Information available in brief tactile presentations[1]

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Two experiments investigated characteristics of immediate recall for brief tactile stimuli applied to the 24 interjoint regions of the fingers of both hands (thumbs excluded). The obtained immediate-memory span varied from 3.5 to 7.5 stimulus positions correct after correction for guessing, similar to the results in analogous visual studies. Properties of any hypothetical tactile short-term memory were studied by requiring subjects to report only a specified portion of the stimuli presented, and by varying the time of occurrence of the marker specifying which portion of the stimuli to report. In this partial-report condition, subjects had more stimulus information available at the time of reporting than their immediate memory spans indicated, provided that the stimulus marker occurred within 0.8 sec. after stimulus termination. The data suggest that at least for the amount of training employed here, any tactile short-term memory has much less capacity than an analogous visual short-term memory.

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 & Coriell, 1961; Estes & Taylor, 1964). These experiments have indicated that observers have at least two or three times more information available than they 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.

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 procedures of short-term tactile memory.

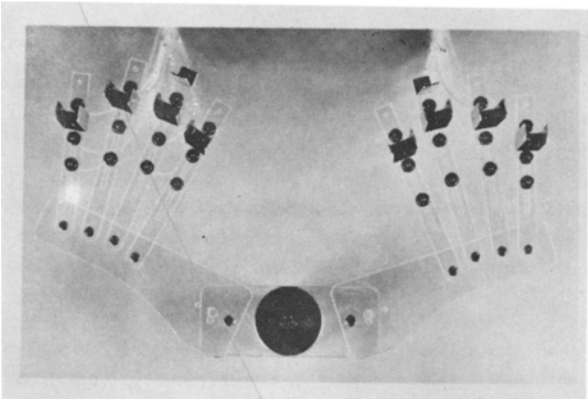
EXPERIMENT 1: Immediate Memory

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 & Bliss, 1966). However, there are 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 presentations 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.

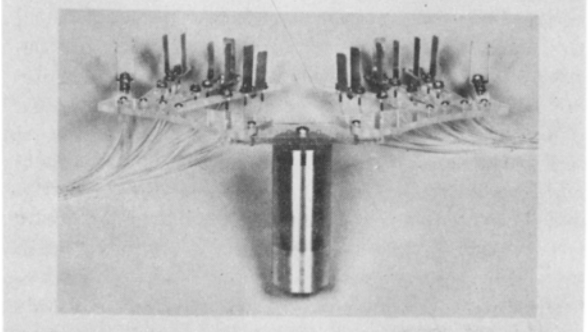
Method

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 & 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 in. above the airjet stimulators shown in Fig. 1, which permitted easy adjustment for each subject's hands. The subject's arms were supported from wrist to elbow, permitting the hands to be suspended in this manner for extended periods without fatigue.

Each jet of air was formed by a 0.031-in. outlet nozzle under control of a high-speed electromagnetic valve. The air pressure pulse, measured 1/8 in. 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 advan-



(a) TOP VIEW



(b) SUBJECTS VIEW

Fig. 1. Apparatus for holding airjet nozzles below the 24 interjoint regions of the fingers.

tages of airjet stimulation for this investigation were that relatively uniform stimulation was produced over nonuniform cutaneous surfaces and that stimulator spacing could be easily adjusted.

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.

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 Fig. 2.

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.

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 subjects' 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 or 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

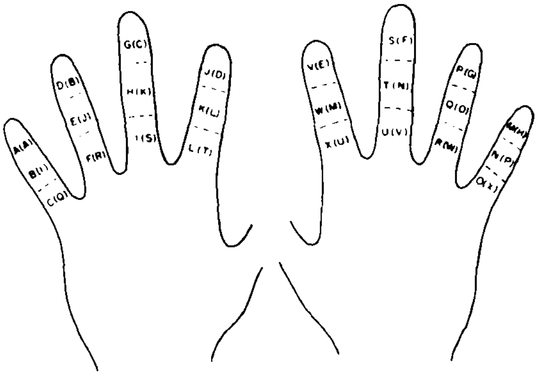


Fig. 2. Finger labeling for two hands. The letters outside the parentheses show the labeling used in Experiment 1; those inside the parentheses show the labeling used in Experiment 2.

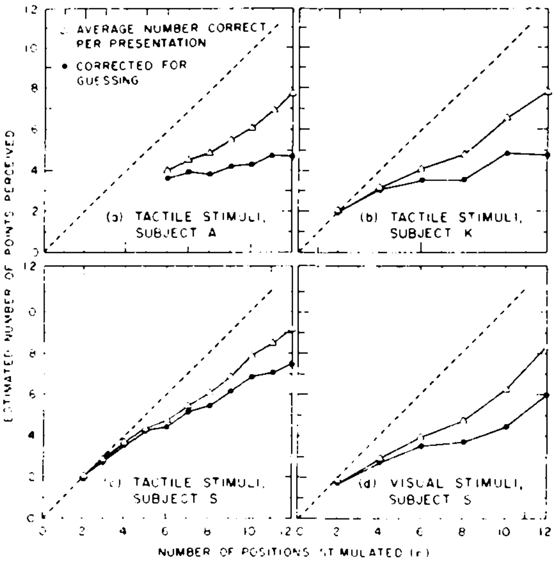


Fig. 3. Whole-report performance curves—estimated number of stimulus points perceived (corrected curves) as a function of the value of n. The diagonal line represents perfect performance. The uncorrected curves are included to show the effect of correction on the raw data.

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.

Results

Figures 3 (a), (b), (c) show 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.

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 3(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 Fig. 4.

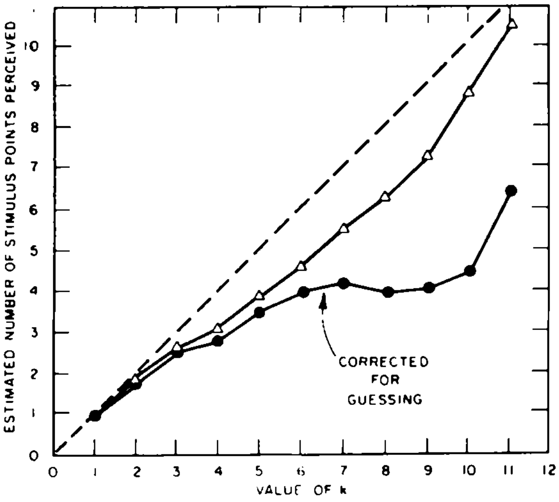


Fig. 4. Partial-report performance, subject S—estimated number of stimulus points perceived as a function of the value of k. The data are averaged across marker delays and hands.

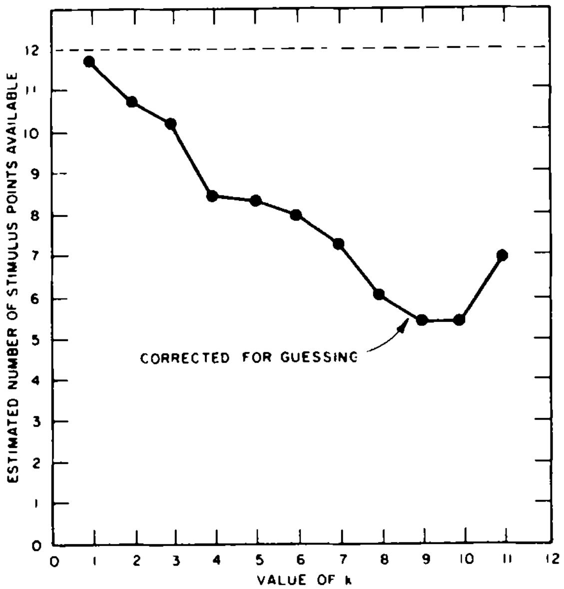


Fig. 5. Partial-report performance, subject S—estimated number of stimulus points available as a function of the value of k.

To estimate the amount of stimulus information available from the partial-report data of Fig. 4, 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 Fig. 5.

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. 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 Fig. 5, 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 corresponding 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 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.

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.

Table I

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
Testing, Whole-Report with Partial-Report Stimuli		
n=12	66	1
n=6	36	1

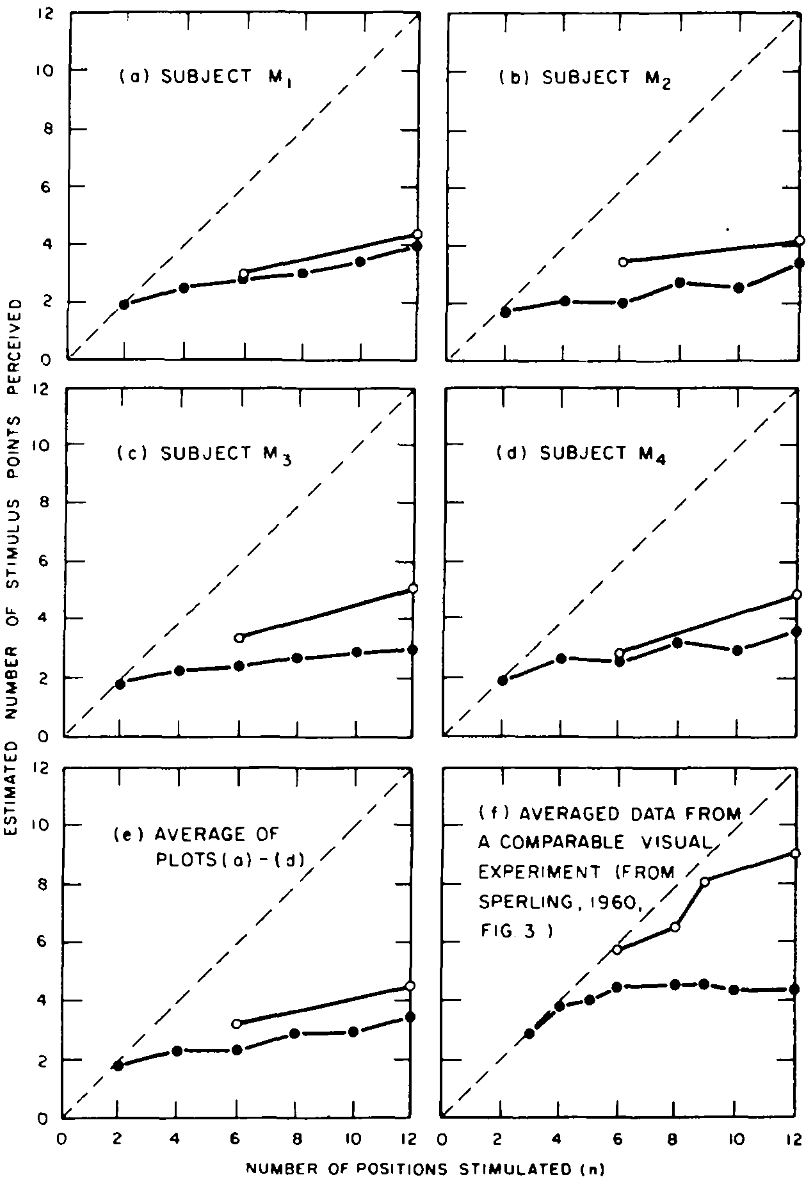


Fig. 6. Whole-report performance curves—estimated number of stimulus points available as a function of the value of n—Experiment 2. Lower curves = whole-report performance; upper curves = estimated number of points available immediately after termination of stimulus (partial report, 0-sec. delay).

Method

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.

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.

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 1. 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 $\leq$ 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:

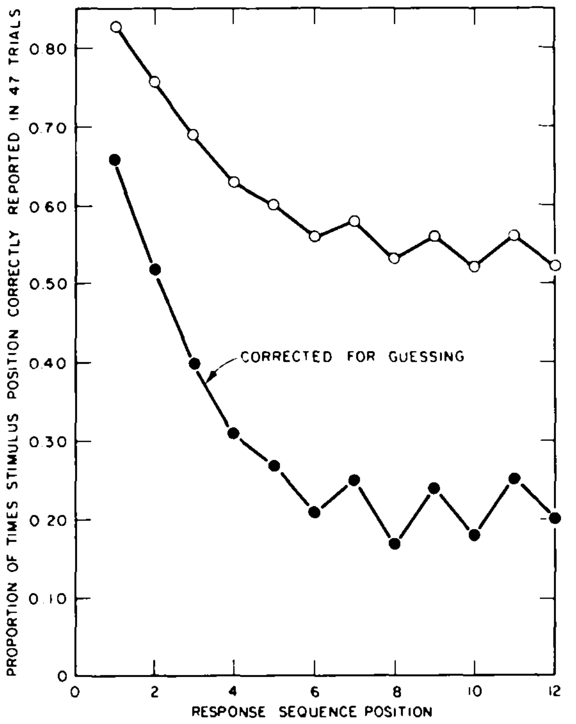


Fig. 7. Average proportion of times, out of 47 trials, that each response sequence position was correctly reported.

(1) the labeling of the interjoint positions was changed, and is shown in Fig. 2; (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 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).

Results

Figure 6 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 7 illustrates the response behavior and the effect of the guessing correction. While the data of Fig. 7 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 throughout the experiment. The guessing correction uses 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 Fig. 8.

Also shown in Fig. 6 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 of the number of

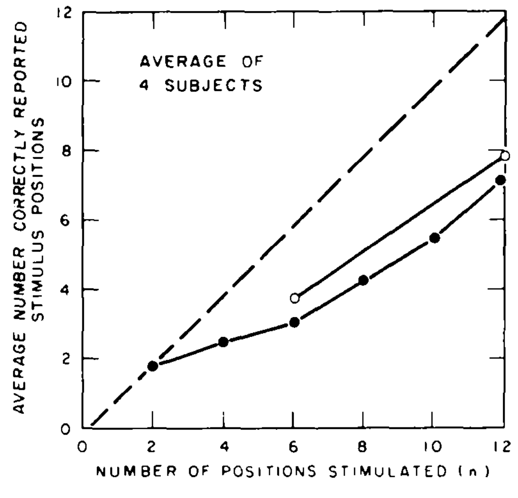


Fig. 8. Same data as Fig. 6(e) except uncorrected for guessing.

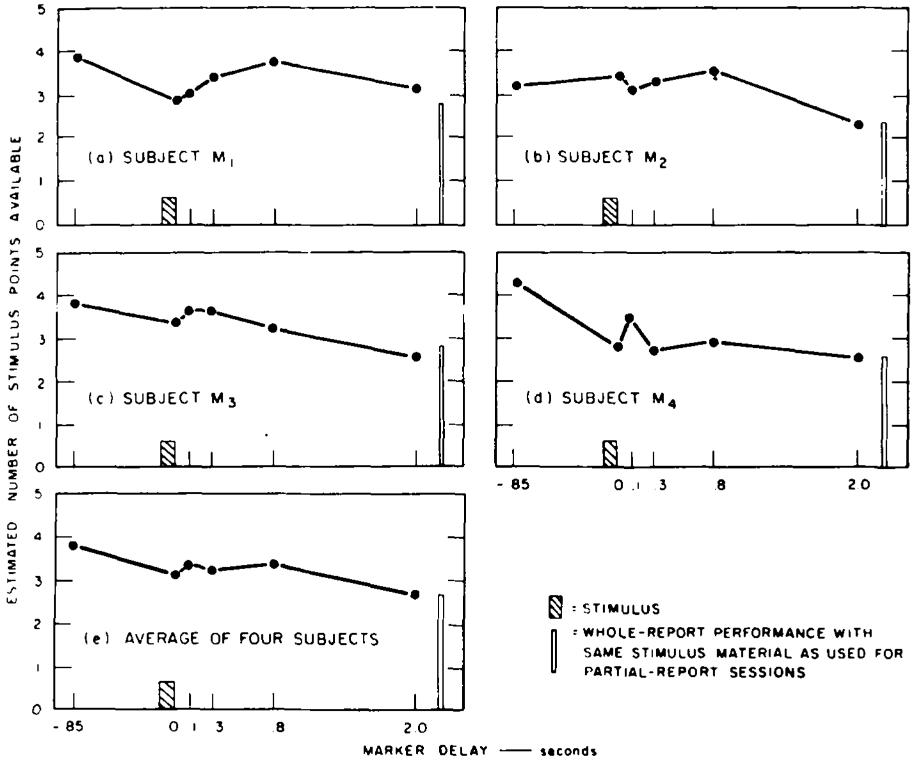


Fig. 9. Partial-report performance (k = 2, n = 6)—estimated number of stimulus points available as a function of time of occurrence of marker (with respect to stimulus termination).

stimulus points available also occurred for n = 12 and was between 4 and 5 for each subject.

Figures 9 and 10 show the partial-report performance, after correction for guessing, as a function of marker delay for all four subjects. The curves of Fig. 9 are for n = 6 and k = 2, and the curves of Fig. 10 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 Figs. 9 and 10 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.

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 3 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.

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 early experiments with doublets, for example, with subjects who scored perfectly on singlets, the authors 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).

The accuracy in reporting for subjects in Experiment 2 was considerably lower than for subjects in Experiment 1 ($p < 0.05$), even though the experiments differed only in procedural factors which were not expected to hamper performance. Figure 6(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 Fig. 6(f), this paper). 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 2, increased performance was found for all subjects, although this

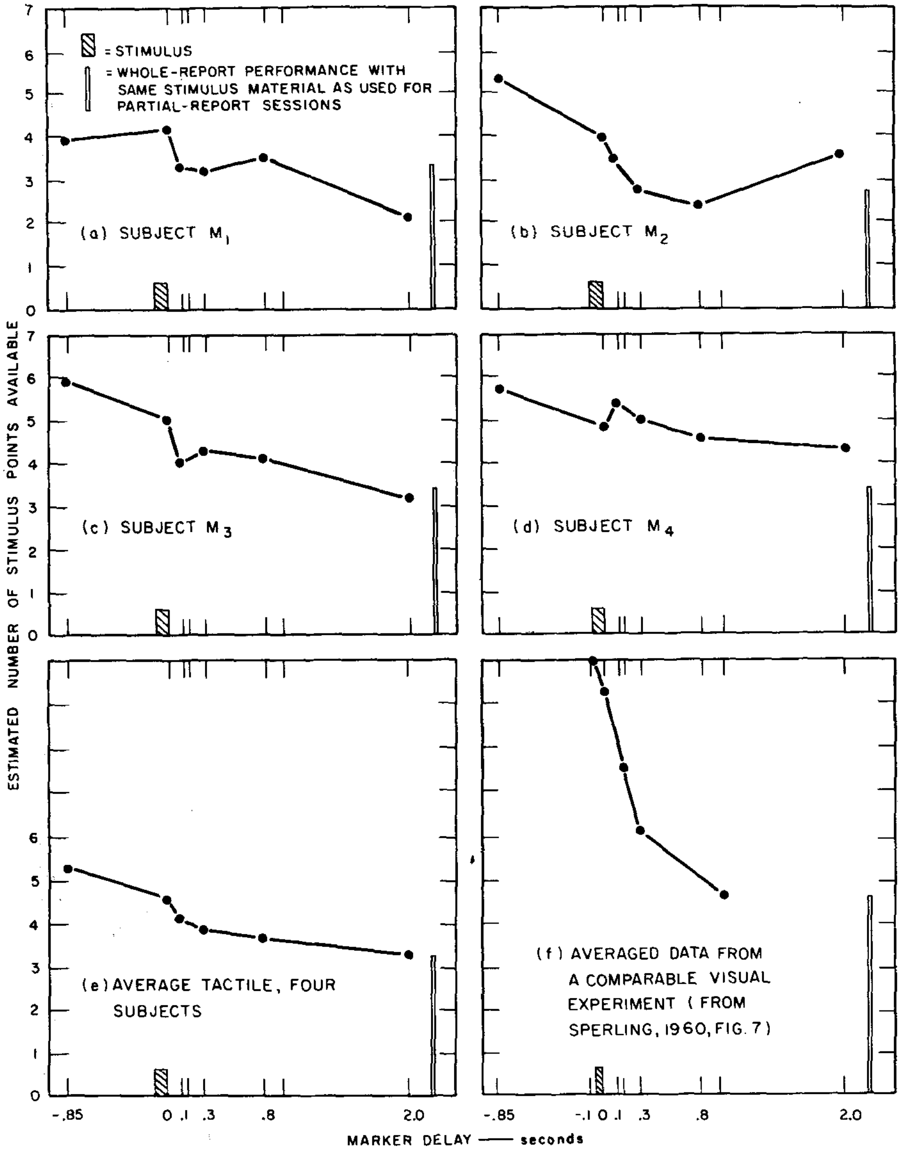


Fig. 10. Partial-report performance (k = 4, n = 12)—estimated number of stimulus points available as a function of time of occurrence of marker (with respect to stimulus termination).

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 (Fig. 6(e)) shows slight rises in performance when the value of n was 4 or 8, compared to performance levels for other values of n. The testing schedule (Table 1) 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' performance 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 Fig. 7. The accuracy of the responses decreases rapidly as each stimulus position is named. If the first four responses in the whole-report session of Fig. 7 are 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 Fig. 7 so obtained is 5.67, which compares with 5.3 from Fig. 10(e), with the marker occurring 0.85 sec. before the stimulus termination.

A similar comparison can be made between the k = 2, n = 6 partial-report results and the data of Fig. 7 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 Fig. 9(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 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 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, 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 9 and 10 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 (Fig. 10(e)) decreases more smoothly with increased marker delay than the corresponding curve for k = 2 and n = 6 (Fig. 9(e)). The reduced variability in the first (Fig. 10(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 (Fig. 9 (e)) is based on the average performance of each of four subjects in only 36 trials.[2]

Table 2. Comparison of performance with two- and four-second intertrial pause duration

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

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 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 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 Figs. 3 and 6 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

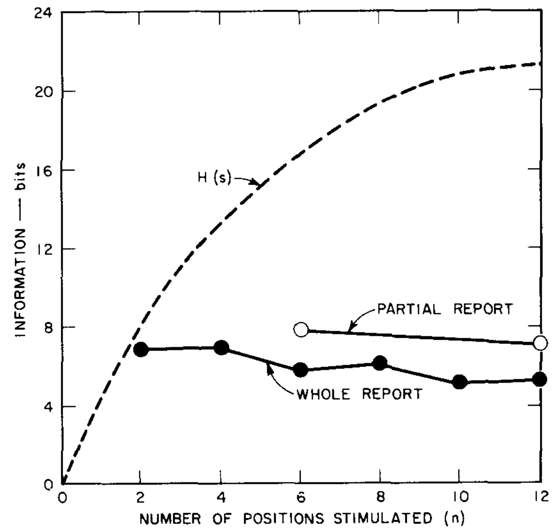


Fig. 11. Lower bound on transmitted information as a function of n. The partial-report curve is for zero marker delay; the dotted curve is the information in the stimulus.

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

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

where H(S) is the stimulus entropy, I (S;R) 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 Fig. 6(e) results in the curves shown in Fig. 11. The curves of Fig. 11 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, 1966a and 1966b), 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.

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

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

where

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

p (correct on response i) = uncorrected observed value of 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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Notes

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