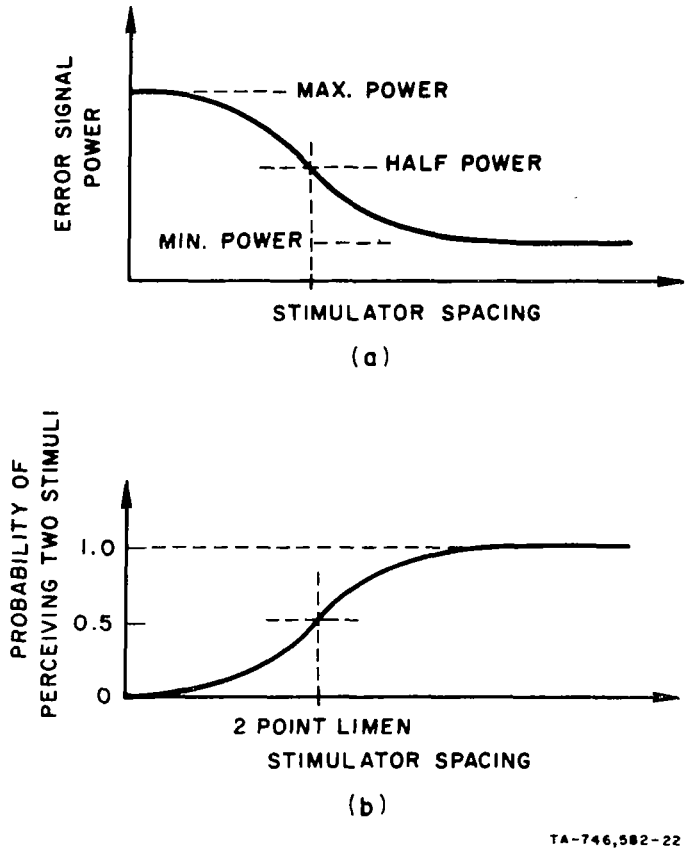

FIG. 59 HYPOTHETICAL RESULTS FROM SPATIAL RESOLUTION RESULTS

One advantage of the tracking method over the yes-no method is the amount of time it takes to collect sufficient data to determine the limen. Determining the limen from the threshold curve of Fig. 59(b), typically requires 10 trials taken at each of 10 stimulator spacings. The time required to collect this data is about one-half hour per limen (Carmon, 1968). To determine the limen from the error power curve, the error power is measured at each of 10 stimulator spacings. The tracking-time interval to accurately measure the error power (with a 0.05-Hz lowest component in the command signal) is 10 seconds. The time required to collect the same data with tracking is thus only a few minutes.

Temporal resolution of the tactile system can be measured as a function of stimulator frequency and intensity by taking the Fourier transform of the subject's open-loop response when the stimulators spacing is larger than the two-point limen or by running the subject in a "critical tracking task" mode (Bliss, 1967). Besides comparing tactile temporal resolution within the experiment, tactile tracking parameters obtained in this fashion can be compared with the visual tracking parameters in the literature (McRuer, Graham, Krendel, and Reisener, 1965). One of the interesting potentials of this experiment is that of measuring the temporal resolution with closely spaced stimulation, i.e. to find the trade off between spatial and temporal resolution.

The main advantages of this tracking paradigm over other methods then are that (1) it is efficient in collecting data, (2) both spatial and temporal resolution are measured by the same experiment, and (3) each neurological tactile system can be stimulated separately, since the transients introduced in making and breaking contact with the skin do not affect the results.

C. Other Possible Experiments

The model proposed here suggests many other possible experiments. For example, an extension of the experiment described above would be to have one stimulator exciting one of the tactile subsystems and the other stimulator exciting the other subsystem. In this way interactions between the two subsystems could be studied.

As another example, Bliss, et al. (1966) and Hill and Bliss (1968a) give evidence for a short-term tactile memory with greater capacity than the immediate memory and a duration of a few seconds. Those experiments on short-term tactile memory were not designed with the two subsystem models of tactile perception in mind so that it cannot be determined from that data just how to apportion the short-term memory between the two tactile subsystems.

Experiments to resolve this question and integrate the tactile memory model described by Hill and Bliss (1968a) with the neurological model described here would be especially relevant to this research.

These findings should also be important to other types of tactile displays; for example, for the deaf and for sensory feedback in prosthesis and orthotics.

D. A Preliminary Experiment

To explore the potential of describing function analysis of tracking behavior as a way of determining the characteristics of tactile information processing, a preliminary experiment has been run. In this experiment, the ability of a subject to track relative tactile intensity changes was tested for two stimulator frequencies and three stimulator spacings.

In choosing the stimulator frequencies, we attempted to pick values that would only stimulate nerve fibers in one of the two neurologically

distinguishable systems. Figure 60 shows a summary of data taken from Figs. 21 and 24 and Table 4 of Talbot et al. (1968).* We chose 10 Hz and 250μ as conditions to primarily stimulate the low-frequency high-resolution system and 300 Hz and 50μ as conditions to primarily stimulate the high-frequency low-resolution system. Stimulator spacings of 4, 6, and 10 mm were chosen on the fingertip.

The computer program described in Sec. V was used with vehicle dynamics of K_I/s and a command signal bandwidth from 0.0073 to 0.36 Hz. Each describing function was determined from a 273-second run. To eliminate any possibility of auditory cues, the modulation frequency was played through earphones that covered the subject's ears.

Only one subject has been tested thus far in these exploratory experiments. Initial training of this subject consisted of the following sequence of trials. An oscilloscope was arranged to display the error signal, and the subject was instructed to track visually while simultaneously feeling the tactile stimulators. The relative intensities of the tactile stimulators also indicated the error, and the frequency of the stimulators was initially set at 10 Hz. After one run of both visual and tactile tracking, the oscilloscope was disconnected and the subject was instructed to track the tactile signals. These two runs were then repeated with the tactile stimulators set to 300 Hz. This sequence of four runs was then repeated.

After this training, testing consisted of alternating runs of 10 Hz and 300 Hz stimulator frequency at each spacing until at least two satisfactory runs at each condition were obtained.

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* Figure 60 was prepared by C. Rogers as part of a course conducted by Dr. J. C. Bliss at Stanford University.

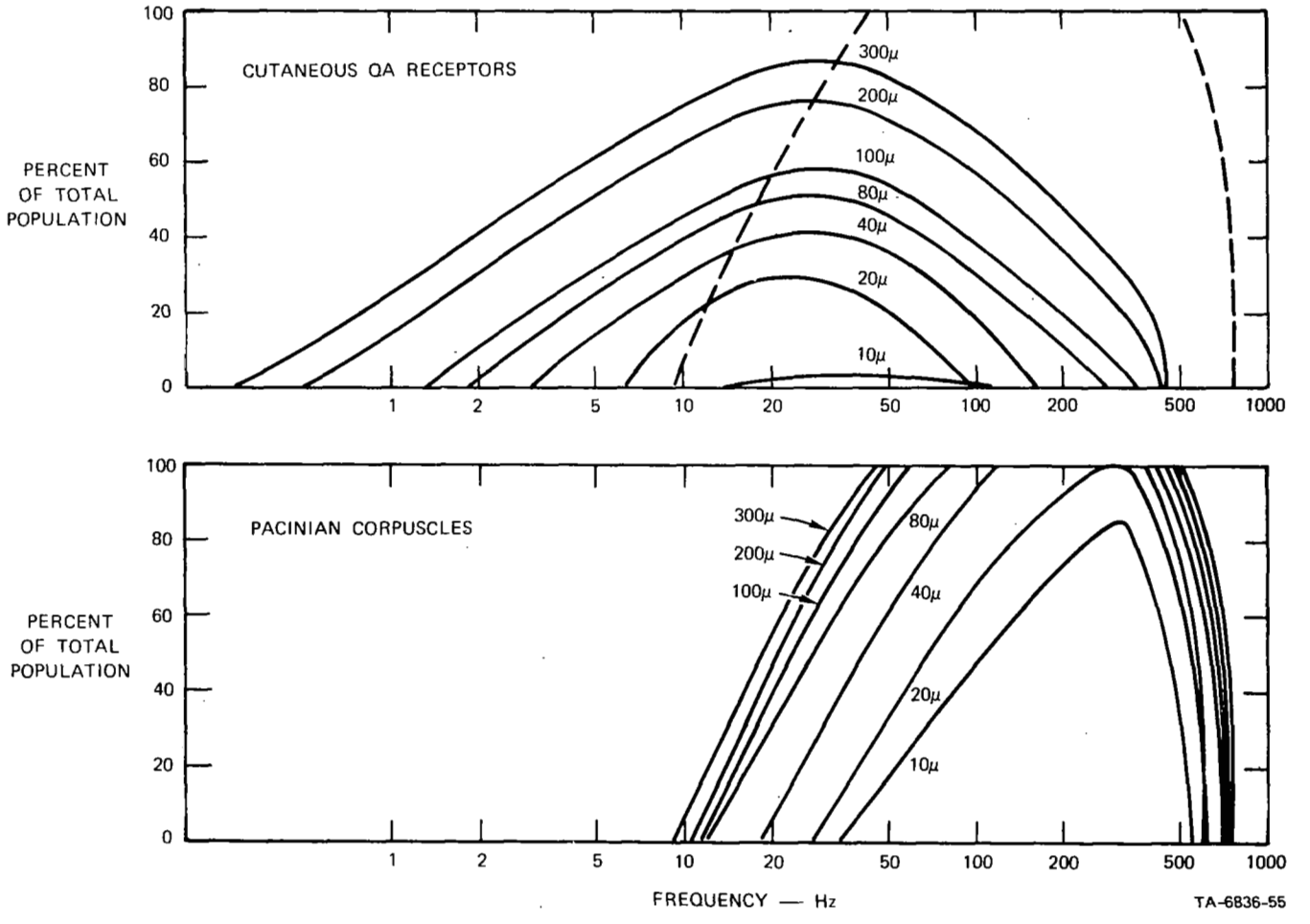

FIG. 60 PERCENT OF POPULATION OF NERVE FIBERS RESPONDING AS A FUNCTION OF STIMULATION FREQUENCY

Several measures of performance were determined from the data. Mean square error (not including dc error) as a function of stimulator spacing and frequency is shown in Fig. 61. While this measure suggests

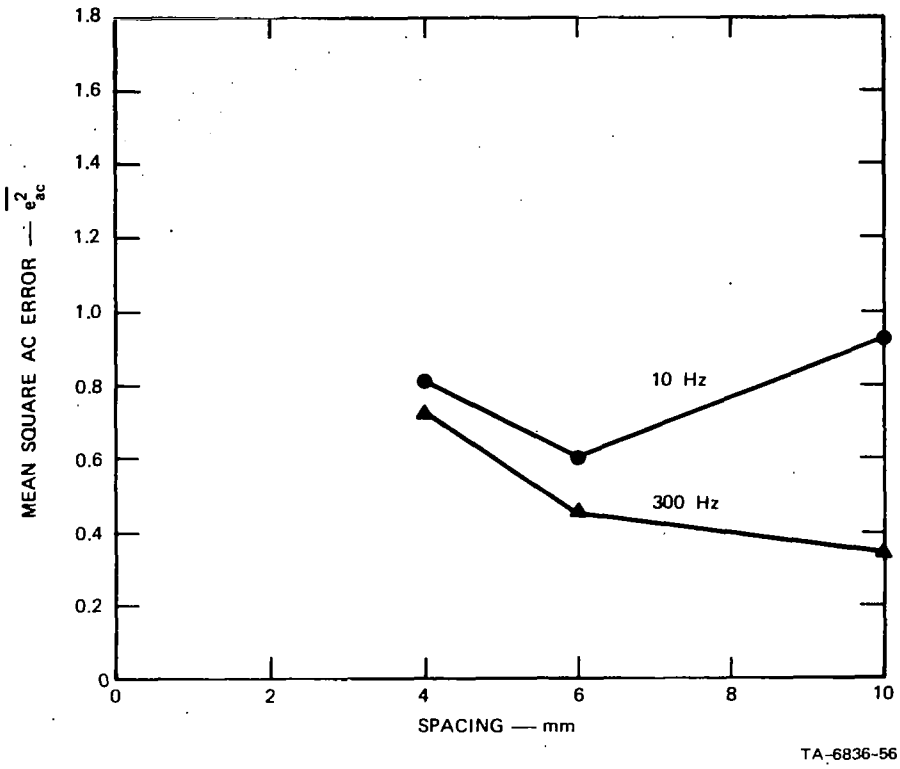

FIG. 61 MEAN SQUARED ERROR AS A FUNCTION OF STIMULATOR FREQUENCY

that better performance was obtained at 300 Hz, this measure is not completely satisfactory, because of its dependence on total response power, which can be highly variable. To overcome this difficulty the correlation coefficient between the commandand vehicle was computed as follows. If c is the command signal, v is the vehicle output, and e is the error signal, then

$$e = c - v$$

and

$$\overline{e}^2 = \overline{c}^2 - 2\overline{cv} + \overline{v}^2 \quad .$$

Solving for $\overline{cv}$ gives

$$\overline{cv} = \frac{\overline{c}^2 + \overline{v}^2 - \overline{e}^2}{2} \quad .$$

Normalizing this function and using only the ac power in the signals defines our correlation coefficient ρ :

$$\rho = \frac{\overline{c}^2 + \overline{v}_{ac}^2 - \overline{e}_{ac}^2}{2\sqrt{\overline{c}^2 \, \overline{v}_{ac}^2}} \quad .$$

Figure 62 shows the value of the command-correlation coeficient as a function of stimulator spacing and frequency. This function increases with stimulator spacing (as it should), and the results also indicate better performance at 300 Hz.

Finally, the describing functions were examined for each set of stimulator conditions. Since the differences due to stimulator conditions were not discernible compared to the run-to-run variability, all runs at 300 Hz were averaged together and all runs at 10 Hz were averaged together. Figure 63 shows the results, which again indicate a slight superiority of the performance at 300 Hz.

Two aspects of these results were surprising. First, the differences in performance as a function of stimulator frequency were extremely small. If different neural systems were involved at the two stimulation frequencies, then widely different performance characteristics would be expected. Second, the performance at 300 Hz was slightly better than the performance at 10 Hz, contrary to the predictions of the neurological evidence.

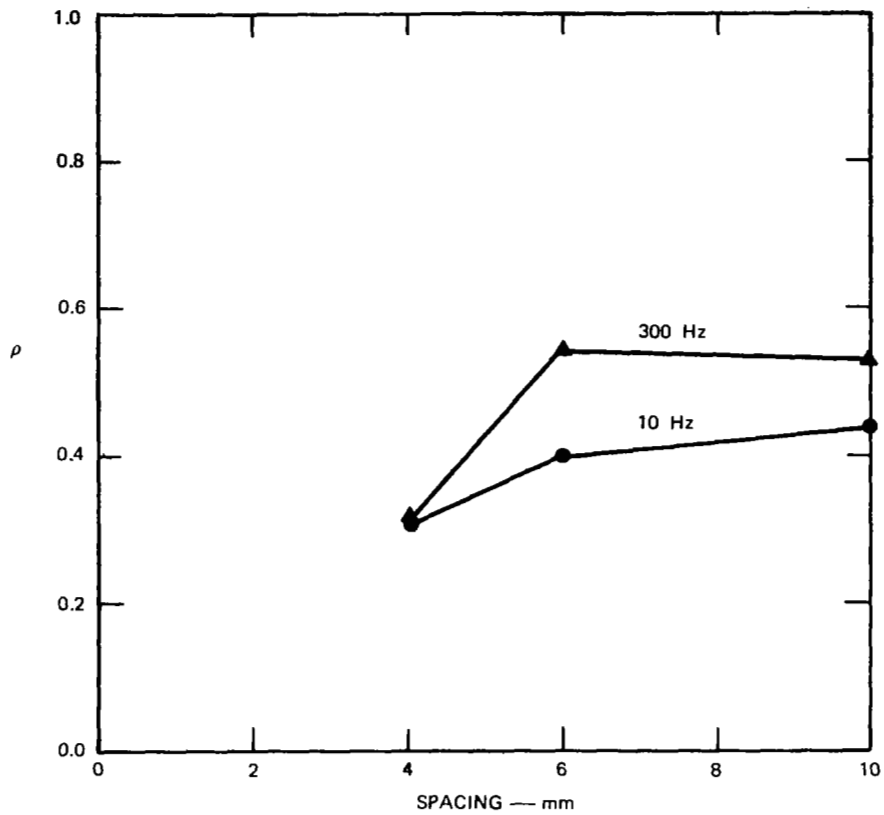

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FIG. 62 COMMAND SIGNAL-VEHICLE OUTPUT CORRELATION AS A FUNCTION OF STIMULATOR SPACING

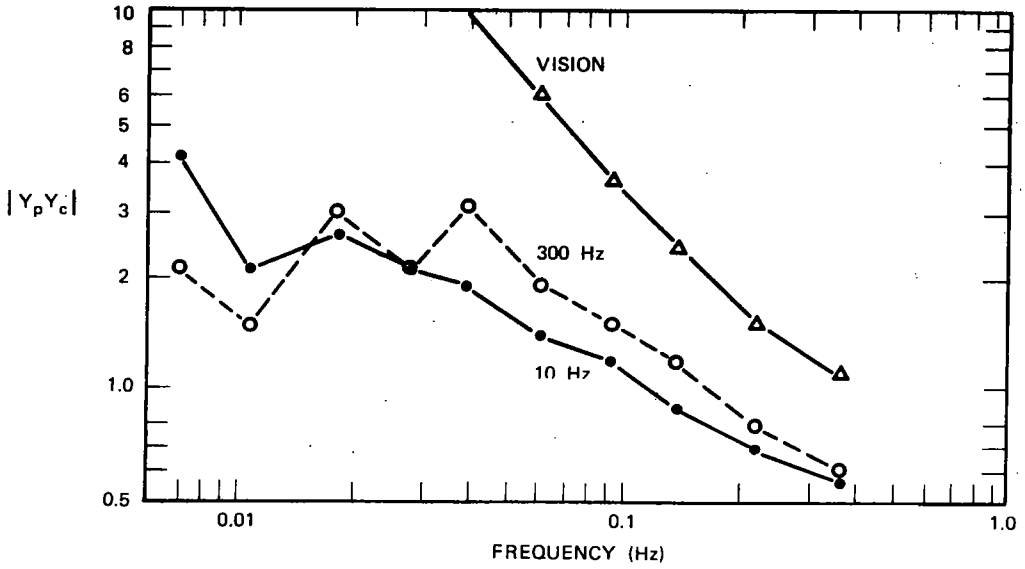

FIG. 63 OPEN LOOP COMBINED GAIN OF SUBJECT AND K_1/s DYNAMICS AS A FUNCTION OF FREQUENCY

A possible explanation for these findings is that our stimulators protruded through a hole 80 mils in diameter and the subject rested his finger on a plate. Mountcastle's experiments were performed with a free stimulator surround. Verrillo (1968) found no difference in intensity threshold as a function of frequency for small stimulators without a free surround.

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

We have been working toward a system to time-share the LINC-8 between the conducting 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 experiments of the psychophysical variety can easily absorb all available computer time and that during these experiments the computer is idle 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 nicely into the time-sharing framework, although the conventional general purpose time-sharing philosophy is not adapted to running our experiments. The time-sharing system we are developing is heavily inspired by the Stanford PDP-1, SDS940, and PDP-6 (and PDP-10) systems, but it inevitably shows signs of implementation on a small computer. In addition, full protection of users from each other will require some 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 program PROGOFOP 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. In addition to supplying almost all of PROGOFOP capabilities, PROTOCROCK permits LINC program input and output communication between the computer and our special peripherals. Included in these peripherals are an extra Teletype and two clocks (a 60 Hz clock and a 1000 Hz clock). The 60 Hz clock is run almost all the time, while the 1000 Hz clock is to be used only during those portions of experiments in which more accurate timing is required; currently PROTOCROCK does not connect the clocks to LINC programs, but this connection will be made available when it is necessary.

PROTOCROCK also does an extremely rudimentary form of time-sharing between LINC programs. In this first version, there are two programs, and for each, a copy of the central program-accessible registers is kept. Scheduling of input/output activities and access to the LINC processor is handled in such a way that, for these purposes, each LINC program can ignore the presence of the other. There is one virtual Teletype, and for each program, this is the (unique) attached real Teletype. Similarly, control actions originating on a Teletype refer only to its (unique) attached program.

On the other hand, there are several reasons why time-sharing is not yet practical. No other real equipment is mapped onto virtual equipment, so there is no other independence or isolation between the programs. A program will not release the LINC processor as long as it neither performs an instruction requiring intervention from PROTOCROCK nor is the object of a control action from its (unique Teletype) console. Finally, and more seriously, the map from virtual to real memory is not changed when the LINC is switched from one program to the other. This means that the programs must necessarily share the same virtual memory. This is a serious drawback, because the current software requires programs to be written especially for the virtual memory they occupy, and

also almost all our programs occupy over half of the available virtual memory. The available real memory is only half again as large as the virtual memory, so it is not sufficient to have PROTOCROCK change the memory map. More serious steps are under way, including plans for the addition of a disk storage unit to greatly increase real memory and extensive software changes to eliminate all three of these problems.

A. Scheduling of Activities

Under PROTOCROCK, the non-idle operations of the computer system are scheduled on three levels. At each level, operations may be suspended for operations at a lower level, i.e. lower levels have higher priorities, and the priorities are strictly followed. Any given routine operates at only one level, and no more than one routine is active at any level.

At the lowest level, scheduling is done by the hardware's interrupt circuitry and by the fact that interrupts are disabled from the time an interrupt is accepted by the hardware to the time the thus activated routine dismisses itself. The action of an interrupt level routine is kept as minimal as possible. Most interrupt routines simply take action to remove the interrupt request and schedule activation of the corresponding routine at the next higher level. There are two exceptions to this. Because of the frequency of the clock interrupts and the nature of their interface to the computer, they cause additional interrupt level processing to the extent of determining whether it is yet appropriate to further process the interrupt at the next level. Another most unfortunate exception is in the case of magnetic tape. Because of the response-time demands of the magnetic tape hardware, almost all the processing of a magnetic tape operation is done at the interrupt level. In fact, the magnetic tape routines descend to the interrupt before they begin their initialization, to emerge only after the tape operation has

been successfully completed. Since the interrupt level is asynchronous with respect to the other levels, it takes precautions to not disturb information used by the higher levels, except to schedule activation of a routine at the next higher level.

The next level is called the deferred level, because its routines perform interrupt actions that can be deferred, since the strict real-time requirements of the interrupts have already been satisfied. We have not attempted to measure the length of time between the request to schedule and the activation of a deferred routine, but we estimate that it is never less than 0.1 ms nor seldom more than a few milliseconds. Scheduling of deferred routines is accomplished as follows. The interrupt level contains a subroutine to put a deferred routine onto the scheduling queue, and the deferred level contains a routine to activate the next routine on the deferred queue. If the deferred queue is empty, then the deferred level is idle. This last routine is called either when a deferred routine dismisses itself, or when the interrupt level queueing routine is called while the deferred level is idle. The queueing discipline used here is last in, first out, so when several routines are queued up at the same time, the order in which they are activated is the reverse of that in which their activations were requested. This is of no consequence, because deferred routines are activated only in response to interrupts, and on this time scale in this system, interrupts are asynchronous. This discipline is used here because it incurs much less overhead than a first in, first out discipline, and the latter is not necessary. All deferred level routines are written so that they dismiss themselves after a relatively short time (no more than 0.6 ms, and usually much less), so a deferred routine can always be allowed to finish (dismiss itself) before another deferred routine is started.

At the highest level of programs are the LINC ("user mode" or "normal state") programs. (In PROTOCROCK, a LINC program is simply

called a "program.") A LINC program is scheduled for activation by a deferred routine. A program (i.e., one for the LINC processor) processes LINC instructions from the time it is activated until an interrupt occurs, and, in fact, it is by means of interrupts that (LINC) programs request action from PROTOCROCK. If the interrupt is neither such a request from the program nor a control action from the active program's console, then as soon as the deferred level becomes idle, the program continues executing LINC instructions. Otherwise, the program is dumped (made inactive) by the relevant deferred routine, i.e., its registers are saved in an area of PROTOCROCK's memory dedicated to that program's registers, and the LINC is marked free. The LINC scheduler also respects magnetic tape operations, which make use of some of the LINC registers. Whenever the deferred level becomes idle, the LINC scheduler is entered. If a magnetic tape operation is in progress, the PDP-8 is idled awaiting a request for activation of a deferred routine. If there is an active program and it has not been stopped by its console, then it is allowed to continue processing of its LINC instructions; if it has been stopped, it is now dumped and the LINC scheduler is re-entered. Otherwise the LINC is free, and the next program in the scheduling queue is activated. (In the case of a LINC program, activiation is the process of loading the LINC registers and starting processing.) If the scheduling queue is empty when the LINC is free, then the LINC is idle.

B. Debugging Aids

If the deferred level is idle and the LINC is idle or doing a magnetic tape operation, the PDP-8 is idle. However, since the hardware does not permit the PDP-8 and the LINC to simultaneously process instructions, the PDP-8 is never idle while there is an active program. Whenever either processor is idle, certain of its registers are loaded with special contents to provide an idle display in the front panel

lights. This has two purposes. First, one can estimate the loading of each processor by looking at its lights. More important, however, is the debugging value of the display. One can tell at a glance whether a processor is idle; it is usually easy to tell whether it should be idle; so some help is available here, for instance one can only detect a loop in a deferred level routine. Some faults even alter the idle display, and these are easily detectable. In any case, the character of the idle display is nearly constant across versions of PROTOCROCK, so anybody using--or even near--the computer can detect any of the faults that alter the idle display.

Extensive use is made of pointers in PROTOCROCK. Very often, just before a pointer is used, it is checked in any of a number of ways. Other conditions are checked in various ways before any action based on these conditions is performed. The universal reaction to an implausible pointer or condition is to immediately execute a PDP-8 halt instruction. Thus, almost the entire state of the universe is preserved for later examination.

Our operating discipline can also be called a debugging aid. We keep one copy of each of the last dozen or so usable versions of PROTOCROCK on one tape, and we normally load PROTOCROCK only once a week, at the end of our preventive maintenance procedure. This way we are always nearly sure of which version is in use; we run it for about 40 hours without reloading, which aggravates rarely occurring or cumulative bugs; and we have always been able to back up as far as we have wanted, to determine at which point a bug crept in. This last is of use only because we keep detailed records of PROTOCROCK's failures, loadings, and modifications.

C. Operations Performed by PROTOCROCK

The PROTOCROCK functions are a substantial subset of PROGOFOP's capabilities so that writing compatible programs presents no problem. In general, the more routine, general-purpose operations are done within PROTOCROCK, with the idea that if a function is "natural" for PROTOCROCK and it would seem to be useful for many LINC programs, then the function is available in PROTOCROCK. An example is the reading of a Teletype key, duplexing it (typing it onto the paper in the Teletype), and giving the LINC program the transliterated representation of the corresponding character. Of course, both carriage return and line feed are echoed as the two-character sequence "carriage return, line feed." Another example is the typing of a certain bit combination to be typed out from a LINC program as the above pair. For compatibility, this combination is neither of those two characters. Another example is the "write and check" magnetic tape operation. In this operation, the tape is searched until the specified block is passing over the heads in the forward direction. The specified data and its checksum are written in that block. The same block is again searched for and its contents read to determine agreement of the data in the block with the checksum there, and the whole process is repeated if there is no agreement. The first and last of these operations are also supplied with PROGOFOP.

The latter supervisor supplies very general means of access from a LINC program to non-standard equipment. The LINC program supplies the location (in real memory) of a subroutine to be executed on the bare machine (i.e., by the PDP-8) and PROGOFOP calls this subroutine. Since a bare machine program has the entire power of the computer system at its command, it is not permissible for a LINC program in a time-sharing environment to have access to the bare machine. For this reason, and because we are a special case and we want to provide higher level functions from PROTOCROCK, we not only do not give the LINC access to

the bare machine, but we provide special service requests for the LINC to access our special devices.

Thus, as well as supplying an as yet rudimentary facility for time-sharing, PROTOCROCK also can be thought of as a modest but useful general purpose subroutine package and execution controller for LINC programs.

XIII. CONCLUSIONS

While the present form of our model for the information processing characteristics of the tactile channel is described in detail in Hill and Bliss (1968a), a brief explanation will be given here. Figure 64 shows the framework for the model. According to this formulation, when a tactile pattern is presented to the system, a filtered image of the pattern is transferred to the sensory register, where it begins to decay. Through analysis of data from experiments in which from two to twelve simultaneous airjet stimuli were presented to the 24 phalanges of both hands (excluding those of the thumbs), we have been able to determine the spatial and temporal filtering characteristics of the sensory register. Two main results of this analysis are that the sensory register has a storage capacity at least 50 percent greater than that of the short-term store, and that the sensory register information decays approximately exponentially with a time constant of 1.4 s. The capacity of the sensory register is limited by spatial resolution. This limitation has the characteristic that localization errors tend to be in preferred directions near the point of stimulation.

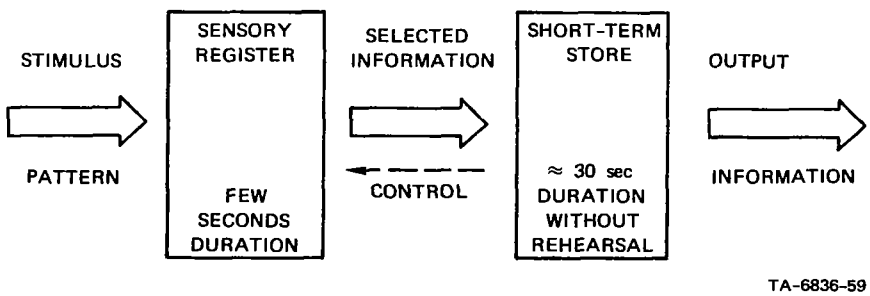

FIG. 64 FRAMEWORK FOR THE MEMORY-SYSTEM MODEL

As the image in the sensory register is decaying, a limited amount of this information is processed and transferred to the short-term store. Either the transferral process or the size of the short-term memory limits the amount of information retained in the short-term store.

This is the first model to describe both the spatial and temporal limitations and capabilities of the tactile system in processing brief, complex tactile patterns. We have shown that this concept, heretofore applied only to vision, also can be applied to taction, i. e. the information presented in one glance is stored in the sensory system for a short duration and a portion of the information can be selectively processed.

The research in this report further verifies and extends this model. Major extensions to the model are summarized below:

(1) The number of stimulus positions perceived tactually increases approximately as the logarithm of the stimulus duration up to at least 500 ms (Sec. IV).

(2) Stimulator frequency in the range 0 to 100 Hz has little, if any, influence on performance (Sec. V). If there is any difference in spatial resolution, it is better at higher frequencies (Sec. XI).

(3) Activation of all the stimulators in the array immediately following a stimulus tends to interfere with, or erase, information in the visual and tactile channels (Sec. VII).

(4) The information from a brief presentation is transferred from the sensory register to higher centers in a parallel rather than sequential fashion (Sec. VII).

(5) Results from analogous visual and tactile experiments are consistent with a model in which the visual and tactile sensory registers are separate but all other components are common between the two channels (Sec. VII). Because of differences between the visual and tactile sensory registers, and because of limitations in the common components, information processed per unit time is considerably less with tactile stimuli than with visual (Sec. VII).

(6) Results from experiments with sequentially presented point stimuli suggest that temporal resolution may be better with small spatial stimulus spacing (Sec. VIII).

(7) Processing of sequentially presented tactile or visual information is more consistent with a first-in-first-out model than a push-down-store model (Sec. IX).

In the future we hope to be able to continue to refine these results and integrate new results into a coherent model that will serve as a guide to the design of tactile displays. While the nature of the research described in this report is largely basic, the techniques employed, the experimental results, and the models all suggest ways in which tactile displays could be developed for practical application. For example, several investigators have proposed tactile communication systems (Foulke, 1968; Sleight, 1968; and Siegel, 1967). Our results are directly relevant to the design of such tactile codes for communication. These results suggest that spatial location is an effective information-bearing dimension, that with 24 locations on the fingers maximum information is transmitted with codes consisting of 3 simultaneously activated points, and that errors will be characterized by the measured spread correlation functions. Up to at least 500 ms, information transmitted increases approximately with the logarithm of stimulus duration, and the way sequentially presented stimuli interfere is described.

In other potential applications it is desired to display an analog signal tactually. For example, a tactile display of airplane attitude may be desirable in certain situations. We have measured pilot-describing functions with several types of tactile displays and shown that performance comparable to that with peripheral vision can be obtained.

Still another application area is in providing sensory feedback to remote manipulators. Here it may be appropriate to have large arrays of tactile stimulators conveying force distribution information. In other research we have put up to 144 tactile stimulators on a single finger and found that alphabetic patterns can be displayed and recognized with good accuracy. This research suggests that fairly complex force distributions could be conveyed to a remote manipulator operator. The basic research described here provides a starting point for making design decisions for such an application regarding type of stimulation, density of stimulators, number of points simultaneously presented, information up-date rate, etc. This data is also pertinent to any application involving arrays of tactile stimulators.

It is easy to think of many more potential application areas. The authors hope that this research will stimulate the development of tactile displays and provide some guidelines to aid in this development.

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