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NASA CR-6

NASA CR-623

TACTUAL PERCEPTION: EXPERIMENTS AND MODELS

by J. C. Bliss

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

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1967

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FOREWORD

This report was prepared by Stanford Research Institute under Contracts NAS 2-2752 and AF 33(615)-1099, with Dr. James C. Bliss as Project Leader. Contract NAS 2-2752 was monitored at the Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, by Mr. Richard Weick. Contract AF 33(615)-1099 was monitored at the Electronics Technology Division, Air Force Avionics Laboratory, Aeronautical Systems Division, by Dr. Mildred B. Mitchell.

While the author is responsible for the material contained in this report, certain sections are primarily the work of others and are so indicated. In addition, we would like to acknowledge the contributions of B.M. Wilber, who wrote the computer programs for most of the experiments; J.G. Crummett, who worked on circuits and displays for the tracking experiments; A.F. Ferrera, who kept the facility operating and ran many of the experiments; B. Lane and W.R. Brody, who conducted the step-response tracking experiments and analog computer simulation; and L.I. Mickelson and F.A. Kopala, who did much of the data gathering and processing.

ABSTRACT

Results from five different studies on tactual perception, involving airjet stimulators and a computer-controlled facility, are presented. In the first study, alphabetic shapes were presented on an 8-by-6 array of airjets, which was physically translated in a small circle. For a rotation diameter of 0.8 cm, a maximum in recognition accuracy occurred at a rotation velocity of 400 rpm. A hypothetical model is suggested which qualitatively accounts for the effects of display motion.

In a second study, pairs of alphabetic shapes were presented in rapid succession at the same anatomical location. As the temporal conditions were varied, three aspects of the interaction were observed: (1) an increase in letter reversals for very short interstimulus intervals; (2) a greater percentage of first-response errors for short-stimulus onset intervals and a greater percentage of second-response errors for long-stimulus onset intervals; and (3) a crossover in the first- and second-response error rates in the range of 100 to 200 msec after the onset of the first stimulus.

In a third study, point airjet stimuli were presented simultaneously to the 24 interjoint regions of the fingers (thumbs excluded). After correction for guessing, the number of point tactile stimulus positions that subjects could report was between 3 and 7. However, in a partial-report procedure in which the subject only had to report from a portion of the field indicated by a marker, it was shown that about one additional stimulus position was available to the subject. These results suggest a tactile short-term memory that has greater capacity than the span of immediate memory but that decays within 0.8 sec.

The fourth study is on cross-modality reaction time, in which visual and tactile stimuli that gave the same mean simple reaction times were used. However, when the number of response alternatives was increased, the mean visual reaction times increased significantly less than the mean tactile reaction times. Moreover, when both visual and tactile stimuli were presented simultaneously, the mean reaction time was significantly shorter than that with either visual or tactile stimuli alone, independent of whether the two simultaneous stimuli required the same or different responses. This result, coupled with the effect of response repetitions on choice reaction time, suggest a model employing sensory and response switching mechanisms. A mathematical interpretation of the increase in reaction time with the number of alternatives in terms of the repetition effect is also given.

The fifth study is on tracking performance with visual and tactile displays. Responses to step commands under various feedback conditions indicated that movements with the visual display tended to be quicker than with the tactile display, but the stationary pauses were longer with the visual display. With continuous command signals, describing functions were obtained which showed less gain and less bandwidth with an airjet tactile display than with a visual display. However, increased bandwidth was obtained with a contacting tactile display that produced tangential as well as normal forces on the skin.

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I INTRODUCTION

As man-machine systems become more complex, it becomes more important to study all potential methods of communication between man and his hardware systems. In this regard, the tactile sense deserves serious attention, because it is certainly capable of high information rates, as evidenced by deaf-blind persons, some of whom are capable of receiving live speech in real time by placing their fingers on the lips, jaw, and throat of a speaker.

This report covers a one-year joint research program investigating basic properties of the tactile channel important to communication systems. The research is an outgrowth of projects initiated in 1962 under Air Force and NASA sponsorship. These previous projects are described in the several reports and papers listed at the end of this section.

Up until a year ago, a relatively large part of the program effort was devoted to the development of a tactile research facility to generate and control rapidly changing tactile-spatial patterns. During the past year, however, the first major studies have been conducted with this facility, and the results of these studies are covered in this report. Since these results are also being submitted to the appropriate scientific journals, the various sections of this report are written in the style and format appropriate for journal publication. Also for this reason, each section is relatively independent of the other sections, even though the subject matter is closely related and basically the same facilities were used in each experiment. An overview of these studies is given in Section IX, which attempts to point out relationships between these various studies and the general problem of tactile communication.

Basically, there are five types of experiments described in the body of this report. These include experiments in the effect of display movement on tactile perception (Section II); temporal effects in spatial pattern recognition (Section III); spatial interaction and memory limitations (Sections IV, V); reaction time

time (Section VI); and tracking with transient and continuous commands (Sections VII and VIII). These sections are summarized below.

In Section II*, an investigation of the effect of display movement on the ability of subjects to recognize alphabetic shapes tactually is described. The display consisted of a computer-controlled 8-by-6 array of small airjet stimulators that could be physically translated in a small circle by means of a mechanical linkage. The experimental parameters were the stimulus duration, the angular velocity of the display, and the amplitude of the rotation. Recognition accuracy increased with stimulus duration between 100 and 400 msec. For a rotation amplitude of 0.8 cm, a maximum in recognition accuracy occurred at a rotation velocity of 400 rpm, or 150 msec per revolution. The optimum angular velocity appeared to decrease as the amplitude of rotation increased.

From these results and certain related neurophysiological evidence, a hypothetical model is suggested which qualitatively can account for the data.

Section III* describes a study on tactile pattern recognition in which pairs of alphabetic shapes were presented in rapid succession at the same anatomical location, the subject being required on each trial to identify both the patterns. Experimental variables were the duration of each stimulus and the time between stimuli. Three aspects of the observed interaction were (1) an increase in letter reversals for very short interstimulus intervals; (2) a greater percentage of first-response errors for short-stimulus onset intervals and a greater percentage of second-response errors for long-stimulus onset intervals; and (3) a crossover in the first- and second-response error rates in the range of 100 to 200 msec after the onset of the first stimulus. These results are consistent with some of the temporal properties of models proposed for analogous visual tasks.

In Section IV*, exploratory experiments on tactile-spatial interaction are presented. In these experiments a number of point tactile stimuli were presented simultaneously to the 24 interjoint regions of the fingers of both hands (thumbs excluded). It was found that although subjects initially had a relatively

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*Supported under Contract AF33(615)-1099.

high error rate when two simultaneous stimuli were presented, after a rather short training time substantially error-free performance was obtained.

As an outgrowth of the exploratory experiments of Section IV, two formal experiments were performed; these are presented in Section V[*]. In these two experiments the number of point tactile stimuli simultaneously presented were varied between 2 and 12. After correction for guessing, it was found that subjects could report a maximum of between three and seven stimulus locations. However, in a partial-report procedure in which the subject only had to report from a portion of the field indicated by a marker, it was shown that about one additional stimulus position was available to the subject. The time of occurrence of the marker was varied with respect to the stimulus, which showed that the additional information was available for less than 0.8 sec after termination of the stimulus.

In Section VI , a cross-modality reaction time study with tactile and visual stimuli is described. In the four separate experiments performed, the stimulus conditions and the number of response choices were varied. The first experiment, on simple reaction time, showed that the tactile and visual stimuli used were balanced so that there was no significant difference between the means of the tactile and visual reaction times when only a single response was to be made. In the second experiment, on two-response reaction times with either visual or tactile stimuli, a longer mean reaction time was obtained with the tactile stimuli than the visual stimuli. Moreover, the standard deviation of the tactile reaction times was significantly greater than the visual. Experiment 3 was the same as Experiment 2 except that two stimuli, one tactile and one visual, were always presented simultaneously. The two stimuli could either indicate that the same response, out of the two possible responses, or different responses. The results from this experiment showed that mean reaction time with the two stimuli was significantly less than that with either stimulus alone. There was no significant difference in the reaction times when the same or different responses were indicated. In Experiment 4, the disparity between

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[*] Supported under Contract AF 33(615)-1099.

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tactile and visual mean reaction times was further widened when the number of response choices was increased to four.

Section VII describes hand responses to step commands presented tactually, visually, or both tactually and visually. While a large amount of variation in the specific time-position course of the hand was found, the data could be classified into a few typical response types. The typically reported "staircase" response with a visual display and positive feedback was also found under these conditions with the tactile display. In agreement with the reaction-time study of Section VI, quicker responses were found when both displays were used simultaneously than when either the visual or the tactile display was used alone. It is suggested that the data can be explained by pure delays in the human operator as well as by the more frequently proposed sampling model.

A continuous-command signal tracking study is presented in Section VIII. In this study, single-axis compensatory tracking was performed with a continuous visual display, a continuous tactile display, and with both of these displays together. The subjects' describing functions were determined, and these data indicated a greater gain and bandwidth with the visual display than with a pulsating airjet display on either the forehead or the hand. However, with a static contacting tactile display, increased bandwidth was obtained, comparable to that with the visual display. The low-frequency gain remained significantly lower than that with the visual display. No significant difference was noted between the describing functions obtained with the visual display and those obtained with both displays together.

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*Supported under Contract NAS 2-2752.

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II EFFECT OF DISPLAY MOVEMENT ON TACTILE PATTERN PERCEPTION

by James C. Bliss, Hewitt D. Crane, and Stephen W. Link

Bliss and Crane (1965) and Linvill and Bliss (1966)* found considerable improvement in subject performance when tactually displayed letters were presented sequentially along a moving ticker-tape (Times Square) display rather than just a single stationary letter at a time. To study these tactile spatial-temporal interaction effects further, it was decided to test a different mode of stimulus pattern movement, namely a small circular translation (or nutation) of the entire display apparatus. In this mode, a single letter is presented in a fixed position on the display, and the display itself is translated about a circular locus, which is small compared to the size of the array. Each activated jet therefore follows a circular locus on the skin. By changing the diameter of the circular path and the velocity of the rotational motion, a fairly wide range of parametric conditions is obtained. Except for a slight increase in the total excited area because of the movement, the pattern remains fixed over the same anatomical position. Thus, a measure of performance with and without nutation over the same anatomical position can be readily obtained.

There were three reasons for the interest in this particular stimulus movement. First, it is reminiscent of vibrations in the eye, which are important for continuous vision. It is well known that if these eye vibrations are effectively cancelled, as in "stabilized image" experiments, vision rather quickly fades. Moreover, Krauskopt (1957), who introduced controlled motion in visual stabilized-image experiments, reported some improvement in acuity for oscillations at frequencies below 10 cps and of sufficient amplitude.

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*References are given at the end of this section.

Second, when lettering is read through a piece of shattered glass, where the average size of the intact glass is smaller than the size of the lettering, significant improvement can be achieved simply by vibrating the shattered glass in its own plane. In this way the distortion introduced by the fine structure of the shattered glass is averaged out. (Less improvement is obtained if the source material is vibrated instead of the glass.) For the tactile perception experiments, it was felt that since the dimensions of the overall tactile display are generally not more than a dozen or so two-point limen distances (i.e., close to the limit of spatial resolution on the skin), the effects of distortion introduced by nonuniform afferent receptor fields might similarly be averaged out by vibrating the pattern over the skin.

Third, some neurophysiological evidence suggests the probability of improved tactual perception with pattern vibration. Mountcastle (1957, page 427), for example, from a study of cortical recordings observed:

> "It is a common observation quickly confirmed that tactile sensation is more acute if the exploring finger pad moves lightly over the test surface than if held motionless against it--for example, in differentiating fine grades of sandpaper, in the finger movements of the blind in reading Braille, or in assaying the quality of cloth. Oscillatory movement of the sensory receptor sheet will produce sharper peaks in the grid of cortical activity, with steeper gradients between them. Temporal alternation in the activity of two widely overlapped groups of cells will accentuate the role of refractoriness of those cells common to both, rather than spatial facilitation, thus greatly steepening the gradients of activity between the two peaks."

Three different experiments are reported here:

(1) In the first experiment, static and "rotated" patterns were presented in alternate sessions, with various values of the stimulus duration, interstimulus interval, and angular velocity of rotation. The quantitative results clearly indicate better performance with the rotating display.

(2) The results from the first experiment were sufficiently positive that a second experiment was performed to study more precisely the effects of overall stimulus duration and pattern rotation velocity. In this experiment the subject was self-paced, since results from the first experiment indicated that a forced response interval caused errors unrelated to the parameters of interest.

(3) In the third experiment, the effect of rotational amplitude was studied.

A. APPARATUS AND PROCEDURE

The experiments were carried out under control of a computer system described elsewhere by Bliss and Crane (1964). In this system a CDC 8090 Computer is used to store stimulus patterns and to control the sequence in which the patterns are presented. For each frame of presentation the computer transmits a sequence of eight 12-bit words (each word representing one row of the spatial pattern to be displayed) to specially constructed external equipment. The external equipment stores up to 96 bits (8 words) and activates the specified tactile stimulators in 8 msec. In the experiments reported here, only half the array, 8 by 6, was used. The basic tactile stimulator generates bursts of air from an 0.031-inch outlet port, under control of a sensitive high-speed electromagnet. The pulse pressure, measured 1/8 inch above the airjet outlet, is about 3 psi, with a rise and fall time of about a millisecond and an overall pulse width of about 2.5 msec. A 200-cps pulse repetition rate was used throughout the experiments, implying that the airjet is turned on and off 20 times, for example, during a stimulus duration of 100 msec.

The advantages of airjet stimulators are that relatively uniform stimulation is produced over nonuniform cutaneous sufaces and that stimulator spacing can be easily changed. The stimulator array used is shown in Figure 1, and the location of the stimulators with respect to the palmar side of the hand is shown in Figure 2. The subjects suspended the fingers of the right hand over the matrix, with the arm and palm of the hand supported by a rest.

Inexperienced or "tactually naive" subjects initially have considerable difficulty reading a simple capital letter alphabet of the form shown in Figure 3.

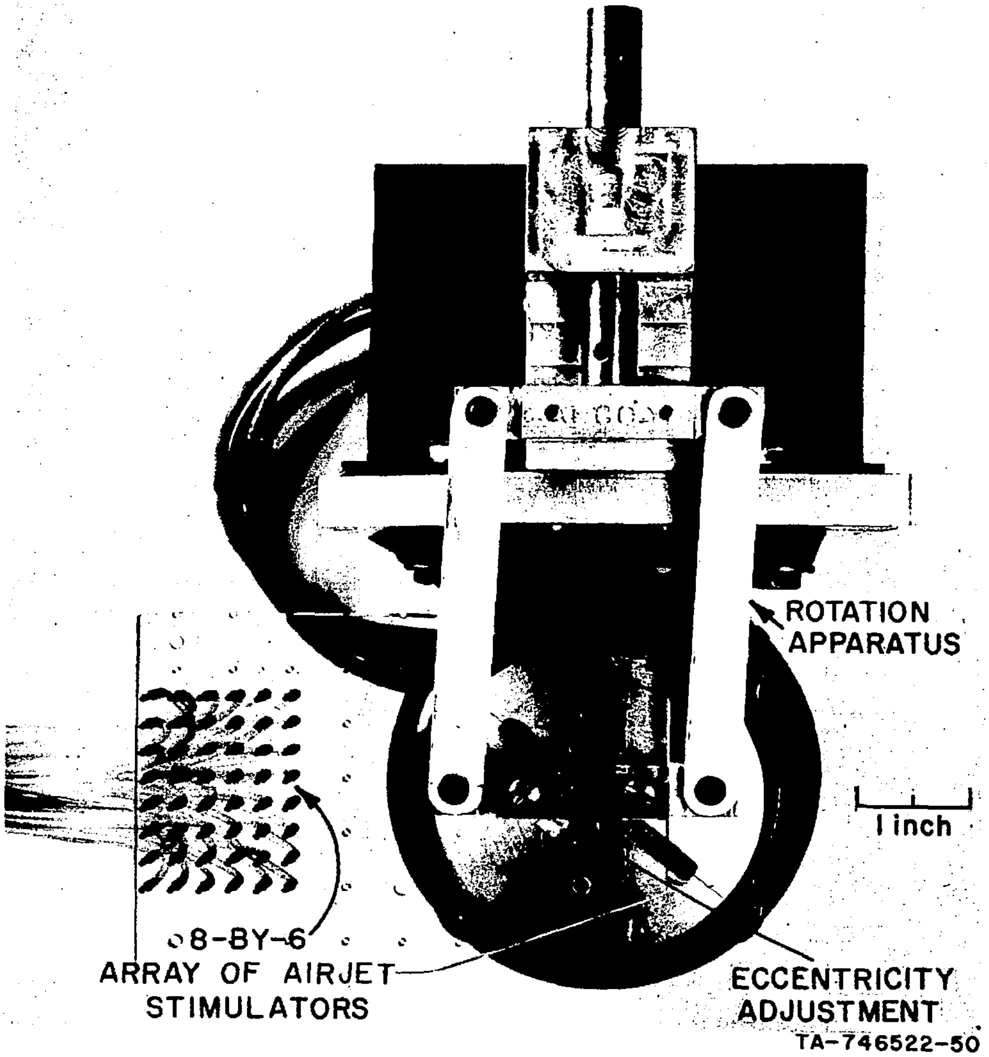

FIG. 1 TACTILE STIMULATOR APPARATUS (Top View)

The general reaction is that there is just too much air; each letter seems to feel like a blast of air without much structure. For this reason the more abstracted alphabet forms of Figure 4 were developed. The procedure for designing this alphabet was subjective and based on trial and error methods. To take advantage of possible positive effects from the transfer of visual imagery to tactile imagery, a progressive process of modifying the block letters was pursued, and an attempt was made to maintain as much similarity to the

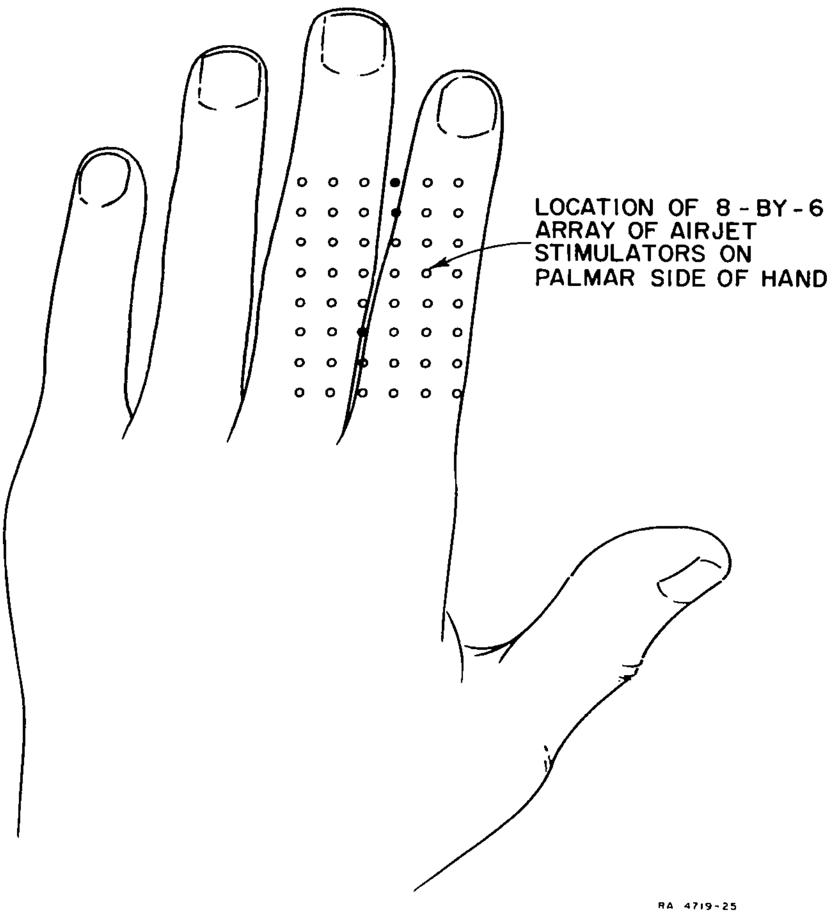

FIG. 2 POSITION OF AIRJET ARRAY (Airjets Position about 1/8 inch below Paimar Side of Hand)

standard letters as possible. In many cases this was possible, but in others, unrelated symbols were substituted to facilitate rapid discrimination. Letter modifications continued until each letter could be recognized with almost perfect accuracy when the letters were presented in random order in a fixed (nonmoving) position for about 150-msec duration and with an interstimulus interval of approximately 1 sec.

The specially designed alphabetic symbols of Figure 4 were used in the first two experiments reported here; the block letters of Figure 3 were used in the third experiment.

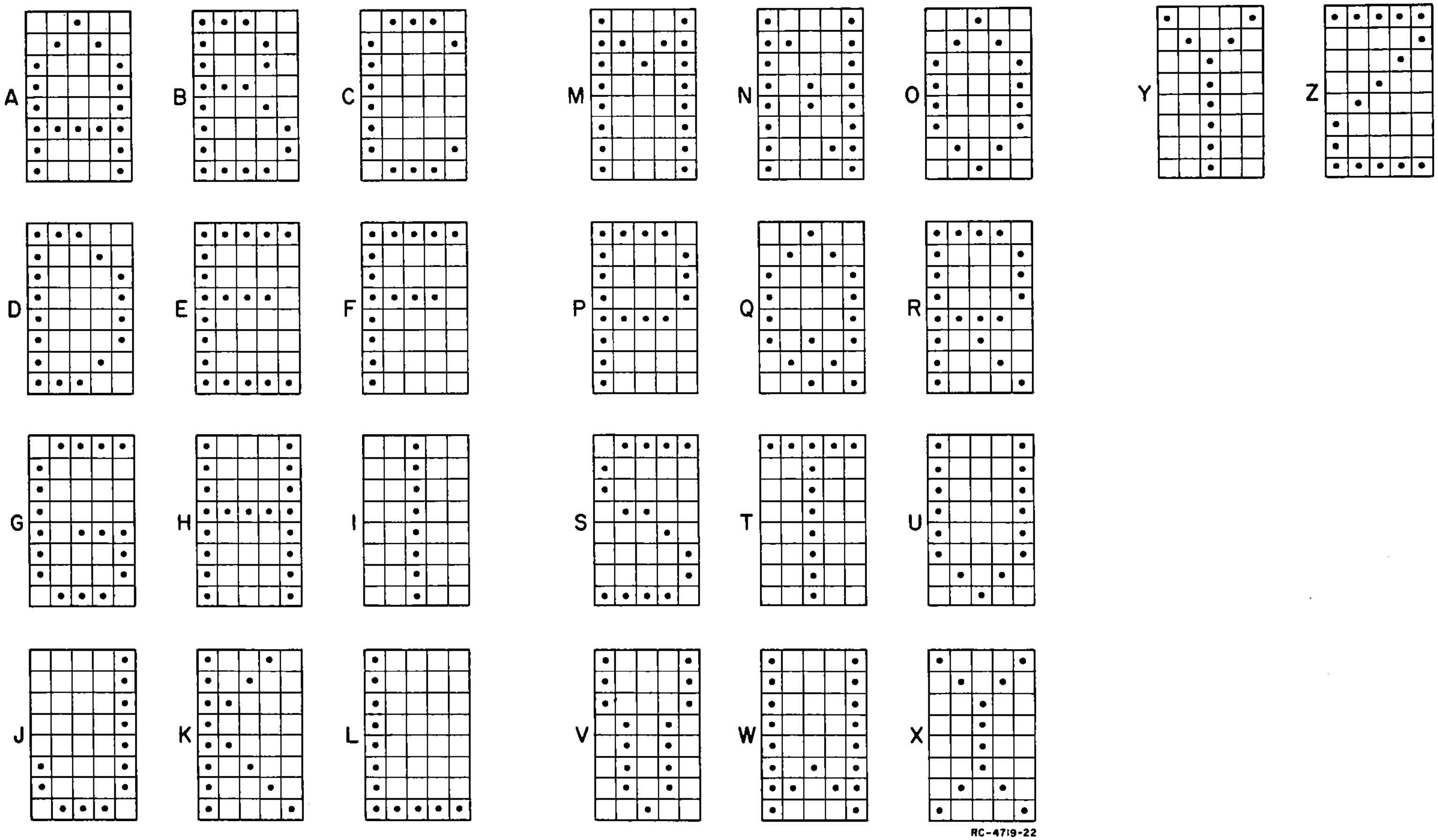

FIG. 3 BLOCK-LETTER ALPHABET

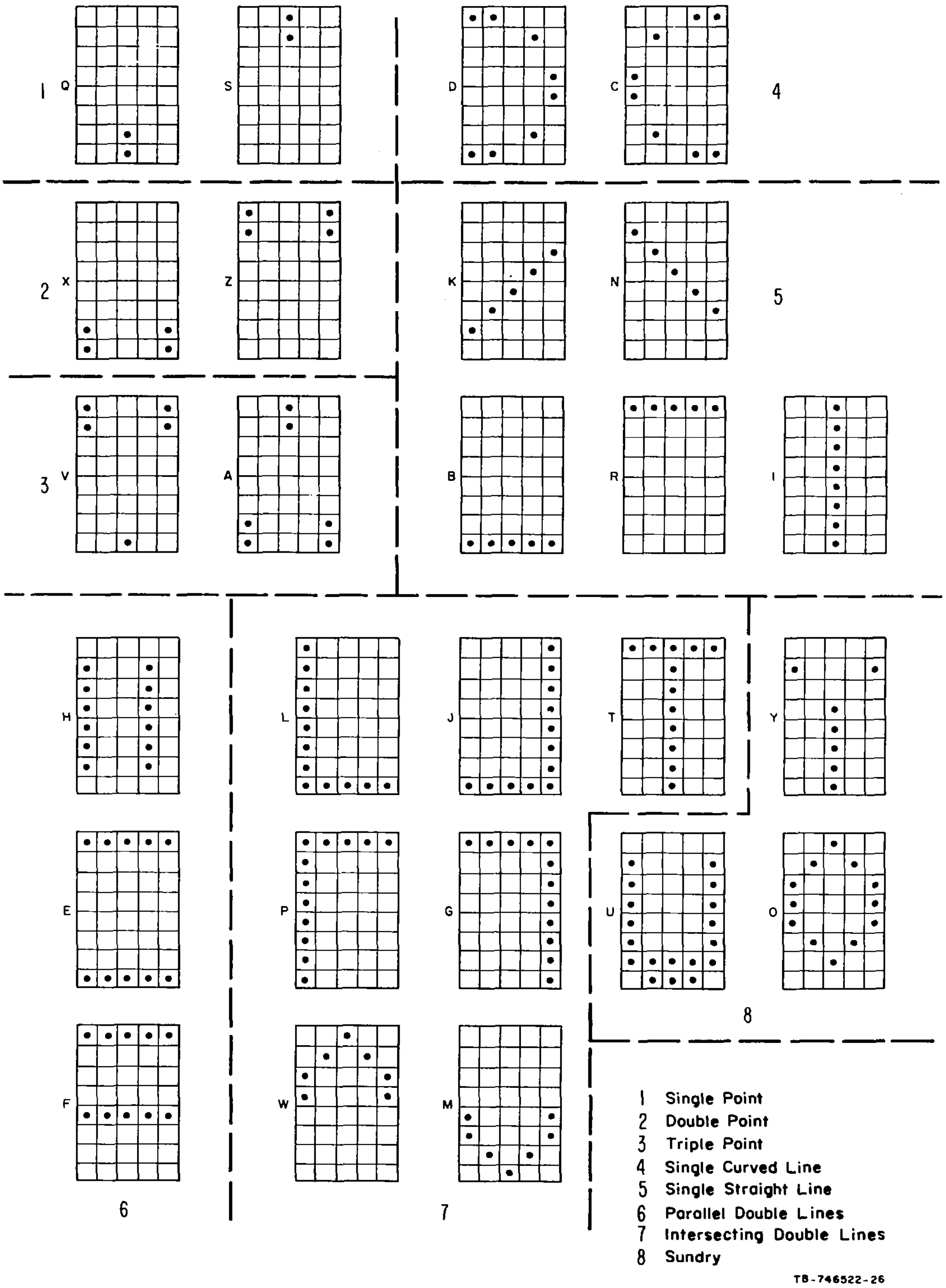

FIG. 4 EXPERIMENTALLY DEVELOPED ALPHABET

Subject S_1 was trained in a series of one-hour sessions in which the stimulus duration was 300 msec and the interval between stimuli was progressively decreased from 1.5 sec to 0.6 sec. Display rotation was introduced in alternate double sessions as shown in Figure 5. For these sessions, the angular velocity was 870 rpm and the amplitude of rotation was 0.8 cm. Figure 5 indicates that even during training, display movement improved performance. By the 13th session the subject had reached the asymptote of his performance.

B. EXPERIMENTS

1. Experiment 1--Performance With and Without Stimulus Pattern Motion

This experiment helped to determine under what stimulus conditions nutation of the stimulus apparatus improved a subject's performance. Two factors were investigated: (1) motion versus nonmotion of the stimulating apparatus, and (2) variation of the total number of display revolutions per presentation, accomplished by varying the stimulus presentation time.

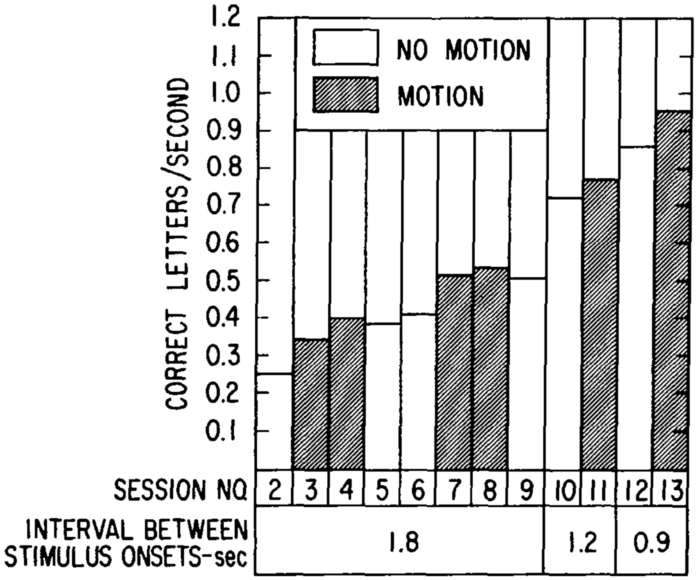

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FIG. 5 PERFORMANCE DURING TRAINING FOR S_1
STIMULATION DURATION = 0.3 sec;
ROTATION VELOCITY = 870 rpm

The rotation frequency and stimulus duration for each session is shown in Figure 6, along with the performance scores. These results are for Subject S_1, who was highly practiced in making verbal responses to briefly presented tactile stimuli. In each trial of this experiment, a letter was presented to the subject, and 900 msec after the onset of the stimulus, a new stimulus was presented. The fixed trial time required the subject to respond faster when stimulus duration was increased. During each experimental session, presentation time, and hence the number of revolutions per presentation, was held constant; but presentation time was varied from session to session over a range of 50 to 450 msec. Rotation speeds of 435, 870, and 1250 rpm were used. Each session consisted of four test runs of approximately 90 trials each. The correct letters per second from the twelve sessions, 36 to 43, 48, and 50 to 53, were analyzed according to a two-way analysis of variance. The results of this analysis are shown in Table 1.

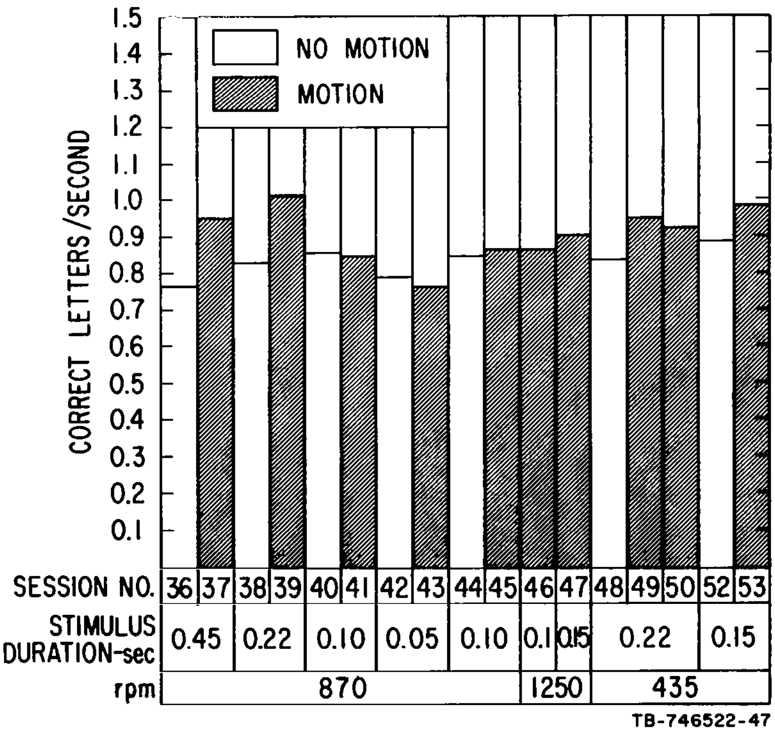

FIG. 6 AVERAGE TEST SCORES FOR EACH SESSION
INTERVAL BETWEEN STIMULUS ONSETS = 0.9 sec

Table 1

ANALYSIS OF VARIANCE FOR SESSIONS 36-53

Source	Sums of Squares	df	Mean Square	Level of Significance
Motion vs. Nonmotion	78.65	1	78.65	$\alpha < 0.005$
Sessions	96.35	5	19.27	$\alpha = 0.010$
Interaction	73.25	5	14.65	$\alpha < 0.050$
Error	187.28	36	5.20	
Total	435.53	47		

Considering the order of magnitude of the interactions (Table 1), it cannot be concluded that the component due to interaction is insignificant. However, it may be safely concluded that averaged over revolutions per letter, there is a significant ($\alpha < 0.005$) difference between the motion versus nonmotion methods of stimulus presentation, motion resulting in a marked increase in the number of correct responses by the subject.

As shown in Figure 6, for each session a different response time and a different number of revolutions per letter of the airjet array were used. It can be concluded ($\alpha < 0.01$) that there are significant differences among the six pairs of sessions.

An analysis was made of the frequency of occurrence of error-error pairs on successive trials during a session. The purpose was to determine whether the paced response resulted in a greater number of errors, owing to the decrease in time allowed to respond with decreased inter-stimulus interval. It was found that error-error pairs increased with presentation time and hence with reduced response time, assuming that the response time started after the stimulus was turned off.

In summary, Experiment 1 indicated:

(1) Motion (versus nonmotion) of the tactile pattern results in a substantial increase in the number of correct responses.

(2) Limiting the time to respond resulted in increased errors.

These results suggested more careful control of the presentation factors as well as introduction of a self-paced stimulus presentation rate.

2. Experiment 2--Effect of Stimulus Pattern Rotation Velocity and Stimulus Duration Time

In order to examine more carefully the influence of stimulus presentation time and the rotation velocity of the display, a complete factorial experiment was designed. Of the two male subjects and one female subject participating in the experiment, S_1 had extensive prior training in tactile perception, and S_2 and S_3 were given 9 hours of prior training. Each subject's task was to identify a letter presented tactually, make a verbal response, and then depress a foot switch to signal the computer to proceed with the next stimulus presentation. Each experimental session consisted of a control test followed by three tests under a new experimental condition. During both control and experimental tests, subjects were presented the alphabet of 26 letters three times (i.e., a total of 78 letters) in a random order.

Two factors, consisting of four levels of presentation time and five levels of rotation velocity, were replicated by each subject. Factor I, presentation time, consisted of levels 100, 200, 300, and 400 msec, factor J, rotation velocity, consisted of levels 0, 200, 400, 800, and 1200 rpm. At the beginning of each control session, a test was run at 400 msec and 800 rpm.

The data for each subject were corrected for guessing using the formula

$$p = \frac{P(c) - g}{1 - g}$$

where

$P(c)$ = observed proportion of correct responses
p = probability of a correct response without guessing
g = probability of guessing correctly.

The only substantial changes in the data due to this correction were for Subject S_3, who performed very poorly throughout the experiment. In spite of several additional hours of training, S_3 averaged less than half the number of correct responses recorded for either S_1 or S_2. Because of this rather poor performance, the data for S_3 were analyzed to obtain only information concerning the effects of motion vs. nonmotion of the tactile display. The average number of correct responses (out of a possible 234) was 76.7 in the nonmotion condition and 89.4 in the motion condition. A simple analysis of variance showed that the effect of motion contributed substantially toward improved performance ($\alpha < 0.001$).

The results for S_1 and S_2 are reported in Tables 2 and 3. Since the control variable contained little variation, it was not included in the analysis. Figures 7 and 8 show the performance versus "treatment."

Table 2

DATA FROM STIMULUS MOVEMENT EXPERIMENT 2 FOR S_1 AND S_2

Entries are Means of Number Correct (out of a possible 234) from Three Tests Averaged Over S_1 and S_2

Factor I (msec)	Factor J (rpm)					Row Means
	0	200	400	800	1200	
100	212	208	227	212	216	215
200	210	226	232	227	227	224
300	214	225	222	227	228	223
400	220	230	230	227	224	226
Column Means	214	222	228	223	224	222 = overall mean

Table 3

ANALYSIS OF VARIANCE FOR EXPERIMENT 3

Source	df	Sums of Squares	Mean Square	Level of Significance
Rows	3	753.58	251.19	$\alpha < 0.05$
Columns	4	812.70	203.18	$\alpha < 0.05$
Interaction	12	597.85	49.82	n.s.
Error	20	857.40	42.87	
Total	39	3021.53		

The data in Figure 7 show that for the range of stimulus durations explored, a maximum rate of performance occurred at 400 rpm, corresponding to a rotation period of 150 msec. Figure 8 shows improved performance with increasing stimulus presentation time. (Subject S_1, who was highly trained in tactual perception, showed a strictly linear increase in performance as a function of presentation time. The deviation from linearity shown in Figure 8 resulted from the performance of subject S_2, who was not as highly trained as S_1.) Viewing the maximum row and column means, it is apparent that a maximum in performance occurred at 400-msec presentation time and 400 rpm. These conditions correspond to 2-2/3 complete revolutions of the display during each stimulus presentation, with 150/5 (or 30) separate presentations of the pattern per rotation, spaced 360/30, or 12 degrees apart along the circumference.

3. Experiment 3--Effect of Amplitude of Stimulus Pattern Movement

In this experiment the effect of rotation amplitude was investigated. In order to lower the percentage of accuracies below those of the previous experiment so that improvements would stand out, and also to reduce the effects of

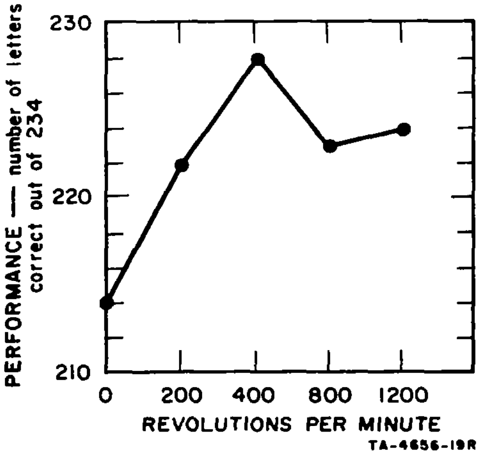

FIG. 7 PERFORMANCE AS A FUNCTION OF rpm

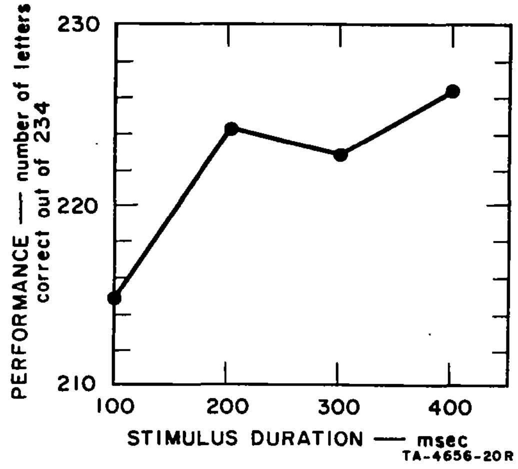

FIG. 8 PERFORMANCE AS A FUNCTION OF STIMULUS PRESENTATION TIME

previous training, it was decided to run this test using the more difficult block-letter alphabet of Figure 3 rather than the specially designed alphabet used in the previous experiment.

Subject S_1 was given two hours of training on the block-letter alphabet, which he had never felt before. Then he was given a series of tests with different amplitude settings. Four tests were run for each amplitude setting. In Figure 9 are plotted the results for each setting, the spread in results for the four tests, and the average. The numbers next to the plotted points indicate the sequence of these tests. The sequence is significant because the subject was not very well trained on this alphabet before starting the experiments, and therefore some learning during the sequence was expected. The relatively small extent of this learning can be seen from the slightly increased performance between the first and last experiment for the same conditions, namely 0.8 cm and 400 rpm.

C. HYPOTHETICAL MODEL

It is clear from the results described here that certain amplitude and rotation velocities improve performance. Subjects commented on the sharpened and

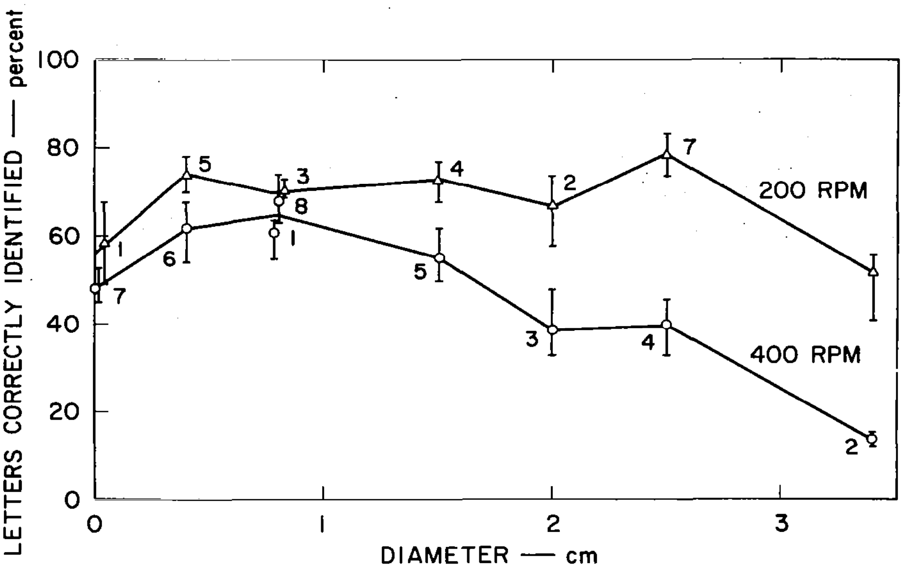

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FIG. 9 EFFECT OF AMPLITUDE OF CIRCULAR TRANSLATION OF STIMULATOR ARRAY ON RECOGNITION OF BLOCK LETTERS

enhanced sense of perception in these ranges of quantitative improvement. Subjects' reports also indicate that the "best" frequency of rotation tends to decrease monotonically as the amplitude of rotation increases, suggesting that best performance may be obtained for a certain linear velocity of the display. What this velocity might be can be estimated from the second and third experiments. For an amplitude of about 0.8 cm, a peak in performance for S_1 and S_2 was obtained with a display rotation frequency of 400 rpm (or 150 msec per revolution), leading to a velocity along the circular locus of about 15 cm/sec. (This velocity corresponds to a moving-belt display of 67 words per minute, reported in Linvill and Bliss, 1966.)

A possible neurological mechanism underlying these results is suggested by Mountcastle (1957), who found that in response to each point stimulus at the periphery (say, point A in Figure 10) there appears a corresponding point A' of maximum excitation at the cortex, with lesser magnitudes of excitation surrounding this central point and a circular band of inhibition even further removed from the center. Of particular importance is a monotonic

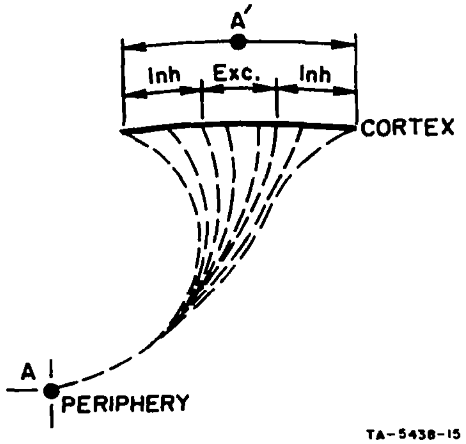

FIG. 10 CORTICAL RESPONSE TO A PERIPHERAL POINT STIMULUS

increase in latency of response as the recording point moves from the strong central point toward the inhibitory surround. In terms of such observations, the results of this paper might be interpreted according to the following model.

Visualize, for each point stimulus at the periphery, a "wave" of activity propagating from a central point at the surface of the cortex, as suggested in Figure 11, excitation becoming weaker with further and further distance until a zone of inhibition is reached. Consider now a second peripheral location B with corresponding central point B′. Let point B be stimulated T seconds after point A. If the interval T is very short, then excitation appears at points A′ and B′ essentially simultaneously, and similar waves propagate subsequently from each of these points. If T is very long, the effects of the wave from A are substantially dissipated before excitation of B, and the subsequent course of excitation from B′ resembles that from A′ except for a shift in position and time. For an intermediate range of T values, excitation at B′ tends to occur during the interval of inhibition from A′.

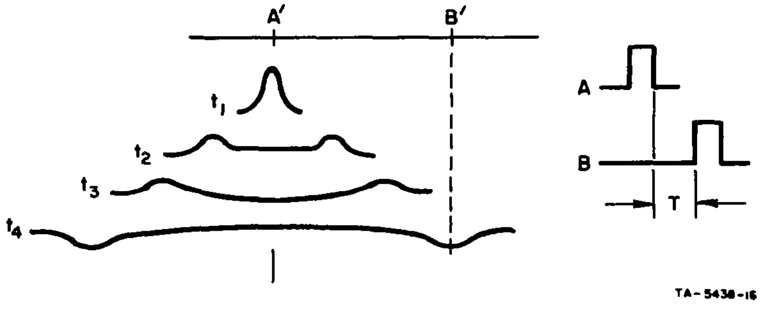

FIG. 11 TRAVELING WAVE FROM THE MAXIMUM POINT OF EXCITATION A′ IN RESPONSE TO STIMULATION AT PERIPHERAL POINT A

In this case, a significant decrease, or even complete elimination, of the excitatory response at B′ could be expected. At points intermediate between A′ and B′, however, a summation of excitation from A′ and B′ would be possible.

A subsequent excitation at A, following the excitation at A and then B, involves similar considerations. Thus, with repetitive stimulation, ..., A, B, A, B, ... one could expect to find a rate of excitation, of period 2T, at which the net sensation is strongest at an intermediate position between two even relatively widely spaced points A and B. These arguments can be extended to consideration of an airjet stimulator traveling in a circular locus, where the pulsating air causes excitation at point a′, and then b′, then c′, and so forth, as in Figure 12. In the critical frequency range, we visualize the excitation summing at the central region, with the peripheral responses diminished by inhibition.

Of particular interest with regard to this interpretation of cortical events is the experimental finding that the optimum frequency of rotation tends to decrease inversely with the diameter of the rotation. In terms of the two-point arrangement of Figure 11, if A and B were separated further so that the inhibition wave took correspondingly longer to become effective in the region of the other point, then for the optimal cancellation of excitation, interval T would have to be correspondingly increased. Similarly, if the radius of rotation were doubled, then as a first approximation, the optimum time for the stimulator to arrive at its diametrically opposite location would be doubled--or, the optimum rotation frequency would be halved.

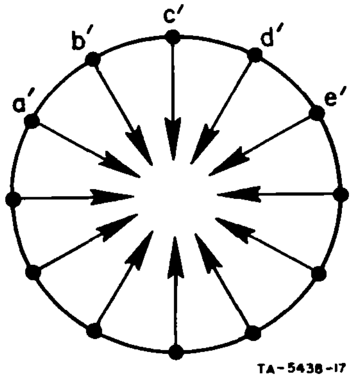

FIG. 12 EXCITATION ON THE CORTEX IN RESPONSE TO A CIRCULAR LOCUS OF STIMULATION AT THE PERIPHERY

Because the stimulus pattern with the rotating display is complex (due to simultaneous excitation of many rotating jets), a simple qualitative experiment was performed using a single jet traveling in a circle over the tip of the index finger. The prediction based on this simple model was that at very low rotation frequency, the subject would mentally be able to follow the slowly moving path of the stimulator. At a very high rotation frequency, the subject would have the sensation that a sharp circular rim was pressing into his skin, since, at high rotation frequencies, all parts of the path are essentially excited simultaneously. One might think that there would be a relatively smooth transition from the slow-speed sensation to that of the solid rim; however, the arguments in connection with Figure 12 predict an intermediate sensation at which there is primarily a strong central sensation with perhaps little, if any, sensation of rotation. An intermediate sensation of this form is indeed found, and at a rotation rate close to that found to be optimum for the complex display patterns. However, the sensations are by no means geometrically perfect. Below are some verbatim responses of subjects as the rpm was progressively increased:

(1) At very low rpm: "... feel point moving around but not a good circular feeling--perhaps more elliptical, or if finger is not positioned accurately only perhaps half an arc."

(2) At higher rpm: "... begin to feel more of a closed locus but again more elliptical with axis changing randomly, although there seemed to be a preferred direction. Sometimes felt circular."

(3) Still higher: "There seemed to be a zone in which the feeling was more like a solid disk of air with some edge modulation--like a coin settling down on a table." [Note: The sensation still remained as a single central zone even with the finger moving about.]

(4) At high rpm: "... felt like a rim of air, especially if the finger moved around; in an exploring manner."

D. SOME RELEVANT NEUROPHYSIOLOGICAL DATA

Such a mechanistic model leads to a search for inhibitory phenomena involving interaction over periods of the order of a 100 msec or so. It would indeed be interesting to obtain physiological recording data with a stimulator array moved over the skin, or even a point stimulus rotating over the skin, in the manner discussed. However, data are generally available only for a single fixed stimulator. Even so, there does appear to be scattered data indicating such periods of inhibitory effects. Below is a sampling of such evidence.

A relevant study is that of Towe and Amassian (1958), in which the digits of rhesus monkeys were stimulated electrically and single-unit responses were recorded in the somatosensory cortex. It was found that the discharge of 40 of the 110 units encountered could be prevented by prior or simultaneous stimulation at a nearby point, even when this nearby point stimulated alone would not itself cause the unit to fire. This inhibition lasted about 80 msec and was followed by a period of slight facilitation. The duration of this inhibitory effect was directly proportional to the intensity of the testing stimulus and the spatial separation of the conditioning and testing stimuli.

Phenomena found in the components of compound evoked potentials recorded from the scalp of humans suggest similar inhibitory effects, lasting about 100 msec, followed by facilitation (Uttal and Cook, 1964; Allison, 1962).

Related phenomena have also been noted on a peripheral level. Lindblom (1965) found long-duration inhibition phenomena in dorsal root units of monkeys as a result of mechanical stimulation of the distal glabrous skin. By means of threshold studies, he demonstrated that each impulse is followed by a relative refractory period that lasts more than 100 msec. Repetitive discharge delayed the recovery further and produced a cumulative increase in threshold which rendered maintained firing at frequencies above about 60 impulses per second difficult or impossible.

In addition, Uttal (1966) reports an amplitude oscillation in the compound evoked potentials recorded at the superficial point (i.e., the point closest to the surface of the skin) of the ulnar nerve above the elbow. Pulse electrical stimuli were applied to the superficial point of this nerve at the wrist. The magnitude of the oscillation was found to depend on stimulus intensity and interstimulus interval, although the period of the oscillation was very nearly constant at about 100 msec.

While these results are suggestive, more definitive data are needed before the physiological mechanisms underlying the behavioral results are clearly understood. From a practical standpoint, however, spatial pattern rotation appears to produce effects which may be important for tactile communication systems.

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III TACTILE PERCEPTION OF SEQUENTIALLY PRESENTED SPATIAL PATTERNS

by James C. Bliss, Hewitt D. Crane, Stephen W. Link,
and James T. Townsend

Visual recognition of patterns presented sequentially in the same retinal location has been studied by many investigators (e.g., Kolers and Katzman, 1963; Massa, 1964; Averbach and Coriell, 1961; Eriksen and Collins, 1956)*. Phenomena described as temporal interaction, erasure, forward and backward masking, etc., have been observed, and the results from experiments with these phenomena have led to postulated models (e.g., Sperling, 1963) describing the temporal properties of the visual channel. In investigations with patterned tactile stimuli, similar phenomena are observed, the understanding of which is crucial to attempts at tactile communication and development of a "tactile language."

The experiments reported here were aimed at determining temporal effects in the tactile channel. In these experiments tactile-spatial patterns were presented in rapid succession at the same anatomical location.

A. APPARATUS AND PROCEDURE

The experiments were carried out under control of a computer system that is described in detail elsewhere (Bliss and Crane, 1964). In this system, a CDC 8090 computer is used to store stimulus patterns and the sequence in which the patterns are to be presented. Figure 4 shows the patterns used in these experiments. These patterns comprise an experimentally developed alphabet that has been found to be convenient for experimentation because the patterns are easily distinguished and learned. To make the results easier to

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*References are given at the end of this section.

integrate, the relatively more difficult letters (H, M, O, U, Y, and Z) were not used (except for the preliminary experiment described here), leaving an effective alphabet size of 20 characters.

The computer was programmed to output these alphabetic shapes in the appropriate temporal sequence. To present one such shape the computer transmitted a sequence of eight 12-bit words to specially constructed external equipment. Each word represented one row of the spatial pattern to be displayed. The external equipment stored the 96-bit pattern in 8 msec and simultaneously activated the specified tactile stimulators.

The tactile stimulators used were airjets. Each jet was formed from a 0.031-inch outlet port and was activated by an electromagnet. The air pressure pulse, measured 1/8 inch directly above the airjet outlet, was about 3 psi in these experiments, with a rise and fall time of about a millisecond and an overall pulse width of about 2.5 msec. A 200-cps pulse repetition rate was used throughout the experiments, implying that, for example, the stimulators were actually turned on and off 20 times during a presentation time of 100 msec.

The advantages of airjet stimulation are that relatively uniform stimulation is produced over nonuniform cutaneous surfaces and stimulator spacing can be made quite small. The stimulator array used is shown in Figure 13, and the location of the stimulators with respect to the palmar side of the hand is shown in Figure 14.

Two male and one female college students were used in these experiments.

B. EXPERIMENTS

1. Preliminary Experiment

The importance of temporal sequence in tactile perception of alphabetic shapes was first noted in an experiment in which a subject was presented with random letters in two different temporal sequences but at the same average rate of letter presentation. In the first sequence, every 0.9 sec a letter (chosen at random) was presented for 0.3 sec and was followed by a 0.6-sec rest. The subject had to respond in the 0.6-sec "off" time between the end of one letter and the onset of the next. In the second sequence, sets of three

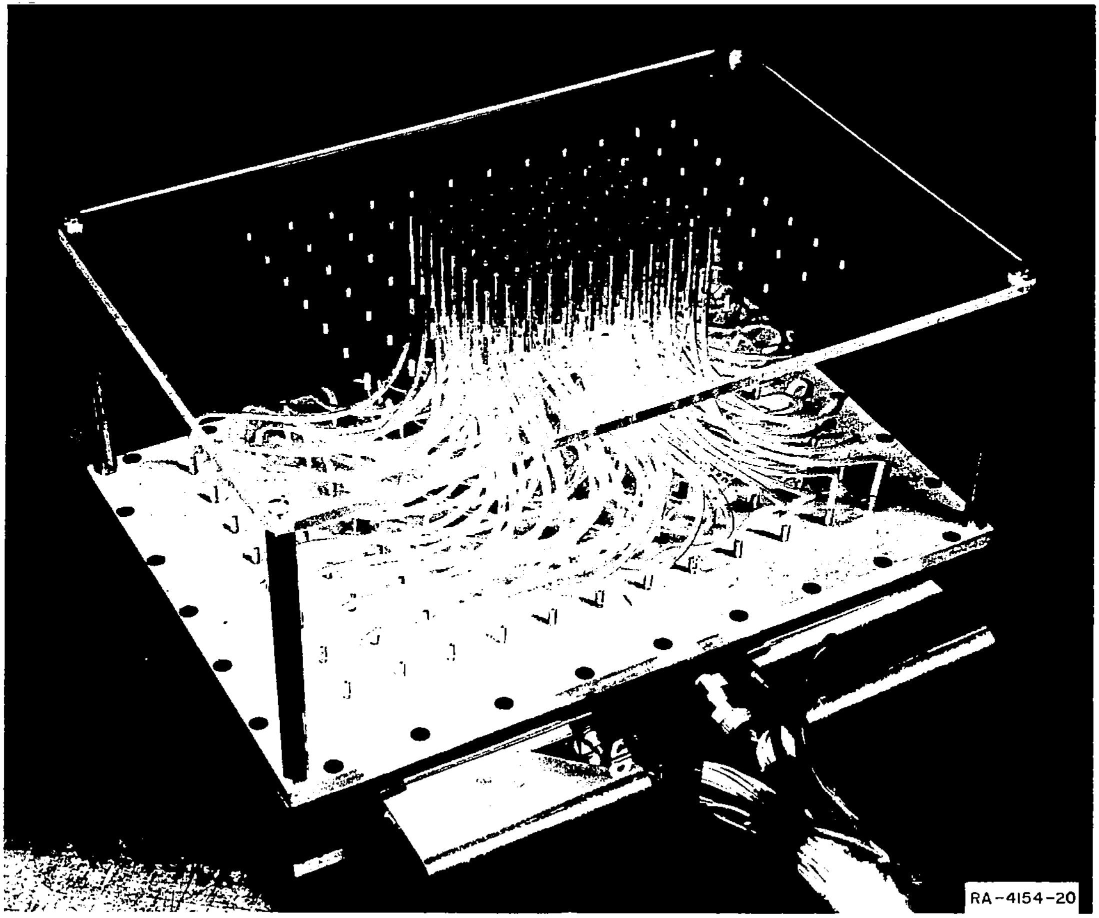

FIG. 13 TACTILE STIMULATOR ARRAY

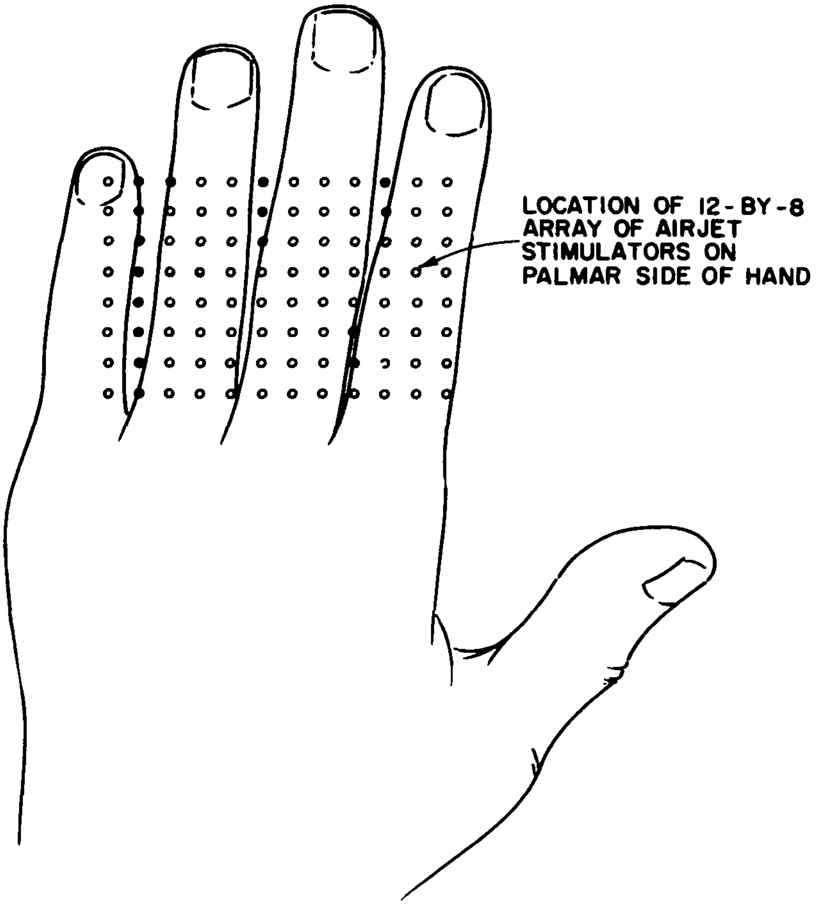

FIG. 14 POSITION OF AIRJET ARRAY ABOUT 1/8 INCH BELOW THE PALMAR SURFACE OF THE HAND

random letters were presented in rapid succession during 0.9 sec, each letter being on for 0.3 sec. In the following 1.8 sec the subject had to name all three letters. He then received three more letters, followed by 1.8 sec of off time, and so on. Four sessions of one hour each were run, two sessions with each temporal sequence. During each session there were four tests, separated by rest and practice periods. Each test consisted of 81 letters. The results of this experiment are shown in Figure 15.

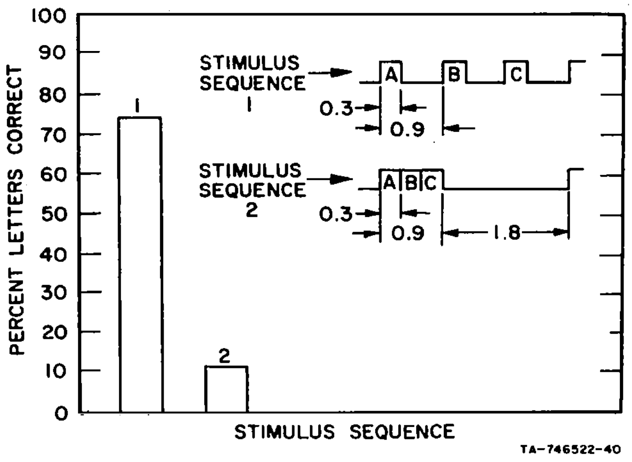

FIG. 15 LETTER RECOGNITION ACCURACY FOR TWO TEMPORAL SEQUENCES

Under the second-sequence conditions, the performance was extremely poor. The fact that the subject missed almost every middle letter of each triplet suggested that some type of masking was in part responsible for the poor performance. It was also found that by counting a response correct when it was simply in the wrong sequence, the subject's performance (after correction for guessing) was essentially doubled. Thus, by counting KJP in response to PJA as two letters correct (the P and J) instead of just one (the J), the subject's accuracy--corrected for guessing--increased from 11 percent to 20 percent. This is in agreement with the results reported by Kolers and Katzman (1963) for a visual experiment in which the subject was asked to name English letters sequentially presented in groups of three at letter rates approximately twice as fast as the ones used in the tactual experiments described here. Kolers and Katzman determined that this kind of letter reversal was a common phenomenon. This similar finding, for both touch and vision, implies that the major problem in the triplet experiment may not be at a peripheral neural level, since more letters are recognized than indicated by the performance scores, but their sequential ordering is not being preserved.

2. Doublet Experiments

The preliminary experiment led to a series of sessions in which random pairs of alphabetic characters were given each of the three subjects according to the temporal sequence shown in Figure 16. Following each doublet presentation, a subject responded at his own rate. His responses were then typed on the on-line typewriter by the experimenter, thus automatically activating the next stimulus sequence. The subjects were very well practiced in this task, each subject having at least ten hours of training before the tests began.

During each one-hour test session, four separate tests were given, with rests between. Each test consisted of a presentation of 66 pairs of equally probable random letters. The tests with Subjects R and K were run first, using a predetermined set of time intervals (T_0, T_1); the tests with Subject Ke were run later. The results from Subjects R and K were used to select a better set of time intervals (T_0, T_1) for Subject Ke.

In one set of test sessions, T_1 (the off time between the letters of each pair) was held constant at 22 msec, and T_0 (the on time of each letter) was varied from 100 to 400 msec for Subjects R and K, and from 50 to 300 msec for Subject Ke. The results are shown in Figure 17, in which the percent of errors on the first response and the percent of errors on the second response are plotted separately as a function of T_0. For all three subjects, the error rate decreased as T_0 increased, more first-response errors occurring with values of T_0 less than 100 msec, and more second-response errors occurring with

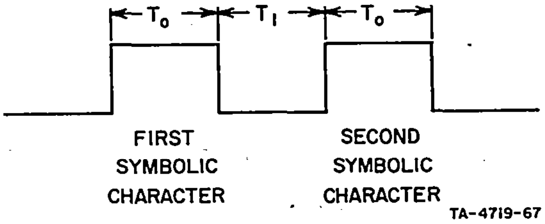

FIG. 16 TIMING ARRANGEMENT FOR SEQUENTIAL PRESENTATION OF THE PAIR OF ALPHABET CHARACTERS

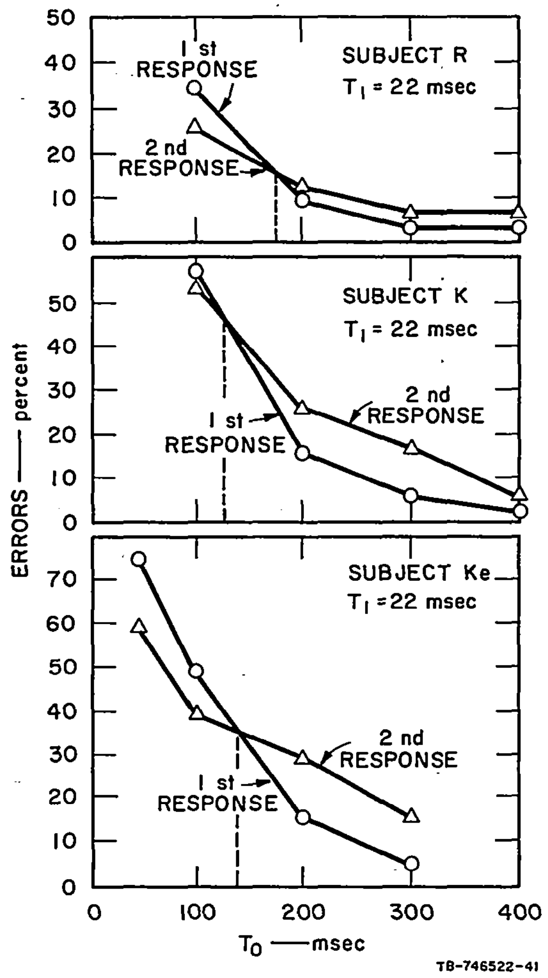

FIG. 17 PERCENT ERRORS AS A FUNCTION OF STIMULUS ON TIME WITH THE BETWEEN-STIMULI INTERVAL HELD CONSTANT

values of T_0 greater than 200 msec. The crossover occurred for T_0 between 100 and 200 msec. In other words, for short letter durations, there seemed to be more interference of the second letter with perception of the first, while for longer durations the reverse seemed to be true.

In a second series of test sessions with Subjects R and K, T_0 was held constant at 100 msec while T_1 was varied from 22 to 300 msec. For Subject Ke, T_0 was held constant at 50 msec while T_1 was varied from 22 to 400 msec. These results are shown in Figure 18, where both first- and second-response

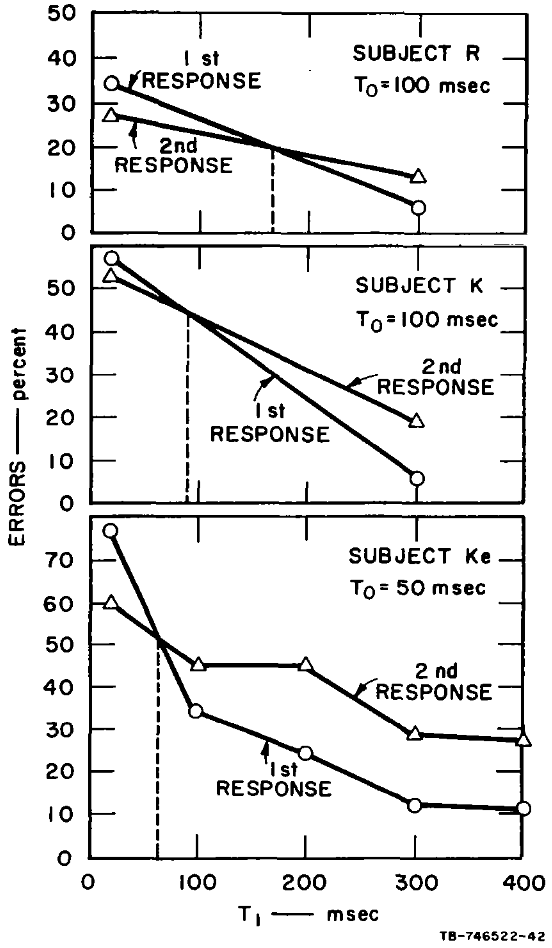

FIG. 18 PERCENT ERRORS AS A FUNCTION OF THE BETWEEN-STIMULI INTERVAL WITH THE STIMULUS ON TIME HELD CONSTANT

errors are independently plotted as a function of T_1. Again, there is a crossover between first- and second-response errors, first-response errors being more prevalent for short T_1 intervals and second-response errors more prevalent for longer T_1 intervals. Each of the error rates decreased with T_1 to values of about 10 percent.

In a third sequence of tests with Subjects R and K, the time between letter onsets was kept constant at 400 msec, while T_0 was varied from 100 to 400 msec. These data are shown in Figure 19, where total errors are plotted as

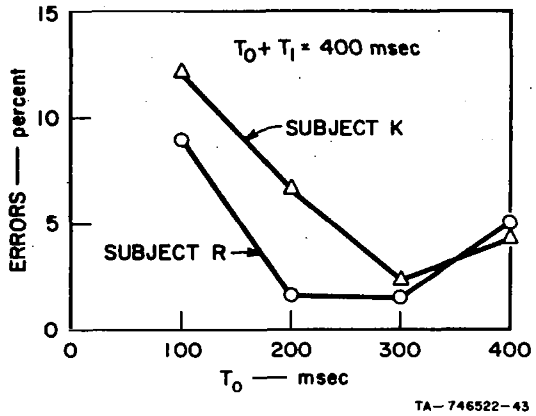

FIG. 19 PERCENT ERRORS AS A FUNCTION OF STIMULUS ON TIME WITH THE STIMULI ONSET INTERVAL HELD CONSTANT

a function of T_0. These curves indicate a minimum in error rate for values of T_0 between 200 and 300 msec, implying that a period of no stimulation for about 100 msec between letters is beneficial.

A final result apparent from the data is that letter reversals occur only for small values of T_0 and T_1. Letter reversals accounted for about 4 percent of the errors for $T_1 + T_0$ less than 150 msec (for Subjects K and Ke) and accounted for a negligible percentage of the errors for $T_1 + T_0$ greater than 150 msec. Subject R had a total of only five letter reversals in all of the sessions; these reversals were all for T_1 equal to 22 msec and T_0 between 100 and 300 msec.

C. DISCUSSION

Since the subjects had to identify both of the temporally separated stimuli in each of the doublet trials, these experiments may be considered as a pattern masking study in which both forward and backward masking phenomena are involved simultaneously. That there should be interference between two stimuli presented too closely in space or time is, of course, not unexpected, since any system, including the human nervous system, has limited resolution. However, the following three aspects of the interaction results reported here are worth special mention: (1) an increase in letter reversals for very short interstimulus intervals; (2) a greater backward masking effect for small values of T_0 and T_1, and a greater forward masking effect for longer values of T_0 and T_1; and (3) a crossover in (2) occurring in the range of 100 to 200 msec after the onset of the first stimulus.

While the picture is far from complete, many investigators have suggested models of perception based on input quantization of time. Eriksen (1966), for example, suggests that the visual system sums the luminance from two or more successive stimulations distributed within a brief time interval of the order of 100 msec.

Although there have been some well-stated objections to models involving constructs like "epoch," "read-in time," and "erasure," such models can help structure thinking on masking and interference phenomena, even though these constructs are oversimplifications. In particular, it is worth considering whether such models can be applied to tactile memory tasks. For example, in a model proposed by Sperling (1963) for visual memory tasks, there is a read-in interval of roughly 50 to 100 msec. Stimuli occurring wholly within this interval tend to summate and superimpose. Normally, without interferring stimuli, the read-in period is followed by a short-term storage, processing, and read-out interval lasting perhaps as long as several seconds. However, a second stimulus occurring immediately after the read-in interval of the first stimulus, just before or during the short-term memory readout, may tend to initiate a new read-in interval and cancel or replace the first stimulus before it is read out. With still further separation, the two stimuli occur in separate "memory epochs," and their mutual interference is reduced. Thus, according to this model there are at least three intervals of concern: (1) a summation interval of 50 to 100 msec; (2) an interval immediately after (1), in which a second stimulus may tend to replace a first stimulus; and (3) a later interval of little interference.

In terms of such a model, whether there should be more first- or second-response errors in the experiments reported here is determined by which of these intervals is involved. Of course, for simultaneous presentation of two patterns, the number of errors on the first stimulus must equal the number of errors on the second stimulus. Presumably this would also be true for two stimuli occurring wholly within interval (1) above. Since the curves of Figures 17 and 18 show no tendency to come together again for the short values of T_0 and T_1, the interpretation would be that the minimum values of T_0 and T_1 employed in these experiments were sufficiently long that in most cases only conditions (2) and (3) mentioned above occurred. This is also suggested by the fact that the percentage of reversal errors never became very great. The fact that the percentage of reversals increased somewhat above a chance level for the shortest times employed indicates that in a few cases interval (1) phenomena were involved.

According to this interpretation, then, when the second letter occurs immediately after the read-in time, the first letter may tend to be cancelled or replaced, thereby producing more first-response errors. With further temporal separation, the first letter gets safely tucked away in immediate memory before the second letter is presented, thereby reducing the first-response errors. The first- and second-response crossovers shown in Figures 17 and 18 suggest that the interval in which the second stimulus tends to replace the first is from about 75 to 200 msec.

Also consistent with a tactile epochal model are the results from tactile apparent-motion studies. These apparent-motion phenomena occur strongly for stimuli temporally separated by 50 to 150 msec (e.g., Kotovsky and Bliss, 1963; Sumby, 1965), which would place the stimuli in adjacent read-in intervals. When the stimuli are separated by one or more memory epochs, the system should be able to resolve the ambiguity, and the perception should be that of two spatially separate stimuli instead of one moving stimulus.

A number of tactile neurophysiological experiments have indicated response phenomena involving intervals of the order of 100 msec, which are suggestive of underlying mechanisms for masking or erasure. In a pertinent experiment, Towe and Amassian (1958) recorded action potentials from single cortical cells in somatosensory area 1 of rhesus monkeys (Macaca mulatta). On stimulating the palmar surface of the digits and hands, they found that the evoked discharge of 40 of the 110 units encountered could be prevented by a prior or simultaneous stimulation at a nearby point, even when the nearby point, stimulated alone, would not fire the unit. The duration of this inhibitory effect was as long as 100 msec, and it was followed by a facilitation period. Presentation of the efficacious stimulus up to 2 msec prior to the ineffective "conditioning" stimulus resulted in complete inhibition of discharge in only three of the units studied.

This inhibitory phenomena, followed by a period of facilitation, is also found in compound cortical-evoked potentials with cutaneous stimuli. In a review of this work, Uttal (1965) points out that several investigators have found that components of the second of two evoked responses were diminished in size in the 100 msec following the initial stimulus, and that these temporal inhibitions led to vast deviations from a simple additive process.

On a more peripheral level, Lindblom (1965) found long-duration inhibition phenomena in dorsal root units of monkeys as a result of mechanical stimulation of the distal glabrous skin. By means of threshold studies, he demonstrated that each nerve impulse is followed by a relative refractory period which lasts more than 100 msec. Repetitive discharge delayed the recovery further and produced a cumulative increase in threshold which rendered sustained firing at frequencies about 60 impulses per second difficult or impossible.

While the mechanism underlying forward masking may be the physiologically observed inhibition, it does not appear likely that this could account for the backward masking. However, backward masking could result from some process associated with the facilitation stage following the inhibition phase observed in neurophysiological responses. This facilitation stage occurs at about the same time, with respect to the onset of the first stimulus, as the period in which fewer second-response errors occurred in the tactile experiments reported here.

Whether these and other findings will eventually "fall into place" cannot be foreseen. At this point, more direct evidence is needed before any model of information processing in the tactile system can be considered more than crude and speculative.

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IV EXPLORATORY EXPERIMENTS ON TACTILE-SPATIAL INTERACTION

by Hewitt D. Crane and Stephen W. Link

In order to obtain a more quantitative understanding of spatial interaction, a series of exploratory experiments was initiated, involving simultaneous presentation of a number of point stimuli to different locations on the fingers. The areas of stimulation were the 12 interjoint regions on the palmar side of the hand (thumb omitted), making a total of 24 locations when both hands were used. In some experiments only a single hand was used, in others only a portion of the hand. Single point stimuli (singlets) and simultaneous stimulation of two points (doublets) were used in these experiments.

A. METHOD OF PRESENTATION

The interjoint positions of each hand were labeled as shown in Figure 20. A modified version of an airjet display designed for this purpose employed four pivotal plexiglass fingers, each containing three adjustable airjets. This provided ample flexibility for adapting the apparatus to each subject's hand, which was fixed with respect to the apparatus by an arm rest and finger stops at the end of each plexiglass finger. There were two such arrangements, one for each hand.

Each session consisted of four sets of presentations, each set containing 66 doublets, with a rest between each set. Sixty-six is the total number of possible doublets for a single hand, that is, a field of 12 positions (12 x 11/2 = 66). During a single session, then, each subject received a total of 264 doublets, which for a single hand resulted in 44 stimulations of each of the 12 anatomical positions. Stimulus duration was 400 msec. Each subject's response to a doublet was typed into the control computer by the experimenter, and after a fixed delay, the next doublet was automatically presented. There was no fixed time within which a subject was forced to respond.

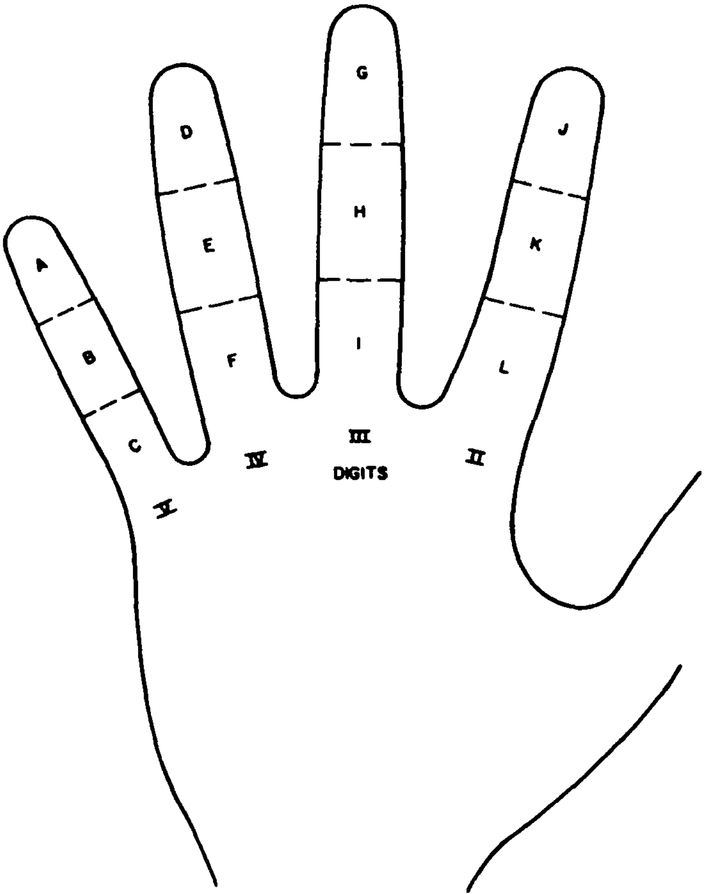


FIG. 20 SCHEME OF ANATOMICAL LABELING FOR THE DOUBLET EXPERIMENT

For experiments involving two hands, the number of possible doublets was 24 x 23/2, or 276. The same session format was used in the two-hand experiments as in the single hand experiments, except that in the former, each run of 66 doublets represented a different random sample from the possible 276 doublets.

Four male college students (Subjects A, D, K, and S) were used in these tests. Each subject was right-handed.

B. METHOD OF RESPONSE ANALYSIS

Only single errors were extensively analyzed. The two methods of analysis reported here point to different aspects of performance which a theoretical account of the data must explain. First, we considered "confusions" made by the subject. For example, if upon presentation of the doublet (a, b), the subject reported the occurrence of the stimuli (a, c), then a single confusion was said to have been made. Second, we considered whether a confusion occurred on the first or on the second response. Since the order in which the subject made his replies was preserved, the first-vs-second response analysis is quite straightforward.

Apparently the subjects developed different strategies of response. For example, Subject K reported that if the stimulus pairs formed a meaningful word (e.g., familiar initials or a two-letter word), he always reported them in that order. Subject S, on the other hand, claims to have always responded in a given direction--either right to left or left to right.

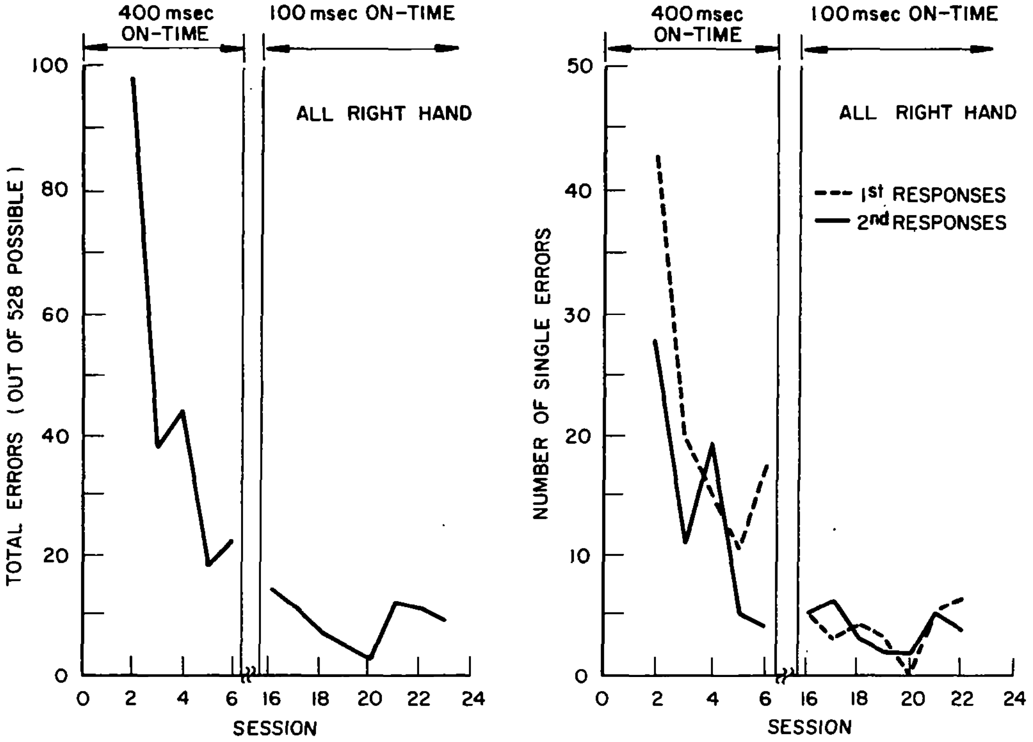
C. ERROR FACTORS

1. Singlets

Two of the four subjects were tested for singlet localization after several sessions of doublets. Typically, the error rate was less than half of one percent (one error in 240 presentations). A third subject, Subject A, was tested before any doublet training. For this subject there was initially a large number of errors in localization; however, after approximately five stimulations per anatomical position, the percent of error was zero. Hence, it seems that any learning that may be involved is quite rapid. In view of later experimental results showing no interhand confusion, we might reasonably conclude that identification of a single stimulus at a time over a field of 24 locations is a rather simple task.

2. Doublets

The data shown in Figures 21 through 24 reveal that all subjects had a rather high initial rate of error on doublets. This was especially interesting in view of the substantially error-free performance on singlet presentations.



(a) TOTAL ERRORS VERSUS SESSION

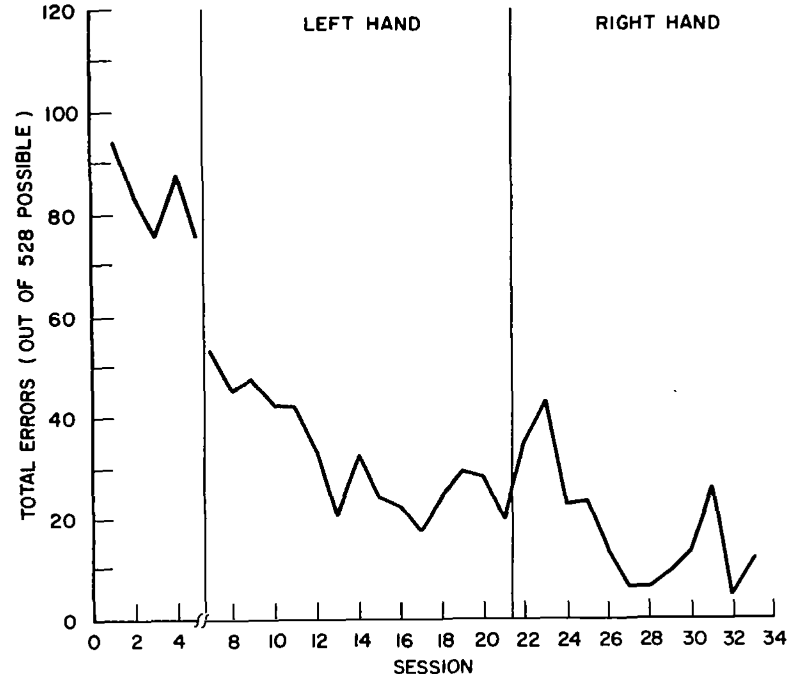
(b) SINGLE ERRORS VERSUS SESSION

FIG. 21 TWELVE-POINT ERRORS VERSUS SESSION FOR THE DOUBLET EXPERIMENT — SUBJECT A (on time as indicated)

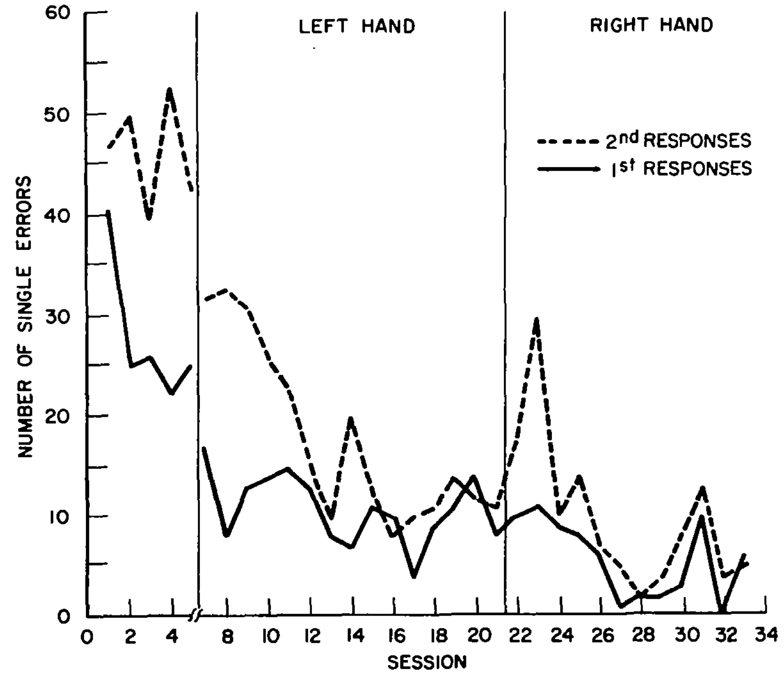
Secondly, the learning curves represent those typically found in psychological learning experiments, with a seemingly exponential decline in errors. The errors reported here were of several types: both responses were in error, a single response was in error, or an omission of either one or two responses was made. A more critical look at the data reveals some surprising differences in the kinds of errors made.

3. Reinforced and Unreinforced Learning

In terms of a learning model, one might reasonably expect faster learning with reinforcement after each presentation (indication of the correct response when there was an error) than with a purely self-learning situation in which there was no feedback whatever. Only Subject K was given feedback in this



(a) TOTAL ERRORS VERSUS SESSION



(b) SINGLE ERRORS VERSUS SESSION

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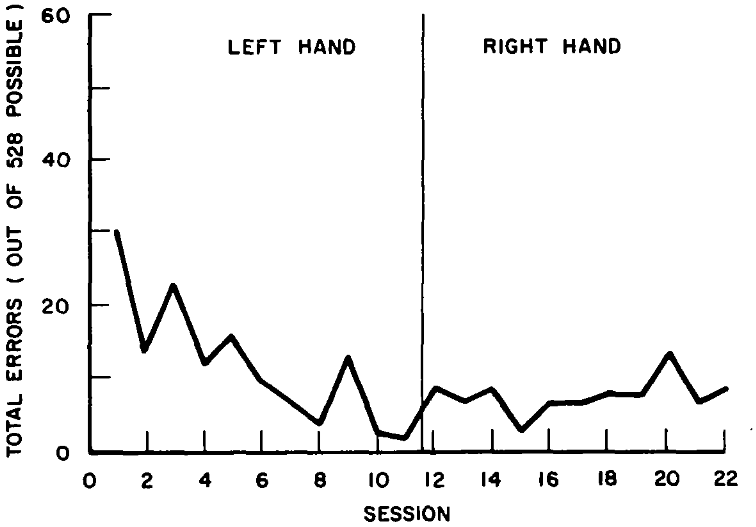
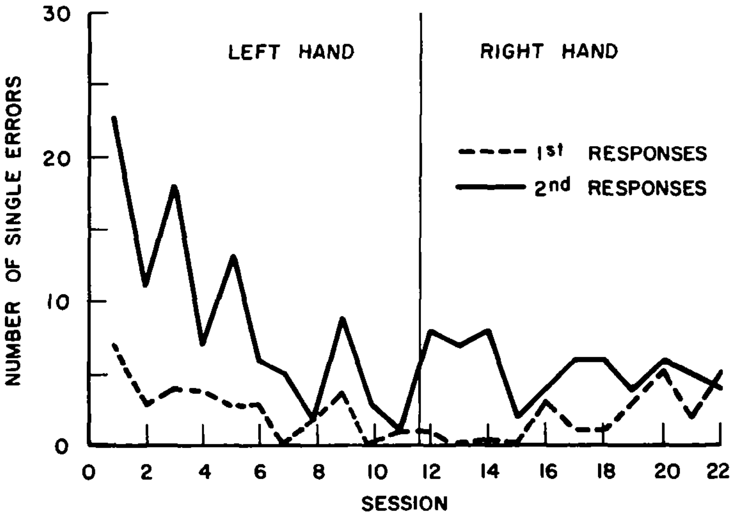
FIG. 22 TWELVE-POINT ERRORS VERSUS SESSION FOR THE DOUBLET EXPERIMENT — SUBJECT D (400-msec on time)



(a) TOTAL ERRORS VERSUS SESSION



(b) SINGLE ERRORS VERSUS SESSION

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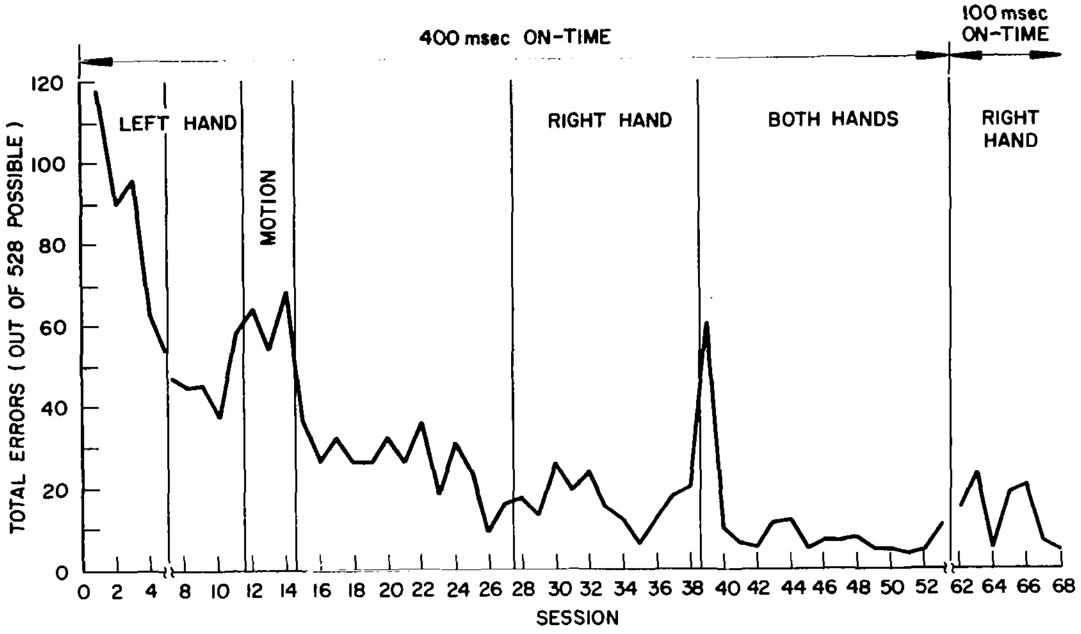
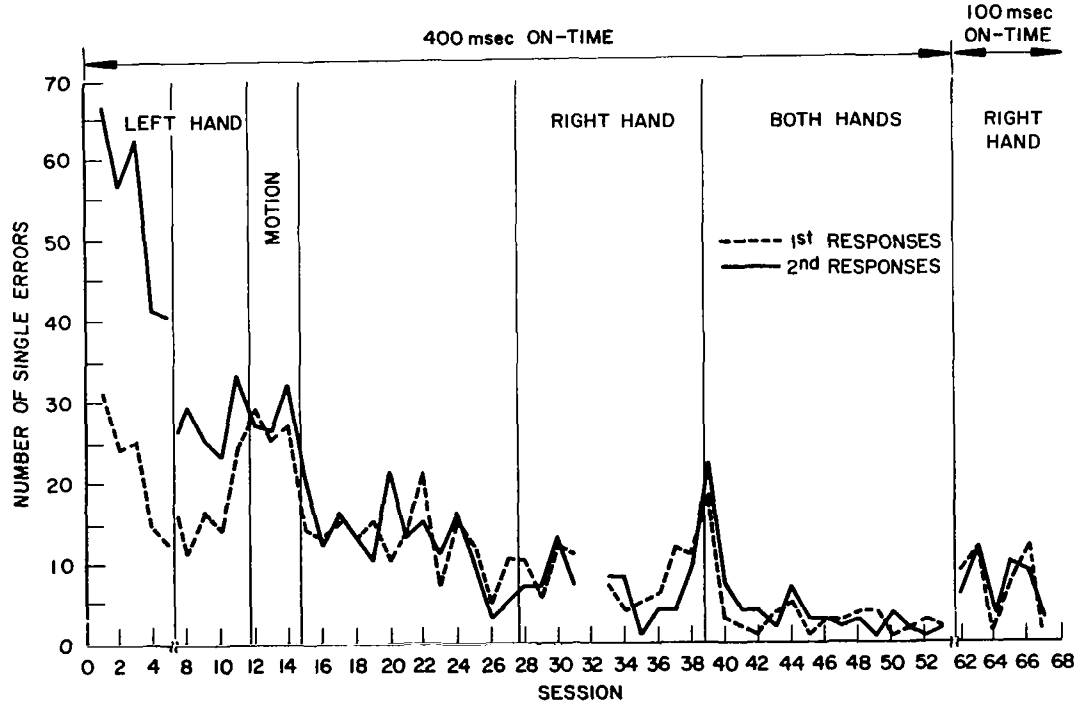
FIG. 23 TWELVE-POINT ERRORS VERSUS SESSION FOR THE DOUBLET EXPERIMENT — SUBJECT K (400-msec on time)



(a) TOTAL ERRORS VERSUS SESSION



(b) SINGLE ERRORS VERSUS SESSION

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FIG. 24 ERRORS VERSUS SESSION FOR THE DOUBLET EXPERIMENT — SUBJECT S (on time as indicated) manner, and we see that he had a relatively short learning time, at least as compared with Subjects S and D. By the sixth session, Subject K had almost reached his learning asymptote, whereas both Subjects S and D still had a high error rate.

It is interesting that Subject A also almost reached his learning asymptote by about the sixth session, although he had no reinforcement. He is somewhat distinguished from the others, however, by having been presented with singlets during his very first session. Exposure to the more simple forms (i.e., a single stimulus at a time) might be an important factor in learning. Knowledge of the singlet sensations might be thought of as helping the subject to some extent supply his own feedback about right and wrong responses.

4. Inter- and Intrafinger Errors

Confusion matrices for each of the four subjects are given in Part A of Table 4. Each matrix represents the single errors pooled over the three interjoint locations of each finger for the first four sessions of training. In Part B of the table, identical matrices for the last four sessions are presented. In general, these data support the conclusion that during the course of training a subject's "perceived" field of stimulation becomes narrowed until only intrafinger errors occur.* Thus, residual errors after training are almost completely intrafinger errors. This may be partially due to variability in placement of jets along the plexiglass fingers. (The jets must be repositioned for each subject.)

5. Interhand Transfer

Each subject was initially trained on one particular hand. After his error rate had reduced to a low value, the area of stimulation was switched to his other hand (except for Subject A). In each case, we see that the performance curves maintained their relatively low values, indicating significant transfer of learning. In two of the cases, the curves for the first and second response separated again to some extent, with the higher error occurring on the same

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*Some confusions seem to be attributable to the use of a verbal response, e.g., d and g were frequently confused by most subjects; hence, there appear confusions between digits III and IV.

Table 4
CONFUSION MATRICES

	STIMULUS	FIRST FOUR SESSIONS				LAST FOUR SESSIONS			
		RESPONSE							
		V	IV	III	II				
SUBJECT A	V	17	16	1	2	7	4	0	0
	IV	8	8	3	0	2	1	1	0
	III	2	41	10	3	0	5	3	1
	II	0	2	14	25	1	1	2	3
SUBJECT D		34	52	7	0	19	15	0	0
		7	11	37	1	3	9	1	1
		1	23	36	19	0	14	12	2
		25	9	11	26	2	1	3	8
SUBJECT K		12	1	1	1	5	0	0	0
		0	1	8	0	0	1	1	0
		0	23	3	4	0	2	0	0
		0	0	3	20	0	0	2	11
SUBJECT S		21	13	8	0	10	10	0	1
		7	25	37	5	3	4	12	1
		1	24	58	16	0	13	4	0
		1	5	36	62	1	2	4	11

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response position as initially. But after relatively few more sessions, the error rate again reduced to a low value.

6. Display Jitter

For one subject, display jitter was introduced during sessions 12, 13, and 14. In previous experiments involving the presentation of complex patterns (Section II), we noted an improvement in performance when the entire display was rotated in a small circular pattern during the presentation. A similar rotation was attempted here with Subject S. For these sessions the display arrangement was altered to separate the finger stops from the plexiglass fingers that held the airjets, so that the latter could be rotated under the stationary fingers of the hand. Though the diameter of rotation was relatively small (0.2 cm), there was nevertheless a significant adverse effect on performance. (The subject also reported that the movement tended to confuse him.)

The significance of this result is not readily apparent. If the display movement sharpens the central representation of the pattern, as we have previously assumed, then one might expect an even faster learning time with this movement and perhaps an even lower residual error rate. However, the fact that jitter actually increased the error rate is not necessarily contrary to this assumption, since the subject was not given any reinforcement (feedback) and learning was still incomplete when the jitter was applied. Stimuli with superimposed movement might, for all practical purposes, appear to the subject like a new character set, although not a completely unknown set, since the error rate with movement was not as high as his initial error rate. Further experiments would be required before more definite statements could be made.

7. First and Second Responses

The subjects were not given any instructions as to a desired order of response to each stimulus of the doublet pair. The actual order of response was preserved, however, and the error data (single-error only) were plotted separately for first response and second response. These errors are shown in Figures 21 through 24. The data are similar to those reported for total errors, shown in the same figures. However, for all subjects but one, the initial number of errors made on the second response was substantially higher than the corresponding number of errors for the first response. Later, either response appeared equally often in error. It is interesting to note that although substantial training tended to equalize errors in either response, a shift to the other hand again produced a distinct difference between the two error curves.

8. One Hand versus Two Hands

Only Subject S was given a full field of 24 positions (i.e., two hands). It is interesting to note that the error rate for both first and second response increased about equally during the first double-hand session (session 39), but then rapidly decreased to a low value once again. (The subject reported great confidence in being able to score very accurately even in this expanded presentation.) Of special interest is the fact that there were no interhand errors at all during this series of tests.

9. Decreased Stimulus Duration

With Subjects A and S, a stimulus duration of 100 msec was used for the last few sessions, compared with 400 msec for all other sessions. It was expected that the shortened duration might result in again driving apart the first and second response curves. However, it is clear from the results that there was actually very little effect from this decrease in duration.

10. Summary

Several points already seem clear from these experiments:

(1) There is a considerable amount of learning involved in discriminating doublets.

(2) Even singlets take a short amount of learning.

(3) There is a significant difference between first and second response error rates.

(4) There is no interhand confusion.

(5) There is interhand learning transfer.

(6) A subject can improve to substantially error-free doublet performance for a field of 24 positions.

(7) Residual errors are intrafinger errors.

(8) The performance of Subject A appears substantially different from the performances of the other three subjects in a number of ways. The differences are not yet clear.

D. DISCUSSION

A cursory analysis of these results requires some discussion of peripheral interaction and learning. The fact that singlet localization is an apparently simple task indicates that some locality differentiation is highly developed in these subjects. Benton (1959)* has noted the developmental course of finger differentiation, which terminates at approximately 12 years of age. It is not surprising, then, that for college students, interjoint localization is easy. Similarly, hand discrimination is simple; seldom have we observed any cross-hand confusions by subjects.

A more surprising result pertains to the difference between first and second errors. In this regard it seems clear that focus of attention and memory are operating together. For example, suppose a subject is engaged in a localization task in which two stimuli are presented, and, barring movement of the hand, both stimuli are far above the threshold for two-point discrimination. If the subject first localizes one of the stimuli and then the other, the time required for the first localization may be of such length as to require the subject to localize the second stimulus via trace stimulation. However, for the first stimulus to be remembered, it must be sent to long-term storage before the second stimulus can be localized. As the mechanism for localization and storage is used repeatedly, the length of time required may become shorter, so that additional time would be available for localizing and storing the second stimulus. Thus, the second-response errors would be reduced.

The fact that there are few interhand errors indicates that the hands are perceived as separate units. Hence, one would not expect any transfer of training of singlet localization from one hand to the other. Since none of our subjects was given singlet localization training of the second hand that received

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*References are given at the end of this section.

doublet training, it is not surprising that initially there was a small increase in the number of errors. The transfer of learning does not seem to be in the ability of the subject to discriminate, but rather in his ability to use a previously practiced central mechanism. At present the best guess is that the ability to fixate rapidly on the particular stimulus, define it, and put it into long-term storage before moving on to the next stimulus leads to improved performance.

These results, though only partially complete, both corroborate and extend previous research in tactile localization. Results obtained by Weber and Fechner, reported by Volkmann (1858) for tactual discrimination of two points from one, are in substantial agreement with the results reported here. Weber obtained a marked increase in the sensitivity of the practiced skin area as well as bilateral transfer to the other hand. Similarly, Krohn (1893) reported that "... the skin can be progressively educated to localize sensations of air pressure more and more correctly." Mukherjee (1933), investigating discriminative delicacy on the forearm, also concludes that discriminative ability can be improved by practice but that the improvement is greatly reduced after a one-week delay in training.

Thus a broad range of different tactile loci have been examined. Results continue to point toward the conclusion that tactile perception of localized stimulation can be greatly improved by training. However previous studies have focused attention primarily on the two-point discrimination threshold, so that little experimental evidence was accumulated on the problem of peripheral versus central or cognitive aspects of spatial stimulation. The present study, by definitely excluding the two-point limen, tentatively suggests that tactile-spatial localization involves a trainable central process in addition to the peripheral processes.

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V. INFORMATION AVAILABLE IN BRIEF TACTILE PRESENTATIONS

James C. Bliss, Hewitt D. Crane,
Phyllis K. Mansfield, and James T. Townsend

When visual stimuli, consisting of a number of items, are briefly shown to an observer, only a limited number (usually less than six) of the items can be correctly reported. This limit defines the so-called span of attention, apprehension, or immediate memory (see, e.g., Miller, 1956).* However, observers assert that they can see more than they can report. Several investigators have used sampling procedures to circumvent this immediate-memory limitation (Sperling, 1960; Averbach and Coriell, 1961; Estes and Taylor, 1964). These experiments have indicated that observers have at least two or three times more information available than they can later report. The availability of this information declines rapidly, so that within one second after the exposure the available information no longer exceeds the memory span. Sperling (1960) has tentatively identified this short-term information storage with the persistence of visual sensation that generally follows any brief, intensive visual stimulation.

If the mechanism for this short-term memory is part of the peripheral visual apparatus (see, e.g., Massa, 1964) then analogous results would not necessarily be expected from tactile experiments. The experiments reported here were aimed at determining whether or not, with brief tactile presentations, there is also more information available than can be reported. If so, the characteristics of the corresponding short-term tactile memory could be ascertained from techniques analogous to those employed in the visual case. Such characteristics are, of course, of considerable relevance to tactile language construction for tactile communication.

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*References are listed at the end of this section

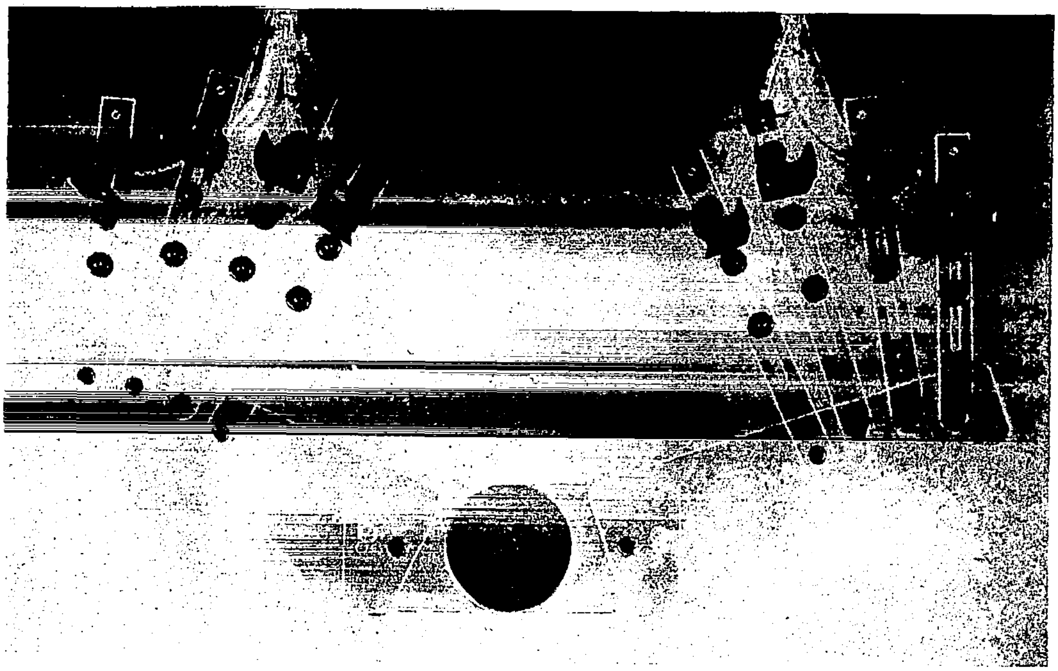
The first experiment reported here investigates the span of immediate memory for brief tactile point stimulations of the interjoint regions of the fingers. The second and main experiment in addition employs a sampling procedure to investigate the properties of short-term tactile memory.

A. EXPERIMENT 1: IMMEDIATE MEMORY

Many visual information-processing experiments have involved tachistoscopic presentation of geometrical patterns such as letters and numbers. In these experiments, the information is contained in the geometrical shape of the symbols, not in their retinal location. However, anatomical location has much greater significance in tactile displays, aided by the many anatomical landmarks. Moreover, tactile spatial interaction is much greater than visual, so that normal adult subjects cannot clearly perceive a brief simultaneous tactile presentation of even two spatially separated alphabetic shapes (Linvill and Bliss, 1966). However, there at least several anatomical locations that can be identified when tactually stimulated simultaneously. For this reason, point stimulation of specific anatomical locations was used in the experiments reported here rather than presentation of geometric patterns. The subject's task was to identify which locations were stimulated. This use of anatomical position rather than symbol shape as the information bearing element is a basic difference from the previous visual experiments with geometric patterns.

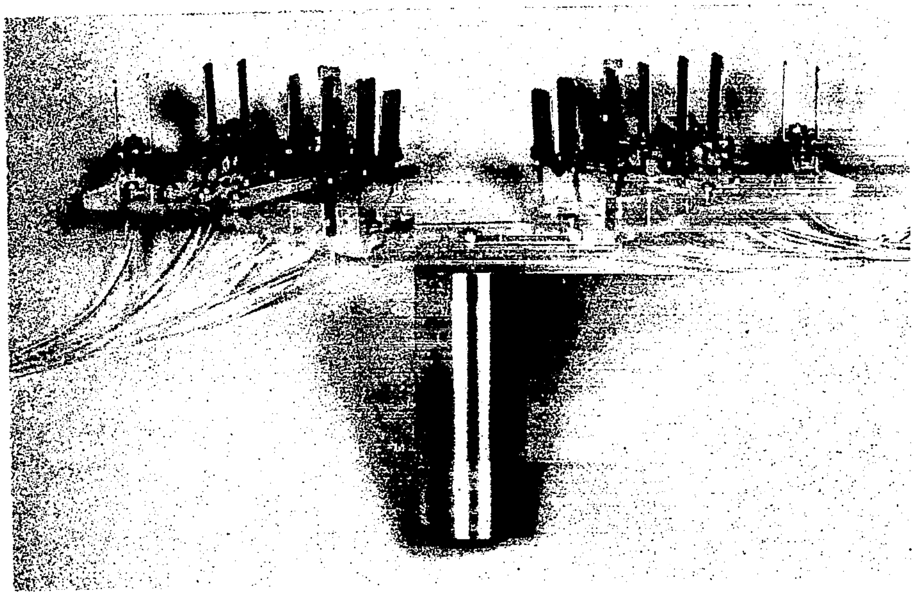
1. Method

a. Apparatus. The experiments were carried out under control of a CDC 8090 computer system, which was used to store stimulus patterns and the sequence in which the patterns were to be presented (Bliss and Crane, 1964). This system was designed for use with up to 96 tactile or visual stimulators. Only 24 tactile stimulators were used in these experiments, one for each of the 24 interjoint regions of the fingers (thumbs excluded). The palmar side of the fingers were suspended about 1/8 inch above the airjet stimulators shown in Figure 25, which permitted easy adjustment for each subject's hands. The subjects' arms were supported from wrist to elbow, permitting the hands to be suspended in this manner for extended periods without fatigue.



TOP VIEW

FIG. 25 APPARATUS FOR HOLDING AIRJET NOZZLES BELOW THE 24 INTERJOINT REGIONS OF THE FINGERS



SUBJECTS VIEW

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FIG. 25 Continued

Each jet of air was formed by a 0.031-inch outlet nozzle under control of a high-speed electromagnetic valve. The air pressure pulse, measured 1/8-inch directly above the airjet outlet, was about 3 psi, with a rise and fall time of about a millisecond and an overall pulse width of about 2.5 msec. A 200-cps pulse repetition rate was used throughout the experiments. Thus, all stimulators were simultaneously turned on and off 20 times during the 100-msec stimulus presentation time. The advantages of airjet stimulation for this investigation were that relatively uniform stimulation was produced over non-uniform cutaneous surfaces and that stimulator spacing could be easily adjusted.

b. Training. The subjects were three male college students in their late teens and early twenties. Each had previously been involved with experiments of this type involving point tactile stimuli. By the end of these previous experiments, Subject A was making fewer than 2-percent errors with the double stimulation on the right hand (i.e., two stimulus positions out of a field of 12); Subject K had achieved the 2-percent error rate on both his left and right hands separately; and Subject S, who had previously participated in about twice as many single and double presentation sessions as Subjects A and K, was consistently below a 2-percent error rate for double presentations with both hands (field of 24). Thus all three subjects were well trained for this task.

c. Procedure. Each subject had before him at all times a visual replica of the letter-to-interjoint assignment. On any one trial, n stimulation points were randomly chosen (by the computer) out of the possible 24 interjoint locations, and the corresponding stimulators were then activated for 100 msec. In any one session the number of positions simultaneously stimulated, n, was constant and known by the subject. The subject orally reported the locations perceived, using the alphabetic labels shown in Figure 26.

Each response was typed into the control computer by the experimenter, and after a fixed delay the next stimulus was automatically presented. There was no fixed time within which a subject was forced to respond. Initially, verbal feedback was given after each response, but inspection of the data and each subject's introspections led to a discontinuance of this after the first few sessions. The influence of the feedback on the subjects' performances seemed negligible, perhaps because of their previous long experience in this situation.

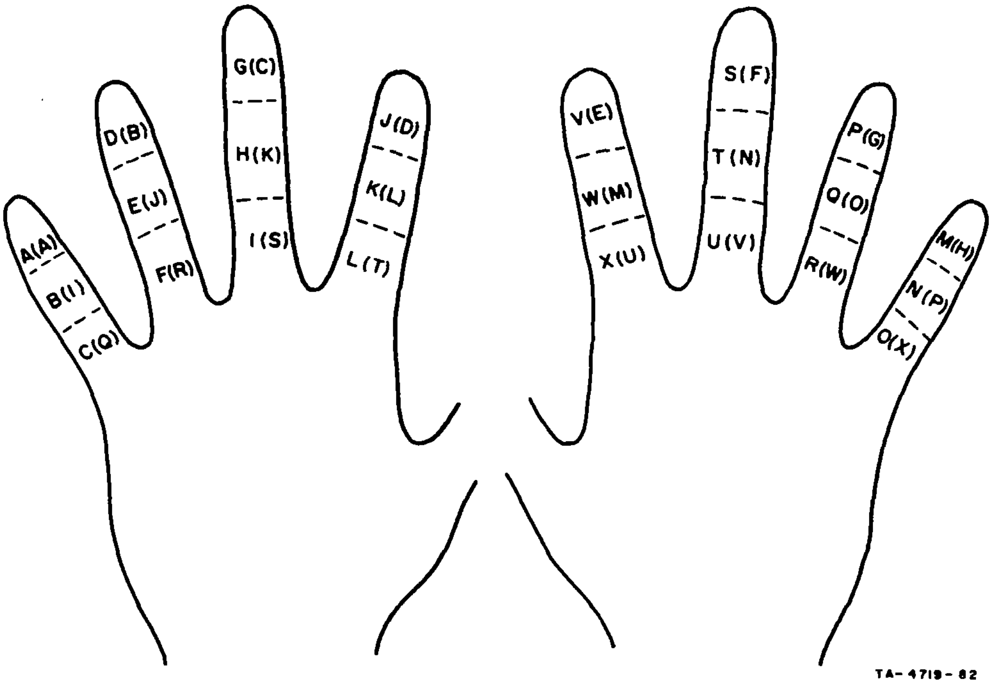

FIG. 26 FINGER LABELING FOR TWO HANDS
The letters outside the parentheses show the labeling used in Experiment 1; those inside the parentheses show the labeling used in Experiment 2.

For Subject S the number of stimulators simultaneously activated was increased by one in each succeeding session, from n = 2 to n = 12. The schedule for Subject K was similar, except that n was increased in steps of two in each succeeding session from n = 2 to n = 12. Subject A was initially given six stimuli simultaneously, and after seven sessions under this condition, n was increased by one in each succeeding session until n equaled 12.

In deciding on the number of trials per session, either the total number of simultaneous presentations or the number of stimulations of each interjoint position could be kept constant. The former would yield an increasing number of presentations per interjoint position per session, while the latter would force the total number of presentations per session to vary. Since the subject's task was to identify each of the stimulated positions rather than a pattern composed of the stimulated positions, the number of presentations per position per session was kept constant, namely, 22 presentations per interjoint position per session, or a total of 22 x 24 = 528 individual point stimuli per session. The total presentations per session for each value of n was therefore as follows:

n	2	3	4	5	6	7	8	9	10	11	12
Number of Presentations in a Session	264	176	132	104	88	75	66	59	50	49	44

This procedure kept the binominal variance for the mean number correct for each point of stimulation, after correction for guessing, approximately constant across the different values of n. It allowed the variance for the mean number correct out of the n points to increase as a function of n. Thus, in analyzing number correct per anatomical position, the data are as stable for n = 12 as for n = 2; however, when observing total number correct, more confidence may be placed in the smaller n data.

2. Results

Figure 27(a), (b), (c) shows the tactile results, after application of the correction for guessing given in the appendix. The magnitude of this correction increases with n. For Subjects A and K, the correction produced a negligible effect for values of n less than 6, about a 10-percent reduction for n = 6, and about a 40-percent reduction for n = 12. The correction for Subject S was generally less, being only about 20 percent for n = 12.

The curves for Subjects A and K were remarkably similar to those of Sperling (1960) for visual stimuli, showing a span of immediate memory of about 4.5 stimulus positions. However, the number of positions correctly reported by Subject S continued to increase with n until he achieved an average of 7.5 positions correct out of 12 after correction for guessing.

Introspections by Subject S suggested that he was able to recode simple tactile patterns into larger units (e.g., all three stimuli on one finger representing one "chunk" of information). This would help to explain why his immediate-memory level appeared so high, and a cursory examination of the data indicated that he was able to utilize patterns more than Subjects A or K.

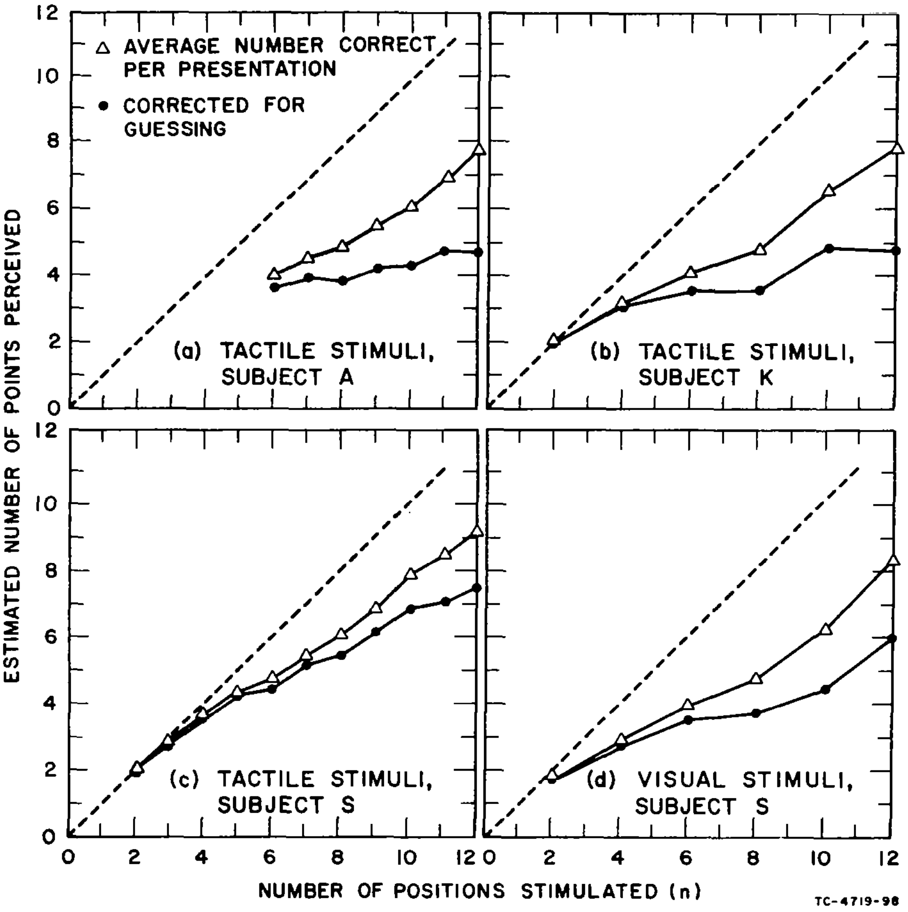

FIG. 27 WHOLE-REPORT PERFORMANCE CURVES — ESTIMATED NUMBER OF STIMULUS POINTS PERCEIVED (corrected curves) AS A FUNCTION OF THE VALUE OF n
The diagonal line represents perfect performance. The uncorrected curves are included to show the effect of correction on the raw data.

To test the immediate memory of Subject S further, an analogous visual experiment was run in which the stimulus display consisted of a 3-by-8 array of panels illuminated by individual incandescent lights. The procedure was the same as with the tactile experiments, and the number of lights simultaneously activated was increased each session by two from n = 2 to n = 12. Figure 27(d) shows these results, after application of the correction for guessing. Although he was not performing quite as well as in the tactile experiments, a level of performance of 6 out of 12 positions correctly identified was achieved.

In addition, as a preliminary to Experiment 2, Subject S was tested in a partial-report experiment with tactile stimuli. In this experiment, the number of stimulators simultaneously activated was always equal to 12, chosen randomly out of the 24 positions possible. From 22 to 300 msec after the termination of this tactile stimulation, a light was flashed for 400 msec, either on the left or on the right. If on the left, the subject's task was to report the letters representing the positions stimulated on the left hand; if on the right, the subject's task was to make a similar report for the right hand. The number of positions stimulated on the designated hand was called k, and each value of k between 1 and 11 occurred on 100/11 percent of the trials. Each hand was designated on 50 percent of the trials. Sixty-seven trials were run for each value of marker delay; however, since the effect of marker delay was small, the data were averaged over marker delay. The results, corrected for guessing, are shown in Figure 28.

To estimate the amount of stimulus information available from the partial-report data of Figure 28, the average percentage of positions correct for each value of k (after correction for guessing) was multiplied by 12. Since the marker position was randomly chosen and was presented after the tactile stimulation had terminated, the average percentage of positions correct must represent the fraction of the 12 stimulus positions available to the observer. The results of this calculation are shown in Figure 29.

Since for k less than 7 the average number of stimulus points available was greater than the number reported in the whole-report experiment, the presence of some sort of short-term tactile memory is indicated.

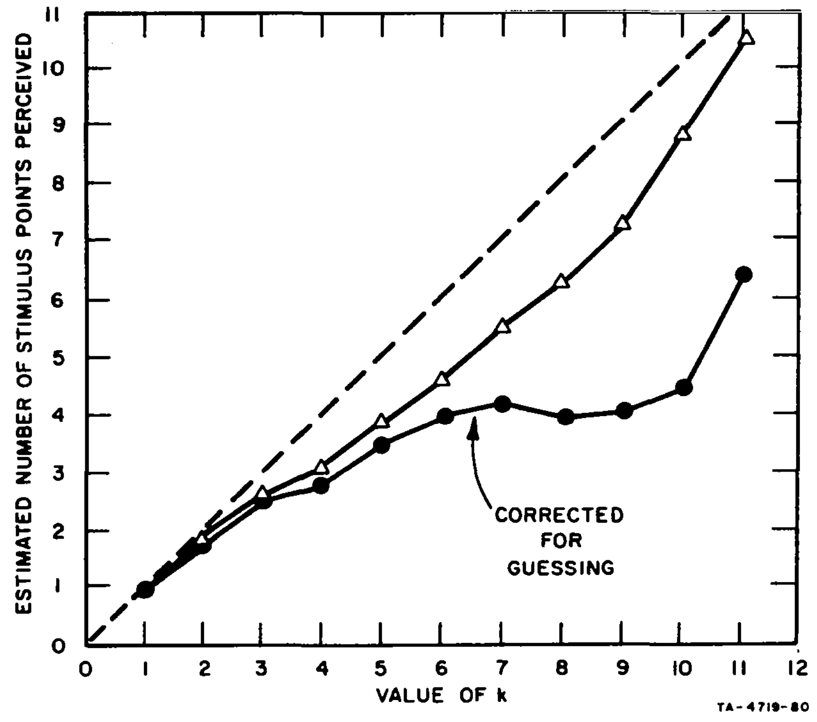

FIG. 28 PARTIAL-REPORT PERFORMANCE, SUBJECT S — ESTIMATED NUMBER OF STIMULUS POINTS PERCEIVED AS A FUNCTION OF THE VALUE OF k
The data are averaged across marker delays and hands.

In analogy with related visual experiments, it was expected that the estimate of the number available would be independent of k, for k less than the immediate memory level. However, as shown in Figure 29, the number of letters available decreases from greater than 11 to slightly more than 7, as k is increased from 1 to 7. This means that a small number of stimuli on one hand, with a correspondingly large number on the other, are reported correctly a greater percentage of the time than when the number of positions designated is about n/2. A likely explanation for this is that the subject adopted the strategy of paying greater attention to the hand with the fewer stimuli even before the marker appeared (see Sperling, 1960, pp. 8-10). If this was the case, values of k in the range 4 to 6 would give the best estimate of the number of stimulus positions available. This yields a value of about 8.5 stimulus positions available compared with a whole-report performance of about 7.5 for this subject.

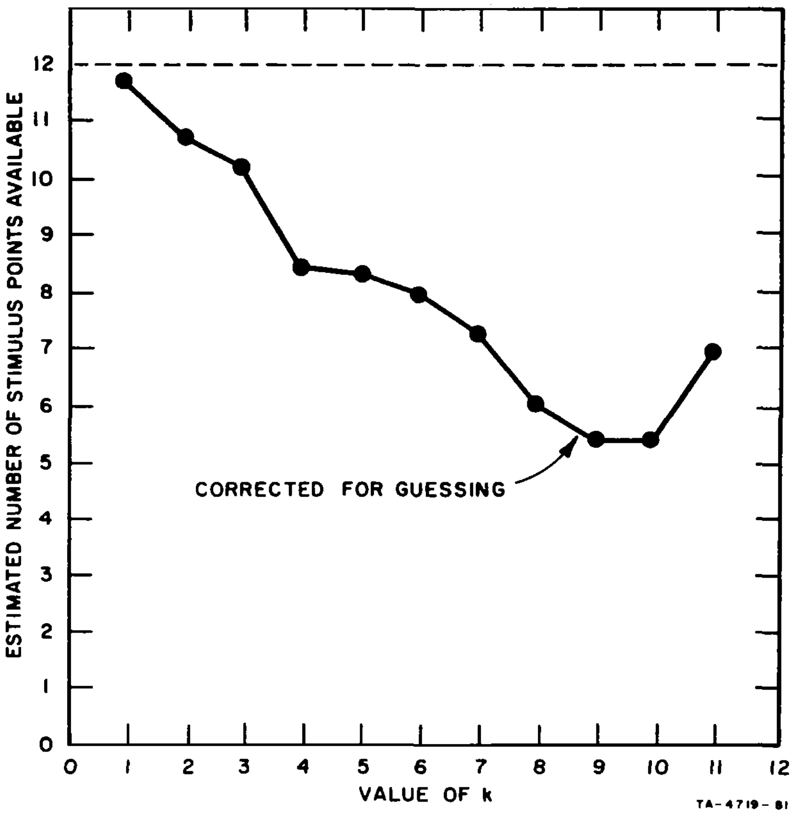

FIG. 29 PARTIAL-REPORT PERFORMANCE, SUBJECT S — ESTIMATED NUMBER OF STIMULUS POINTS AVAILABLE AS A FUNCTION OF THE VALUE OF k

B. EXPERIMENT 2: SHORT-TERM MEMORY

The purpose of Experiment 2 was to investigate further the capacity and temporal properties of any short-term tactile memory. This experiment was designed to yield both whole-report and partial-report data (with various values of marker delay) from several identically trained subjects. Several improvements in the procedure were instituted.

1. Method

a. Apparatus. The apparatus was the same as that described in Experiment 1, with one modification. In Experiment 1, only one airjet nozzle holder was available, making it necessary to readjust the airjet nozzles each time a subject was run. In this experiment, each subject had his own airjet nozzle holder, which was initially adjusted to his hand and never reset unless the subject requested that a particular jet be readjusted. This ensured better constancy in the positioning of the airjets from session to session.

b. Subjects. Four male college students in their twenties were used. Subjects M_1, M_2, and M_3 were normally sighted; M_4 had been totally blind since the age of 14. None of the subjects had ever participated in an experiment of this nature.

c. Procedure. Each subject was tested in two 30-minute sessions per day, with one hour between sessions. The training and testing schedule is shown in Table 5. The number of total presentations for each value of n during training was determined by the apparent difficulty of the task for each value of n; more presentations were given at the higher values. 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.

On any whole-report trial, the procedure was similar to that described in Experiment 1, with certain changes: (1) the labeling of the interjoint positions was changed, and is shown in Figure 26; (2) subjects were required to report the same number of response positions as the stimulus contained and to report in alphabetical order (this latter restraint was introduced so that all the subjects would utilize the same reporting strategy); (3) tactile and visual reinforcement were introduced. As soon as the experimenter finished typing the response, the 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 1-1/6 sec for $n = 1$, to 3 sec for $n = 12$, increasing linearly by 1/6 sec whenever n was increased by one. Subject M_4, who was blind, received only tactile reinforcement, except for sessions with $n = 1$, 2, or 4, when, in addition, the

Table 5

TRAINING AND TESTING SCHEDULE, EXPERIMENT 2.

Order of Conditions	No. of Stimulus Presentations Per Condition	No. of Sessions
Training		
n=1, left hand	72	1/2
n=2, left hand	360	2-1/2
n=1, right hand	72	1/2
n=2, right hand	360	2-1/2
n=2, both hands	144	1
n=4, both hands	96	1
n=6, both hands	88	1
n=8, both hands	180	2
n=10, both hands	100	2
n=12, both hands	141	3
Testing, Whole-Report		
n=2, both hands	36	1/4
n=6, both hands	96	3/4
n=10, both hands	156	3
n=12, both hands	188	4
n=8, both hands	126	2
n=4, both hands	66	1
Testing, Partial-Report		
k=4, n=12, 0.1 sec marker delay	66	1
k=4, n=12, 0.8 sec marker delay	66	1
k=4, n=12, 0.3 sec marker delay	66	1
k=4, n=12, 2.0 sec marker delay	66	1
k=4, n=12, 0.1 sec marker delay	66	1
k=4, n=12, 0.3 sec marker delay	66	1
k=4, n=12, 0 sec marker delay	66	1
k=4, n=12, -0.85 sec marker delay	66	1
k=4, n=12, 0.8 sec marker delay	66	1
k=4, n=12, 2.0 sec marker delay	66	1
k=2, n=6, 0.3 sec marker delay	36	1/2
k=4, n=12, -0.85 sec marker delay	66	1
k=4, n=12, 0 sec marker delay	66	1
k=2, n=6, -0.85 sec marker delay	36	1/2
k=2, n=6, 0.1 sec marker delay	36	1/2
k=2, n=6, 0.8 sec marker delay	36	1/2
k=2, n=6, 2.0 sec marker delay	36	1/2
k=2, n=6, 0 sec marker delay	36	1/2

Table 5 (concluded)

Order of Conditions	No. of Stimulus Presentations Per Condition	No. of Sessions
Testing, Whole-Report with Partial-Report Stimuli		
n=12	66	1
n=6	36	1

experimenter called out the correct response. The termination of reinforcement was followed by a 2-sec pause and then the next stimulus.

On a partial-report trial, subjects were informed by a marker as to the row from which their response should come. The eight topmost interjoint positions (A-H) were considered the top row, positions labeled I-P the middle row, and Q-X the bottom row. The marker onset occurred either 0.85 sec before or 0, 0.1, 0.3, 0.8, or 2.0 sec following stimulus termination. For the sighted subjects, the marker was one of three lights (top, middle, or bottom) on the visual display box, lasting 250 msec. For the blind subject, the marker was a high (910 pps), medium (357 pps), or low (133 pps) tone, lasting 30, 80, or 240 msec, respectively. Each marker position occurred an equal number of times in each session. Marker position order was random and varied from session to session.

During partial-report sessions, the total number of stimulation points was either 12 (with 4 points in each row) or 6 (with 2 points in each row).

2. Results

Figure 30 shows the results, after correction for guessing, from the whole-report test sessions for all four subjects. The maximum estimate of the number of correctly perceived stimulus positions was between 3 and 4 for all of the subjects, and this value occurred for n = 12.

Figure 31 illustrates the response behavior and the effect of the guessing correction. While the data of Figure 31 are averaged over subjects for a single session with n = 12, the result--that the proportion correct decreased as the position in the response sequence increased--was generally observed

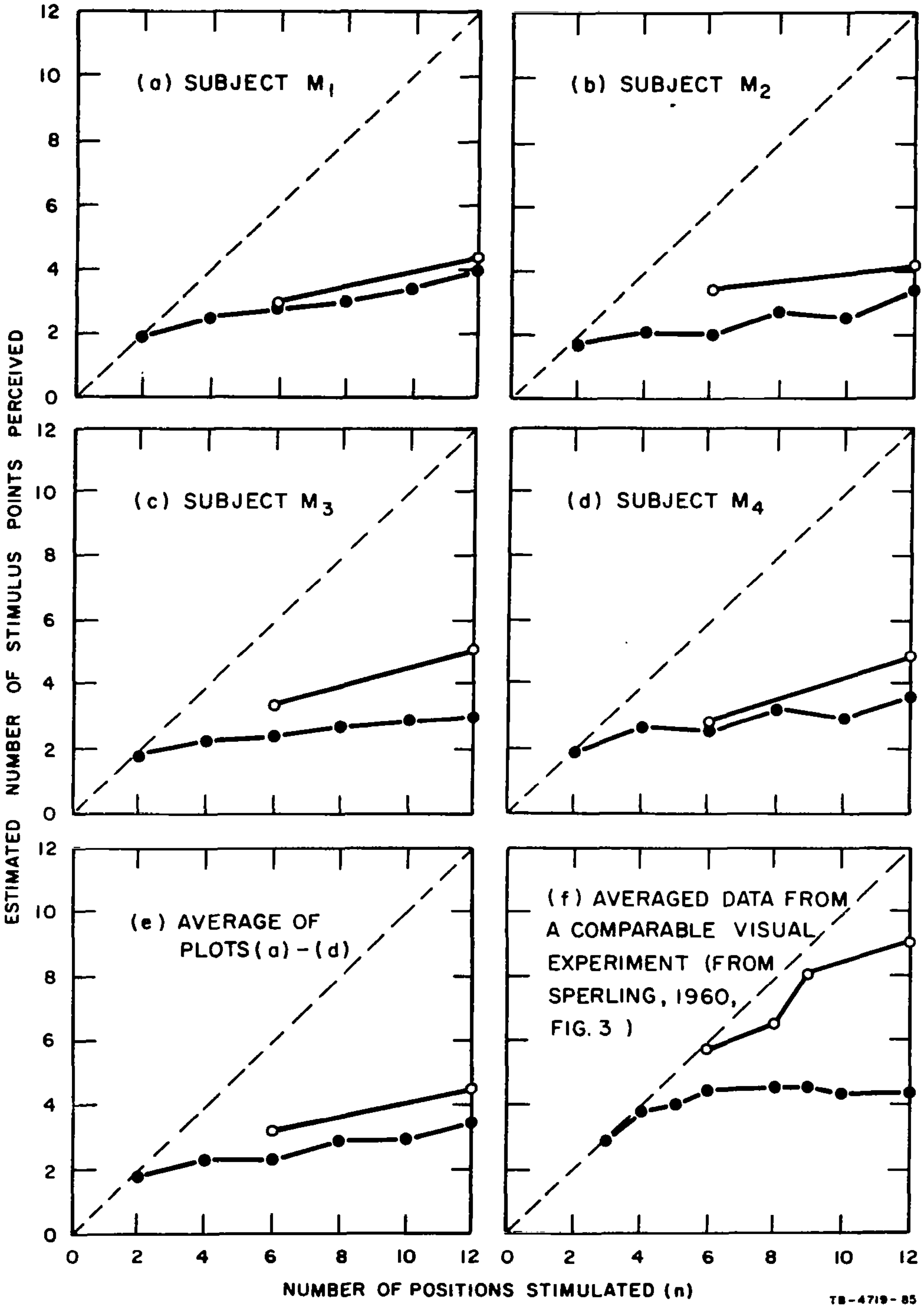

FIG. 30 ESTIMATED NUMBER OF STIMULUS POINTS PERCEIVED AS A FUNCTION OF THE VALUE OF n — EXPERIMENT 2

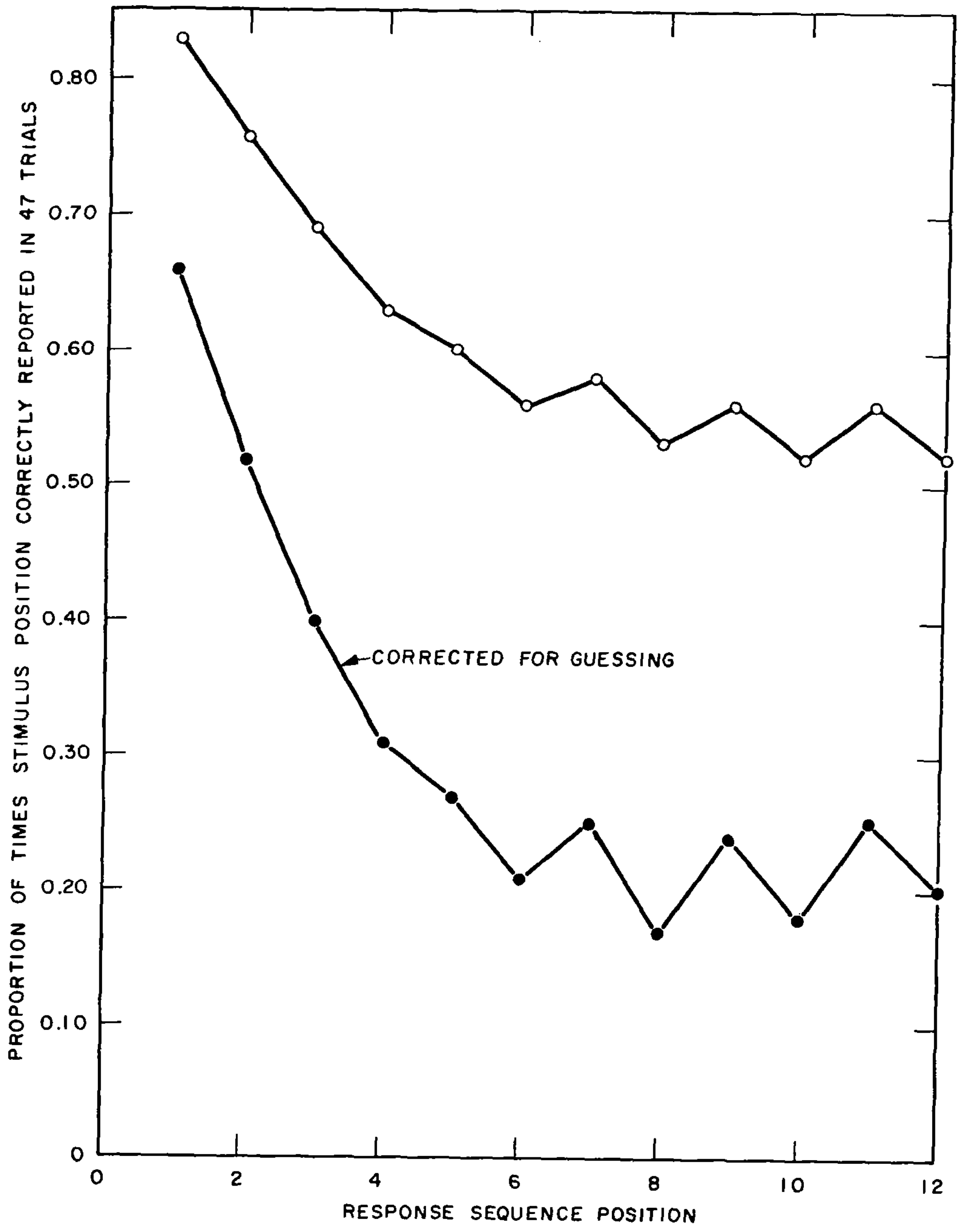

FIG. 31 AVERAGE PROPORTION OF TIMES, OUT OF 47 TRIALS, THAT EACH RESPONSE SEQUENCE POSITION WAS CORRECTLY REPORTED

throughout the experiment. The guessing correction uses the proportion correct for each position in the response sequence to estimate the proportion perceived in the same sequence position. Then the total number perceived is determined by summing the estimates of proportion perceived in each sequence position. The results, averaged over subjects, before correction for guessing, are shown in Figure 32.

Also shown in Figure 30 are the results of the partial-report sessions for the condition in which the marker appeared immediately after stimulus termination. These results are also corrected for guessing, using the formula given in the appendix with N=8 and n=k, the total number of points stimulated in each row (i.e., 2 or 4). After this correction for guessing, the estimate of the number of points perceived was multiplied by 3 to obtain an estimate of the number of stimulus points available. The maximum estimate on the number of stimulus points available also occurred for n=12 and was between 4 and 5 for each subject.

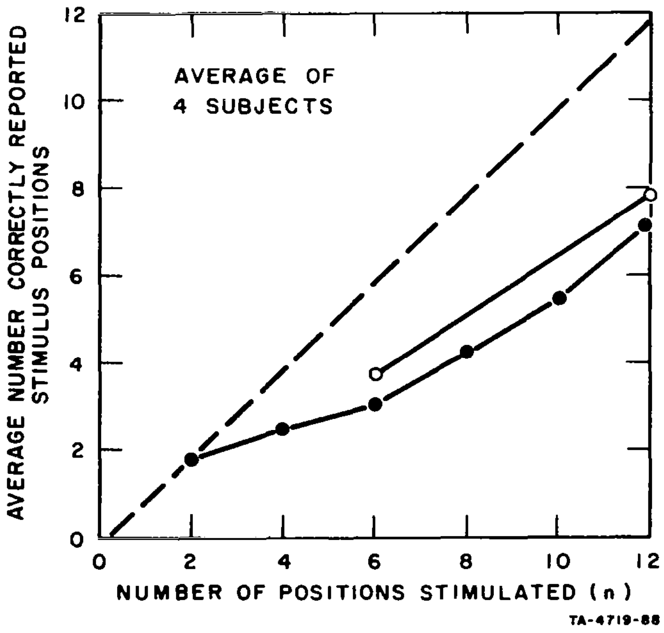

FIG. 32 SAME DATA AS FIGURE 30(e) EXCEPT UNCORRECTED FOR GUESSING

Figures 33 and 34 show the partial-report performance, after correction for guessing, as a function of marker delay for all four subjects. The curves of Figure 33 are for n=6 and k=2, and the curves of Figure 34 are for n=12 and k=4. Also shown, as a bar at the right of each curve, is the whole-report performance for the subject on the same stimuli (constrained to k stimulus points in each row) used for the partial-report sessions. Since the number of stimulus points in each row was constrained, these whole-report data were corrected for guessing by considering the experiment to be three whole-report experiments, each with N=8 and n=k, and by summing the three estimates of the number of points perceived from the formula given in the appendix.

While there is considerable variability among the subjects, the partial-report curves averaged over subjects in Figures 33 and 34 are always above the whole-report bar, except for the 2-sec marker delay, in which the partial-report and whole-report values are approximately equal.

C. DISCUSSION

The experiments described here employed multiple tactile stimuli with two kinds of report, whole and partial. In a whole report the subject names as many stimulus locations as he can. The upper limit on the number of correctly reported items may be called, after Miller (1956), the span of immediate memory. In previously reported studies, this span typically ranged from 4 to 7 stimulus items (e.g., see Miller, 1956; Sperling, 1960).

Figure 27 indicates an immediate-memory span with tactile stimuli of about 4.5 items for Subjects A and K. However, Subject S reported more than 7 correct positions out of 12 (after correction for guessing), and his performance did not appear to be leveling off at n=12. Introspections by Subject S suggested that he was able to recode the stimulus patterns into larger units, or "chunks" of information, much as in visual experiments in which enhanced performance is obtained by recoding binary numbers into octal numbers. These tactile results were unexpectedly high, in view of past reports of extraordinary interaction (Geldard, 1966) with two or more simultaneous stimuli on the fingers.

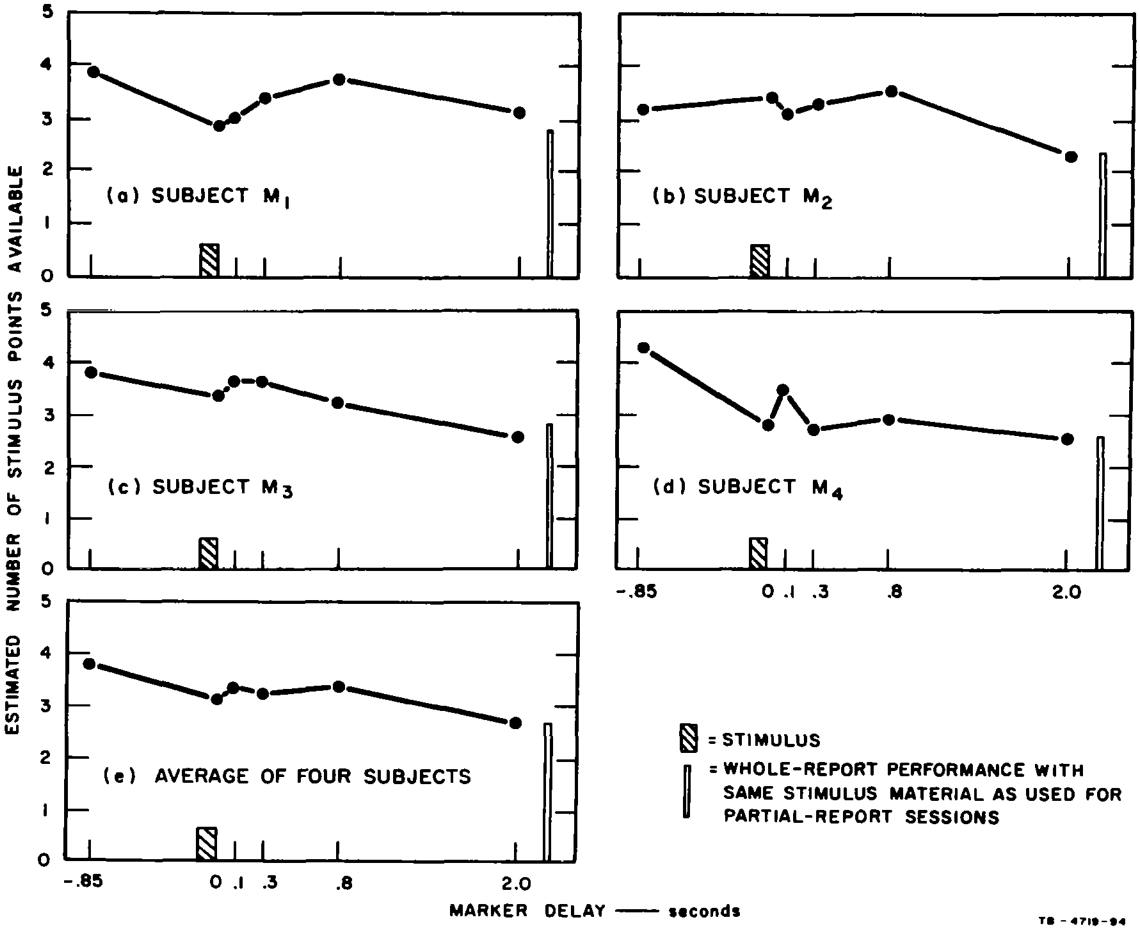

FIG. 33 PARTIAL-REPORT PERFORMANCE ($k = 2$, $n = 6$) — ESTIMATED NUMBER OF STIMULUS POINTS AVAILABLE AS A FUNCTION OF TIME OF OCCURRENCE (with respect to stimulus termination) OF THE MARKER

In spite of the surprisingly good tactile performance reported here, the reader is cautioned that the effect of long-term tactile training is not yet known. When visual data are compared with tactile data, the comparison is between results from a highly trained modality and those from a generally poorly trained modality. In our early experiments with doublets, for example, with subjects who scored perfectly on singlets, we found very high initial errors (typically 30-40 percent) which, after five to ten training sessions, dropped to only a few percent (Bliss, et al., 1965).

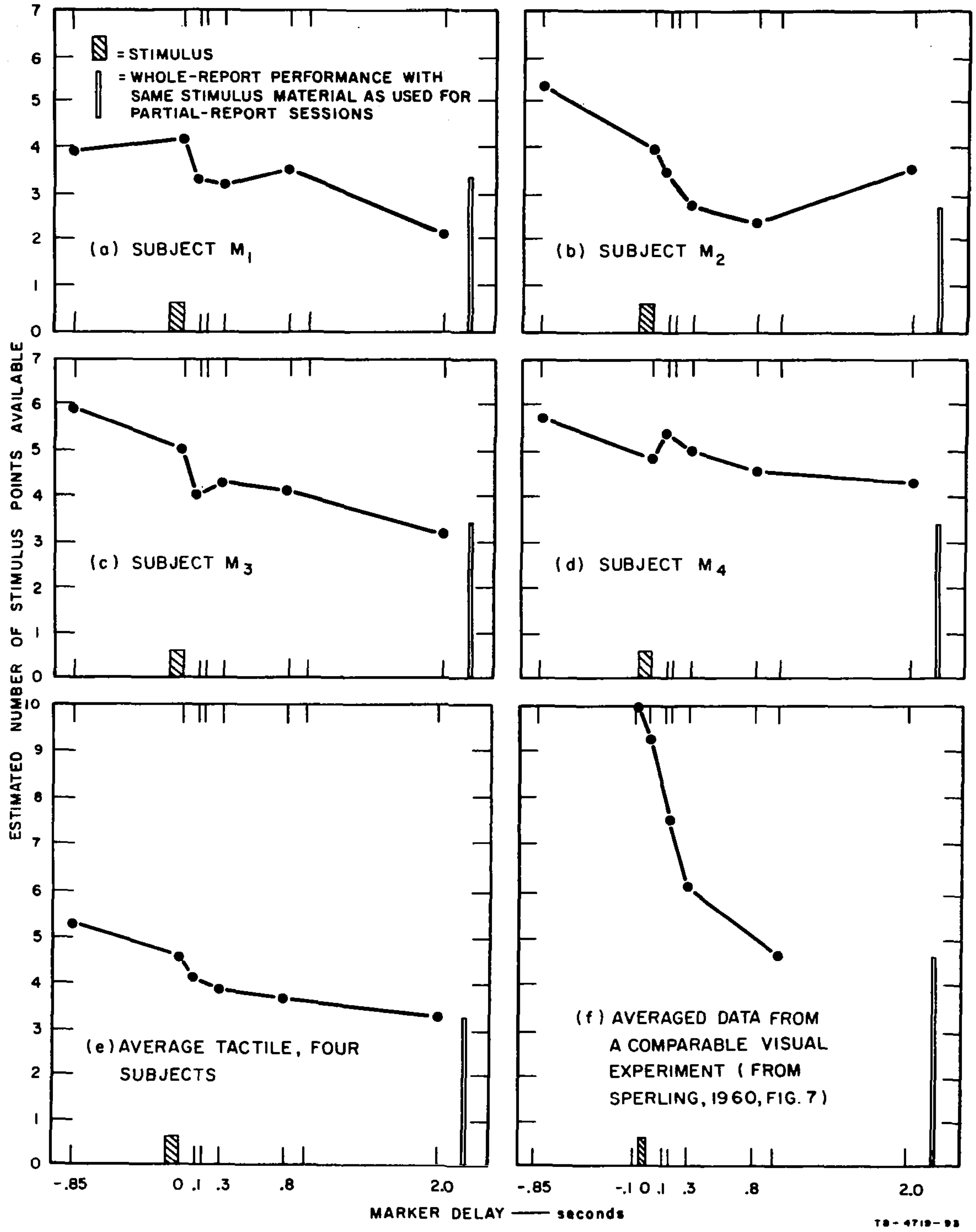

FIG. 34 PARTIAL-REPORT PERFORMANCE ($k = 4$, $n = 12$) — ESTIMATED NUMBER OF STIMULUS POINTS AVAILABLE AS A FUNCTION OF TIME OF OCCURRENCE (with respect to stimulus termination) OF THE MARKER

The accuracy in reporting for subjects in Experiment 2 was considerably lower than for subjects in Experiment 1 ($p \leq 0.05$), even though both experiments differed only in procedural factors which were not expected to hamper performance. Figure 30(e) shows that the average immediate-memory span in Experiment 2 was between 3 and 4 stimulus positions. This average span size is also lower than that reported by Sperling (1960), who, in a somewhat similar task using visual stimuli, found an average immediate-memory span of between 4 and 5 stimulus items [see Figure 30(f)]. Usually the number of items to be reported in a partial-report experiment is selected to be less than the span of immediate memory so that an estimate of items available that does not reflect immediate-memory limitations can be made. While that was the intention in these experiments, it appears from the results of Experiment 2 that the $k = 4$, $n = 12$ conditions must have taxed the immediate-memory capacity beyond its limit, resulting in a low estimate of number of positions available when $k = 4$.

Three explanations can be suggested for the poorer performance in Experiment 2. First, the introduction of tactile reinforcement in Experiment 2 (lasting from 1-1/3 to 3 sec) might have interfered with the subject's performance by partially masking the next stimulus. At least one subject reported that a tingling sensation in his fingers produced by the reinforcement still remained when the next stimulus occurred (2 sec following the last reinforcement). To investigate this hypothesis, each subject in Experiment 2 participated in one extra session, which was identical to another session held that day except that the pause between the end of reinforcement and the next stimulus was increased to 4 sec. If the hypothesis was correct, then the longer pause would be expected to increase the level of performance by increasing the recovery time (see Bliss, et al., 1966a). As shown in Table 6, increased performance was found for all subjects, although this increase is hardly significant for Subject M_1.

Secondly, poorer performance in Experiment 2 may have been due to the fact that the subjects in Experiment 2 were not trained as well as those in Experiment 1. The average whole-report curve of Experiment 2 [Figure 30(e)] shows slight rises in performance when the value of n was 4 or 8, compared to

Table 6

COMPARISON OF PERFORMANCE WITH 2- AND 4-SECOND INTERTRIAL PAUSE DURATION

(Uncorrected Values Only)

Subject	Session	Average Number of Stimulus Positions Available	
		Two-Second Pause	Four-Second Pause
M_1	Whole report with partial-report stimuli (k=2, n=6)	3.53	3.56
M_2	Partial report (k=4, n=12), 2.0-second marker delay	7.54	7.82
M_3	Partial report (k=4, n=12), 0.1-second marker delay	8.14	9.09
M_4	Whole report with partial-report stimuli (k=2, n=6)	3.42	3.67

performance levels for other values of n. The testing schedule (Table 5) indicates that the last three of the 11 whole-report sessions were with n = 4 and n = 8. Thus, despite the fact that Experiment 2 subjects had 16 training sessions before whole-report testing, they apparently continued to improve at the task during testing. Subjects M_2 and M_4 particularly show this improvement during testing.

Finally, it may be that the constrained-report strategy which the subjects in Experiment 2 had to follow may have introduced a slight disabling factor. The alphabetical-order-report strategy may have introduced into the experimental paradigm an extra subtask which could have impaired the subjects' performances relative to that in Experiment 1.

As is typically found in partial-report experiments, results from the partial-report sessions in both Experiments 1 and 2 indicated more information available than could be reported in a whole report. The magnitude of this difference was not, however, as great as previous investigators have found in visual studies. Sperling (1960), for instance, reports that with visual stimuli, more than 9 stimulus items out of 12 were available when the partial-report marker immediately followed the stimulus termination, compared with 4.5 items out of 12 for the whole report. In Experiments 1 and 2 of this paper, however, partial report resulted in an increase of only about one stimulus item out of 12 over the number of items indicated by the whole-report sessions. This result suggests that any hypothetical tactile short-term memory has considerably less capacity than the analogous visual short-term memory.

A dynamic aspect of the responses is illustrated in Figure 31. The accuracy of the responses decreases rapidly as each stimulus position is named. If the first four responses in the whole-report session of Figure 31 were used to calculate the number of positions available, one would expect this value to agree with the value obtained from a partial-report experiment with $k = 4$, $n = 12$, and the marker occurring before the stimulus. The value from Figure 31 so obtained is 5.67, which compares with 5.3 from Figure 34(e), with the marker occurring 0.85 sec before stimulus termination.

A similar comparison can be made between the $k = 2$, $n = 6$ partial-report results and the data of Figure 31 to predict the number of items available in a hypothetical $k = 2$, $n = 12$ "marker-first" experiment. Using the proportion perceived in the first two responses, one obtains the value 7.08 items. From Figure 33(e), 3.81 items available out of 6 were obtained from the $k = 2$, $n = 6$ "marker-first" partial-report experiment, which would give a value of 7.62 items available out of 12. As one might expect, a higher value resulted with $n = 6$ than with $n = 12$, perhaps due to greater spatial interaction with $n = 12$.

Spatial interaction may in part explain the lower number of items available in these tactile experiments as compared to previously reported visual experiments. The data presented here suggest that two or more simultaneously presented air blasts at different spatial locations on the fingers may mask one another. For instance, for the whole-report sessions in Experiment 2 with n = 2, the estimated number of stimulus points available was 1.8 positions. Yet, for the partial-report sessions in Experiment 2, the estimated number of stimulus points available (averaged over subjects) was never higher than 3.81 positions out of 6 (or 1.27 positions available out of 2), and this value occurred with the marker 0.85 sec before stimulus termination. In both these cases, the subject had to report only two stimulus positions, therefore the reporting was not responsible for the lower partial-report performance. Since the only difference between the two cases was that only two stimulus points were activated in the first case whereas six were activated in the second case, then there must have been interference among the six stimulus points, causing a decrement in accuracy of reporting over that with only two stimulus points.

Figures 33 and 34 show that the accuracy of the partial report was superior to the whole report only when the marker occurred within 0.8 sec after stimulus termination. When the partial-report marker occurred 2.0 sec after stimulus termination, the accuracy of both reports was approximately equal. Sperling reports similar temporal results with visual stimuli. It appears, then, that any hypothetical tactile short-term memory can be no more than 0.8 sec in duration.

The averaged partial-report curve for k = 4 and n = 12 [Figure 34(e)] decreases more smoothly with increased marker delay than the corresponding curve for k = 2 and n = 6 [Figure 33(e)]. The reduced variability in the first [Figure 34(e)] may be due to the fact that each data point is based on the average performance of each of four subjects in 132 trials, whereas each data point in the second [Figure 33(e)] is based on the average performance of each of four subjects in only 36 trials.*

There appears to be a reduction in performance for k = 2 and n = 6 when the marker immediately follows the stimulus (0-sec delay). The individual curves show this effect more clearly, particularly the curve for M_4, who was

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*Thirty-six stimulus presentations with k = 2 and n = 6 are sufficient to ensure that the probability of the mean number correct exceeding the true mean by more than 0.4 stimulus positions is ≤ 0.1. This probability is reduced to 0.05 for 132 stimulus presentations with k = 4 and n = 12.

blind and received the tone marker. He reported that he was forced to pay less attention to the stimulus when the marker followed immediately in order to distinguish which tone occurred. The use of the tone marker did not, however, appear to reduce M_4's overall performance. In fact, his performance approximated that of the sighted subjects in both whole- and partial-report conditions, despite the fact that he received only tactile reinforcement while the sighted subjects received both tactile and visual reinforcement.

The slight rise in partial-report performance for $k = 2$ and $n = 6$, when the marker followed the stimulus by 0.8 sec, may have been due to the subjects' choice of strategy while awaiting the marker. A subject could choose, for example, to pay equal attention to each of the three rows, to attend to the same row, or to guess which row would be specified and pay attention to that row only. Sperling (1960) tried to illustrate the effect on performance of switching from the first to the third strategy. His subject RNS made this switch at marker delays longer than 0.15 sec. His performance curve shows a dip at 0.15 sec, followed by a rise at longer marker delays, and Sperling attributes the dip to the subject's failure to switch strategies at marker delays of 0.15 sec or shorter. The subjects showing the most marked performance rise in the 0.8-sec marker-delay condition were M_1 and M_2. Subject M_1 reported using the third strategy and M_2, the first and third strategies. Subject M_3, who reported that he paid equal attention to the three rows throughout partial testing, showed the least variable performance curve.

The results of the present experiments are relevant to the construction of tactile codes for communication using point stimulation of specific anatomical locations as the information-bearing dimension. The data shown in Figures 27 and 30 suggest that a 90-percent individual point or an 81-percent symbol accuracy could be obtained with a code using 2 out of 24 stimulus positions to indicate a particular symbol out of an alphabet of 276 possible symbols. Similarly, a 70-percent individual point or a 34-percent symbol accuracy should be obtained with a 2024-symbol alphabet, each symbol consisting of 3 out of 24 stimulus positions.

The question arises whether or not more information could be transmitted per presentation if greater values of n were used to make up the symbols. To overcome the loss in accuracy, redundant codes could be used, permitting error correction.

While the calculation of information transmitted is difficult if the particular confusion matrices obtained are taken into account, a lower bound on the information transmitted can be easily obtained by assuming that there is no stimulus-related information in the errors. For this case the appropriate formulas are

$$H(S) = \log \binom{24}{n}$$

$$I(R;S) \geq p \log \binom{24}{n} + p \log p + (1 - p) \log (1 - p),$$

where H(S) is the stimulus entropy, I(R;S) is the information the response gives about the stimulus, and p is the estimated proportion of stimulus positions perceived. This transformation of the average data in Figure 30(e) results in the curves shown in Figure 35. The curves of Figure 35 indicate that the transmitted information is relatively independent of n, being about 6 bits per presentation for a whole report and 7.5 bits per presentation for a partial report. Thus, one is tentatively led to the conclusion that, at least with the amount of training employed here, information per presentation cannot be increased by constructing codes with high values of n.

Finally, the results of this paper, combined with our previous results [Bliss, et al., 1966(a) and 1966(b)], suggest that tactile information processing has some of the characteristics accounted for in a model proposed by Sperling (1963) for visual memory tasks. A short-term tactile memory with slightly greater storage capacity than the span of immediate memory is indicated by the results of this paper. This short-term memory appears to decay in less than 0.8 sec. The results also suggest that overall performance is limited by spatial interaction of the stimuli, except that, again, we do not yet know the effects of longer training.

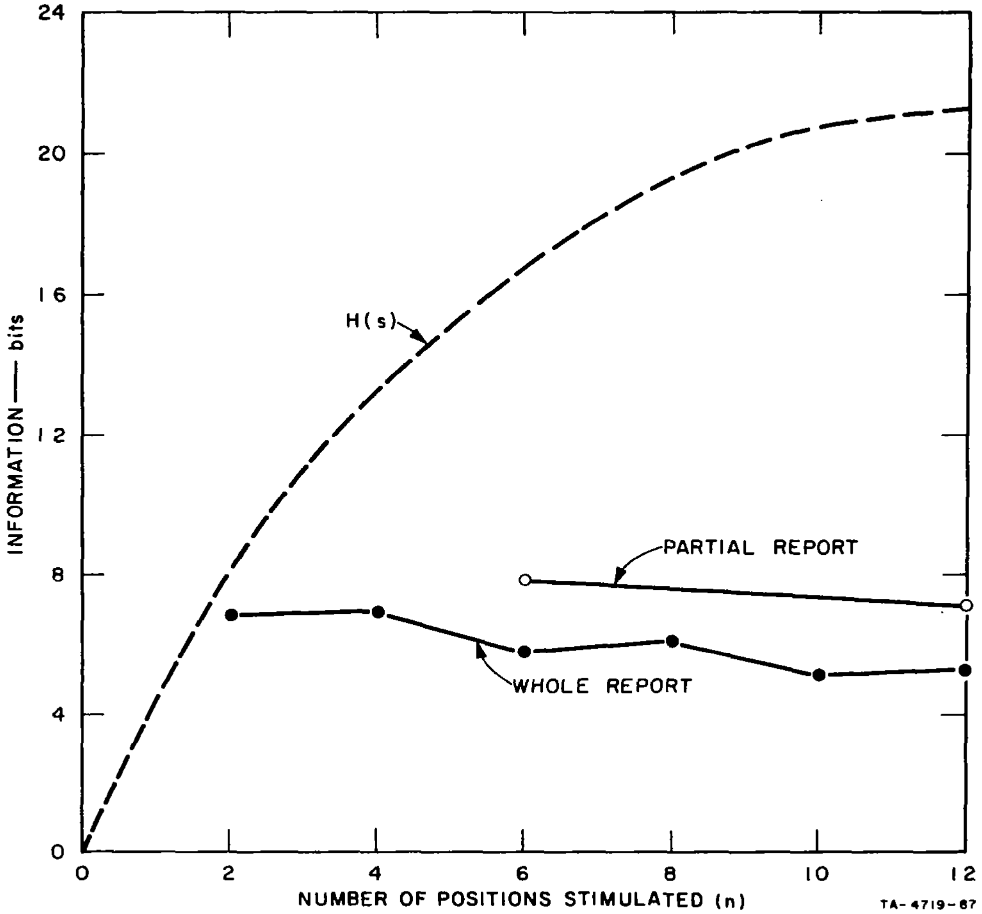

FIG. 35 LOWER BOUND ON TRANSMITTED INFORMATION AS A FUNCTION OF n. The partial-report curve is for zero marker delay; the dotted curve is the information in the stimulus.

APPENDIX

A standard correction for guessing in psychophysical experiments assumes some probability correct due to the sensory process under consideration, and if this process fails, then the subject guesses from the available alternatives. Thus,

$$p(c) = p + (1 - p)g \tag{1}$$

where

$p(c)$ = probability correct

p = probability correct by result of perception alone

g = probability correct by guessing if stimulus is not perceived.

If we have an estimate for g, we may solve for the "true" value of perceiving or knowing the answer, p, as follows:

$$p = \frac{p(c) - g}{1 - g} . \tag{2}$$

In the present experiment the subject must make more than one response on any one trial. The accuracy of each response may affect the guessing probabilities on later responses in that trial for a large number of models of the subject's behavior. The present method of estimating p for each response represents a relatively severe correction, since, when the subject has to guess, it is assumed that he guesses from all the unreported positions. Therefore, the corrected data are probably lower bounds on the subject's performance. Furthermore, it is assumed that the number of stimulus-activated positions not yet correctly reported at any response on the trial are distributed in a uniform manner across all unreported positions.

Thus, the appropriate form of Eq. (2) is

$$p_i = \frac{p\text{ (correct on response i)} - \dfrac{n - \sum_{j=1}^{i-1} p\text{ (correct on response j)}}{N - i + 1}}{1 - \dfrac{n - \sum_{j=1}^{i-1} p\text{ (correct on response j)}}{N - i + 1}} \qquad (3)$$

where

p_i = estimated probability correct by perception on response number i, $1 \le i \le n$

p (correct on response i) = uncorrected observed value proportion correct on response number i

n = number of interjoint positions activated on each trial

N = total number of interjoint positions in possible stimulus field, i.e., the population from which the n are chosen on each trial.

Finally, the corrected value for the estimated total number of the n positions reported correctly on each trial is obtained by summing the estimated p_i:

$$A = \sum_{i=1}^{n} p_i .$$

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VI CROSS-MODALITY REACTION – TIME EXPERIMENTS WITH TACTILE AND VISUAL STIMULI

by Stephen W. Link

A. PURPOSE, APPARATUS, AND PROCEDURE

1. Purpose

Previous investigations of cross-modality reaction time (CMRT) have shown an apparent facilitation in reaction time when stimuli are presented randomly to either of two sensory channels instead of to a single sensory channel. Howell and Donaldson (1962)* used visual and auditory stimuli, equated for subjective intensity, to demonstrate that intra modality reaction time was generally longer than intermodality reaction time. The purpose of the experiment discussed here was to examine this finding for tactile and visual stimuli and then investigate changes in reaction time as a function of simultaneous stimulation of both channels.

A second aim of this experiment was to examine reaction time in a conflicting stimuli paradigm. It has been suggested that man's information processing capacity is partially determined by a sensory sampler which gives rise to sensory epochs (Kristofferson, 1965). It has been assumed that a sensory sampler provides times during which information arriving over one channel is first processed and then the sampler may switch to a different channel, much in the same way as a homunculus governing a sensorium. Recent experiments (Falmagne, 1965; Kristrofferson, 1965) suggest that only one channel can be monitored at a time. Thus, in a choice-reaction-time experiment in which stimuli were simultaneously presented over different sensory channels, one would expect no difference in reaction time for stimuli which require the same response to be made versus stimuli which require conflicting responses.

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*References are given at the end of this section.

A third reason for our interest in CMRT is the highly possible result that processing times for tactile and visual stimuli may be quite different. By varying the number of response alternatives per sensory channel, we can easily compare reaction time as a function of the number of alternatives and then compare response times to visual and tactile stimulation.

2. Apparatus

The experimental apparatus is shown in Figure 36. Neon bulbs mounted on top of the four posts corresponding to the positions right, forward, left, and backward provided visual stimuli. Inside the joystick, airjets pointing in the same four directions provided tactile stimuli. Mounted on top of the joystick was the warning light. An arm rest was used to ensure that the pivotal point of the response was at the wrist.

The experiments were carried out under control of a CDC 8090 computer system, which was used to store stimuli, measure reaction times, record responses, and control the sequence in which the stimuli were presented. For each presentation the computer transmitted a word of 12 bits to specially

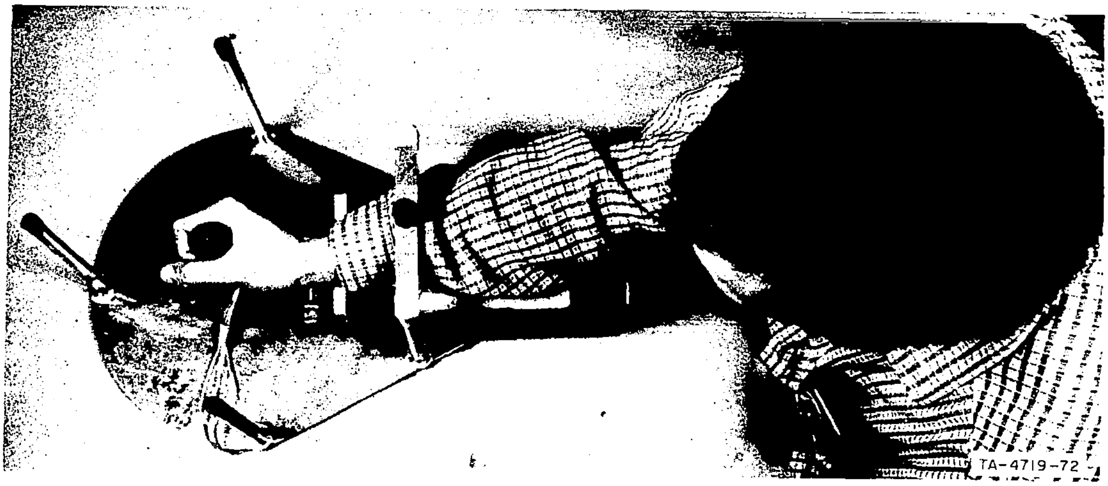

FIG. 36 STIMULUS-RESPONSE APPARATUS FOR REACTION-TIME EXPERIMENT

designed external equipment. The external equipment then simultaneously activated the tactile and visual stimuli.

The tactile stimulator generated bursts of air from a 1.4-mm outlet port under control of a sensitive high-speed electromagnet. The pulse pressure, measured 1/8 inch above the airjet outlet, was about 3 psi, with a rise and fall time of about a millisecond and an overall pulse width of about 2.5 msec. A 200-cps pulse repetition rate was used throughout the experiments, implying that the airjet was turned on and off 10 times during a stimulus duration of 0.05 sec. The positions of the tactile stimulators with respect to the palmar side of the hand are shown in Figure 37. Visual stimuli were provided by GE NE2 neon bulbs. These were of low intensity, but to a slightly dark-adapted subject they provided ample indication of the direction in which a response was to be made. All experimental sessions were run in a sparsely illuminated room in which the only light source was external light filtering through a shaded skylight.

Responses were made by moving a joystick to any of the four positions: left, right, forward, and backward. Special circuits were designed to detect when movements of the joystick exceeded any of the four boundaries shown in Figure 38. These thresholds were set to be about 6 degrees (or 1/2 inch) from the center position. Whenever a threshold was exceeded, the computer was signaled and the position of the response and the reaction time were recorded. Response times were measured with an accuracy greater than a millisecond.

3. Experimental Procedure

Four subjects were trained in making responses to eight possible stimuli. Four experiments were performed to determine the speed, accuracy, and processing characteristics of the tactile-visual system. All experiments consisted of a series of trials. As shown in Figure 39, on each trial the subject was presented with a warning light 0.5 sec after returning the joystick to the center position. After another delay of 1.15 sec, the stimulus was presented. If, during these delays, the subject moved the joystick from the center position, brief pulses were sent to all stimuli. To a slightly dark-adapted subject,

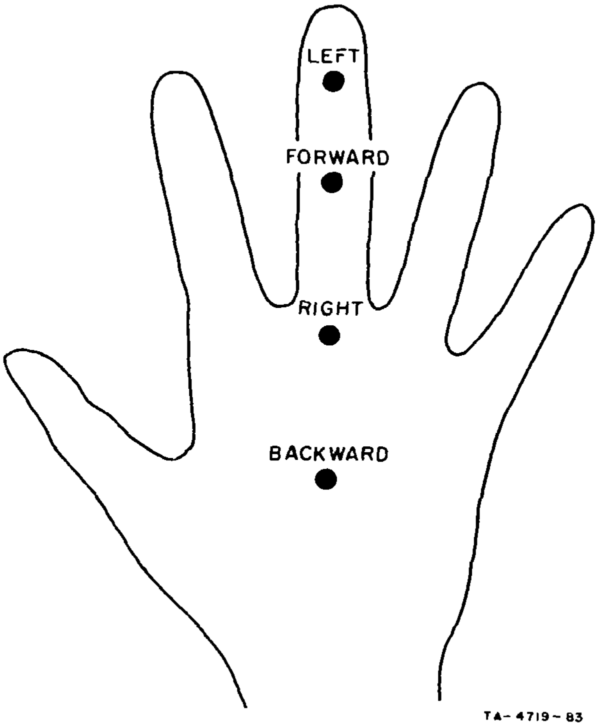

FIG. 37 POSITIONS OF STIMULI ON THE HAND, CORRESPONDING TO RESPONSES SHOWN IN FIGURE 38

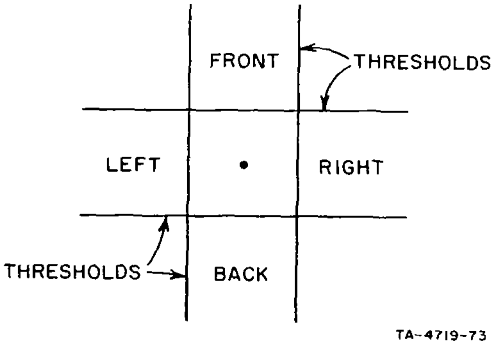

FIG. 38 *METHOD OF RECORDING* RESPONSES

this provided a clear, if not noxious, indication that the joystick should be repositioned. After repositioning, a new trial began.

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

In all, there were two modes of stimulation: tactual and visual. As indicated in Figure 38, there were four positions of stimulation for each sensory modality. Thus, there were eight distinct stimuli but only four different responses. For the sake of brevity, we will refer to the stimuli and responses by using a code of two letters; the first letter indicates the sensory mode and the second letter the position. Thus "tactile right" becomes TR.

B. EXPERIMENTS

1. Experiment 1 – Simple Reaction Time

To obtain data concerning the experimental apparatus, a simple reaction-time experiment was run. This served the dual purpose of providing subjects with extensive training before the succeeding experiments, as well as indicating

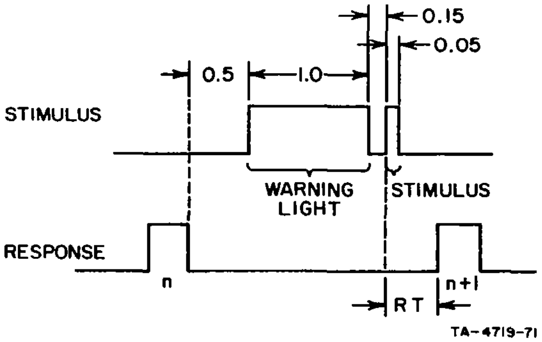

FIG. 39 TIMING ARRANGEMENT FOR REACTION-TIME EXPERIMENTS

Table 7

TABLE OF MEANS OF MEDIAN RESPONSES FOR EXPERIMENT 1

Center entries are mean reaction times in msec; numbers in upper right corner of entries are number of medians

Subject	Forward		Backward		Right		Left	
	Tactile	Visual	Tactile	Visual	Tactile	Visual	Tactile	Visual
1	18 207.6	18 210.3	18 177.9	18 206.6	17 244.8	18 235.6	18 234.4	18 230.4
2	15 194.2	15 214.1	15 173.3	15 182.7	20 186.1	20 185.5	20 235.3	20 219.6
3	10 253.6	10 241.2	10 182.1	10 208.0	10 234.3	10 253.5	10 217.8	245.5
4	10 217.9	10 235.6	10 196.8	10 212.2	15 226.5	15 227.2	15 233.1	15 227.1
Average	53 214.4	53 222.0	53 187.8	53 201.2	62 219.6	63 220.5	63 231.7	63 228.6

which responses might be considered similar. In this experiment, each subject received four sessions of 900 trials. During a single session, one of the eight possible stimuli was presented on 20 consecutive trials, followed by a different stimulus presented for 20 consecutive trials, and so on until all eight stimuli had been presented. In addition, occasional rest periods were provided by illuminating for 20 consecutive trials the warning light in lieu of a stimulus. Each subject was presented with a random ordering of eight stimuli and one rest per period five times, making a total of 900 trials per session.

Results

For analysis of this experiment, several restrictions were placed on the data. First, criteria were selected such that any response either less than 90 msec or greater than 700 msec was discarded. Second, the initial trial of 20 consecutive stimuli was excluded, because the subjects typically made an inappropriate response to a new stimulus. Response errors were also excluded. The medians of the remaining trials were then computed.

For each subject a one way analysis of variance was run using the medians. The results shown in Figure 40 are averaged over all subjects but are typical of the individual data (Table 7). In general, there was no significant difference between responses to right and left stimuli, regardless of the sensory modality. Subject 2 deviated from this finding; his reaction time to a right stimulus was 185 msec, while that to a left stimulus was 228 msec.

Averaged over all subjects, the mean reaction time to right or left visual stimuli was 224.5, while the corresponding mean for tactile stimuli was 225.7. This difference is hardly significant. However, an analysis of the variances for these data, using Bartlett's test, revealed significant differences, the tactile standard deviation being 30.97 and the visual, 33.33 msec. A one-way analysis of variance performed on the eight responses was significant, $F(7, 455) = 11.75$ or $\alpha < 0.01$.

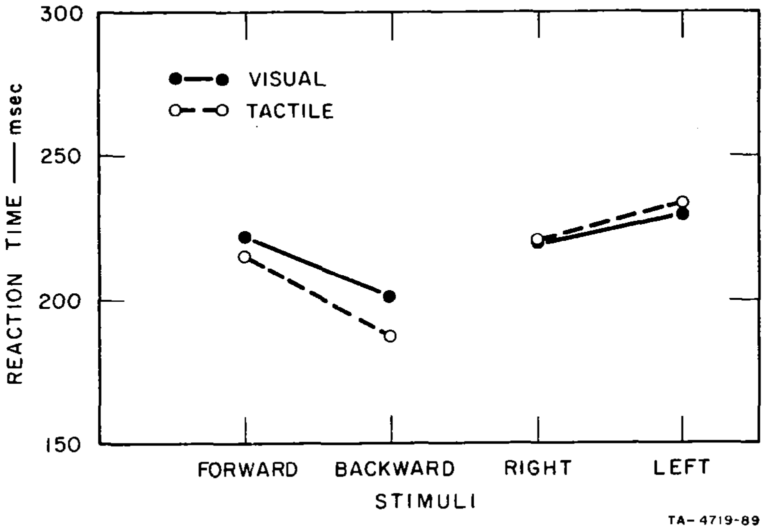

FIG. 40 MEANS OF MEDIAN RESPONSES AVERAGED OVER ALL SUBJECTS

Hence, although there were substantial differences, for individual subjects the responses to right and left stimuli were more similar than those to either forward or backward stimuli. Given a particular response, the difference between reaction times for different sensory modalities, was relatively small.

For a single subject different responses are easily identified by the associated mean reaction times. The backward response mean is lower than others because the response is quite similar to a reflex. The required response is akin to jerking the hand away from a hot burner. Averaged over sensory modalities, the differences in response times for the various positions appear attributable to motor characteristics of the response.

For analysis of the later experiments it is sufficient to note that the right and left responses were very nearly similar. Moreover, for either position the differences between tactile and visual stimuli were quite small.

2. Experiment 2 – Two-Response Reaction Time with Either Visual or Tactile Stimuli

A straightforward generalization of Experiment 1 provided the paradigm for Experiment 2. In this experiment the trial structure remained unchanged (Figure 39) but the set of stimuli was changed to TR, TL, VR, VL (tactile-right, tactile-left, visual-right, visual-left). Each session of 500 trials consisted of the four stimuli presented in a random order. The subjects were instructed to respond in the direction of the stimulus. Thus, the experiment amount to cross-modality, four-choice reaction time. Herbart (1816) would label it as simply a complication experiment.

Results

The data in Table 8 represent the mean reaction times of the last 375 trials of the last two sessions for each subject. Occasional errors, anticipatory responses, and latent responses were omitted from the analysis. Moreover, although the generation of the stimuli was random, not all stimuli had the same probability of occurrence. Thus, the number of presentations of the stimuli, shown in the upper corner of each cell in Table 8, varies considerably from subject to subject. Reaction time, as is well known, is quite sensitive to the presentation probabilities.

As can be seen from Table 9, the mean reaction times to tactile and visual stimuli were nearly identical. Similarly, there appears to be little difference between the responses to right and left stimuli. There are, however, substantial individual differences. Subject 2, for example, responded faster to the right than to the left, a fact noted in Experiment 1. Examination of the data for each subject indicates that the observed differences are in part dependent upon effects solely attributable to the response mechanism. Thus, we may conclude that cross-modality reaction time is similar to single-modality choice reaction time. Moreover, the differences between response times in Experiment 1 and Experiment 2 are of the same order as in other experiments in which only visual stimuli have been used. Of course,

Table 8

REACTION TIMES FROM EXPERIMENT 2

Center entries are mean reaction times in msec;
numbers in upper right corner of entries are number of observations

Subject	Tactile		Visual	
	Right	Left	Right	Left
1	138 406	155 342	212 350	166 336
2	236 257	163 312	313 267	203 317
3	149 356	165 351	203 361	162 363
4	233 378	252 355	317 364	249 335
Average	756 341	735 342	1045 332	750 336

each stimulus is unique; therefore, if the peripheral sensory mechanisms feed a central decision mechanism, the resulting differences in reaction times among stimuli should be small, given the results from Experiment 1.

A major difference between tactile and visual stimuli can be seen in the variances. The means and standard deviations for each subject are given in Table 10. The differences are quite large except for Subject 4, who had participated in experiments in tactual perception for nearly two years.

3. Experiment 3 – Two-Response Reaction Time with Simultaneous Visual and Tactile Stimuli

The four stimuli presented singly in Experiment 2 were presented in pairs in Experiment 3. Thus, on a single trial, a subject could receive any one of

Table 9

REACTION TIMES FROM EXPERIMENT 2

Center entries are mean reaction times in msec;
numbers in upper right corner of entries are number of observations.

Subject	Tactile	Visual	Right	Left
1	293 372	378 344	350 372	321 339
2	399 279	516 287	549 263	366 315
3	314 353	365 362	352 358	327 357
4	485 366	566 351	550 370	501 345
Average RT	1491 341	1825 334	1801 336	1515 339
SD	85.0	62.4		

the following four stimuli: VR-TR, VL-TL, VR-TL, or VL-TR. Again the subject was told to respond in the direction of the stimulus. Thus, if he received the combination TR-VR, his task was simply to respond to the right; however, if the combination TR-VL was presented, the subject was instructed to decide which stimulus occurred first and then respond accordingly. In fact, both stimuli were presented simultaneously. We have labeled the events TR-VR and TL-VL the "identical" response case, and the events TL-VR and TR-VL the "conflicting" response case. In all other respects this experiment was the same as Experiment 2.

Results

The mean reaction times in msec are given in Table 11. The overall mean reaction times for the two conditions are approximately equal. Furthermore, the mean reaction time in this experiment is

Table 10

REACTION-TIME MEANS AND STANDARD DEVIATIONS AVERAGED ACROSS RESPONSES IN EXPERIMENT 2

Subject 1

	Visual	Tactile
RT	344	372
SD	45.1	88.4

Subject 2

	Visual	Tactile
RT	286	280
SD	58.6	74.4

Subject 3

	Visual	Tactile
RT	362	354
SD	63.8	88.2

Subject 4

	Visual	Tactile
RT	351	366
SD	50.5	59.3

substantially lower than the mean reaction time in Experiment 2. There are, however, some individual subject differences worth noting. Subject 2 is again quite fast in producing a response to the right, an effect that has persisted through both Experiments 1 and 2. Subject 4 also appears to respond faster to a stimulus on the right.

Interesting results are shown in Table 12, where we have entered the number of responses made to the right and left in the conflicting stimuli

Table 11

REACTION TIMES FROM EXPERIMENT 3

Center entries are mean reaction times in msec;
numbers in upper right corner of entries are number of observations.

Subject		Same Stimuli		Different Stimuli	
		Right	Left	Right	Left
1		199 310	173 316	166 312	185 310
2		198 230	113 313	242 225	104 285
3		144 314	164 297	122 320	162 336
4		192 379	170 336	173 396	175 360
Average	RT	1353 311		1329 315	
	SD	71.8		87.3	

Table 12

RESPONSE PATTERNS FOR EXPERIMENT 3 – CONTRADICTORY STIMULI

Entries indicate number of responses for each condition.

Subject	Visual Right – Tactile Left		Visual Left – Tactile Right	
	Right	Left	Right	Left
1	150	10	16	175
2	118	40	124	64
3	81	45	41	117
4	25	134	148	41

condition. Here it is noted that Subjects 1 and 3 favor responding to the visual stimulus, while Subject 2, of course, favors responding to the right. Also Subject 4 favored responding to the tactile stimulus.

Table 13 shows that fewer errors were made in response to a visual stimulus (Experiment 2) than were made in response to a simultaneous presentation of the same stimuli (Experiment 3). However, there were fewer errors in response to identical stimuli than there were in response to a single presentation of a tactile stimulus in Experiment 2 (Table 8).

4. Experiment 4 – Four-Response Reaction Time with Either Tactile or Visual Stimuli

An eight-choice reaction-time experiment was run to examine the information processing characteristics of the sensory system. As in previous experiments, subjects were presented with either a tactile or visual stimulus which indicated the direction in which a response should be made (F, B, R, L). The trial structure remained unchanged from previous experiments (Figure 39). Each subject had six sessions of 500 trials each, with average presentation probabilities for each of the eight stimuli, as shown in Table 14.

The data in this experiment were again confined to the interval $90 < t < 700$ msec. This resulted in a loss of 188 observations from the 9000 responses analyzed (from each session only the last 375 trials were included in the data analysis).

Results

Individual data for each sense modality and each response position are reported in Table 15. It can be seen that there is considerable variability in the number of correct responses per cell. This result is due in part to unequal stimulus probabilities and in part to errors in responding. The average rate of error for this experiment was 15 percent when calculated over the last 375 trials per session.

Such an extraordinarily large error rate, nearly twice that expected, demanded a fine scrutiny of the data. In Table 16 the total errors for

Table 13

ERROR RATES IN EXPERIMENT 2

Subject	Tactile	Visual	Both – Same Stimuli
1	0.080	0.010	0.032
2	0.115	0.068	0.116
3	0.060	0.019	0.119
4	0.050	0.017	0.042
Average	0.078	0.031	0.077

Table 14

AVERAGE PRESENTATION PROBABILITIES FOR EIGHT STIMULI – EXPERIMENT 4

	Forward	Backward	Right	Left	Total
Tactile	0.10	0.24	0.10	0.10	0.54
Visual	0.11	0.12	0.10	0.13	0.46
Total	0.21	0.36	0.20	0.23	1.00

all subjects, all sessions, and all trials indicate that out of 12, 000 observations nearly 17.5 percent were response errors. These data support the hypothesis that the largest factor affecting the error rate was the rather fine bounds placed on the response by the thresholds of the external equipment (Figure 38). Response bias must be ruled out, since the number of errors in either F-B or R-L are about equal. Secondly, since there appeared to be no substantial improvement in the error rates as sessions progressed, we cannot conclude that discrimination of the stimulus was a major factor. Also, all subjects had, immediately prior to the present experiment, engaged in an exclusively left and right response experiment, and yet there seems to be no clear indication that there exist marked differences between the number of errors in the F-B and R-L classes of responses, regardless of the sensory modality stimulated.

Table 15

REACTION TIMES FROM EXPERIMENT 4

Center entries are mean reaction times in msec;
numbers in upper right corner of entries are number of observations

Subject		Forward	Backward	Right	Left	Mean
1	Tactile	31 487	337 453	96 437	186 399	650 437
	Visual	232 401	243 442	227 353	271 331	973 381
2	Tactile	186 397	475 306	191 428	172 411	1024 363
	Visual	245 348	259 348	201 362	251 371	956 357
3	Tactile	163 405	389 299	156 397	185 343	893 345
	Visual	233 343	232 345	176 362	227 330	868 344
4	Tactile	130 548	380 452	178 503	165 513	853 489
	Visual	220 459	230 431	180 459	236 435	866 444

Finally, it must be remembered that the subjects were told to respond in the direction of the stimulus. Thus, the means of arriving at the final position of the joystick is highly dependent upon the initial position of the subject's hand. If, for example, a left stimulus is given and the subject is holding the joystick at a position near the threshold for a forward response, then it is quite possible that a slight movement forward could surpass the threshold and result in the recording of the response as an error. Only the position of the first threshold crossed was relayed to the computer by the external equipment.

Table 16

TOTAL ERROR DISTRIBUTION FOR EXPERIMENT 4

numbers in upper right corner of total column entries are number of trials

Stimulus		Response		No Response	Total
		F-B	L-R		
Visual	L-R	182	17	81	2700 280
	F-B	23	141	101	2760 265
Tactile	L-R	542	87	118	2400 747
	F-B	101	611	141	4080 853
Total		848	856	441	12, 000 2145

Thus, although the terminal position of the joystick may have been correct, the response was recorded as an error.

A final suggestion that the initial position was indeed the reason for the rather large error rate comes from the fact that visual stimuli produced fewer errors than tactile stimuli. Since the subject was told to respond in the direction of the stimulus, the response to tactile stimuli is more dependent on the position of the hand than is the visual stimulus. Hence, more errors would be expected for the tactile stimulus.

For each subject the mean reaction times to visual stimuli are shown in Table 15 to be shorter than the mean reaction times to tactile stimuli. Since the TB stimulus has probability 0.24 of occurring, nearly twice that of any other stimulus, it is likely that repetition effects associated with this stimulus yield a lower mean reaction time to tactile stimuli than would be expected if all stimuli had the same probability of occurrence. To determine whether or not responses to the TB stimulus were unduly influencing the mean, we calculated the repetition effect for the TB stimulus and compared this with the effect for VB. These results are shown in Figure 41.

The repetition effect is clearly more severe for TB than for VB.* Hence, to adjust the data and obtain a more representative estimate of reaction time to equally probable stimuli, we eliminated TB and then calculated mean reaction time to the remaining tactile stimuli. These results are given in Table 17. All subjects showed an average difference of 40 to 50 msec between tactile and visual responses in Experiment 4. The fact that this

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*Also, we note that there appears to be a recency effect at the fourth repetition. This phenomenon is a result of the often cited "gambler's fallacy," wherein the subject begins to expect a different stimulus. This result is found in numerous data.

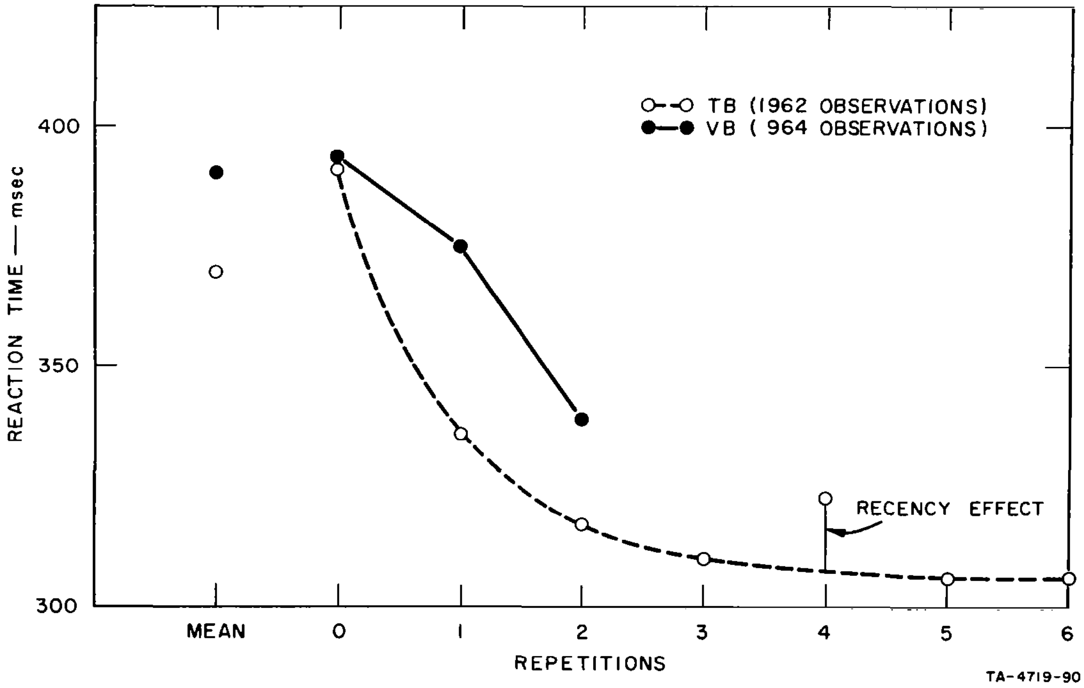

FIG. 41 REACTION TIME AS A FUNCTION OF NUMBER OF REPETITIONS OF THE TB AND VB STIMULI — EXPERIMENT 4

Table 17

TACTILE* AND VISUAL REACTION TIMES IN EXPERIMENT 4

Subject	Tactile	Visual
1	313 420	973 381
2	549 412	956 357
3	504 381	868 344
4	473 519	866 444

* The tactile reaction times are computed excluding the response to the tactile backward stimulus, that is, the most prevalent stimulus.

difference was not found in Experiment 1 indicates that the decision time may be longer for tactile input than for visual input.

A second feature of these data is shown in Figure 42, where we have plotted mean reaction time as a function of repetitions of a stimulus, indicating the position of the response. Here any sequence of correct responses in the form TB, TB, VB, TB contributes one value to each of the means for repetitions of length 0, 1, 2, and 3. Thus, if the probability of a position being presented is 1/4 and the trials are independent, then the probability of observing the above sequence is $(1/4)^4$. Therefore, unless the probabilities are quite high, few responses are recorded for repetitions of, say, length ten. Although the data are not as orderly as might have been expected, they do show a definite decrease in reaction time when responses are repeated, regardless of sensory channel. This result suggests that a switch might govern the responses in such a way as to capitalize on the probability of the occurrence of a particular stimulus. Such a model has been discussed by Falmagne (1965), who assumes

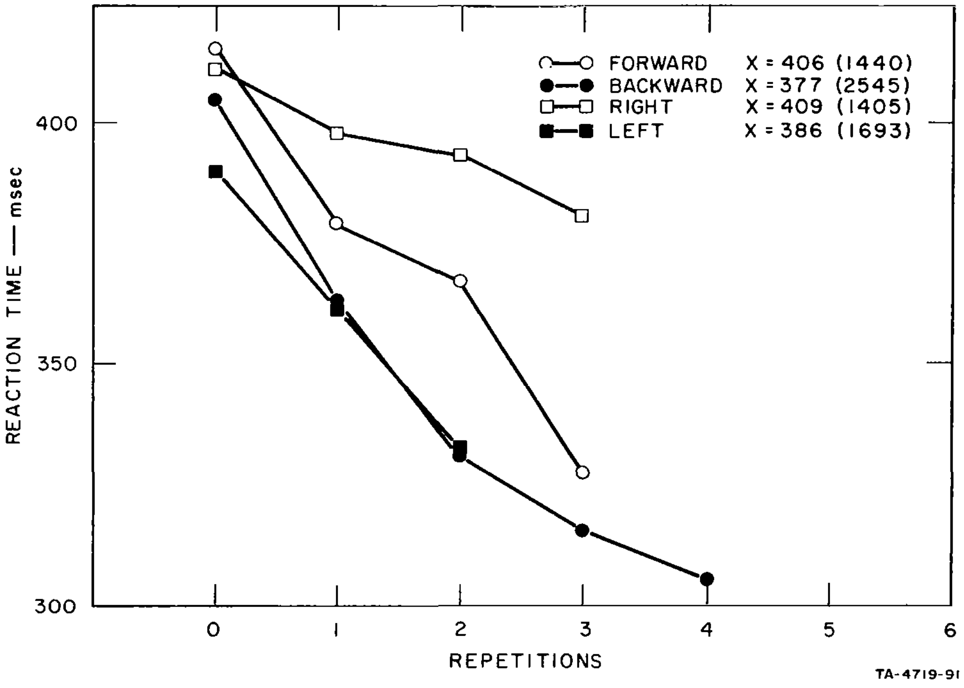

FIG. 42 REACTION TIME AS A FUNCTION OF NUMBER OF REPETITIONS OF RESPONSE INDEPENDENT OF SENSORY CHANNEL — EXPERIMENT 4

unique responses to each stimulus. The case here, where the same response is made to either of two stimuli (i.e., either the visual or tactual stimulus), indicates that the idea of a response switch may have a somewhat more general interpretation.

To explore the switching idea in greater detail, we examined repetitions to the modality previously stimulated. The results are shown in Figure 43. It is quite clear that if a switch with the function of providing for sensory epochs exists, it has no effect on the reaction time to sequentially presented stimuli. That is, the switch operates independently of the stimulus.

Another interesting result shown in Figure 43 is the difference in reaction time between tactile and visual repetitions. Assuming there exists a sensory switch that operates independently of the stimulus, the reaction times for the two modes of stimulation should be roughly equal. However, a visual warning signal was used during these experiments; therefore, if the switch acts as postulated, and if during the 1-sec warning light the visual channel was being

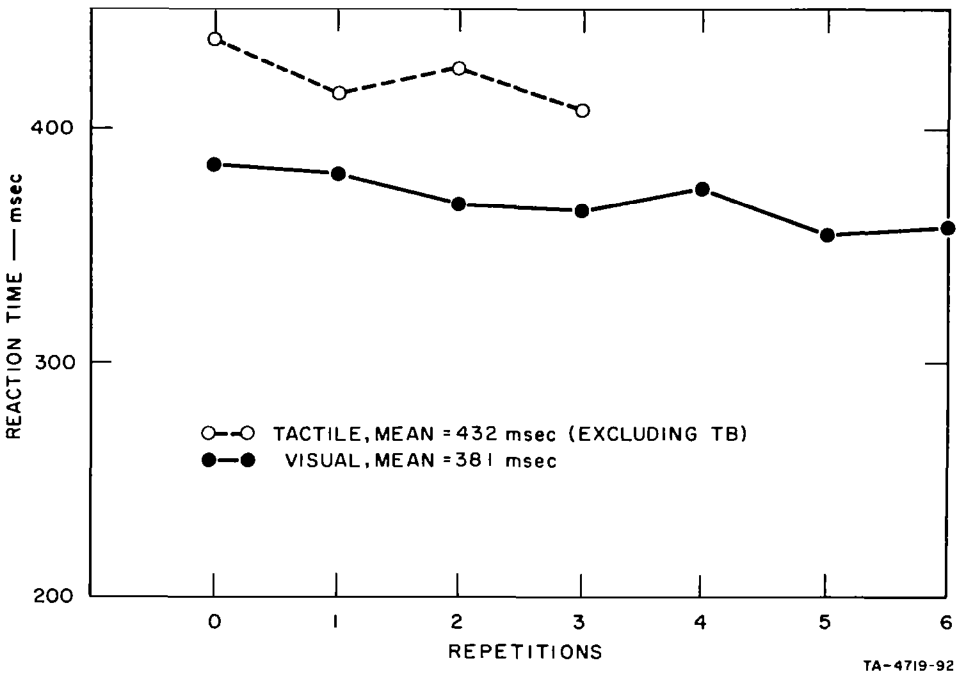

FIG. 43 REACTION TIME AS A FUNCTION OF NUMBER OF REPETITIONS OF SENSORY CHANNEL INDEPENDENT OF RESPONSE POSITION — EXPERIMENT 4

sampled, then the lapse of 0.15 sec between the offset of the warning signal and the onset of the stimulus might be small enough to capture the switch in the visual mode more often than in the tactile mode. This would, in effect, cause a biasing of reaction time in favor of visual stimuli. Moreover, the warning signal occurred on every trial, and hence the effect of channel repetitions should have been small.

C. DISCUSSION

These numerous experiments suggest several hypotheses concerning information in the tactile and visual systems. These major results suggest that the human information processing system consists of (1) an input switch governing the time during which information can be read from the sensory channels; (2) some form of higher-level association of stimuli and responses; and (3) the response switch, which seems to have a large probability of staying in the position of the last response.

In Experiment 4 it was shown that if a switch governed reading information from the sensory channels, it had little, if any, effect on repeated presentation of stimuli indicating where the response should be made. This indicates that if there is a switch it is apparently independent of the stimulus and merely acts as a gate through which information may flow. More substantial evidence that there is, in fact, a sensory switch comes from Experiment 3, where we found that when subjects were simultaneously stimulated in both channels, with stimuli indicating conflicting responses, no increase in the mean reaction time was observed when compared to the case in which the indicated responses were identical. One hypothesis concerning this result is that the presumed sensory switch is either in one of two positions. In either position, tactile or visual, it allows incoming information to pass, and then (and only then) it switches to a different channel.

Assuming that the subject responds with high probability to the first information to pass the switch, we would predict that the average responses to two stimuli presented simultaneously would be faster than the average reaction times to either stimulus presented alone. Comparing the average reaction times for Experiments 2 and 3, we see that this is indeed the obtained result. The average reaction time for Experiment 3 is 313 msec, while that for Experiment 2 is 335 msec.

Final evidence of the existence of a sensory sampler is the result obtained upon comparing the repetition effects for Experiments 2 and 3, shown in Figure 44. The repetition curve for simultaneous presentations requiring identical responses is the result of averaging two curves, one for sequences indicating that left responses should be made and another for sequences indicating right response. Both experiments involve four choices, each choice having probability 0.25. In Experiment 2, the four stimuli were TR, TL, VR, VL, while in Experiment 3 the stimuli were combinations of the stimuli used in Experiment 2, namely TRVR, TRVL, TLVR, TLVL. Assuming a sensory sampler, we see that a response can be made in Experiment 3 regardless of the channel the switch may be monitoring, while in Experiment 2 the switch may be forced to change channels. Since some time must be involved in the process of changing channels, we expect the mean reaction time in Experiment 3 to be lower than it is in Experiment 2. Furthermore, the differences in repetitions should be

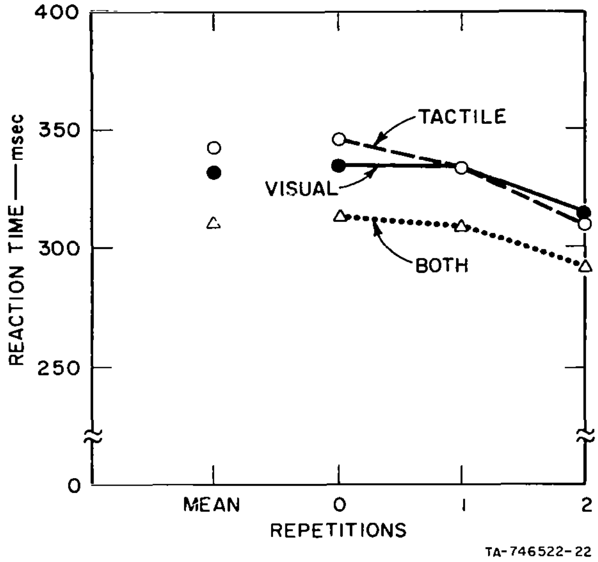

FIG. 44 REACTION TIME AS A FUNCTION OF NUMBER OF REPETITIONS OF STIMULUS — EXPERIMENTS 2 AND 3

marked. The results shown in Figure 44 are in agreement with these speculations.

A rigorous formulation of such a switching mechanism must account for other aspects of our data. For example, it was observed in Experiment 4 that repetitions of visual stimuli produced reaction times which were, on the average, some 40 to 50 msec faster than tactile stimuli. (Figure 43.) Moreover, in Experiment 3, one subject who had received extensive training in tactual perception showed a distinct bias toward responding to tactile rather than visual stimuli. There are several possible explanations for these results. It is possible that the biases revealed in Experiment 3 reflect a bias in the sensory sampler. If this is in fact true, then one should be able to bias the switch through experimental manipulations. A variety of conditions for a warning signal would produce a bias of the sensory sampler.

Figure 45 shows that reaction time increases more per alternative for tactile stimuli than it does for visual. An apparent explanation for the increase in tactile reaction time as the number of alternatives increases is that the subject

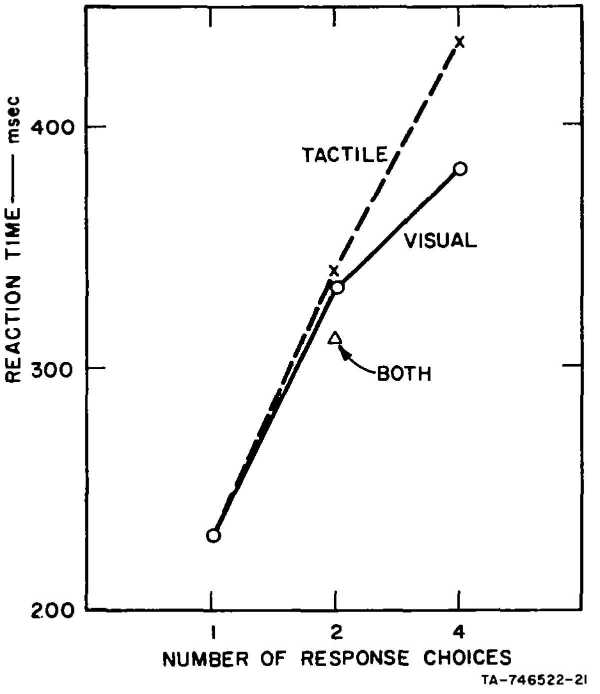

FIG. 45 MEAN REACTION TIME AS A FUNCTION OF NUMBER OF ALTERNATIVES — EXPERIMENTS 1, 2, 3, AND 4

may more closely attend to visual stimuli. This conjecture is supported by the following facts:

(1) It has been shown in numerous simple reaction-time experiments that $RT_{\text{tactile}} < RT_{\text{visual}}$.

(2) The reaction time of one subject who favored tactile stimuli in Experiment 3 was, in every case, higher than that of the other subjects.

(3) Repetitions of visual stimuli produce lower reaction times than repetitions of tactile stimuli.

(4) The visual warning light may have tended to bias the subject to attend to the visual channel.

In choice reaction time (CRT) some controversy has centered around the question of whether or not the number of alternatives in the experiment affects the mean reaction time. Some investigators claim that for well-trained subjects there should be no difference in reaction time for experiments with varying degrees of choice. Essentially this amounts to stating that choice reaction times should not vary as a function of stimulus probability. Furthermore, the assertion that reaction time is independent of stimulus probabilities implies that either (1) repetition effects must be identical for all stimuli, or (2) that there should be no repetition effect at all for well-trained subjects. Figure 42 shows that for subjects who had received extensive training in making right and left responses, a repetition effect persists; hence (2) may be ruled out. In addition, the assumption that repetitions must be identical for all stimuli is also voided. Finally, it is quite clear that reaction time varies as a function of stimulus probability.

We conclude that since repetition effects are more extreme for stimuli that occur more often, observed differences between CRT experiments of varying degrees of choice are attributable to the effects of repetitions. In experiments with a large number of alternatives, N, the probability of a lengthy sequence of a particular stimulus is lower than the corresponding probability for an experiment with a smaller number of alternatives, M. Thus, when all data from a CRT experiment of degree N are averaged, there will be fewer lengthy repetitions and hence fewer low values of reaction time contributing to the mean reaction time than there will be for a CRT experiment with degree M.

These ideas suggest an alternative to the rather elaborate mathematical model proposed by Falmagne (1965). If we assume that there are fixed time constants associated with the repetition of a response, then we may be able to account for the observed differences in reaction time for CRT experiments with varying degrees of choice on the basis of how often a particular repetition effect is observed. We formalized these notions as follows:

Let T_N = the overall mean reaction time for an experiment of degree N

t_i = the mean reaction time for the i^{th} repetition

$S(N) = (s_1, \ldots, s_N)$ be the set of stimuli for a CRT experiment of degree N

$p(s_i)$ = probability of occurrence of s_i

$p(s_{i,k})$ = probability of observing at least k repeated presentations of s_i.

Now, it can easily be shown that for multinomially distributed s_i,

$$p(s_{i,k}) = [1-p(s_i)]\,[p(s_i)]^k. \tag{4}$$

Suppose that $p(s_i)$ is uniformly distributed over S(N) then

$$p(s_{i,k}) = (N-1)(N)^{-(k+1)}$$

$$T_N = \sum_{i=1}^{N} \sum_{k=1}^{\infty} p\,(s_{i,k})\, t_k.$$

Since there are N such sequences for S(N), the marginal probability becomes

$$p(s_{i,k}) = (N-1)(N)^{-k}.$$

Or, using only the marginal distributions $p(s_{i,k})$, we can write

$$T_N = \sum_{i=1}^{N} p\,(s_{i,k})\, t_k \tag{5}$$

There are several reasons for believing that reaction time in CRT is solely a function of stimulus probability. Data from Stone and Calloway (1964) and Link (1964) indicate that mean reaction times to stimuli of, say, probability 0.5 are the same regardless of the degree of choice in a CRT experiment.

Estimates of the t_k may be obtained if several experiments of differing degrees of choice are run. As a first approximation, we may use the marginal probabilities $p\,(s_{i,k})$ as the estimate of the k^{th} repetition of a stimulus. Then for every T_N, Eq. (5) holds. We can write this in matrix form as

$$T = Pt,$$

where

T is a column vector containing the various values of T_N

P is a matrix whose first row is $p(s_{i,1})\ p(s_{i,2})\ \ldots$ for S(N)

and whose second row is $p(s_{i,1})\ p(s_{i,2})\ \ldots$ for S(N+1) and

t is a column vector containing the t_k of Eq (5).

Then

$$P^{-1} T = t.$$

For a finite number of trials in an experiment, the expected number of occurrences of a sequence of repetitions of length k becomes small as k becomes large. Moreover, such occurrences become even smaller as N is increased. Hence it is in most cases sufficient to treat P as a matrix of finite order, depending upon the number of trials in the experiment.

The fact that as N becomes large the values in the columns of P become small simply illustrates the fact that fewer and fewer repetitions are likely to be observed. This dictates that estimates of the t_k for large values of k will be insignificant in their contribution to the mean for large values of N. If one could estimate the first few t_i, apply these values to values of N larger than those used in the estimation, and predict the mean reaction time, then a close fit to observed values would indicate that our assumptions may be valid.

However, due to the effects of intervening items, the first point on the repetition curve is often larger than expected on the basis of Eq. (5). To account simultaneously for both the effects of repetition and intervention of stimuli, we derive the probability that there are exactly m intervening stimuli between the last presentation of s_i and a run of at least k repetitions of s_i.

Let $$(s_i, k, m) = \left\langle s_{i,n}, s_{j \neq i, n+1}, \ldots, s_{j \neq i, n+m}, s_{i, n+m+1}, \ldots, s_{i, n+m+k} \right\rangle$$

Then

$$p\,(s_i, k, m) = \begin{cases} p(s_i)\,[1-p(s_i)]^m\, p(s_i)^k & \text{if } k, m > o \\ 0 \text{ otherwise} \end{cases}$$

We show that

$$\sum_{i=1}^{n} \sum_{k=1}^{\infty} \sum_{m=1}^{\infty} p(s_i, {}_k, {}_m) = \sum_{i=1}^{n} \sum_{k=1}^{\infty} [1-p(s_i)]^{m}$$

$$= \sum \sum p(s_i)^{k+1} \left(\sum_{m=o}^{\infty} [1-p(s_i)]^{m} - 1 \right)$$

$$= \sum \sum p(s_i)^{k+1} \left[\frac{1}{p(s_i)} - 1 \right]$$

$$= \sum \sum p(s_i)^{k+1} \left[\frac{1-p(s_i)}{p(s_i)} \right]$$

$$= \sum_{i=1}^{n} [1-p(s_i)] \sum_{k=1}^{\infty} p(s_i)^{k}$$

$$= \sum_{i=1}^{n} [1-p(s_i)] \left[\sum_{k=0}^{\infty} p(s_i)^{k} - 1 \right]$$

$$= \sum_{i=1}^{n} [1-p(s_i)] \left[\frac{1}{1-p(s_i)} - 1 \right]$$

$$= \sum_{i=1}^{n} p(s_i) = 1$$

The joint distribution is shown in Table 18 below:

Table 18

JOINT DISTRIBUTION OF REPETITIONS AND INTERVENTIONS

		Repetitions						
	m^k	1	2	3	4	5	. . .	∞
Interventions	1	$p(s_i)^2[1-p(s_i)]$						
	2							
	3							
	⋮							
	∞							

Values of $p(s_{i},{}_{k},{}_{m}) = p(s_i)^{k+1}[1-p(s_i)]^m = p^{k+1}\, q^m$

For the marginal distributions we have

$$p(s_{i},{}_{k},\cdot) = \sum_{m=1}^{\infty} p(s_{i},{}_{k},{}_{m}) = p(s_i)^{k+1} \sum_{m=1}^{\infty} [1-p(s_i)]^m$$

$$= p(s_i)^{k+1}\left(\sum_{m=o}^{\infty} [1-p(s_i)]^m - 1\right)$$

$$= p(s_i)^{k+1}\left(\frac{1}{p(s_i)} - 1\right)$$

$$= p(s_i)^{k+1}\left(\frac{1-p(s_i)}{p(s_i)}\right)$$

$$= [1-p(s_i)]\; p(s_i)^k$$

Similarly

$$p(s_i, \cdot\cdot, {}_m) = \sum_{k=1}^{\infty} p(s_i, {}_k, {}_m) = [1-p(s_i)]^m \sum_{k=1}^{\infty} p(s_i)^{k+1}$$

$$= [1-p(s_i)]^m \, p(s_i) \sum_{k=o}^{\infty} p(s_i)^k -1$$

$$= [1-p(s_i)]^m \, p(s_i) \left[\frac{1}{1-p(s_i)} -1\right]$$

$$= [1-p(s_i)]^m \, p(s_i) \left(\frac{p(s_i)}{1-p(s_i)}\right)$$

$$= p(s_i)^2 \, [1-p(s_i)]^{m-1}$$

Given the marginal distributions, or the probabilities of $(s_i, {}_k, {}_m)$, we can easily calculate the mean reaction time for any CRT experiment, provided that some previous estimate of the times for repetitions are also given. Our data, at present, are hardly sufficient to allow a test of these hypotheses. However, the fact that we are able to specify a probabilistic design for at least part of the response indicates that the development of an integrated mathematical statement of characteristics of the sensory sampler, decision mechanism, and response mechanism is within easy reach. Additional experiments are needed to support even a simplified model of tactile and visual processing systems.

D. SUMMARY

In summary we have shed some light on the functioning of a central switching mechanism that may govern information flow from the sensory channels. A single switch operating more or less at random and independent of the particular stimulus allows such a mechanism to create in its wake a series of sensory epochs, times during which information can be read from the sensory channels. This gives rise to the seemingly bizarre prediction that for simultaneous presentation of stimuli requiring conflicting responses, the reaction time will be lower than the reaction time to either stimulus presented separately.

Furthermore, it predicts that reaction time for simultaneously presented stimuli requiring conflicting responses will be equal to the reaction time for simultaneously presented stimuli requiring identical responses.

Secondly, we have shown that reaction time for tactile stimuli is longer in CRT than it is for visual stimuli, and we have accounted for this on the basis of a central sensory monitor. On the basis of these experiments we conclude that the differences in reaction time between tactile and visual stimuli, as the number of alternatives in CRT are increased, is due to the effects of:

(1) The channel which the sensory switch is monitoring at the time of stimulation

(2) The effects of repetitions and interventions of stimuli in the sequence of trials during the experiment.

Hence, under our experimental conditions, we find that postulating a sensory sampler will account for differences between reaction time to tactile and visual stimuli. In general, other factors such as stimulus intensity will also influence reaction time. The more intense a stimulus, the more likely it is to reach the sensory sampler before a weaker stimulus presented simultaneously. However, it appears that decision time is quite probably of the same duration regardless of the stimulus.

Finally, a simple mathematical model that attributes the differences in reaction time for differing numbers of alternatives to the effect of interventions and repetitions of stimuli has been presented. With this model we are able to show that the well-known repetition effect is appropriately localized in the output mechanism of the subject.

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VII VISUAL AND TACTILE TRACKING WITH STEP COMMANDS

By James C. Bliss, William R. Brody, and Barton Lane

A useful technique in developing models for human operator performance in manual control is to compare the responses obtained with different sensory inputs. In this way, sensory effects can be distinguished from response features primarily caused by the central and neuromuscular systems

Several experiments described here are relevant to the development of models to describe the eye-hand and skin-hand coordination control systems. In the basic experiment, hand responses were recorded for various step commands and feedback conditions, and with analogous visual and tactile displays. Similar experiments involving eye tracking and hand tracking are reviewed by Young and Stark (1965)*.

A. INITIAL EXPERIMENT

An important factor in tracking experiments with abrupt changes in the command signal and feedback conditions is the adaptive behavior of the subject. In fact, once a subject has made a particular response to a new situation, that subject may choose a new mode of behavior, which means that any model describing his initial behavior probably does not describe his new behavior. To illustrate this point, an initial experiment performed on three untrained subjects is described below. The responses presented are the very first responses they made with the apparatus. When these experiments were repeated (described in subsequent sections) with more subjects, more trials per subject, and under more carefully controlled conditions, several features of the results were not substantiated. A possible explanation for this is the difference between initial behavior and the behavior after even a small amount of experience.

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*References are given at the end of this section.

1. Method

The experimental arrangement was for a single-axis pursuit tracking task. It is shown in Figure 46 for the tactile input and in Figure 47 for visual input. In the tactile case, the subject's task was to move his hand so that the activated airjet stimulator was always aimed at a specific anatomical position near the proximal end of the index finger. This position was marked with a gummed reinforcement for loose-leaf notebook paper holes. Similarly, in the visual case the subject's task was to keep the pointer aligned with the neon light that was illuminated. In a few cases, the subject was presented both the tactile and visual displays simultaneously. The subject always kept his hand fixed with respect to the side arm controller, which provided an electrical indication of his hand position.

The command signal, hand position, display position, and error were recorded on a four-channel chart recorder. Even though the displays were discrete, with 13 stimulators in each case, it appeared from the records with step commands of several quantization levels in amplitude, that the quantization was fine enough that the display could be considered continuous for these conditions.

A Donner 3100 analog computer was used to close an external feedback loop around the subject, as shown in Figure 48. The gain of this loop was varied from -2 to +2. In this situation, the subject presumably notes the position of the activated display stimulator, compares it with his hand position visually and kinesthetically, and estimates an error, which he translates into corrective hand movements. According to the terminology used here, the display position d is related to the command signal c and the hand position r by the following equation:

$$d = c + Hr,$$

where H is the feedback gain. Thus for a feedback gain of +1, the command and response are simply summed to determine the display position. The error, d-r, is then equal to the command, and the subject's internal feedback is cancelled, producing an open-loop situation. Thus, with a step command, the activated stimulator always stays a fixed distance ahead of the hand position (constant error), and we should expect the subject to rapidly go off scale.

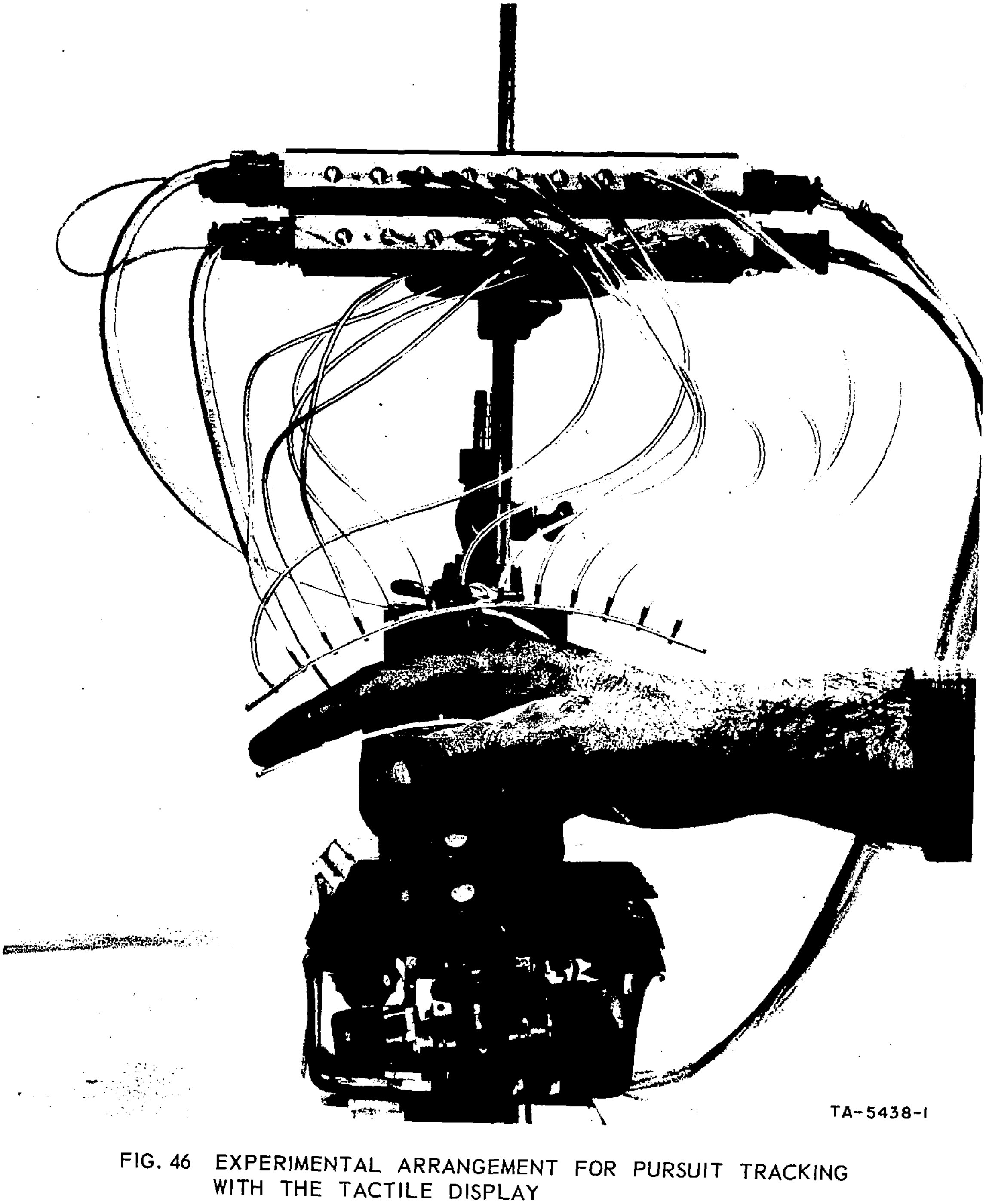

FIG. 46 EXPERIMENTAL ARRANGEMENT FOR PURSUIT TRACKING WITH THE TACTILE DISPLAY

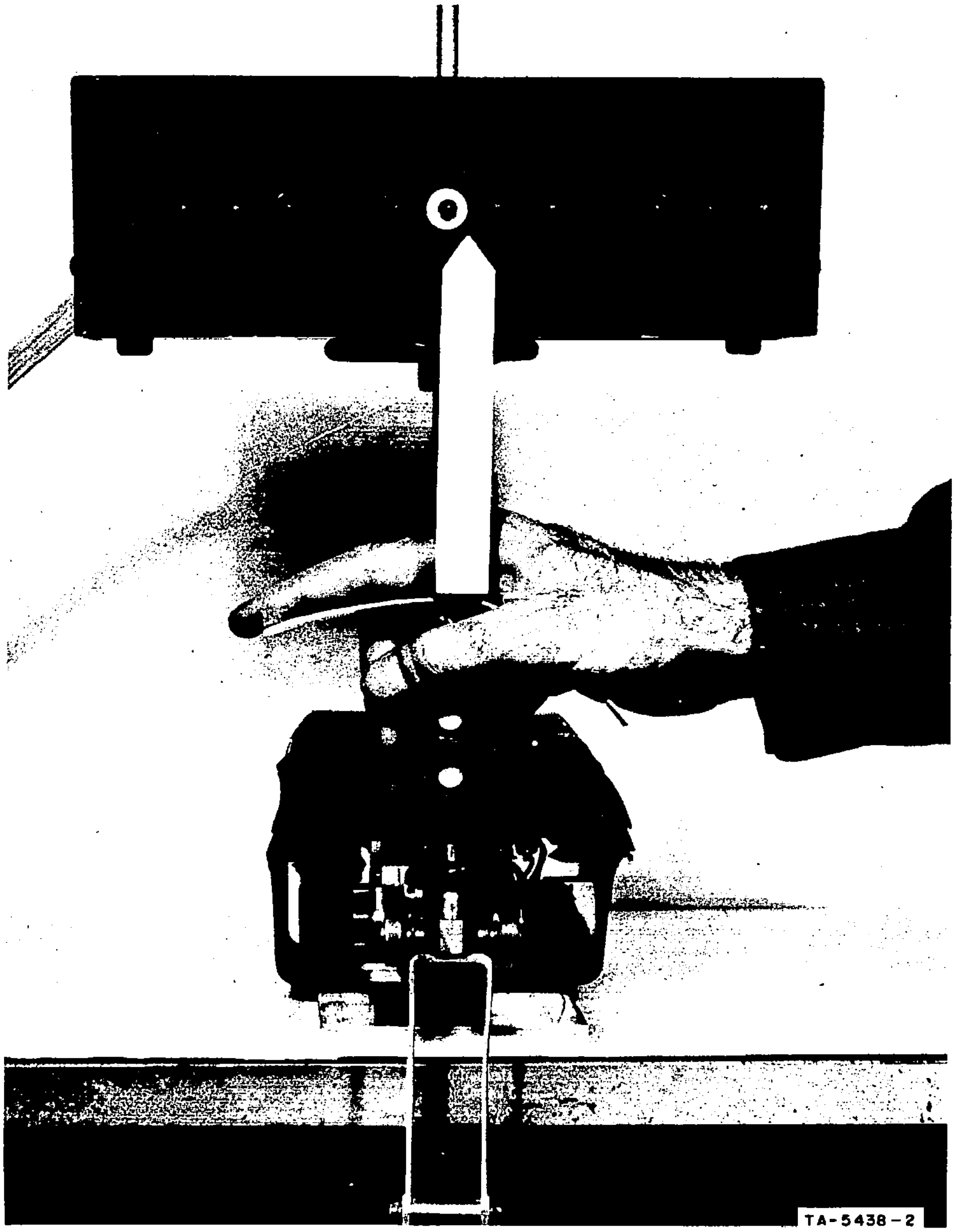

FIG. 47 EXPERIMENTAL ARRANGEMENT FOR PURSUIT TRACKING WITH THE VISUAL DISPLAY

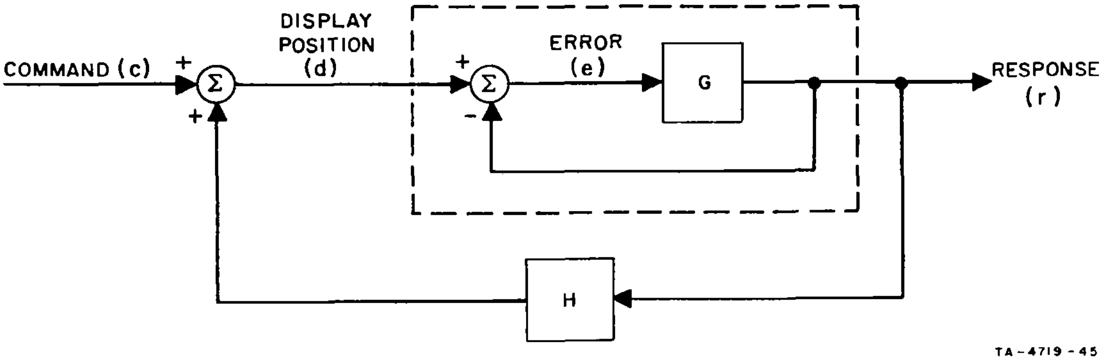

FIG. 48 COMPLETE SYSTEM ILLUSTRATING EXTERNAL FEEDBACK LOOP WITH VARIABLE GAIN

The amplitude and sign of the step commands and the value of feedback gain were varied randomly. Thus, preceding each trial, the subject was unaware of the direction or magnitude of the next step command and the feedback gain. Three subjects were used, and a total of 98 trials were performed.

2. Results

Figure 49 shows responses of the three subjects with +1 feedback, step commands of various sizes and polarities, and the visual and tactile displays. Note that in these examples, for both tactile and visual displays, the hand movements are separated by stationary periods, giving a "staircase" appearance to the responses. Also note that, consistent with each subject, the duration of these stationary hand periods is longer with the visual display than with the tactile display.

If the feedback gain is negative, then as the subject moves to reduce the error, the display position moves in the opposite direction, which also tends to reduce the error. Figure 50 shows responses of three subjects for a feedback gain of -1, step command signals of various amplitudes, and the tactile and visual displays. Note the striking difference between the responses with the tactile display and the responses with the visual display. The tactile responses show a slight overshoot, while the visual displays are oscillatory with a period ranging from 750 to 1070 msec.

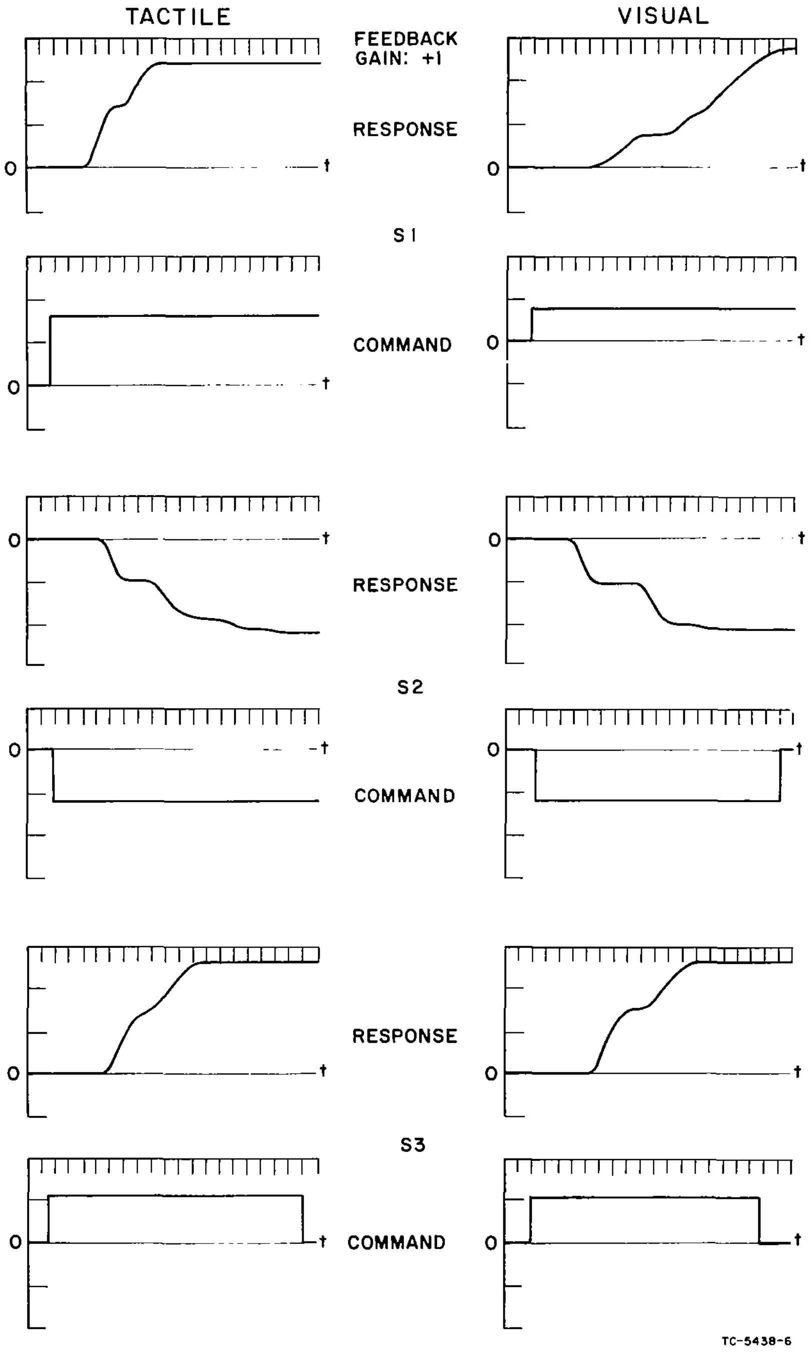

FIG. 49 RESPONSES TO STEP COMMANDS WITH EXTERNAL FEEDBACK GAIN OF +1 (Time scale: 0.1 sec/div)

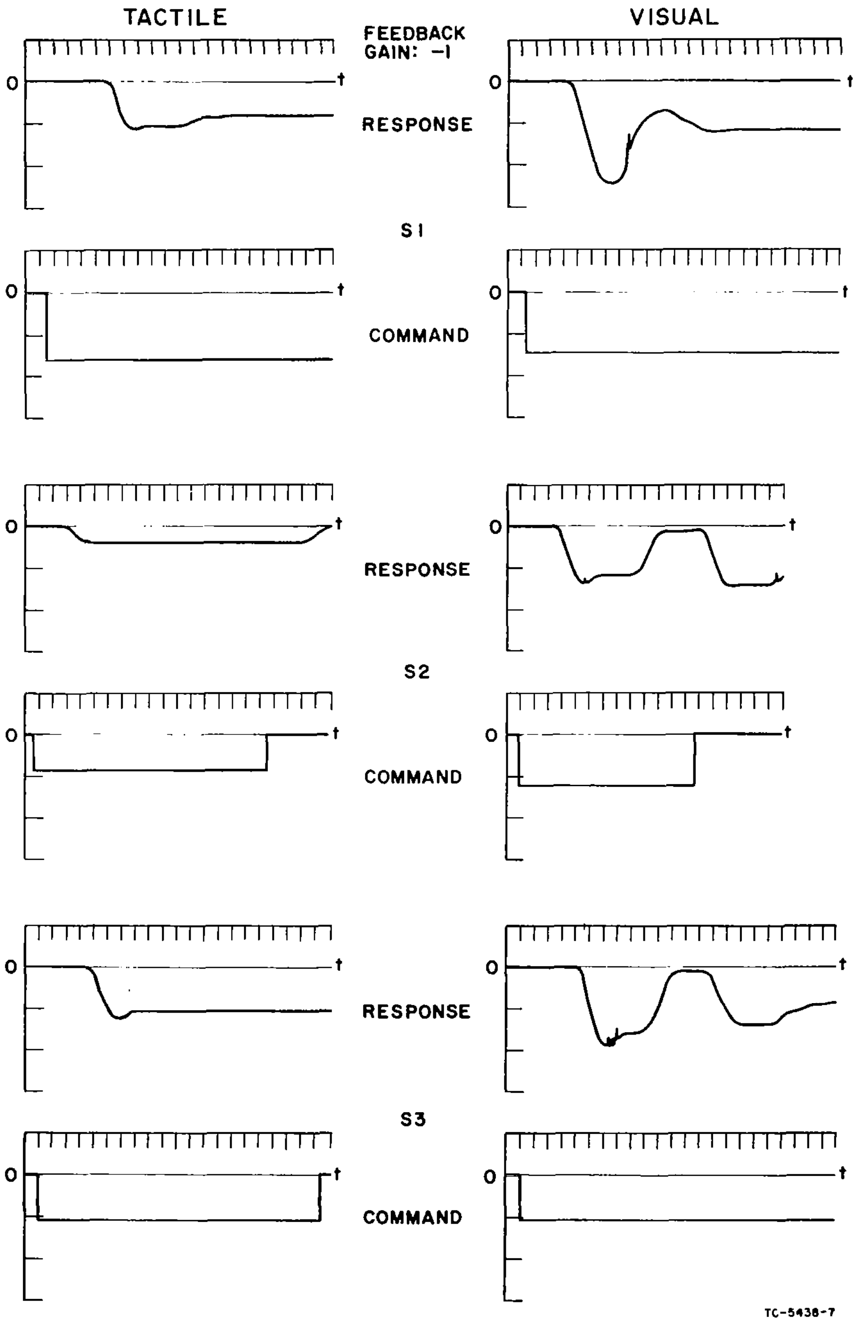

FIG. 50 RESPONSES TO STEP COMMANDS WITH EXTERNAL FEEDBACK GAIN OF -1 (Time scale: 0.1 sec/div)

Figures 51 and 52 illustrate responses for feedback gains over the range -2 to +2. Note the progression from decaying oscillations to expanding oscillations for the visual display and feedback gains of -1/2, -1, and -2, respectively. Also note the "staircase" with increasing size steps, the "staircase" with uniform steps, and the "staircase" with decreasing size steps, for the tactile display and feedback gains of +2, +1, and +1/2, respectively.

Figure 53 illustrates the performance when the tactile and visual displays were used simultaneously. For positive feedback gains, note that, like the results with the tactile display alone, the stationary parts of the response are relatively short. Also note that for negative feedback gains, the responses are less oscillatory than those with the visual display alone.

B. EXPERIMENT 1: BASIC EXPERIMENT

The experimental paradigm of the initial experiment was repeated with several improvements in procedure and over a wider range of experimental conditions. Since more trials were run on each subject, the subjects were of necessity more experienced than in the initial experiment.

1. Method

As described in the initial experiment, a row of 13 neon lights and a row of 13 airjet stimulators were arranged above a joystick. The airjets were collinearly spaced 1/2 inch apart, from the top of the ventral side of the index finger of the right hand to the wrist. In the tactile experiment, the subject's task was to move his hand so that the activated airjet stimulator was always aimed at a specific position near the proximal end of the index finger. Similarly, in the visual experiment, the subject's task was to keep the pointer aligned with the illuminated neon light. In some cases the subject was presented both the tactile and visual displays simultaneously.

The subject always kept his hand fixed with respect to a side arm controller, which provided an electrical indication of hand position. A Donner 3100 analog computer was used to close an external feedback loop around the subject, as shown in Figure 48. In this situation, the subject presumably (1) noted the position of the activated display stimulator; (2) compared it with his hand position, as estimated visually and proprioceptively; and (3) estimated the

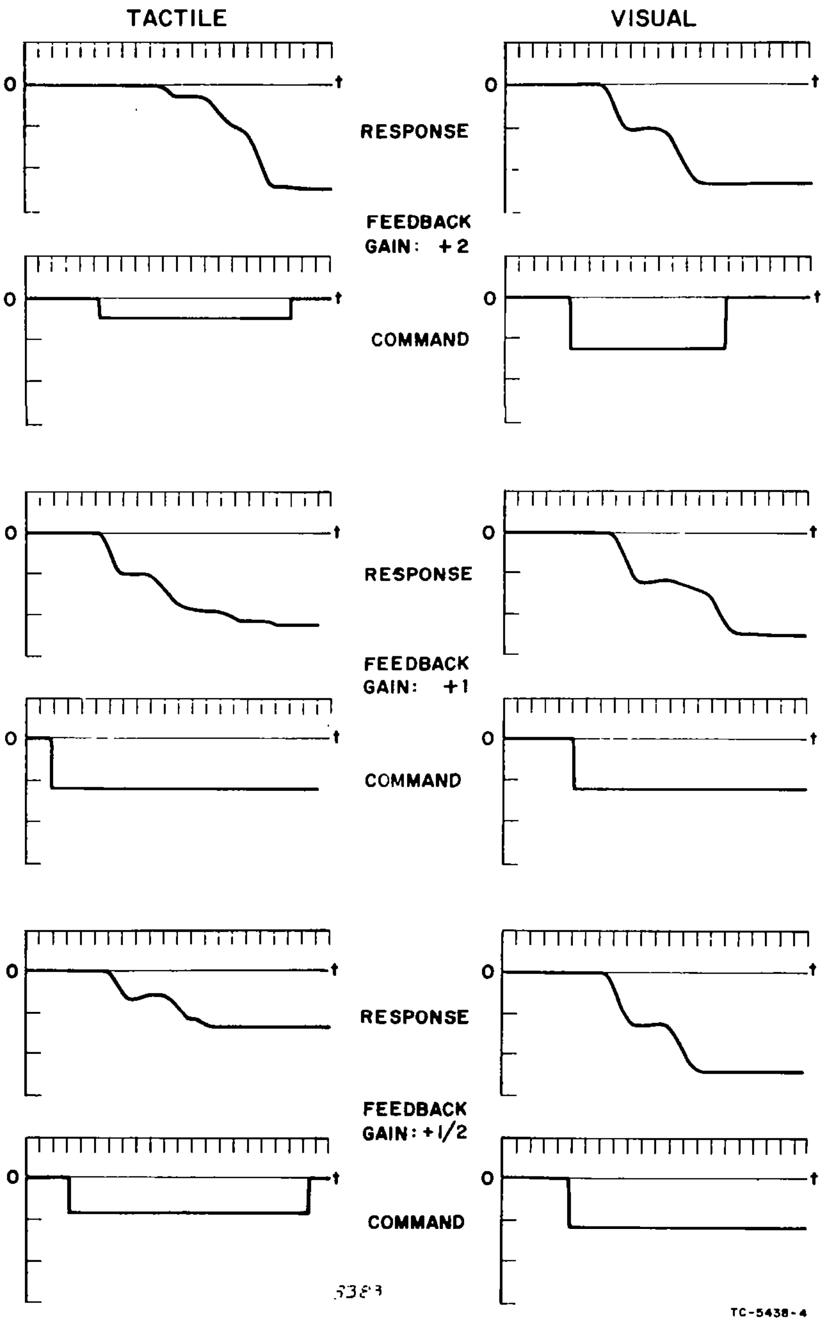

FIG. 51 RESPONSES TO STEP COMMANDS WITH VARIOUS POSITIVE EXTERNAL FEEDBACK GAINS
(Time scale: 0.1 sec/div)

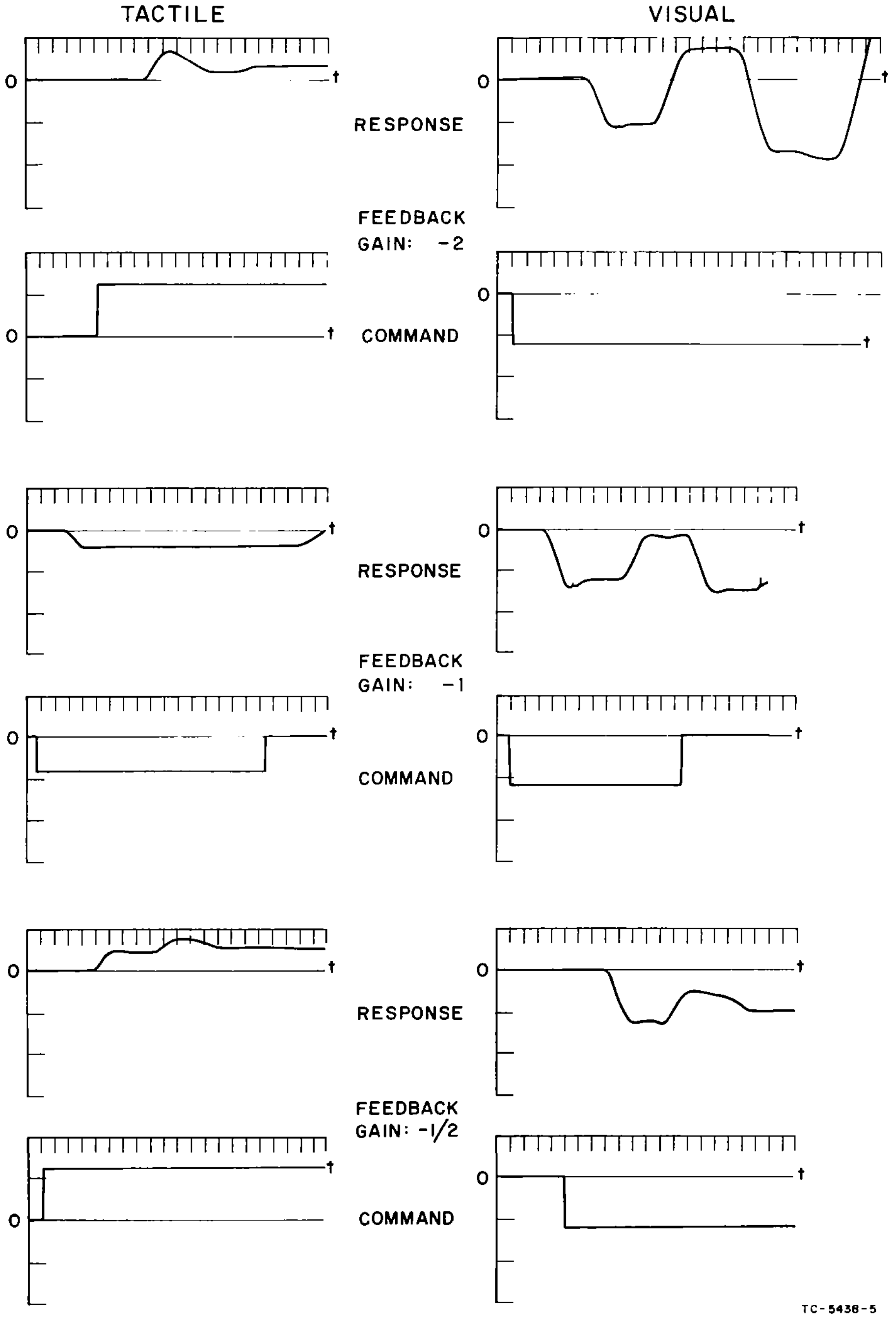

FIG. 52 RESPONSES TO STEP COMMANDS WITH VARIOUS NEGATIVE EXTERNAL FEEDBACK GAINS
(Time scale: 0.1 sec/div)

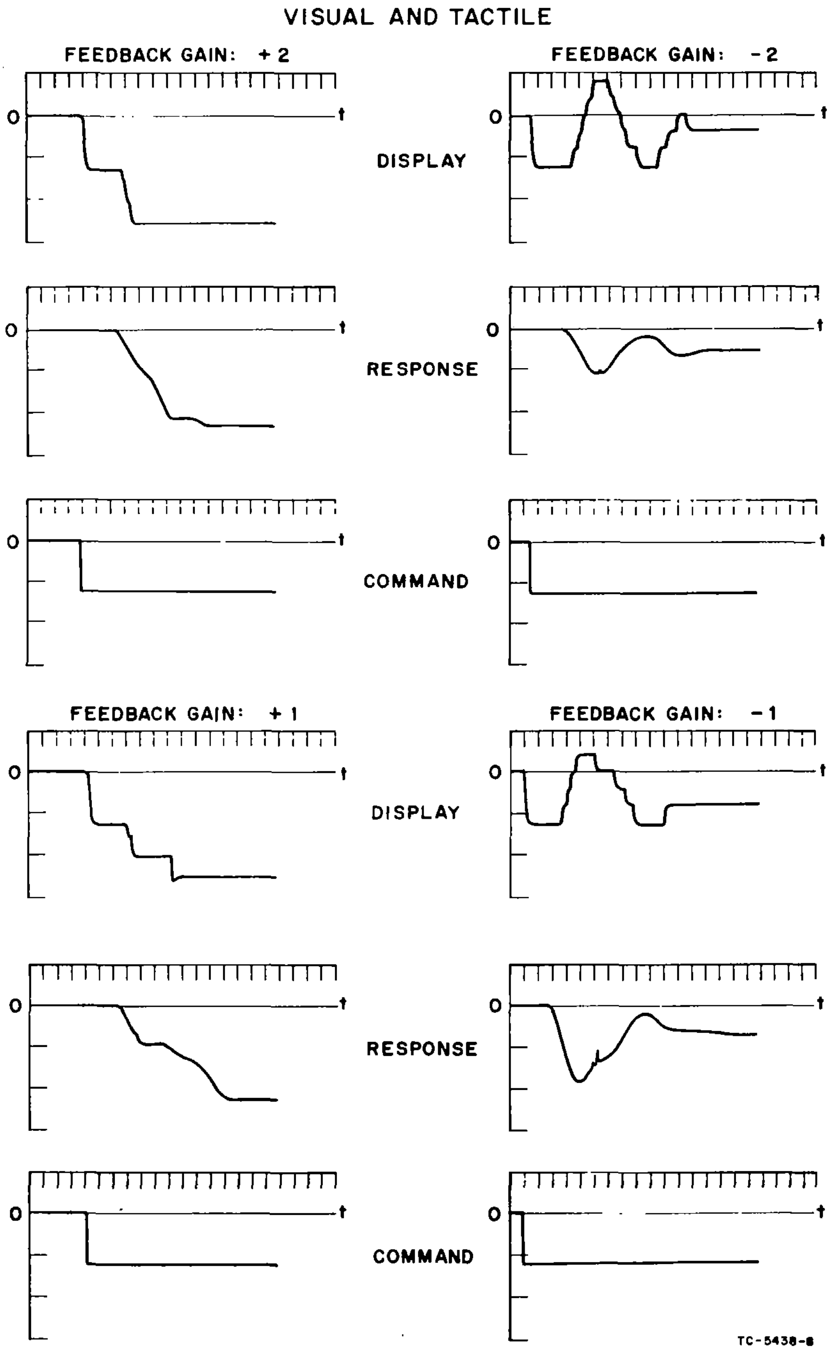

FIG. 53 RESPONSES TO STEP COMMANDS WITH SIMULTANEOUS TACTILE AND VISUAL DISPLAYS AND VARIOUS EXTERNAL FEEDBACK GAINS (Time scale: 0.1 sec/div)

error, which he translated into a corrective hand movement. Thus, the experiment was a single-axis pursuit tracking task.* The instructions given each subject were:

> "In this experiment you are to move the control stick either forward or backward in response to visual or tactile command signals, or both visual and tactile simultaneously. The visual command signal will consist of a light turned on; the tactile signal will be a corresponding airjet turned on; or they could both be on simultaneously.
>
> "Your task is to move the control stick as quickly as possible to point to the proper light or airjet, and continue to move until the error is zero. That is, in the visual case, you are to continue to move as quickly as possible until the pointer coincides with whatever light is on; in the tactile case, you are to continue to move as quickly as possible until the airjet points to the designated area at the knuckle.
>
> "In between runs the centerlight and airjet will remain on; I will say 'ready', and at some time immediately following (say, 1 or 2 seconds) you will receive the stimulus. You will then move until the error is zero, after which time you will be told to stop. Each run will take about 10 seconds."

The values of command signal and feedback for which hand responses were obtained are shown in Table 19. Zero final error was possible for all the conditions except those with +1 and +2 feedback. On each session, the 26 different conditions of Table 19 were presented in random order with either the visual display, the tactile display, or the visual and tactile displays simultaneously. Then the display was changed and the conditions were presented again in a

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*Perhaps the visual and tactile displays would have been more closely analogous if an airjet, always activated, had been fixed to the hand and continuously indicated the anatomical reference position. This airjet would then have played the role of the pointer in the visual display. However, an anatomical position can be remembered tactually very well, so that this "pointer" airjet was considered to be unnecessary.

TABLE 19

CONDITIONS FOR TRACKING EXPERIMENT

FEEDBACK (H)

STEP COMMAND HEIGHT (c)

	-2	-1	-1/2	0	+1/2	+1	+2
-6	X	X	X	X			
-5							
-4				X	X		
-3	X						
-2		X	X	X	X	X	X
-1							
0							
1							
2		X	X	X	X	X	X
3	X						
4				X	X		
5							
6	X	X	X	X			

X DENOTES THE TEST CONDITIONS

different random order. This process was repeated with the third display condition, so that there were 78 trials in any session--26 with the visual display, 26 with the tactile display, and 26 with both displays. Four subjects were used and each subject had three sessions, so that three trials at every feedback, command, and display condition were obtained. The order in which the displays (visual, tactile, or both) were presented was balanced over these three sessions.

Special precautions were taken to ensure that prior to the step command signal, the subject was unaware of the feedback condition for the next trial. These precautions included turning off the feedback until the step was presented, so that small preliminary movements of the stick would not convey the feedback information.

2. Results

The first method used to reduce the data was to classify the responses qualitatively according to an arbitrary set of response types. Figures 54 and 55 show the response types used for positive and negative feedback respectively; Figure 56 shows the types used for zero feedback. Histograms, averaged across subjects, resulting from this classification procedure are also shown in these figures.

From these histograms, a type C response for negative feedback was chosen as representative for more quantitative analysis because of its frequency of occurrence. Thus, all of the type C negative feedback responses were examined, and the parameters shown in Figure 57 were measured. Table 20 gives the averages of the time measurements from these responses.

Similarly, for positive external feedback, response types B, C, and D were considered representative, and the parameters shown in Figure 58 were quantitatively measured for each of these responses. The averages from these data are shown in Table 21.

3. Discussion

The response types of Figures 54 and 55 are arranged in order of increasing oscillatory behavior. Thus, the histograms indicate quantitatively the degree of stability of the responses. In contrast with the exploratory results described in the initial experiment, no consistent qualitative difference in the degree of stability was obtained for the visual, tactile, or simultaneous visual

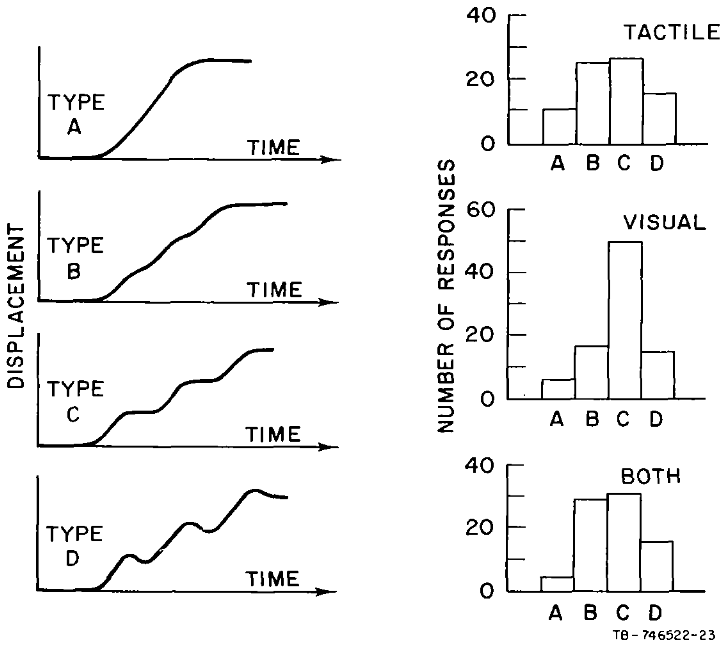


FIG. 54 HISTOGRAMS OF TYPES OF RESPONSES OBTAINED WITH POSITIVE FEEDBACK AND THE TACTILE, VISUAL, AND BOTH DISPLAY CONDITIONS

and tactile displays. In fact, few oscillations (type E responses, negative feedback) were obtained with any display, and there were slightly more type E responses with the tactile display than with the other display conditions. This result suggests that the similarity between responses with visual and tactile displays and negative feedback is greater than was first thought. Moreover, it is difficult to explain the lack of type E (negative feedback) responses with a sampled data model.

Where both displays were used simultaneously, the subjects reported that they only attended to the visual display, ignoring the tactile display. Thus it is surprising that the average simultaneous display histograms are more like a combination of the tactile and visual histograms.

Consistent with the exploratory results of the initial experiment, the mean of the reaction times with both displays used simultaneously was shorter than the means for either the visual or tactile displays. This result is also consistent with many other findings, such as those in Sec. VI of this report.

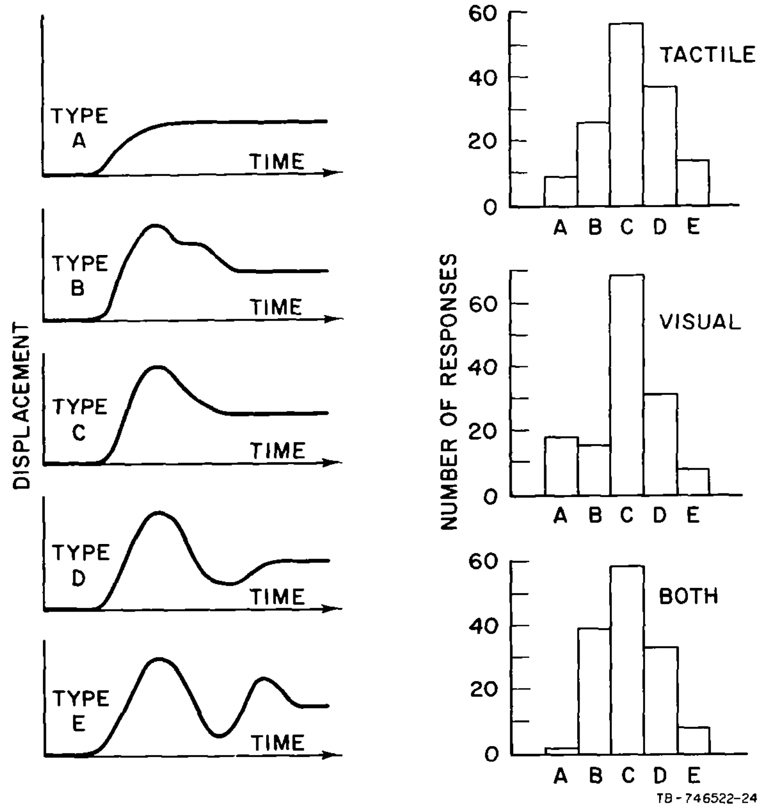


FIG. 55 HISTOGRAMS OF TYPES OF RESPONSES OBTAINED WITH NEGATIVE FEEDBACK AND THE TACTILE, VISUAL, AND BOTH DISPLAY CONDITIONS

Also consistent with the initial experiment, the flat regions in the positive feedback "staircase" responses (T_3) and around the peak of the negative feedback responses (T_3) were longer with the visual display than with the tactile display. However, the actual movement times, T_2 and T_4, were shorter with the visual display than with the tactile display. The overall duration of the response was shortest with both displays used simultaneously, and was shorter for the visual display than the tactile display.

A linearity comparison of the various displays reveals another display-dependent difference in the responses. Figure 59 shows that the responses with the tactile display were much more nonlinear than with the other displays. This result suggests a high-gain saturation element in the tactile model.

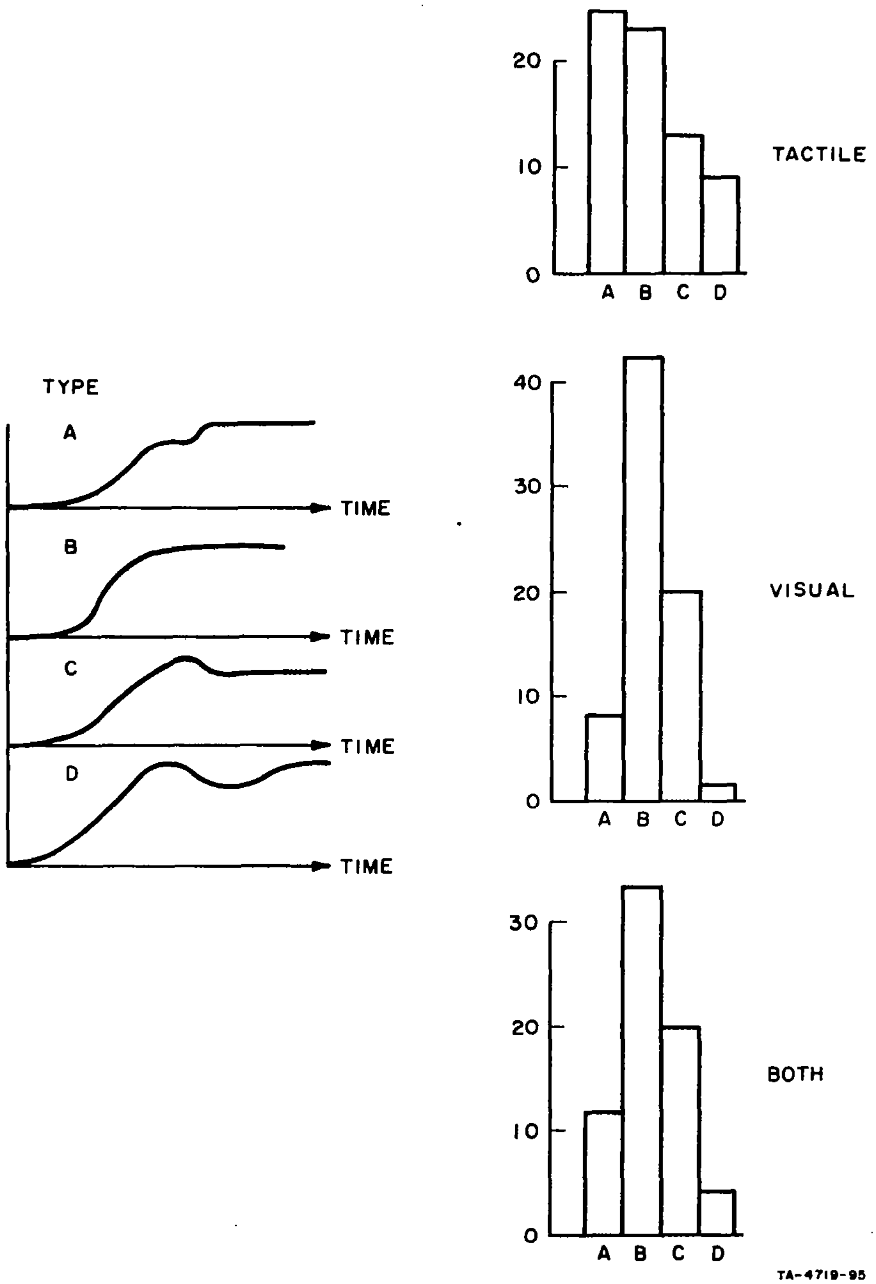


FIG. 56 HISTOGRAMS OF TYPES OF RESPONSES OBTAINED WITH ZERO FEEDBACK AND THE TACTILE, VISUAL, AND BOTH DISPLAY CONDITIONS

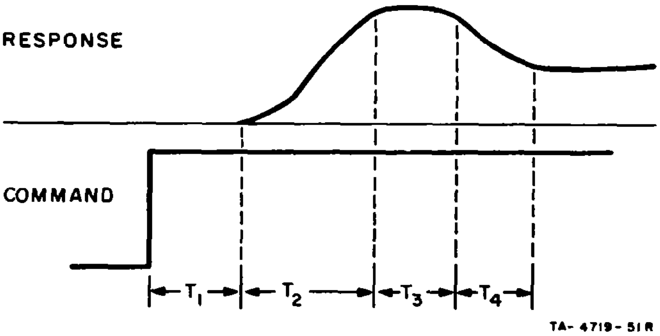


FIG. 57 MEASURED PARAMETERS OF TYPE C RESPONSES WITH NEGATIVE FEEDBACK

TABLE 20
TIME AVERAGES FOR TYPE C RESPONSE — (msec)
NEGATIVE EXTERNAL FEEDBACK

PARAMETER	TACTILE	VISUAL	BOTH
T_1	327	318	294
T_2	257	222	243
T_3	65	129	98
T_4	308	211	235

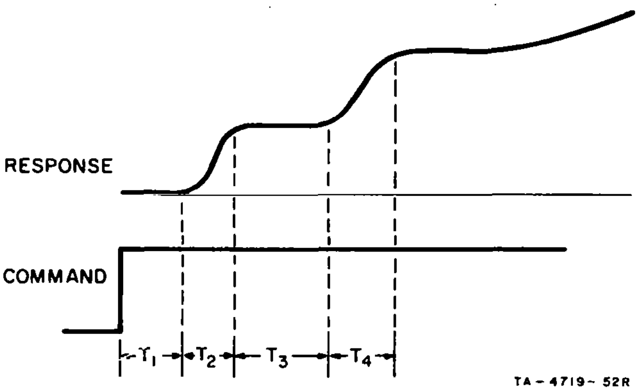
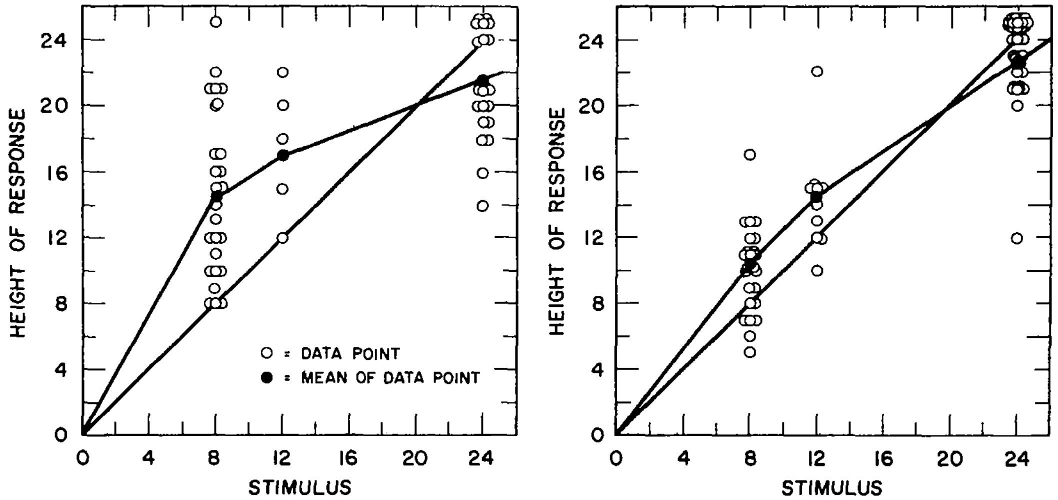


FIG. 58 MEASURED PARAMETERS OF TYPE B, C, D, BC, AND CD RESPONSES WITH POSITIVE FEEDBACK

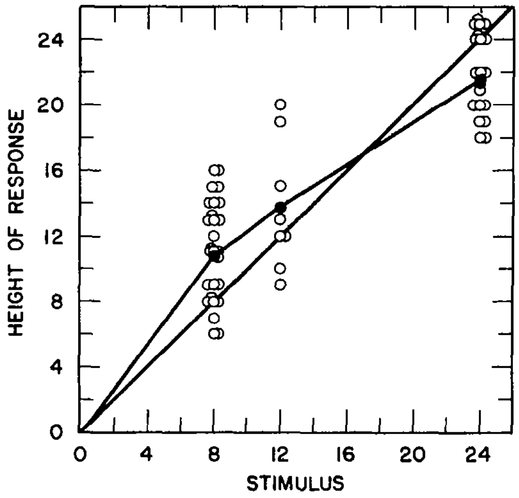
TABLE 21
TIME AVERAGES FOR TYPES B, C, D, BC, AND BD RESPONSES — (msec) POSITIVE FEEDBACK

PARAMETER	TACTILE	VISUAL	BOTH
T_1	359	332	310
T_2	249	202	209
T_3	142	152	133
T_4	297	248	250



(a) TACTILE DISPLAY

(b) VISUAL DISPLAY



(c) BOTH DISPLAYS

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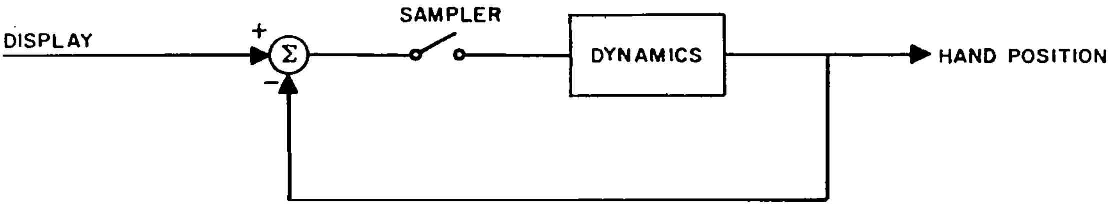
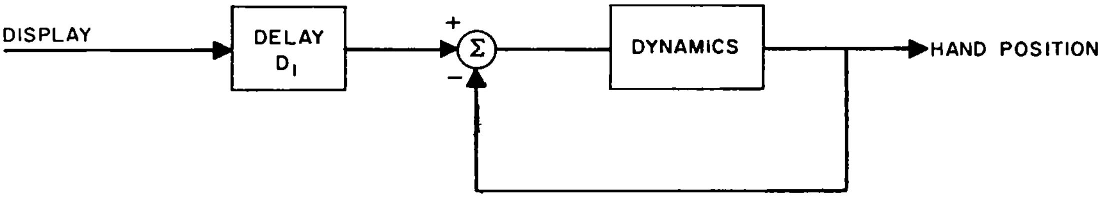
FIG. 59 HEIGHT OF RESPONSE PEAK AS A FUNCTION OF STIMULUS HEIGHT FOR NEGATIVE FEEDBACK

Figure 60 shows three models of the human operator experiments that are appropriate to the initial experiment results and the basic experiment results. The terminology "sampling model," "D_1 Model," and "D^1 Model" will be used to refer to these models.

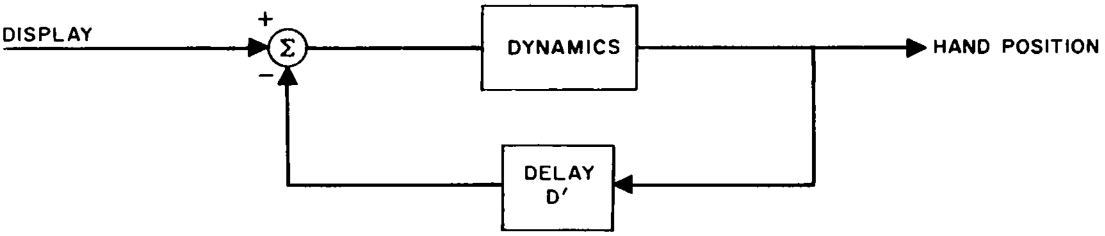
It is easy to see how each of these three models can produce the features characteristic of hand responses to step commands. These response features



(a) SAMPLING MODEL



(b) D_1 MODEL



(c) D′ MODEL

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FIG. 60 HYPOTHETICAL MODELS

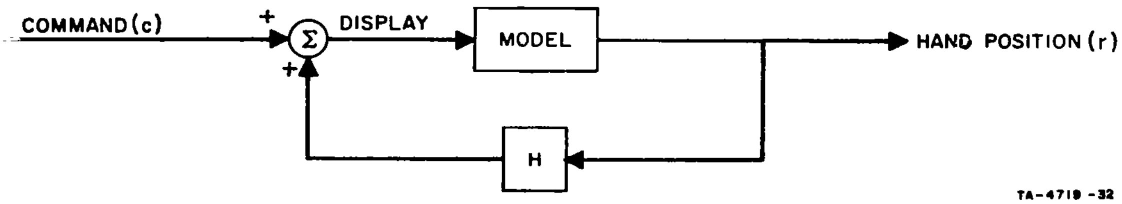

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FIG. 61 MODEL WITH EXTERNAL FEEDBACK

are produced when an external feedback loop with variable gain is introduced, as shown in Figure 61. Then, with the external feedback H equal to +1, a "staircase" response is obtained, with the steps about 0.3 to 0.5 sec apart and of equal amplitude. With H equal to -1, oscillations are sometimes obtained with a frequency of about 1 cps. The "staircase" response for positive external feedback is explained by the sampler in the sampling model, by the delay D_1 in the D_1 model, and by the delay D' in the D' model. The oscillations for negative external feedback are caused by the sampler in the sampling model; whether oscillations are obtained in the other two models depends on the remainder of the system dynamics.

Young and Stark (1965) propose a sampled-data model for eye tracking and analyze it in some detail. For that reason, only the D_1 and D' models are analyzed here. The essential difference in these two models is determined by whether display perception is delayed with respect to hand-position perception or vice versa. Also, D_1 contributes to reaction time in the D_1 model, while reaction time in the D' model is a result of the dynamics only.

Actually, a more comprehensive model might contain both D_1 and D'. In that case, whether D_1 - D' is positive or negative would be of primary interest. The D_1 and D' models can be considered first approximations to the more comprehensive model, with D_1 - D' positive and with D_1 - D' negative, respectively. Also, since delays can be produced in many ways, including sampling, quantization, and filtering, pure delays in the D_1 and D' models can be considered to be crude approximations to these possibilities.

Since stability is a function of the loop gain only, consider the simplified D' model shown in Figure 62 which can either represent a D' model or the loop dynamics of a D_1 model. Because of the pure delay, there are an infinite number of branches of the root locus. Figure 63 is a plot of two branches, the principal branch and the next lowest one. Since the plot is symmetric with respect to the σ axis, only the part for $\omega > 0$ is plotted, the part for $\omega < 0$ being a mirror image of the $\omega > 0$ plot.

The essential characteristics of this root locus are that for very small values of forward gain A, there are two poles on the real axis and an infinity of poles on higher-order branches. As A increases to values greater than the

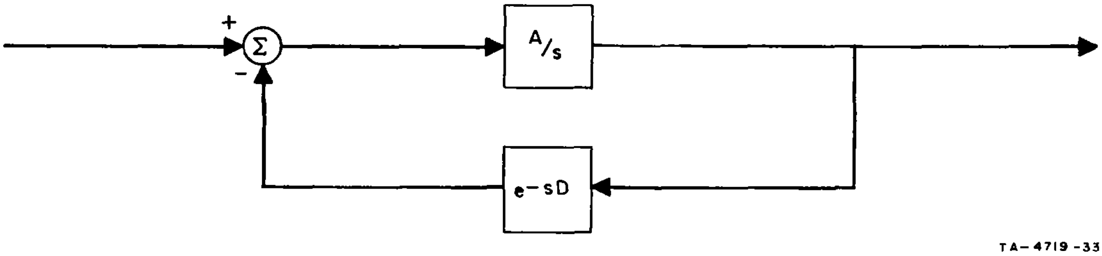


FIG. 62 SIMPLIFIED D′ MODEL

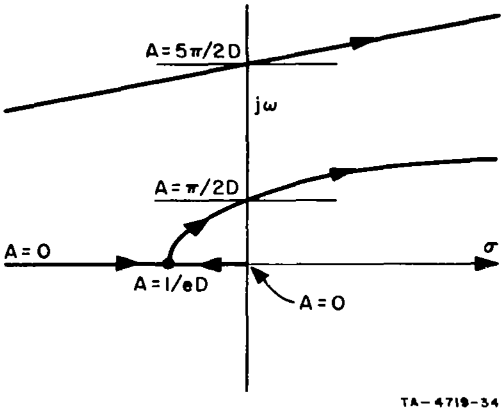
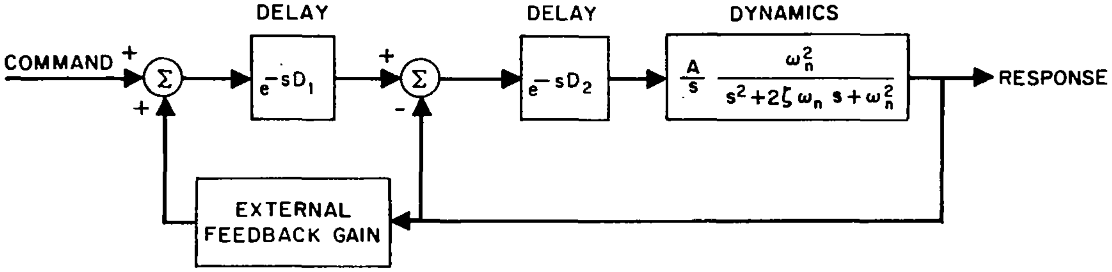


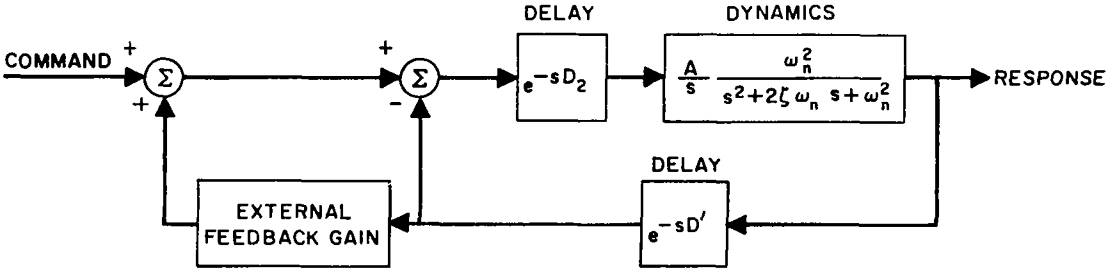
FIG. 63 ROOT LOCUS FOR MODEL OF FIGURE 62

critical value 1/eD, the two low-order conjugate complex poles break away from the real axis. At a value of A = π/2D, these two poles reach the imaginary axis, and the corresponding solutions become sustained oscillations. Higher values of A give right-half-plane solutions as well as the solutions on other branches of the root locus.

Because of stability, the values of A of interest in modeling hand responses are between A = 0 and π/2D. Thus, we should expect behavior resulting from conjugate complex poles or poles on the real axis. Moreover, with fixed delay D, increasing the loop gain A moves the poles along the root locus, as shown



(a) D_1 MODEL



(b) D′ MODEL

FIG. 64 ANALOG COMPUTER SIMULATION MODELS

in Figure 63. Alternately, for fixed A, varying the delay D scales the root locus. An increase in D decreases stability.

To examine the behavior of these systems in more detail, the models of Figure 64 were programmed on a Donner 3100 analog computer, using the model 3770 transport delay for the system delays D_1, D_2, and D'. Responses of these models have been obtained for various values of the parameters A, ω_n, ζ , D_1 , D_2, and D' as well as the external feedback gain K. The method employed in this simulation was (1) to obtain from these models responses which qualitatively resembled the actual hand responses, and (2) to alter the various parameters, one at a time, from these standard values.

Tables 22 and 23 and Figures 65 through 73 illustrate the types of results obtained. In general, similar responses can be obtained from both the D_1 and D' models with proper parametric values. At least qualitatively, both models can produce responses similar to actual hand responses. The value of ω_n needed in the models (about 20 rad/sec) is much greater than the typical values

Table 22

SIMILAR FEATURES OF D_1 AND D' MODELS

External Feedback	Comment	Figures
0	Simple "double parabolic" response. Increasing A changes the character of the response from "staircase" to underdamped and decreases the rise time. Often a second "corrective" response is made after the initial response.	65
+1	"Staircase" response. Increasing A increases the height and rise time of the "staircase" steps. Decreasing ζ increases the oscillatory nature of the responses.	66 68 69
-1	Response varies from slight overshoot to oscillations. Increasing A and decreasing ζ tends to make the responses more oscillatory.	70 71 72

Table 23

DIFFERENCES OF D_1 AND D' MODELS

External Feedback	Comment	Figures
0	For same reaction time, D_1 model has less delay in the loop than the D' model.	--
+1	Character of error signals is grossly different between the two models.	67
-1	Character of responses is grossly different between the two models for the same damping ζ.	70 71
$+ e^{-sD_{ext}}$	The duration of the "staircase" steps becomes greater in the D_1 model and less in the D' model as the external feedback delay is increased.	73

of about 1.5 rad/sec for continuous command-signal tracking models. However, the "freewheeling" ω_n for the hand-arm system is about 40 rad/sec.

For the D' model we were unable to find parametric values which produced as realistic responses as the D_1 model. Moreover, hand responses with external feedback delay resemble the D_1 more than the D' model. In summary,

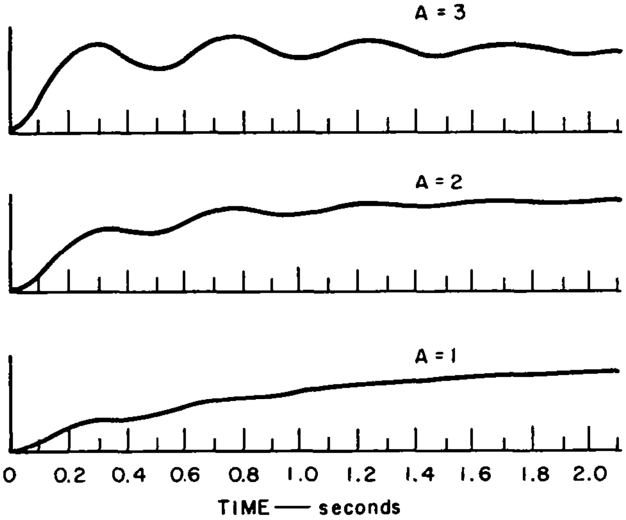


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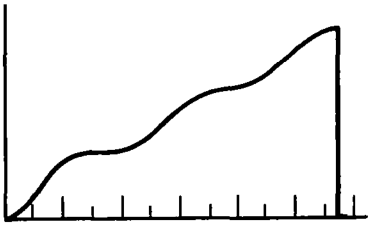
FIG. 65 D_1 MODEL RESPONSES WITH ZERO EXTERNAL FEEDBACK FOR VARIOUS VALUES OF GAIN FACTOR A
(D_1 = 0.2 *sec*; D_2 = 0.1 *sec*; ζ = 0.1; ω_n = *rad/sec*)

in spite of the simplicity of these linear models, they both match actual hand responses remarkably well, with the D_1 model appearing slightly more likely than the D' model.

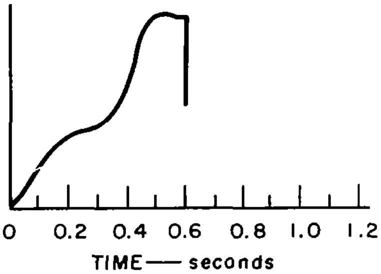
C. EXPERIMENT 2: EXTERNAL FEEDBACK DELAY

In order to help distinguish between the D_1 and D' model possibilities, an experiment was performed in which delay was introduced into the external feedback loop. For the D' model there should be a value of external feedback delay that cancels the internal feedback loop of the model and thus gives an open-loop response. If the open-loop system is as we suppose, this open-loop response should be smooth and free of the steps characteristic of the "staircase" response. On the other hand, for the D_1 model, external feedback delay should increase the duration of the steps, as shown in Figure 73.

The data from this experiment were reduced in the same manner as the positive external feedback data; the parameters measured are shown in Figure 58. Figure 74 shows that the effect of the external delay was to increase the duration of the steps (T_3) for all display conditions except the tactile display



(a) D_1 MODEL $D_1 = 0.24$ sec, $D_2 = 0.06$ sec,
$A = 3$, $\zeta = 0.2$, $\omega_n = 20$ rad/sec



(b) D' MODEL $D' = 0.5$ sec, $D_2 = 0.3$ sec,
$A = 3$, $\zeta = 0.02$, $\omega_n = 20$ rad/sec

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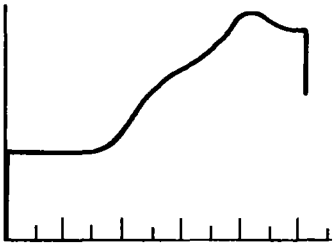
FIG. 66 SIMULATED RESPONSES FOR +1 EXTERNAL FEEDBACK GAIN

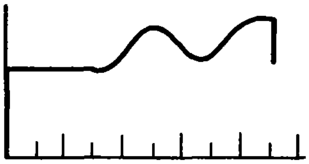
and an external feedback delay of less than 100 msec. Thus, the results support the D_1 model for the visual display and both (simultaneous) displays, but the D' model is suggested for the tactile display.

D. EXPERIMENTS: DISTINGUISHING BETWEEN MODELS

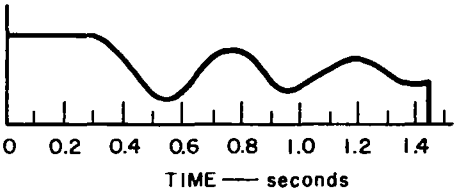
An experiment was conducted to determine if a delay between display perception and hand position perception, or vice versa, could be measured directly. It was felt that if successful, this experiment would provide an independent means of distinguishing between a delay in the feedforward path outside the feedback loop, and one in the feedback path, as suggested by the D_1 and D' models, respectively. In the experiment performed, the subject was told to move a joystick toward a tactually presented target. While the subject moved the joystick in the direction of the target, he received another tactile stimulus called a marker. His task was to decide whether this stimulus was to



(a) D$'$ MODEL WITH D$'$ = 0.4 sec, D_2 = 0.3 sec,
$A = 3$, $\zeta = 0.02$, ω = 20 rad/sec



(b) D$'$ MODEL WITH D$'$ = 0.1 sec,
$A = 3$, $\zeta = 0.02$, ω_n = 20 rad/sec



(c) D_1 MODEL WITH D_1 = 0.24 sec, D_2 = 0.06 sec,
$A = 3$, $\zeta = 0.2$, ω_n = 20 rad/sec

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FIG. 67 SIMULATED ERROR CURVES FOR +1 EXTERNAL FEEDBACK GAIN

the right or left (or forward or backward, respectively) of a predesignated point.

Analogous visual experiments have been reported by Matin (1965). He describes two experiments, one in which the marker position is compared to the target position, and one in which the marker position is compared to the fixation or control position. These two experiments give contradictory results, the latter one suggesting a D' model, the former suggesting no relative delays. [These contradictory results can be neatly explained by the model suggested by Massa (1964).]

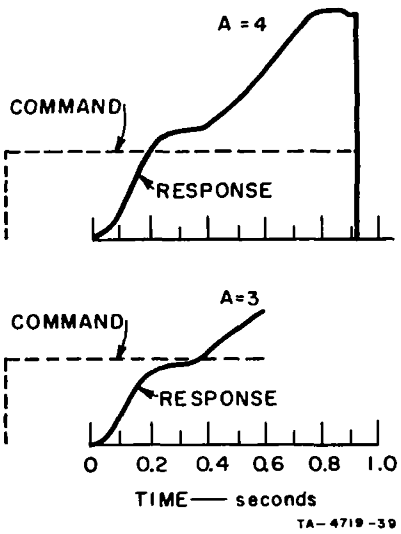

FIG. 68 EFFECT OF A ON STEP HEIGHT AND RATE-OF-RISE OF D_1 MODEL RESPONSE WITH +1 EXTERNAL FEEDBACK GAIN (D_1 = 0.1 sec; D_2 = 0.2 sec; ζ = 0.04; ω_n = 20 rad/sec)

The results of our experiment indicate a high degree of variability between individual subjects and implies that a given subject may employ one of several "strategies" in order to localize the stimulus in space and time. While no definite conclusions can be drawn from our data so far, it appears that valuable insight might be gained from further research in this area.

1. Description of Experiment

In a typical experiment, the subject is seated at a control console with his hand on the handle of a joystick, which is constrained to move along one dimension. Above the joystick is a linear array of 13 airjet stimulators (fixed with respect to the joystick/hand configuration) whose function is to stimulate the upper portion of the outstretched hand from the tip of the index finger to the wrist. In the fixed position, the subject centers the joystick by placing his knuckle directly under the center airjet stimulator. Throughout the experiment, the knuckle acts as a hand/joystick position indicator.

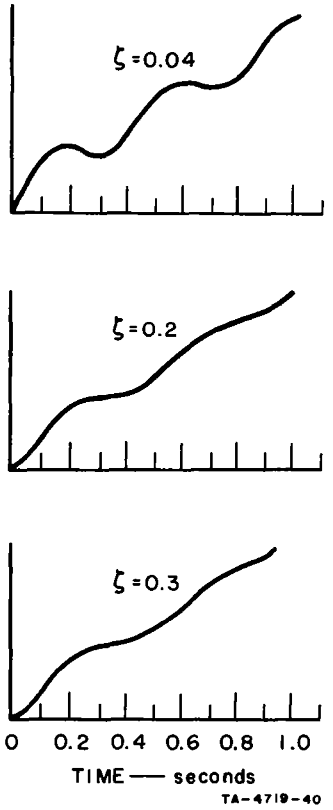

FIG. 69 EFFECT OF ζ D_1 MODEL RESPONSE WITH +1 EXTERNAL FEEDBACK GAIN (D_1 = 0.2 sec; D_2 = 0.1 sec; $A = 3$; ω_n = 20 rad/sec)

With the center (fixed) airjet turned on, the subject centers the joystick for several seconds. At a random time, the center airjet is turned off and a peripheral airjet to the right or left of center is turned on for about 100 msec. In this particular experiment, the peripheral airjet, called the target, was five airjets to either the right or left of center, and the subject was instructed to move the joystick under the target airjet as rapidly as possible.

Since subject reaction time is typically about 300 msec, the target airjet is off before the subject begins moving the joystick. When the subject has moved the joystick a predetermined distance (called the threshold), another stimulus, the "marker" airjet, is turned on for about 25 msec. The marker in this experiment was either zero, one, two, or three airjets away from center,

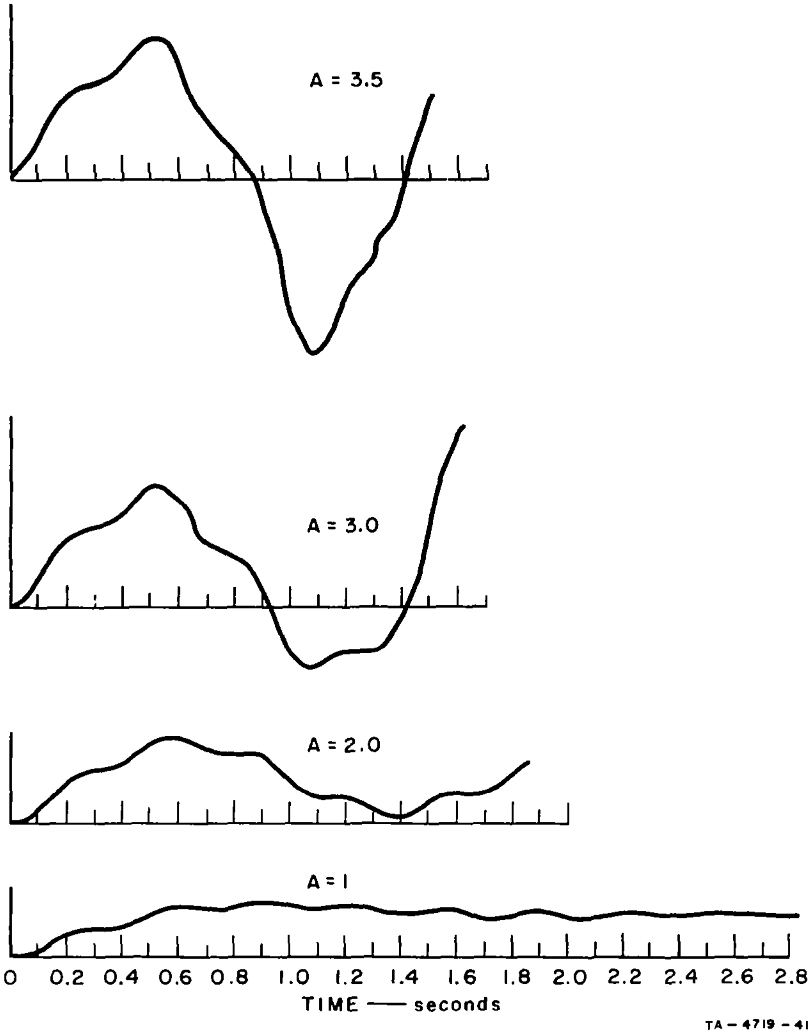

FIG. 70 EFFECT OF A ON D′ MODEL RESPONSE WITH -1 EXTERNAL FEEDBACK GAIN (D′ = 0.1 sec; D_2 = 0.3 sec; ζ = 0.04; ω_n = 20 rad/sec)

to the left or right, and the values of threshold and marker were varied in a random fashion. The subject's task was to report whether the marker was to the left or right of the center fixed airjet.

This experiment included two values of threshold, seven values of marker, and two target values, making a total of 28 different stimulus-threshold

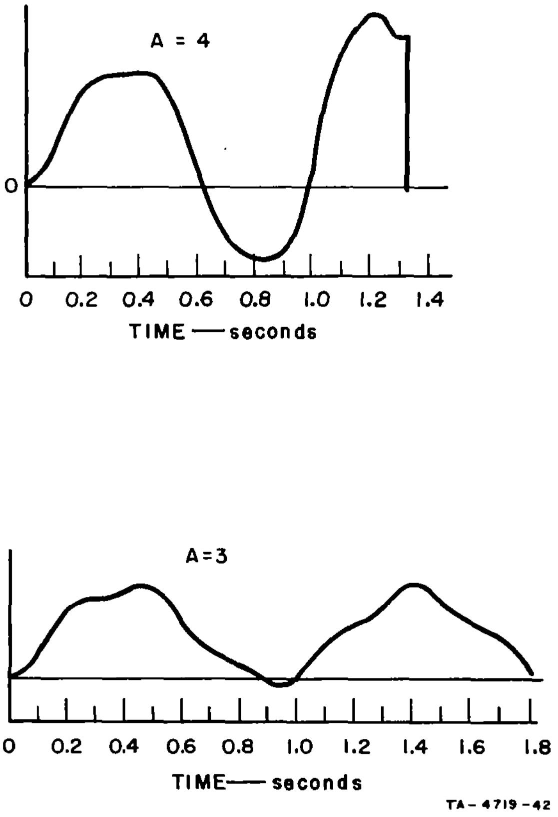

FIG. 71 EFFECT OF A ON D_1 MODEL RESPONSE WITH -1 EXTERNAL FEEDBACK GAIN (D_1 = 0.1 sec; D_2 = 0.2 sec; ζ = 0.04; ω_n = 20 rad/sec)

combinations. Each subject was given a scheduled run consisting of these 28 different conditions repeated four times for a total of 112 trials. These 112 runs constituted about one 1-hour session. Four subjects (Subjects K, F, A, and C) were used, and each subject had three sessions, one session per day. No preconditioning was used, nor was any reinforcement given during or after any of the trials.

All the subjects were familiar with the apparatus, having participated in the experiment in visual and tactual tracking of step inputs conducted previously.

Figure 75 shows a typical position vs. time plot of a subject's responses. Figure 75(a) is a plot for a threshold of 0.05, and Figure 75(b) is the corresponding plot for a threshold of 0.25.

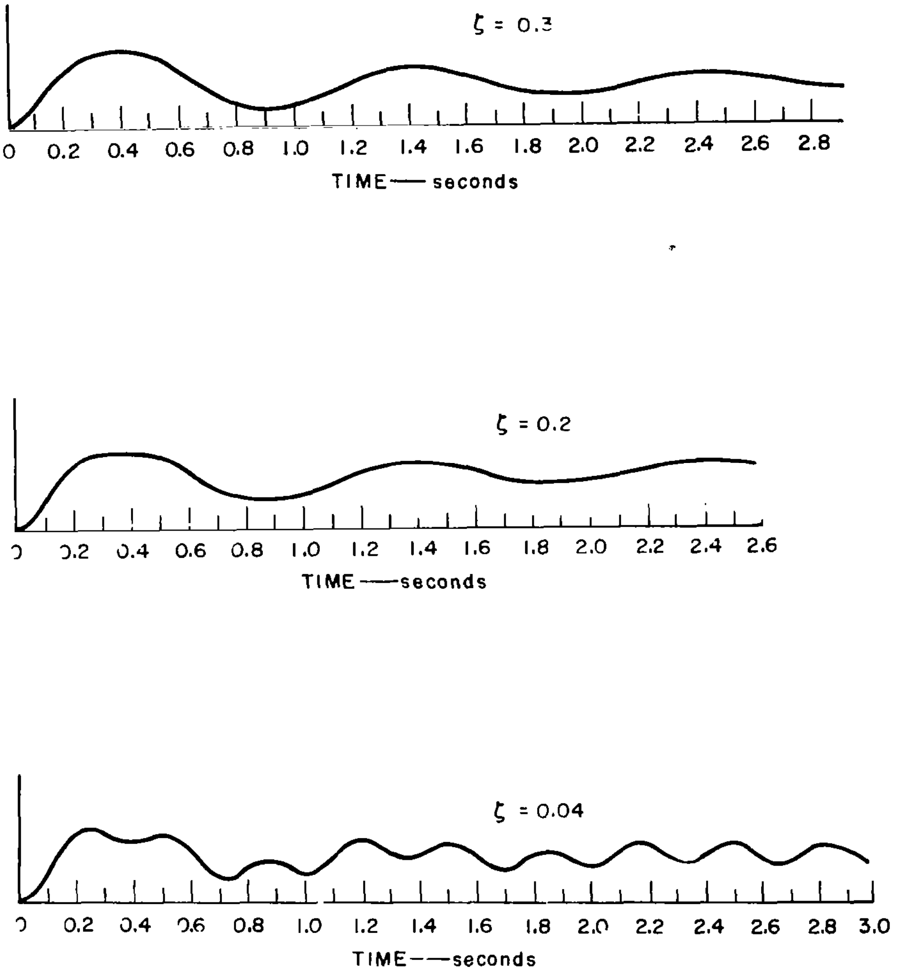

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FIG. 72 EFFECT OF ζ ON D_1 MODEL RESPONSE FOR -1 EXTERNAL FEEDBACK GAIN (D_1 = 0.2 sec; D_2 = 0.1 sec; A = 3; ω_n = 20 rad/sec)

2. Results

The data are best summarized in the histograms of the subjects' responses, shown in Figures 76(a) and (b). These histograms show the number of correct and incorrect responses for various values of marker. In these plots, the plus values correspond to marker values which were on the same side of the center as the target airjet; e.g., if the target was on the left, then a marker value of +2 would correspond to a marker two airjets to the left of

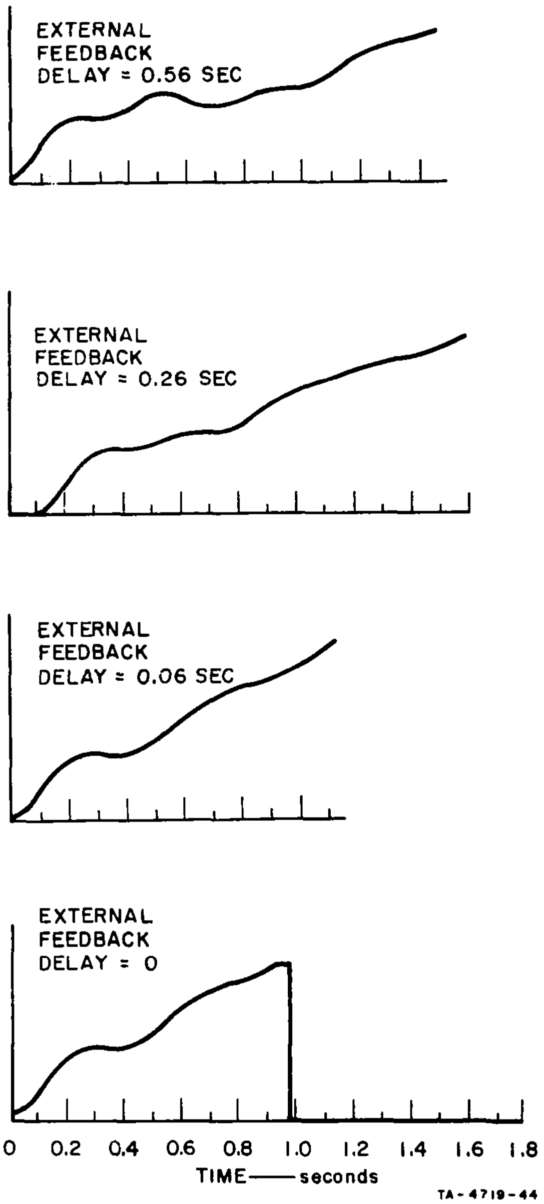
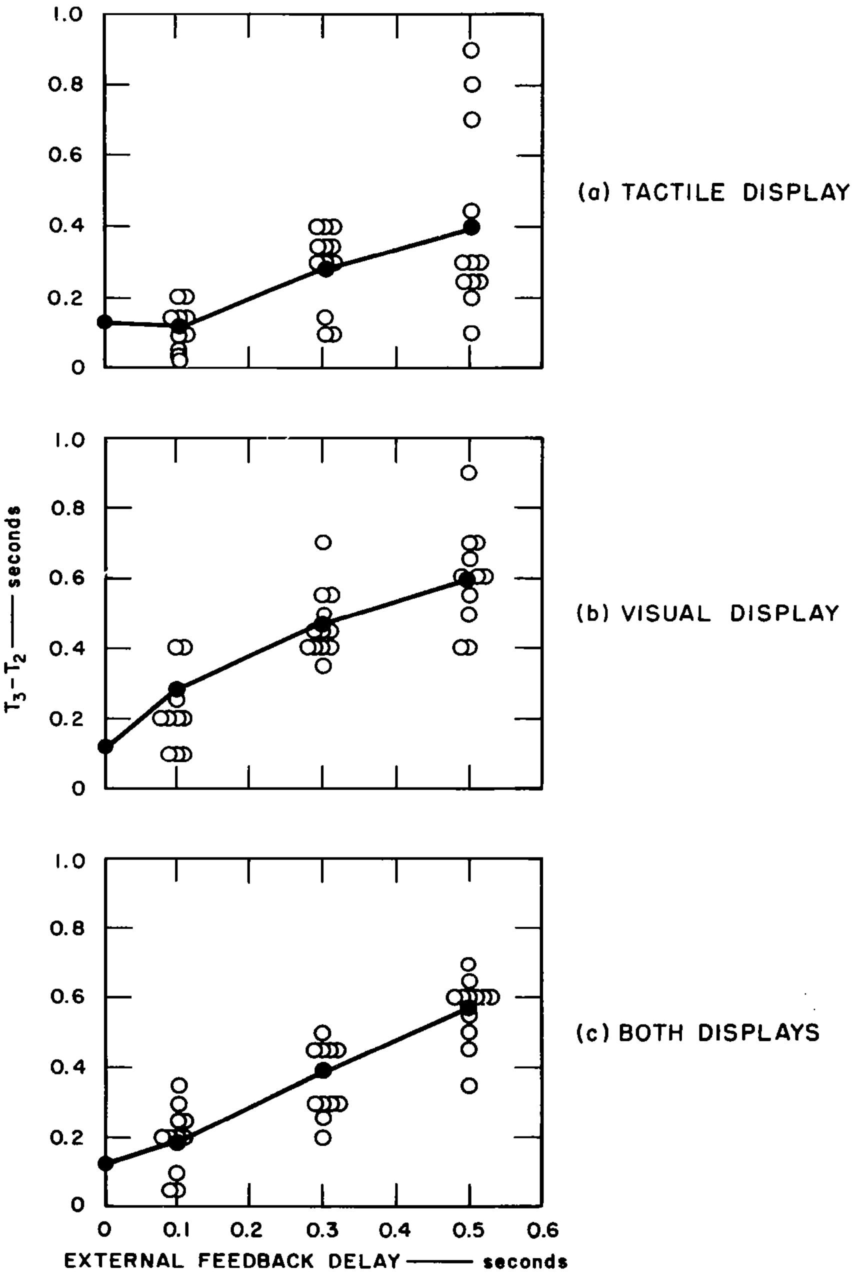


FIG. 73 EFFECT OF EXTERNAL FEEDBACK DELAY ON D_1 MODEL RESPONSE WITH +1 EXTERNAL FEEDBACK GAIN ($D_1 = 0.24$ sec; $D_2 = 0.06$ sec; $A = 3$; $\zeta = 0.2$; $\omega_n = 20$ *rad/sec*)



(a) TACTILE DISPLAY

(b) VISUAL DISPLAY

(c) BOTH DISPLAYS

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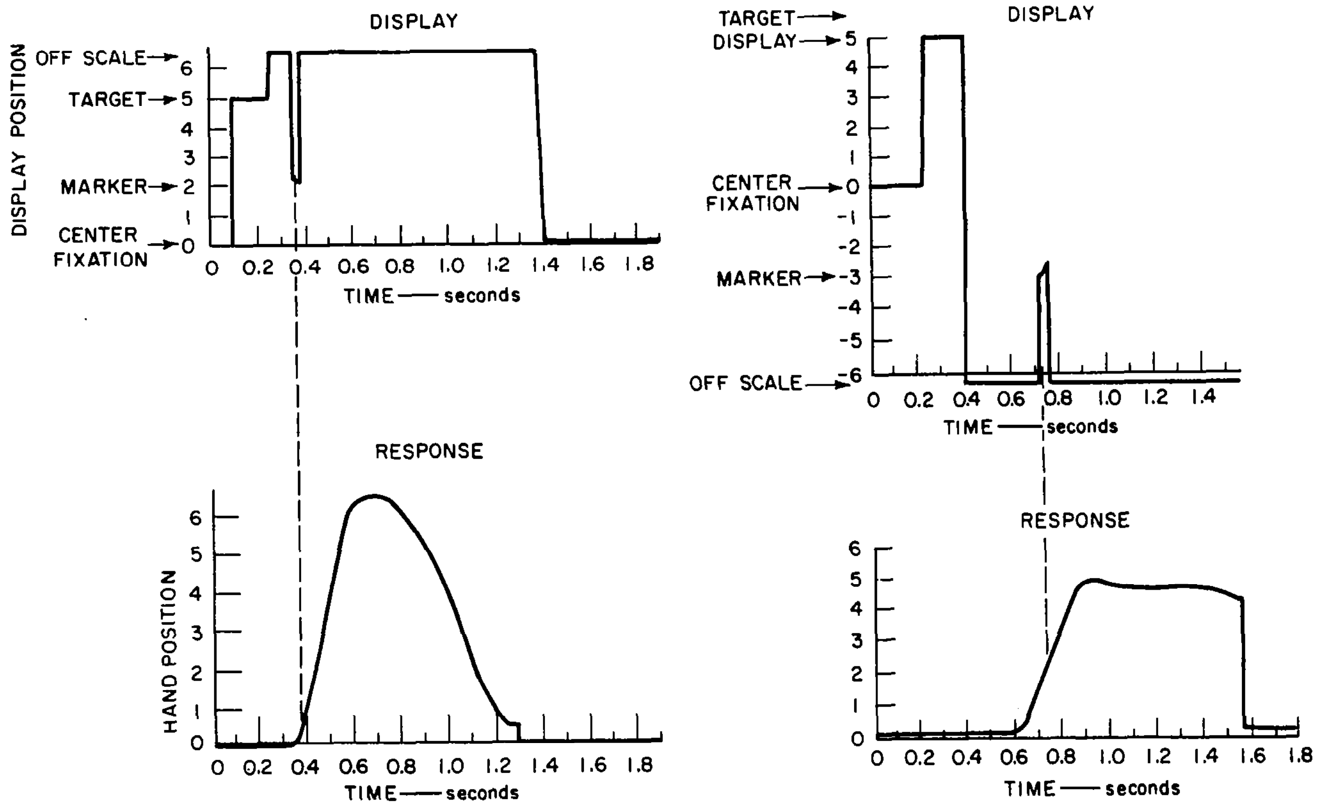
FIG. 74 EFFECT OF EXTERNAL FEEDBACK DELAY ON HAND RESPONSES



(a) 0.05 THRESHOLD

(b) 0.25 THRESHOLD

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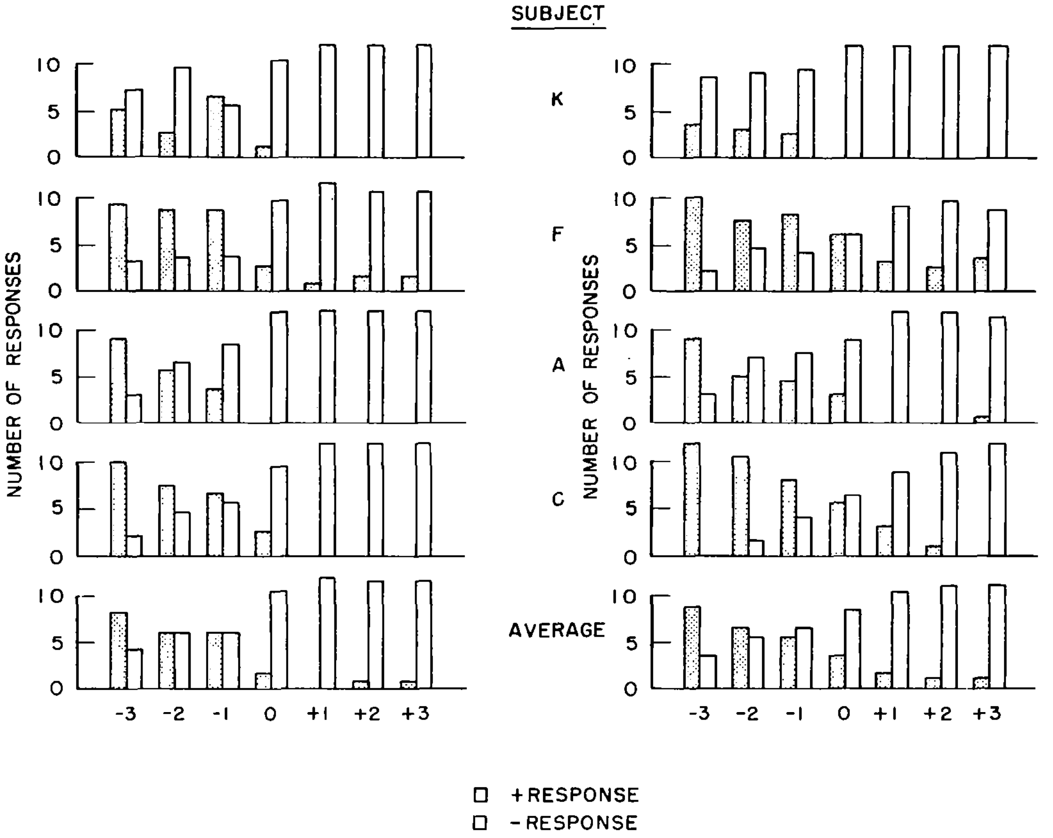
FIG. 75 RESPONSE AND DISPLAY VERSUS TIME FOR EXPERIMENT 3



(a) THRESHOLD = 0.05, TARGET = +5

(b) THRESHOLD = 0.25, TARGET = +5

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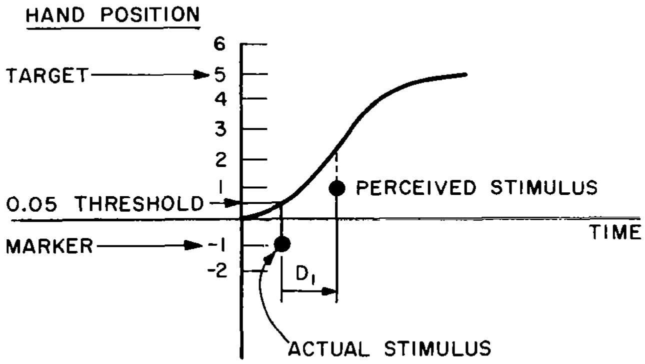
FIG. 76 HISTOGRAMS OF SUBJECTS' RESPONSES

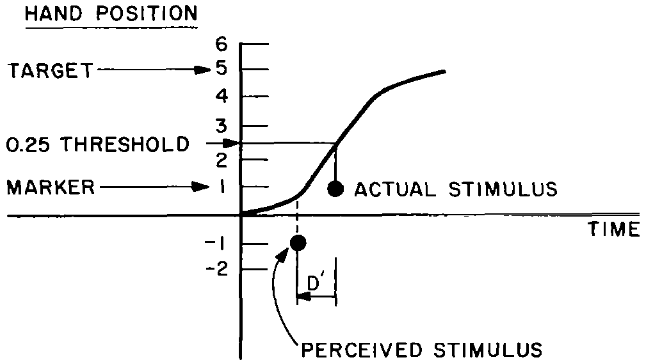
the center fixed airjet. There are two histograms for each subject, corresponding to the two values of threshold.

It is evident from the histograms that there was considerable variation from subject to subject. Subject K, for example, seemed to be heavily biased to reply that the marker was on the same side as the target; his responses are fairly independent of marker position. Although Subjects A, F, and C show dissimilar histograms, they all has a tendency to be more accurate for large negative marker values (e.g., -3) than for small negative marker values (e.g., -1). In addition, the shaded portions of the histograms of these subjects show a shift toward the right when the threshold increased from 0.05 to 0.25.

Initially, it was hoped that some insight could be gained into the process by which a tactile stimulus can be localized when there is relative motion between the stimulus and the stimulus receptor. Of particular interest was the investigation to determine whether any delays, such as a D_1 or a D', existed. In Figure 77(a) a typical response curve (position vs. time) is shown along with the marker stimulus. If the system had an effective D_1 delay, then the perception of the marker would be delayed, or shifted to the right along the time axis. Thus, if $D_1 > 10$ msec and if the marker were at -1, then the delay would shift the perception of the marker positively and the subject would



(a) D_1 INTERPRETATION



(b) D' INTERPRETATION

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FIG. 77 D_1 AND D' INTERPRETATIONS OF ERRORS respond "plus". * On the other hand, as shown in Figure 77(b), if the system had a D' delay, the subject would perceive the stimulus at the proper time, but because of a delay in proprioceptive feedback, he would perceive his hand to be where it actually was D' seconds ago. The net effect would be a negative shift of marker, so that a +1 marker would elicit a "minus" response from the subject.

Referring again to Figures 77(a) and 77(b), one can see that if either a D_1 or D' delay existed, a "crossover" would occur in correct vs. incorrect responses, provided that one of these delays was on the order of 10 msec. From the data of Figure 76 it is apparent that such a crossover occurs in the histograms of Subjects F, C, and A. On this limited basis, one might conclude that a D_1 delay exists in the human operator. However, if one investigates the behavior of the data with an increase in threshold, it appears that the crossover point is insensitive to the threshold value.

The threshold value of 0.25 occurs at a point in the response of the subject when the velocity of the hand is at least as great as, if not greater than, the corresponding value for 0.05 threshold; therefore, if the human operator were operating as a D_1 system, one should predict that the crossover point would move away from center. Because this predicted shift is not observed, we cannot accept the conclusion that our experiment completely specifies a D_1 model.

After some discussion with the subjects, it appeared that there were some problems in the experimental design that led to effects which could not be eliminated from the data and which might have obscured any D_1 or D' delay, if one existed.

3. Problems with the Experiment

There are many problems associated with the design of this experiment which may tend to obscure those properties of the human operator which the experiment was designed to measure. A few of these problems are discussed below.

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*Assuming no errors in hand position perception and perception of the anatomical location of stimulus by the subject.

The first problem is one of poor tactile resolution. The marker pulse is short and somewhat faint, and in addition, airjet spacing is small, so that errors due to poor tactile resolution will occur. Presumably these errors will tend to be random and cancel out as a great many experimental trials are conducted. Nevertheless, it would be much more convenient if a different display scheme could be used to improve the static resolution.

A second and somewhat more difficult problem to settle is the question of how the subject responds to the experiment. The subject is faced with a difficult forced-choice situation for which he is given no prior conditioning. In this situation, the subject tends to develop his own strategy, that is, condition himself to a particular scheme which seems most reliable to him. Along with this situation, one must allow for any preference which the subject might have for saying "right" rather than "left", or vice-versa. The latter conditions is fairly easy to account for and measure; the former condition is more difficult to handle.

At the conclusion of the experiment, one of the subjects (Subject C) was quite effective in delineating his strategy for making his spatial localizations of the stimuli. He stated that his hand was moving too fast to obtain any useful information about where his hand was when the marker stimulus occurred, and he therefore used short-term storage characteristics of the tactile sensation to remember the point on his hand at which the marker stimulus occurred; then he always assumed (independent of threshold) that the reference position on his hand was under the target airjet when the marker occurred. Using this information, he was able to extrapolate and tell whether he thought the marker was to the right or left of center.

According to this scheme, it is a simple matter to convince oneself that increasing the threshold will reduce the number of errors and hence effectively move the crossover point nearer the center. (As the threshold is increased, the marker occurs when the knuckle, or pointer, is closer to the target, and thus the subject's original assumption becomes more valid.)

The interesting point here is that according to this strategy, no temporal information would be used in making the decisions. Thus, this strategy prevents the experimenter from accurately determining the delays in the system.

This interpretation is consistent with our data, although it may not be the correct one. But in any event, it points out the need for more basic experiments, especially experiments in which the subject's strategy can be accounted for.

E. DISCUSSION

With respect to the relative merits of the alternative models, there are four areas from which we have obtained evidence. First, analysis and analog computer simulation indicate that the D_1 model is inherently more stable than the D' model because of the greater loop delay required by the D' model for the same reaction time as the D_1 model. Second, from our basic experiment, quantitative and qualitative data were obtained which permit parametric specification in the models. From these results, the negative feedback responses were found to be surprisingly stable, an area of difficulty with the D' model. Next, the addition of external feedback delay changed the character of the responses as predicted by the D_1 model for the visual display and the simultaneous visual and tactile display, but the result was inconclusive for the tactile display. Finally, the experiment to test directly for D_1 or D' delays supported the preference for the D_1 model over the D' model. It is therefore interesting that Matin's (1965) results for eye position tracking can be interpreted as supporting the D' model.

The choice between the D_1 model and a sampling model is less clear. At this point, both descriptions are sufficiently crude, so that there may be no basis for a choice. However, one set of data suggests that the subject's estimate of error is not made according to the actual time relation between display position and hand position; thus, the location of the sampler within the model is open to question. Perhaps a more accurate model would involve memory epochs like the visual models suggested by Massa (1964) and Sperling (1963).

Several differences appeared in the data as a result of the various display conditions. In general, the tactile responses were not as linear as the visual tracking responses (probably because of the reduced resolution). In addition, the movements were slower, and the "stop" time was shorter. Surprisingly, the characteristics of the responses obtained with the simultaneous visual and tactile display were midway between those obtained with the tactile display and those obtained with the visual display, in spite of the report by the subjects that they were attending only to the visual display. Also, reaction times with the simultaneous display were shorter on the average than those with either display alone.

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VIII HUMAN OPERATOR DESCRIBING FUNCTIONS WITH VISUAL AND TACTILE DISPLAYS

by James C. Bliss

In the attempt to develop models of manual tracking behavior that also incorporate characteristics of the physiological systems underlying the responses, techniques are needed to separate the contributions of the individual physiological systems, including sensory, central, or motor functions. Techniques that have been used in the past involve variations in the type of command signal (e.g., transient, periodic, and random); the type of output response (e.g., continuous or discrete); and the vehicle dynamics. The research described in this section emphasizes varying the sense modality employed (i.e., visual, tactile, or both) with continuous command signals and pure-gain vehicle dynamics.

Two experiments are reported. The first experiment compares the describing functions obtained with (1) a visual display, (2) a tactile display, and (3) both displays used simultaneously. The second experiment explores various tactile display conditions.

A. PROCEDURES

A system for performing tactile and visual tracking experiments and obtaining amplitude and phase measurements of the response as a function of frequency was developed. This system consists of CDC 8090 programs, A/D and D/A conversion channels, and display and response apparatus.

The CDC 8090 computer programs consist of several parts: (1) a signal generator program, (2) a signal analysis program, and (3) an INTERFOR program for calculations on the data. The first two parts cyclically generate a value for the D/A output signal and analyze a response value input through the A/D channel. At the end of an adjustable time, the experimental trial is terminated and control is transferred to an INTERFOR* program, which performs some calculations on the analysis results and outputs the amplitude and phase values on the on-line typewriter.

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

$$c(t_k) = \sum_{i}^{N} c_i \sin(\omega_i t_k + \varphi_i) ,$$

where $c(t_k)$ is the value of the generated signal during interval t_k; c_i is the amplitude; φ_i is the phase; and ω_i is the frequency of the i^{th} sinusoid. Up to eight frequencies can be accommodated by the program, and since the longest program cycle is 75 msec, frequencies up to 6.7 cps are practical with the full eight-signal sinusoids plus eight additional analysis sinusoids. [Higher frequencies are practical if fewer than 16 (total) sinusoids are used.]

The accuracy of the A/D and D/A conversion is eight bits. The arbitrary amplitude of each generated frequency component can be selected with four bits. The eight frequencies can be chosen with four bits and the phases can be chosen with four bits within each quarter cycle.

By positioning a sense switch on the computer console, either the internally generated signal can be subtracted from the response and the difference (i.e., the error) outputed (e.g., for compensatory tracking), or the internally generated signal (i.e., the command) can be outputed directly (e.g., for pursuit tracking).

In the analysis programs, an input signal is multiplied by each of a number of sine and cosine components, consisting of the frequencies generated by the signal generator program plus up to eight additional frequencies. Cumulative sums of the results of these multiplications are updated each program cycle.

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*INTERFOR is a Control Data programming system for the CDC 160-A computer that is relatively easily interfaced with machine language programs.

Thus, if the input signal is $r(t_k)$, then the sums a_j and b_j are formed as follows:

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

$$b_j = \sum_{k=0}^{T} c_j \cos(\omega_j t_k) r(t_k).$$

The input signal to this program is either the response signal directly from the A/D converter or the difference between the response and the generator signal (i. e., the error), depending on the position of a console switch.

The clock for the programs described above is either internally based on the computer memory-cycle time or controlled by an external pulse generator, depending on the position of a console switch. Shorter program-cycle times are possible with the internal clock, but greater time accuracy is possible with the external pulse generator.

The INTERFOR program takes the sums generated during the experimental trial by the analysis program and computes the amplitude r_j and phase φ_j of each of up to 16 frequency components according to the following equations:

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

$$\varphi_j = \tan^{-1} \frac{a_j}{b_j}$$

The results of these calculations are then typed out on the on-line typewriter.

Thus, pursuit or compensatory tracking experiments can be performed with real-time determination of either response or error spectra. Up to eight sinusoids can be used to generate the command signal, and an additional eight sinusoids can be used to determine the characteristics of the remnant. In addition, the total power in the response is computed so that the correlation between the response and the corresponding linear system can be determined.

A continuous tactile display system was constructed for tactile compensatory tracking. This display consisted of a servo-positioned airjet stimulator which moved horizontally across the forehead or the palmar side of the hand over a range of about 4.5 inches. The airjet was positioned according to the computer-generated signal from the D/A channel. Figure 78 shows this display system when used as a forehand display, and Figure 79 shows the display adapted for stimulation on the palmar side of the hand. A visual display that was analogous to the forehead tactile display was obtained by placing a mirror in front of the subject so that he could see the arm that carried the airjet nozzle. A stationary pointer was attached to the forehead rest to give a zero reference for the visual display. The visual counterpart to the tactile display for the palmar side of the hand was obtained by having the subject merely watch the airjet nozzle directly. Again, a pointer was provided to give a visual zero reference.

The computer system was calibrated by connecting the output command signal from the D/A converter to the A/D response channel. The analysis was then performed on a "perfect" response--these results agreed within the expected 8-bit accuracy. As a further check, the system was used to measure the Bode diagrams for a simple resistor and capacitor divider forming a 1-cps low-pass filter. In Figure 80, the computer analysis, the measured values from applying each sinusoid individually, and the calculated values are compared.

The computer system was then used to measure the Bode diagrams for the servo system, and these results are shown in Figure 81. In all of the subject-describing functions, the servo characteristics were removed either by calculation or by analyzing the feedback pot signal and considering this to be the error input to the subject.

Three male subjects in their early twenties were used. Previous to testing, each subject was given from 12 to 30 (depending on his mean squared error scores) two-minute trials, during which (in alternate trials) the display was changed from tactile to visual.

Table 24 gives the frequencies and amplitudes that composed the command signal.

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FIG. 78 TACTILE TRACKING APPARATUS FOR FOREHEAD

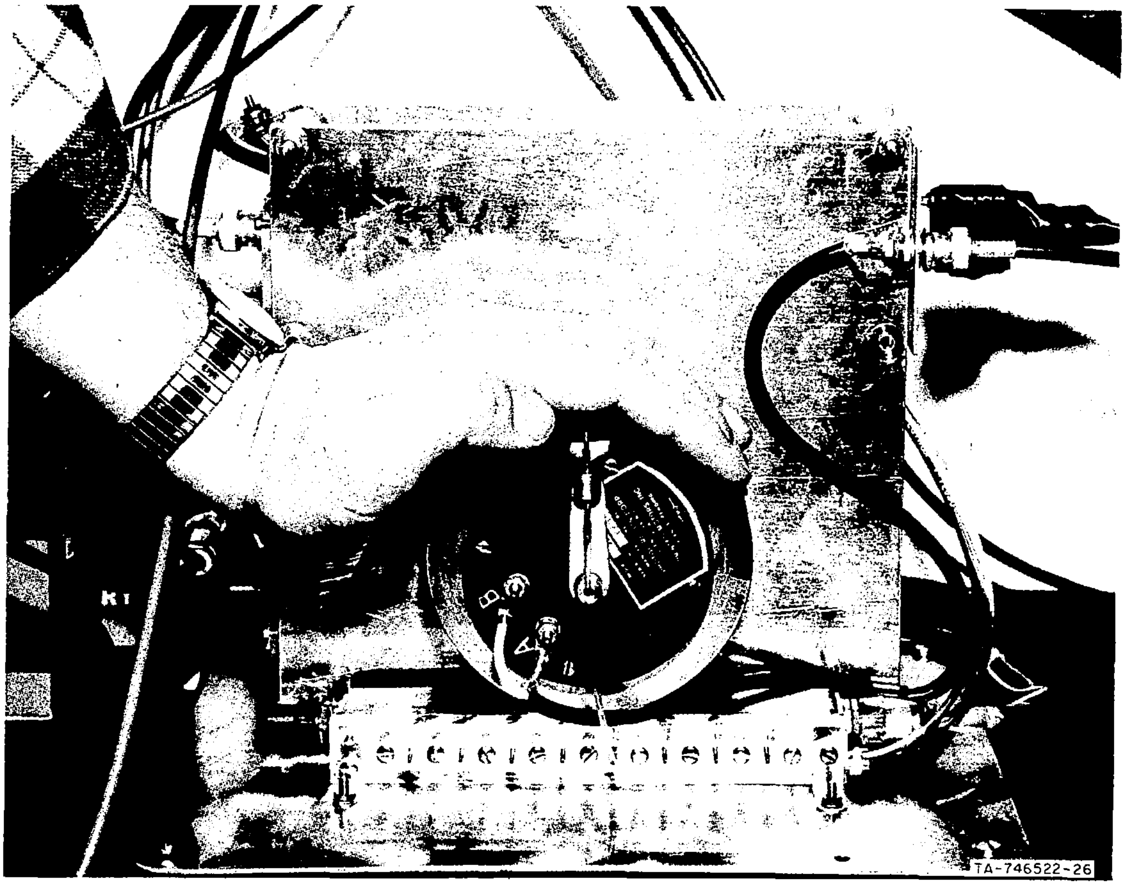

FIG. 79 CONTINUOUS TACTILE TRACKING DISPLAY FOR THE PALMAR SIDE OF THE HAND

Table 24

COMPOSITION OF COMMAND SIGNAL

Frequency		Amplitude
cps	rad/sec	
0.0261	0.164	1
0.0436	0.274	1
0.0960	0.603	1
0.2440	1.53	1
0.4270	2.68	1

Table 24 (Concluded)

Frequency		Amplitude
sec	rad/sec	
0.6730	4.23	1
1.25	7.85	0.25
2.30	14.45	0.25

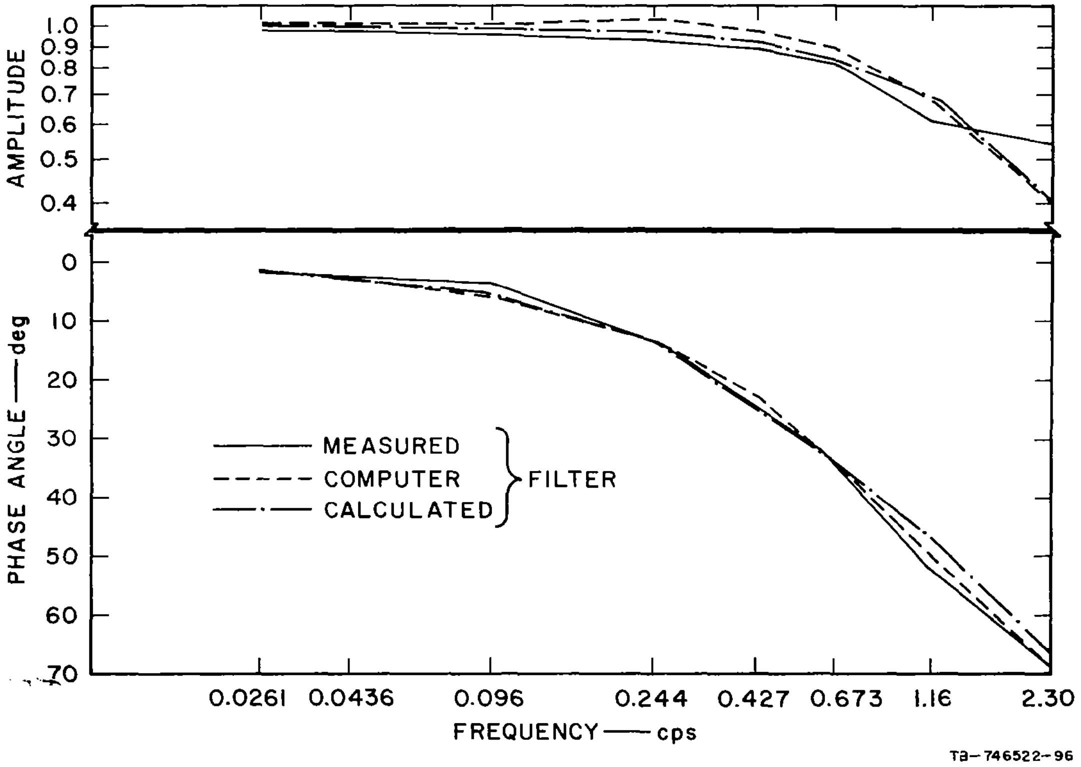

FIG. 80 COMPARISON OF AMPLITUDE AND PHASE CHARACTERISTICS VERSUS FREQUENCY OF A 1-cps FILTER DETERMINED BY DIRECT MEASUREMENT, COMPUTER TRACKING SYSTEM ANALYSIS, AND THEORETICAL CALCULATION

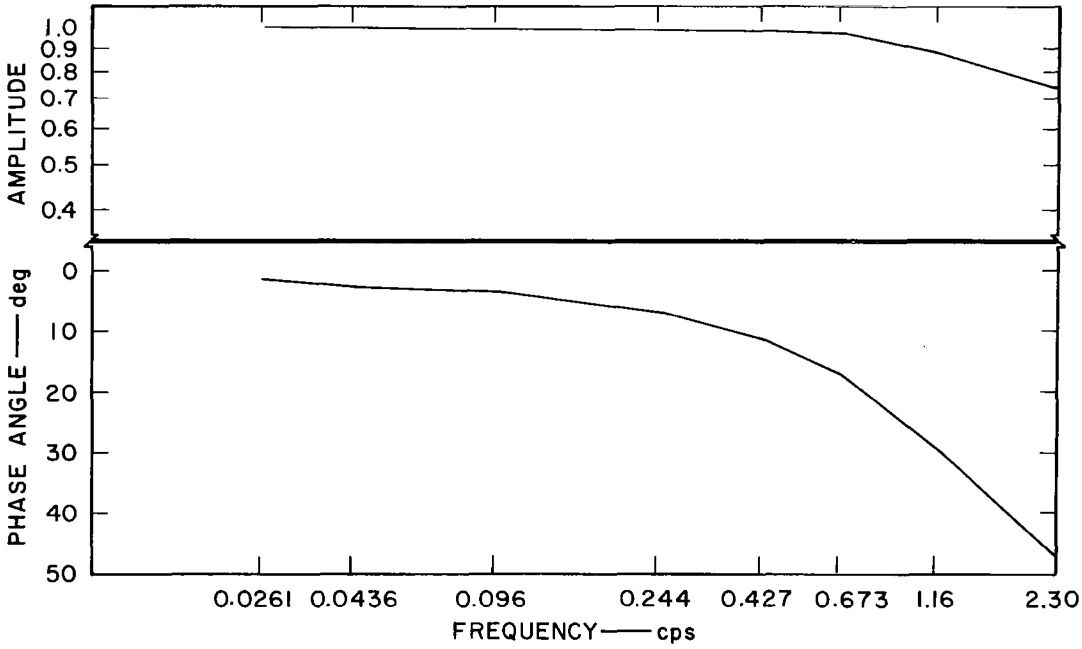

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FIG. 81 BODE PLOTS FOR DISPLAY SERVO SYSTEM AS DETERMINED BY THE COMPUTER TRACKING SYSTEM

B. EXPERIMENTS

1. Experiment 1--Tracking with Visual and Tactile Displays

In this experiment, forehead airjet tactile tracking was compared with tracking by visually observing the tactile display through a mirror. The airjet stimulator was not activated in the visual tracking runs, but six additional tactile stimulators for auditory masking were used in both the tactile and visual tracking runs.

Two sessions were run with each subject. In the first session, twelve 4-minute tracking runs were performed, alternating between the tactile and visual displays. In the second session, six 4-minute tracking runs were performed, alternating between the tactile, visual, and both display conditions.

The individual subject variability among trials was comparable to the variability across subjects, therefore only data averaged over all sessions and subjects with the standard deviation at each point are presented in Figure 82. While there appears to be no difference between the visual and both-display conditions, tracking with the tactile display resulted in much less low-frequency gain and a reduced crossover frequency.

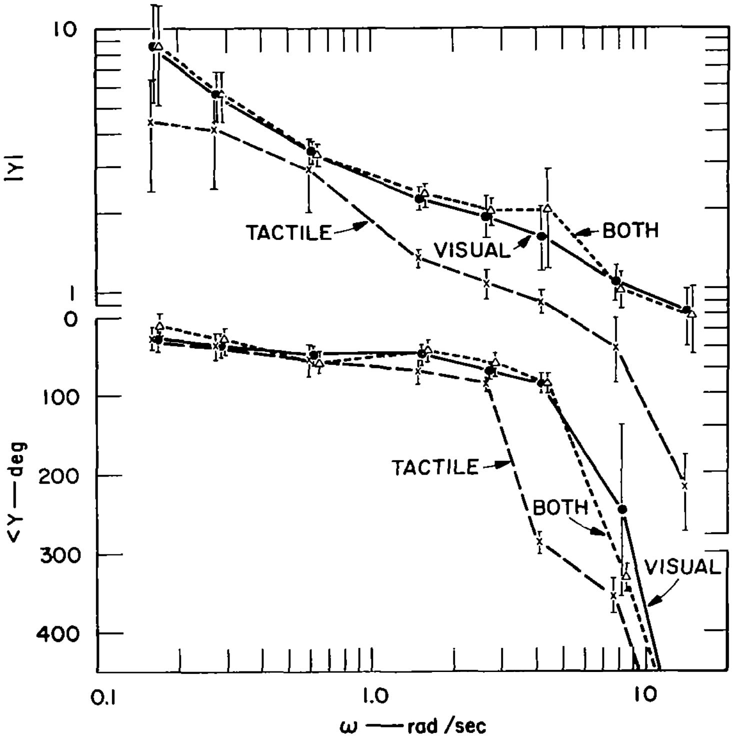

FIG. 82 DESCRIBING FUNCTIONS, AVERAGED OVER SUBJECTS AND SESSIONS, FOR THREE DISPLAY CONDITIONS

2. Experiment 2--Various Tactile Display Conditions

In view of the relatively poor performance with the tactile display in Experiment 1, several modifications were made to determine whether the tactile tracking could be improved. A single subject who gave the most consistent behavior in experiment was selected for these explorations. For these sessions the location of the tactile stimulation was changed to the palmar side of the hand. In addition, the frequency of the airjet stimulation was adjusted to 40 cps and then to 70 cps. Finally, the airjet stimulator was turned off, and the nozzle tip was adjusted so that it lightly touched the palmar side of the hand.

Figure 83 shows the describing functions obtained for each of these conditions. There appears to be little difference between the results with the forehead stimulation and the hand stimulation, and among the results with the various frequencies of airjet pulsation; however, significant improvement was obtained with the contact stimulus.

C. DISCUSSION

The results described here indicate that, at least for this amount of training, performance with a tactile airjet display produces a describing function with less gain and bandwidth than that obtained with the analogous visual display. This result is in agreement with our previous work (Seeley and Bliss, 1966).* Further analysis of these data should also indicate differences in remnant and mean-squared error with the various display conditions.

Several other investigators (Bekey, 1962) have noticed a peak in human describing functions and have suggested that this peak is a result of sampling. One purpose of the present study was to investigate this phenomenon and to determine if it also occurred with a tactile display. The result obtained was that some subjects consistently produce this peak, under each of the three display conditions, whereas others do not. While we have as yet obtained little evidence that this peak can be ascribed to sampling, some support of this type

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*References are given at the end of this section.

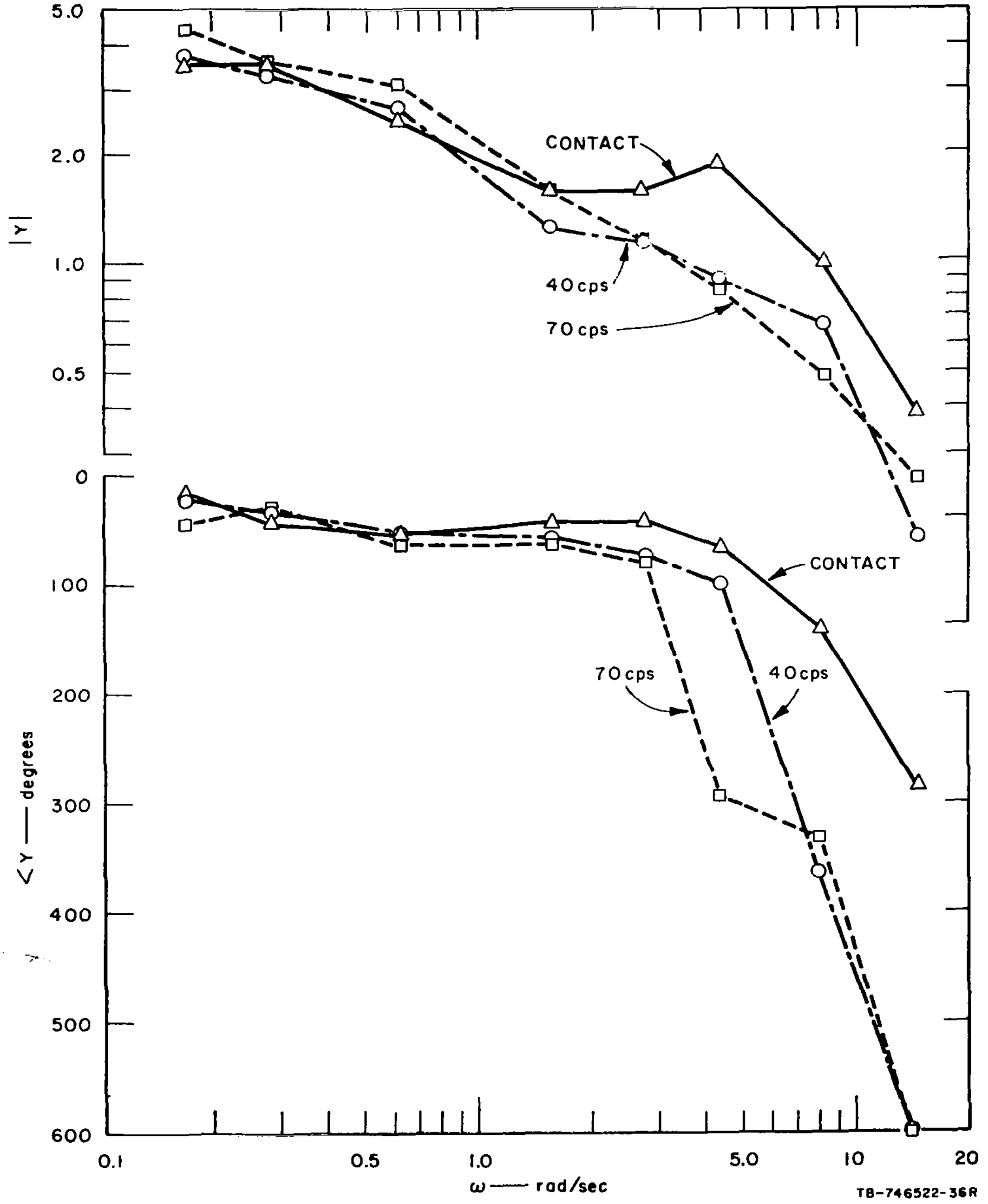

FIG. 83 DESCRIBING FUNCTIONS FOR THREE CONDITIONS OF THE TACTILE DISPLAY

of mechanism is suggested by the results of Sec VI, "Cross-Modality Reaction-Time Experiments with Tactile and Visual Stimuli."

Another area of future research is suggested by the finding that the bandwidth of the describing function can be significantly increased by a contacting tactile stimulator that produces tangential as well as normal forces.

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IX AN OVERVIEW AND SOME CONCLUSIONS

This report covers a year of intensive experimentation in tactile perception. This research represents the efforts of many people, both directly and through consultations. The facility developed for these studies over the past few years greatly enhanced our data-gathering and data-analysis capabilities.

As pointed out in the introduction, Secs. II through VIII of this report are written as independent articles, and each article has its own discussion section in which the specific conclusions that can be drawn from the results are presented. Thus, in this section we will merely attempt to point out relationships that exist among the sections and some of the practical significance of the results.

One of the most impressive aspects of working with subjects in tactile experiments is the effect of training on performance. While this impression is difficult to document and would require many more experiments to quantify precisely, certain indications can be pointed out. Section IV, "Exploratory Experiments on Tactile Spatial Interaction," deals with the effects of training more directly than the other sections. These results show that even on a relatively simple task, such as naming two anatomical locations simultaneously stimulated, subjects initially may make over 20-percent errors. An exception was Subject K, who initially made less than 7-percent errors; he had previously participated in unrelated tactile experiments for over a year. However, with a relatively small amount of training, subjects' performances typically show around 2-percent errors on this task. Another example is the same Subject K's (Subject 4) performance in the reaction-time experiments of Sec. VI. The variability of his tactile reaction time was considerably lower than the other subjects, and he tended to respond to tactile stimuli in preference to visual when faced with a conflict. In Experiment 1 of Sec. V, "Information Available in Brief Tactile Presentations," Subject S performed with an accuracy nearly twice as high as that of the other subjects. He also had considerably more experience in tactile experiments than the other subjects.

Sections II through V deal with experiments of primary practical significance to the design of tactile codes, symbols, or languages for the purpose of communication. If spatial patterns are to be transmitted tactually, the results of Sec. II, "Effect of Display Movement on Tactile Pattern Perception," suggest that a small circular translation of the pattern can enhance pattern recognition. This effect is most pronounced during training, so that one might consider using it in training even if it is proved to be impractical in a final system.

The results of Sec. III, "Tactile Perception of Sequentially Presented Spatial Patterns," specify the temporal limitations of the tactile channel in receiving geometrical patterns. Presentation of patterns closer together in time than about 300 msec results in a marked increase in errors. A period of no stimulation between patterns of at least 100 msec is beneficial.

Section V, "Information Available in Brief Tactile Presentations," describes experiments pertinent to the development of tactile codes. These results show that for codes using anatomical position as the information-bearing element, information transmitted is relatively constant for the number of points simultaneously stimulated between 2 and 12. Up to 5 stimulus positions can be available to a subject for a short period after stimulus termination, even though he may not be able to name all of these positions.

Sections VI through VIII are related to the use of tactile displays for warning and tracking related to vehicle control. A common result in both Sec. VI, "Cross Modality Reaction Time Experiments with Tactile and Visual Stimuli," and Sec. VII, "Responses to Step Commands Presented Visually and Tactually," is that when both visual and tactile stimuli are used together, more rapid responses are obtained than when either stimulus is used alone.

However, the results of Sec. VIII, "Human Operator Describing Functions with Visual and Tactile Displays," indicate that when both visual and tactile displays are used simultaneously to track continuous command signals, there is no significant improvement in performance over that obtained with the visual display alone. This result is consistent with the sensory and response switching theories discussed in Sec. VI and suggests that the primary value of a two-sensory modality display is in a reduced reaction time to abrupt changes in conditions.

The results of Sec. VIII also suggest that under proper conditions, a tactile display can permit reasonable performance in a continuous compensatory tracking situation. If direct contact of the skin is made by a continuous tactile display, thereby producing tangential as well as normal forces on the skin, a describing function bandwidth approaching that obtained with a conventional visual display is approached.

Finally, tactile displays have recently been proposed for several practical applications, from a headway display for an automobile to a communication system for aquanauts. It is hoped that the basic research described here will be helpful in the development of new uses of the tactile channel.

NASA-Langley, 1967 CR-623