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TACTILE PERCEPTION STUDIES RELATED TO TELEOPERATOR SYSTEMS

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16. Abstract

This report presents results of several experiments dealing with tactile information processes, the use of tactile feedback in the performance of remote manipulations (teleoperator) tasks, and the development of a new software system designed for on-line experiment control by a small computer. Results of experiments designed to measure the short-term memory characteristics of visual and tactile perception suggest that short-term membery resides in an area common to both visual and tactile modalities. Results of remote manipulations studies with bilateral manipulators indicate that tactile feedback provides improved performance particularly for remote control situations where visual feedback is either poor or absent. Recommendations for improving system performance are provided.

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ABSTRACT

This report describes three experiments that measure the perception of visual and tactile dot patterns presented with a 3 by 8 matrix of visual or tactile stimulators. These experiments measure characteristics of visual or tactile short-term memory by use of a sampling procedure in which the subject makes a partial report that is cued by an auditory marker. The results suggest that the short-term memory being measured resides in an area common to both visual and tactile modalities.

The authors present a tactile feedback system that is built into a Model 8A Rancho Arm. This system consists of an array of 48 contact points mounted on 0.1-inch centers in a uniformly spaced 4 by 12 matrix on the slave tongs. A corresponding 4 by 12 array of vibrators was mounted to stimulate the operator's finger. Five experiments are described that evaluate the system. Recommendations for improving the system are also given.

The report also describes a new software system that is designed for on-line experiment control by a small computer. Certain concepts such as subfiles, pages, and block structure were implemented in the system to overcome many of the apparent limitations of the small memory of the LINC-8 computer which is used for on-line experiment control.

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I INTRODUCTION

This is the final report on a project consisting of the following tasks:

(1) To improve and extend development of an information-processing model of tactile perception by performing experiments on spatial and temporal localization of tactile stimuli.

(2) To perform experiments with various forms of tactile feedback from a remote manipulator in an attempt to answer important design questions for a tactile feedback system and to estimate the increase in performance that could be expected with such a system.

(3) To experiment with new techniques for tactile stimulation and touch sensing for teleoperators.

(4) To develop computer programs and electronic equipment to extend the capabilities of our facility for on-line computer control of experiments.

The work on Task 1 is described in Section II of this report. Tasks 2 and 3 are described in Section III. Section IV describes the work on Task 4. Conclusions and recommendations from each of these tasks are given at the end of each section.

II PSYCHOPHYSICS EXPERIMENTS

A. Experiment P1: Preliminary Test of Visual Short-Term Memory for Dot Patterns Using an Auditory Marker

1. Background

In a previous experiment (Bliss, Hill, and Wilber, 1968) we attempted to measure visual short-term memory characteristics by using the same dot patterns that we had successfully used to measure tactile short-term memory characteristics (Bliss, Crane, Mansfield, and Townsend, 1966, Hill and Bliss, 1968). The results of the visual experiments, using both visual patterns and a visual marker, failed to show any short-term memory capacity. After further consideration of those results, and results obtained by Keele and Chase (1967), we decided that presentation of both the pattern and the marker to the same sense modality may have caused interference with the perceptual process. This is discussed in Bliss, Hill, and Wilber (1968, p. 100).

In order to make the tactile and visual experimental situations more comparable the following preliminary experiment was carried out. Instead of the visual marker, an auditory marker consisting of three different tones was used to distinguish between the three different rows of the stimulus patterns. This experiment, as the previous tactile experiments, used separate sense modalities to convey the stimulus and the marker information. The experiment was designed to test whether a larger number of positions is available than can be correctly reported in a whole report. The results show that significantly more positions are available than can be reported in the whole report, indicating a visual short-term memory for dot patterns.

2. Method

a. Apparatus

The visual dot-pattern stimuli were produced with the light box shown in Figure 1. The 24 neon lamps are arranged in the same 3 x 8 spatial arrangement as our previous experiments. The light box was placed 114 inches from the subject and subtended a visual angle of two degrees at the subject's eye. The average brightness of the white cardboard mask was 46 fL, and that of the lamps 40 fL. In the training portion of the experiment, four randomly chosen lamps were simultaneously lighted for 100 ms, and in the later portion, 12 lamps were simultaneously lighted for the same length of time.

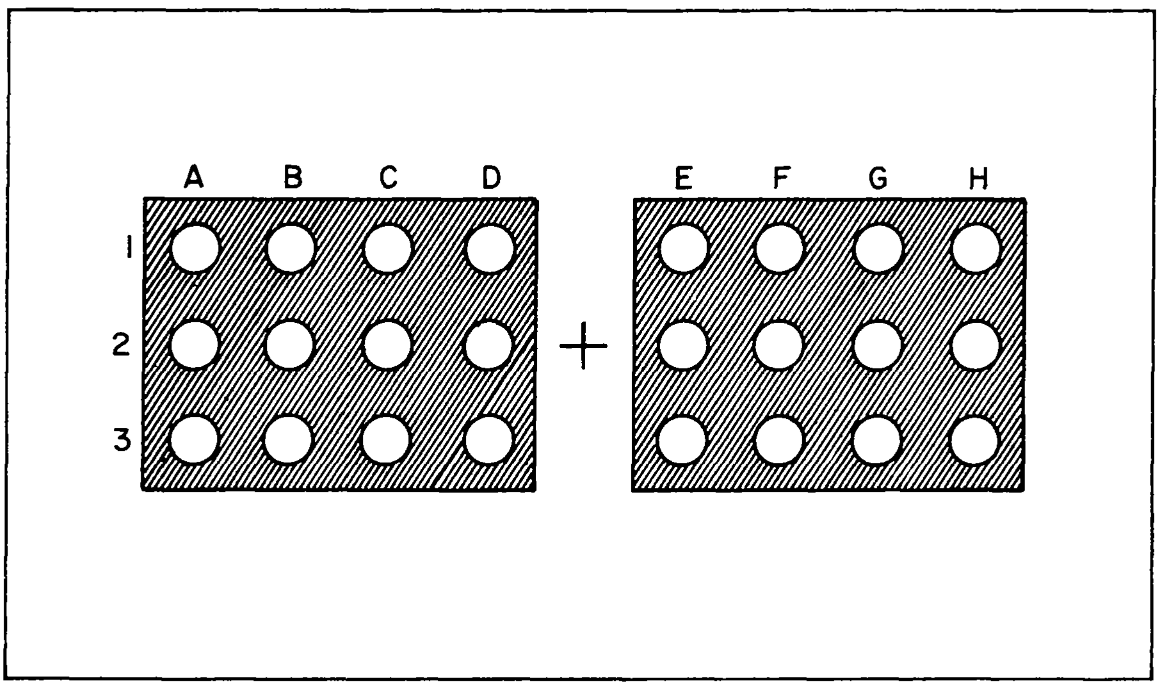

FIGURE 1 FRONT VIEW OF LIGHT BOX USED IN THE EXPERIMENT

b. <u>Subjects</u>

Two male subjects were paid for their services. Neither subject had any previous experience in this type of experiment.

c. <u>Procedure</u>

In the training phase of the experiment, each subject was tested on his ability to report four position patterns until his performance stabilized. After training, the subjects were paced through the remainder of the test schedule, which involved:

(1) Three tests requiring a partial report of the 12 position patterns,

(2) Followed by two tests with a whole report of the same patterns,

(3) Followed by three tests with a partial report of the patterns.

Each subject participated in the experiments for approximately a half-hour period each day. During this period, he completed a variable number of sessions (from two to six).

In each training session, 24 stimulus presentations were made. Following each presentation, the subject orally reported the positions of the lighted lamps, using the alpha-numeric reporting alphabet shown in Figure 1. A typical response would be 1AC2H3A. If a subject reported fewer than four locations, he was asked to continue reporting and to guess when necessary. If he reported more than four locations, only the first four were recorded. These responses were typed into the control computer by the experimenter. There was no fixed time within which a subject was forced to respond. As soon as the experimenter finished typing the last response, a reinforcement (repeat of the stimulus for 1.67 s) was automatically initiated by the computer. The reinforcement was followed by a four-second pause and then the next stimulus.

In the partial-report sessions, 66 stimulus presentations were made. Following the presentation, the subject was informed by a tone as to the row from which this response should come. The eight topmost lamp positions (1A-1H) were denoted by the high tone (1000 Hz), positions labeled 2A-2H were denoted by the middle tone (250 Hz), and 3A-3H were denoted by the low tone (100 Hz). The marker tone began immediately following stimulus termination and lasted for 250 ms. The subject's response to a partial-report trial was a number (1, 2, or 3) corresponding to the row, followed by four letters corresponding to the illuminated lamps in the row (e.g., 3ACDF). Each marker occurred an equal number of times in each session. Marker order was random and varied from session to session. In all partial-report sessions, the total number of illuminated lamps was 12, with four randomly located in each row.

The whole-report sessions were carried out using the same stimulus patterns used in the partial-report sessions described above. The whole-report procedure was the same as the training procedure except that there was no reinforcement. The experimenter's typing of the last response initiated a four-second pause, followed by the next stimulus.

During the sessions, the subjects were asked to fixate on the cross in the center of the display. On any one trial, n lamps were chosen (by the computer) out of the 24 possible lamps. In any one session the number of lamps simultaneously lighted, n, was constant and known by the subjects. In total, there were 132 presentations of the whole-report patterns and 396 presentations of the partial-report patterns for each subject. These numbers were chosen so that the standard deviation for the mean number of positions available or perceived in both of these report conditions would be the same ($\sigma = 0.64$ position).

d. Results

The number of positions correctly reported in the training and whole-report sessions and the number of positions available in the partial-report sessions were corrected for guessing using guessing Model II described by Hill and Bliss (1968) to obtain the number of positions perceived on each session. The results of the training sessions for both subjects are shown in Figure 2. The performance of both subjects increased similarly during the first 10 test sessions and then leveled off at 2.9 positions for the last five sessions. Their visual results were slightly higher than previous tactile results (2.5 positions perceived, reported by Hill and Bliss, 1968), but in close agreement with previous visual results (3.0 positions perceived, reported by Bliss, Hill and Wilber, 1968, Section VI). After the 15th training session, the main part of the experiment was begun.

The results of the short-term memory test are shown in Figure 3. The first three and last three tests use the <u>partial report</u> of the patterns, and the number of <u>positions available</u> is plotted; the intermediate tests use the <u>whole report</u> of the patterns, and the number of <u>positions perceived</u> is plotted. Besides the general upward trend of the partial-report scores with practice, the main result of the experiment is the difference between the whole- and partial-report scores. This difference is significant [$t(14) = 3.49$, $p < 0.005$], indicating the presence of visual short-term memory. With the previous

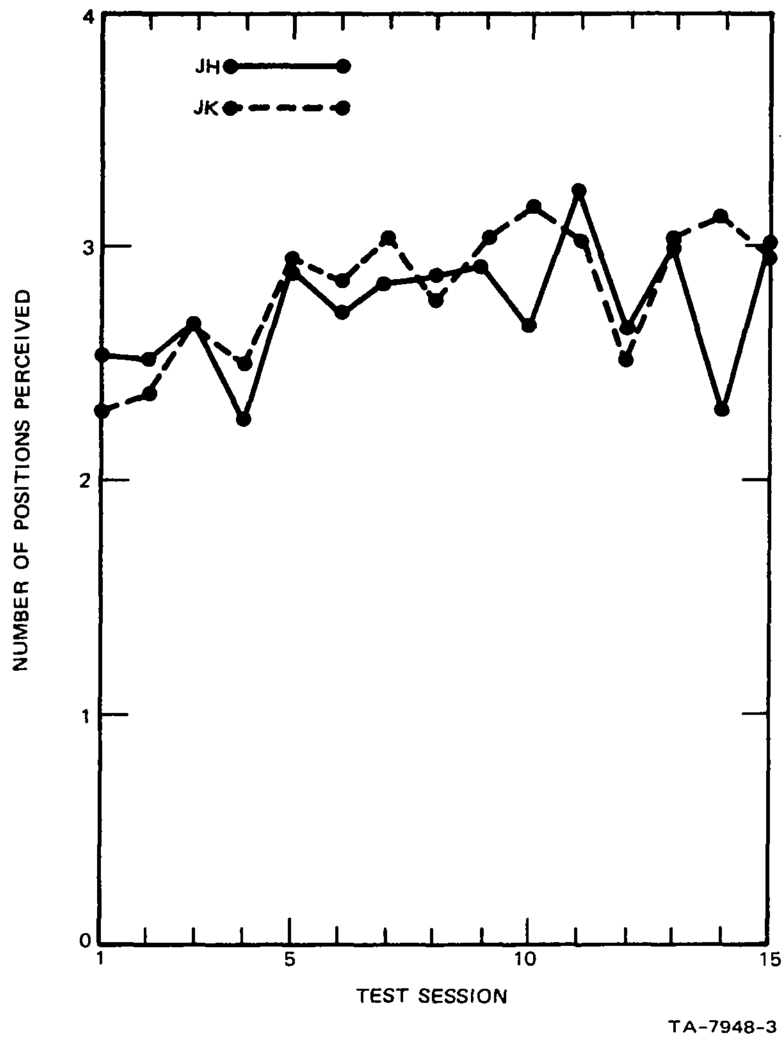

FIGURE 2 NUMBER OF POSITIONS PERCEIVED ON THE TRAINING SESSIONS WITH n = 4.

visual-marker and visual-display condition (Bliss, Hill, and Wilber, 1968, Section VII), there was no measurable short-term memory. The difference between these two experiments shows that the visual marker of the previous experiment interferes with the perception of the pattern, limiting the ability to perceive the pattern, as discussed by Keele and Chase (1967).

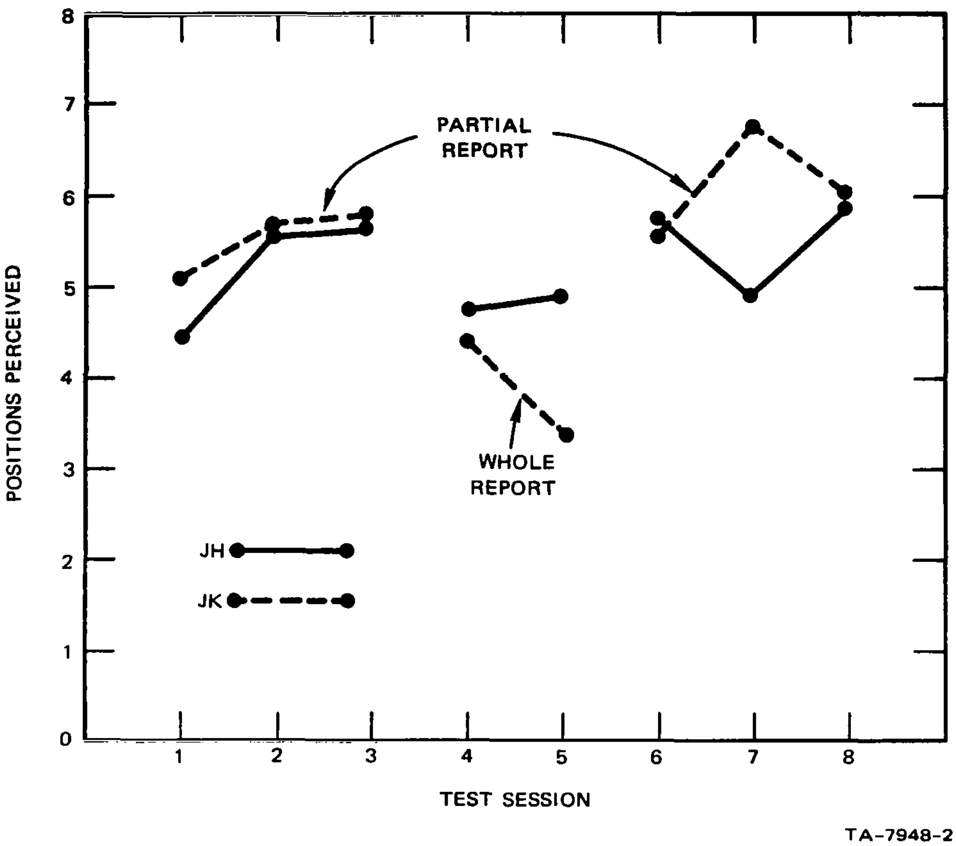

FIGURE 3 NUMBER OF POSITIONS PERCEIVED FROM THE TWELVE POSITION VISUAL PATTERNS

B. Experiment P2: A Study of Visual Short-Term Memory for Dot Patterns under a Wide Range of Stimulus Conditions

1. Background

In Experiment P1 we reported the measurement of a visual short-term memory for dot patterns very similar to that measured in a previous tactile perception study (Hill and Bliss, 1968). Both the overall capacities of the short-term memory (5.0 positions for tactile patterns and 6.0 for visual) and the percentage increase in size over the immediate memory capacity (50% increase for tactile patterns and 30% for visual) indicate that there may be similar processes underlying tactile and visual perception of these patterns. Because of the wide range of visual stimulus parameters that may have influenced the results of the visual short-term memory experiment, we decided to run a small-scale experiment to test the effects of varying the main visual-stimulus variables. The ambient brightness, lamp brightness, distance from subject to display, and stimulus duration were varied over fairly wide ranges. In this way, we hoped to find out whether the visual short-term memory results were due to the particular choice of stimulus parameters chosen or were general properties of the visual information system, relatively independent of the stimulus parameters.

A similar experiment (Bliss, Hill, and Wilber, 1968) measuring the span of visual immediate memory (whole-report capacity) has shown visual performance to be relatively independent of lamp brightness, ambient brightness, display distance, and display duration. If short-term memory capacity is also independent of these variables, as the results of this experiment indicate, then interesting future comparisons can be made between tactile and visual information processing. The advantage of this approach will be to separate the peripheral from the central limitations of the visual/tactile information-processing system. If the visual and tactile results are similar then the properties previously assigned to the tactile channel may be instead central properties of both channels. Using this method of tactile-to-visual comparison, differences may be attributed to the different modalities, and similarities may be attributed to central-processing limitations.

2. Method

a. Apparatus

The experiment was carried out under control of the LINC-8 computer system, described in Experiment P1. The same light box, reporting alphabet, and 12 position patterns described in that experiment were used.

In the experimental design, the two levels of ambient illumination, 0.1 fL and 50 fL, are referred to as "ambient dim" and "ambient bright," and the two levels of lamp illumination, 58 fL and 420 fL, are referred to as "lamp dim" and "lamp bright." The distance from the display to the subjects was either 30 or 90 inches. At these two distances, the angular width of the display from extreme light to the other was either 6.7° or 2.2°. In different parts of the experiment, the length of time that the lamps were simultaneously turned on (stimulus duration) was either 10, 33, 100, or 333 ms.

Upon extinction of the stimulus lamps, one of three tones was sounded for 250 ms on a loudspeaker adjacent to the subject. The three tones (approximately 100, 250, and 1000 Hz) denoted which of the three rows of the stimulus patterns (top, middle, or bottom) the subject was to report.

b. Subjects

One male (PC) and one female (LH) subject of college age were paid for their services. Neither subject had any previous experience in this type of experiment.

c. Procedure

Before the experiment proper was begun, the subjects were given a few practice sessions to become familiar with the task and the three marker tones. The main experiment consisted of a $2 \times 2 \times 2 \times 4$ factorial design (ambient brightness by lamp brightness by display distance by lamp duration). The 32 sessions were undertaken in a separate random order for each subject; thus any variance due to learning is included in the residual variance. Each of the sessions consisted of 24 stimulus presentations. The same partial-report presentation and reporting methods were used as described in Experiment P1.

d. Results

The number of positions correctly reported for each of the three rows was corrected for guessing, using guessing Model II described by Hill and Bliss (1968) to obtain the number of positions perceived in each session. The number of positions perceived on each of the three rows were added together to obtain the number of positions available in each partial report session. This method of measuring short-term memory capacity is explained by Sperling (1960). The number of positions perceived on each row was given an analysis of variance using the data from the two subjects as two replications. The summary of the analysis is given in Table I. Of the 31 sources of variance, only four of the main variables and one of the interactions contribute enough to be statistically significant.

The change in short-term memory capacity (the number of positions available) with ambient light level is shown in Figure 4 (a). Since a 500-fold increase in the ambient light level only causes a 20-percent change in memory capacity, memory capacity is largely independent of ambient light level. Changes with neon lamp brightness are shown in Figure 4 (b). Again, the increased capacity, though statistically significant, is small: a seven-fold increase in lamp brightness producing only a 10-percent increase in capacity. The changes due to

Table I

SUMMARY OF ANALYSIS OF VARIANCE OF THE

NUMBER OF POSITIONS PERCEIVED ON EACH ROW

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	
1 = Ambient Light	1	13.07955	13.07955	**
2 = Lamp Brightness	1	3.47634	3.47634	**
3 = Distance	1	0.24353	0.24353	
4 = Duration	3	5.33806	1.77935	*
5 = Response Row	2	8.52782	4.26391	**
12	1	0.52084	0.52084	
13	1	0.07931	0.07981	
14	3	1.07496	0.35832	
15	2	1.27244	0.63622	
23	1	0.33556	0.33556	
24	3	3.11711	1.03904	*
25	2	0.96908	0.48454	
34	3	0.84744	0.28248	
35	2	0.34236	0.17118	
45	6	1.04155	0.17359	
123	1	0.00430	0.00430	
124	3	2.10557	0.70186	
125	2	0.49494	0.24747	
134	3	0.49443	0.16481	
135	2	1.00254	0.50127	
145	6	1.49273	0.24879	
234	3	1.01768	0.33923	
235	2	1.04385	0.52193	
245	6	1.22754	0.20459	
345	6	1.13809	0.18968	
1234	3	0.30431	0.10144	
1235	2	0.22605	0.11303	
1245	6	1.66572	0.27762	
1345	6	1.97094	0.32849	
2345	6	1.31940	0.21990	
12345	6	1.72598	0.28766	
Within Subjects	95	36.27608	0.38185	
Between Subjects	1	4.85003	4.85003	**

* Significant at the 0.05 level.
** Significant at the 0.005 level.

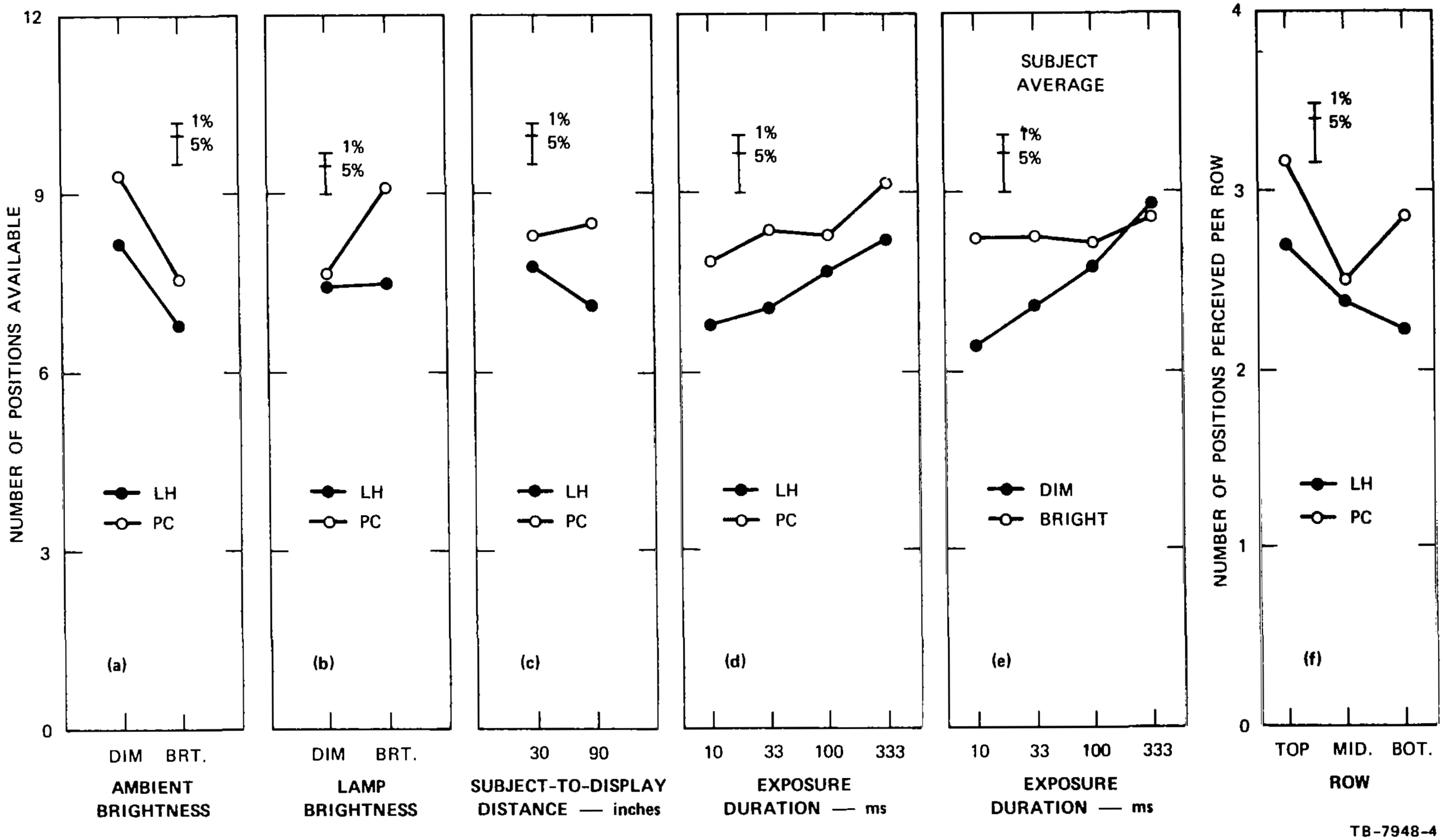

FIGURE 4 EXPERIMENTAL RESULTS AS A FUNCTION OF THE FOUR CONTROL VARIABLES AND ALL OTHER STATISTICALLY SIGNIFICANT VARIABLES

the distance between display and subject shown in Figure 4 (c) are not significant.

The logarithmic change in the number of positions available with exposure duration shown in Figure 4 (d) is better explained in the interaction between lamp brightness and duration shown in Figure 4 (e). Of the total variance attributed to this interaction, the interaction between linear lamp brightness and logarithmic duration accounts for 99.8 percent of the total variance. Figure 4 (e) shows that with the lamps "bright," there is no significant change with exposure duration but with the lamps dim there is a logarithmic change of 1.3 positions available for each decade increase in duration. Choosing the "lamps bright" condition in future experiments makes it possible to measure the number of positions available, independent of exposure durations in the 10-to-333-ms range.

Individual differences between the subjects are best shown in Figure 4 (f). Here the results of the two subjects in reporting from the three rows of lights probably indicate differing strategies. If Subject LH fixated on the top row of lights and Subject PC fixated on the fixation point in the middle row, these results could have been obtained. Significant differences between the two subjects are also shown in Figure 4 (b), where Subject LH's performance does not change with brightness, while Subject PC's performance does.

e. Discussion

The relative independence of visual short-term memory for dot patterns measured in this experiment strongly suggests that central and not peripheral factors are limiting performance. The results of this experiment are similar to those previously found in an experiment measuring the span of attention for dot patterns (Bliss, Hill, and Wilber, 1968, Section VI). The visual span of immediate memory did not depend on lamp brightness, ambient brightness, or display distance (over the 30-to-90-inch range) in that experiment. Since the present experiment is about twice as sensitive as the above-mentioned experiment in determining significant differences, some variables emerged that were not significant in the previous experiment.

Both experiments showed similar logarithmic changes in performance with pattern duration. In the previous experiment, interactions could not be measured and the interesting result shown in Figure 4 (e) cannot be compared. In general, both visual short-term memory capacity (measured using the partial report method) and the visual span of immediate memory for dot patterns (measured using the whole-report method) depend on the visual stimulus parameters in the same way. This similarity indicates that a memory model developed for visual dot patterns would be independent of display conditions and would measure central information-processing limitations.

C. Experiment P3: Visual and Tactile Short-Term Memory for Dot Patterns Measured by Two Different Methods

1. Background

All previous experiments carried out in this laboratory to measure tactile and visual short-term memory parameters have used the same reporting method. Subjects were asked to report one row (containing four stimulated positions) from a total of three rows containing 12 stimulated positions. In order to see whether a different reporting method would yield different capacities for the short-term memory parameters, an experiment requiring <u>only</u> <u>two</u> responses from the 12-point partial-report patterns was designed and carried out. According to the results of Sperling (1960), the size of the short-term memory for letters does not depend on the number of letters used in the response as long as this number is less than the span of apprehension (Miller, 1956). The tactile and visual dot pattern results with two and four responses reported here, however, show that memory capacity depends on the number of responses.

In addition to the usual guessing correction of the previous experiments, a new method of scoring was used in these experiments. The number of perfect two-position responses was used to measure the subject's performance. Since the guessing probability for such a response is only 1/6 compared to 1/2 for the previous measure, a wide range of performance was available without a guessing correction. The relation between these two measures was studied and it was found that the number of perfect patterns could be predicted from the number of positions perceived (and vice versa). The previous model, which measured performance based on the sum of independently perceived positions, was therefore further substantiated.

a. Apparatus

The experiment was carried out under control of a LINC-8 computer system, which was used to store stimulus patterns and the sequence in which the patterns were to be presented. The computer interface was connected either to an array of 24 airjet tactile stimulators or to the visual display box described in Experiment P1 and shown in Figure 1. The airjet array shown in Figure 5 had one stimulator for each of the 24 phalanges of the fingers (thumbs excluded), which were labeled for reporting as indicated in Figure 6. During the experiment, the palmar sides of the fingers were suspended about 1/8 inch above the airjet stimulators. The subjects' arms were supported from wrist to elbow, permitting the hands to be suspended in this

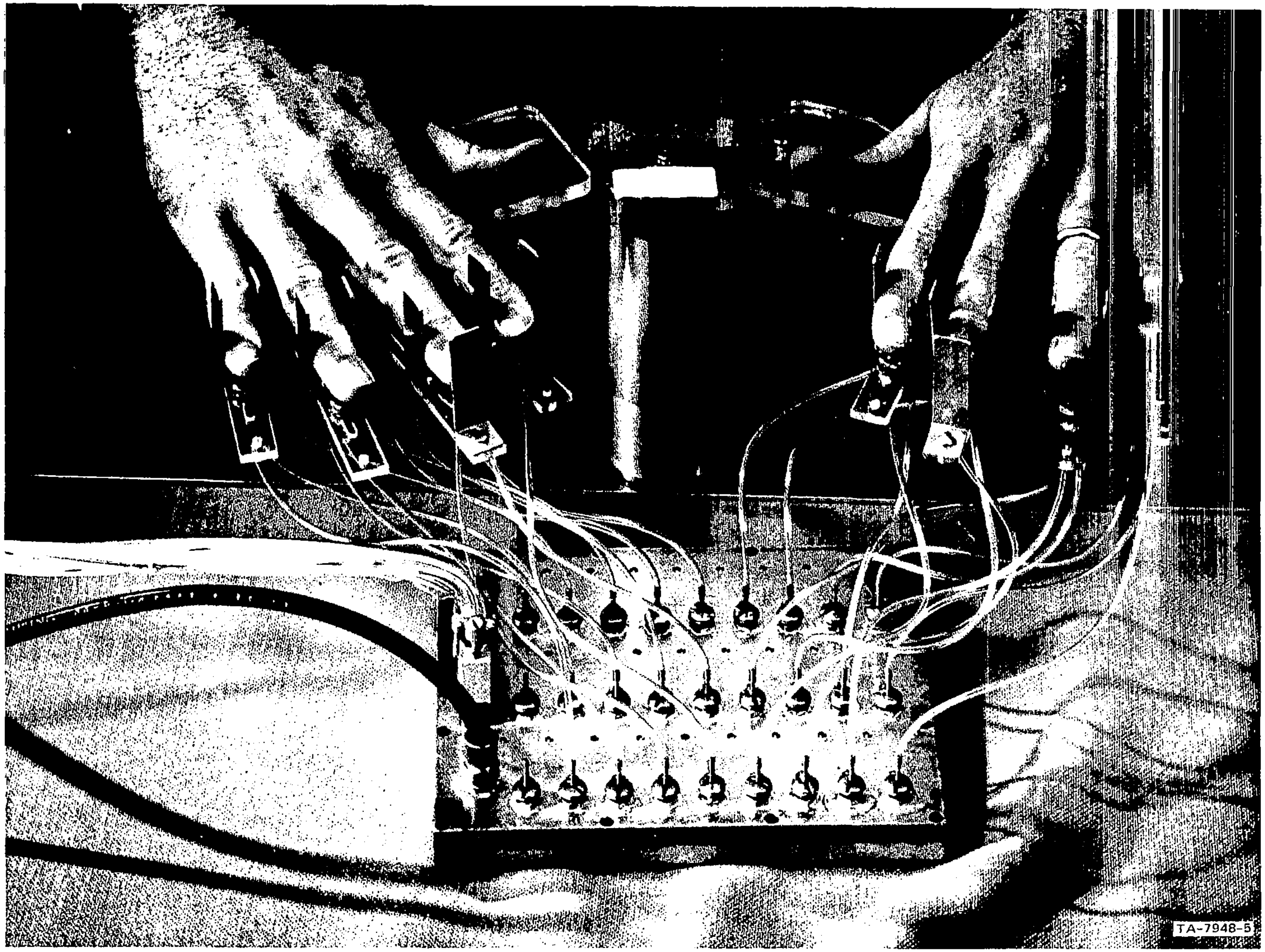

FIGURE 5 ARRAY OF AIRJETS, CONNECTING TUBES, AND HAND HOLDER USED TO PRESENT TACTILE DOT PATTERNS

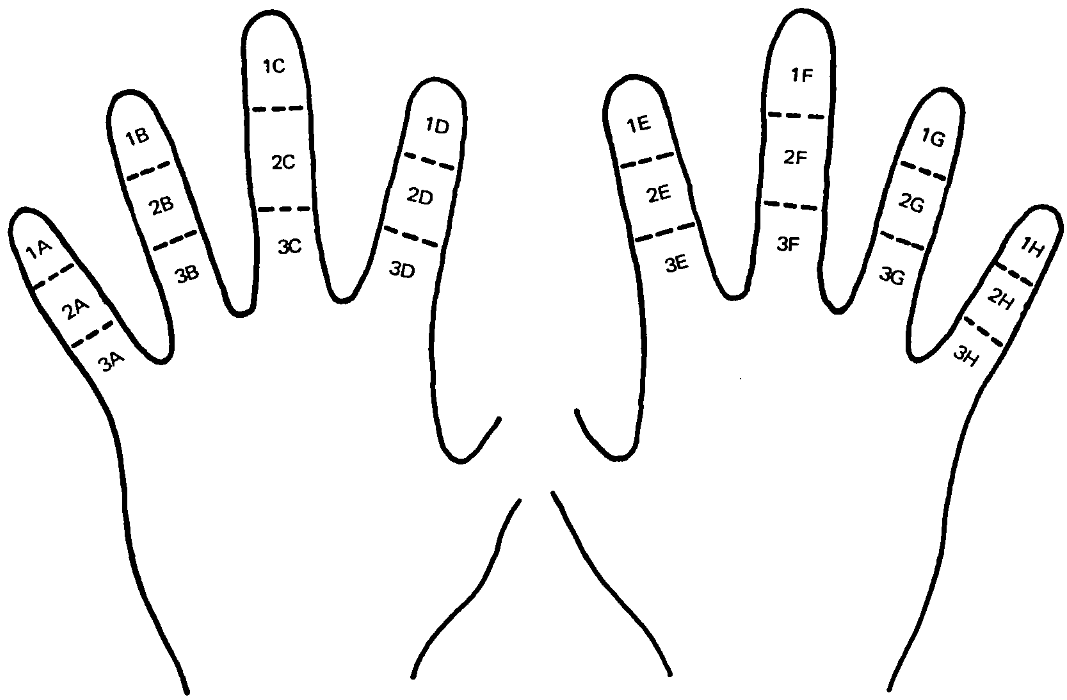

FIGURE 6 FINGER LABELING FOR TWO HANDS

manner over extended periods without fatigue. Each subject had his own set of airjet stimulators, which was initially adjusted to his hands and never reset unless he requested that a particular jet be readjusted. The airjets simultaneously stimulated n (n = 2 or n = 12) phalanges of the fingers. When activated, each jet pulsated at 200 Hz for 100 ms, producing 20 pulses of 2.5 ms duration and of about 1.5 psi peak pulse pressure.

b. Subjects

Two college students served as paid subjects. Both subjects had more than eight hours' experience on similar visual tasks, but neither had experience on similar tactile tasks.

c. Procedure

The testing schedule for both the visual and tactile parts of the experiments consisted of two parts: a training period followed by a testing period. In the training part of each experiment the session consisted of 36 trials, and each trial consisted of a presentation of two positions placed randomly in the arrays. The training procedure was the same described in Experiment P1 except that training sessions were continued until 90 percent of the trials of a given session were perfectly reported. During the tactile experiment a copy of Figure 6 was before the subjects to furnish them with the reporting alphabet.

In the testing part of the experiment, each trial consisted of a presentation of 12 positions, two placed randomly in each of the six half-rows of the arrays. Thus, there were three independently generated ramdom subpatterns in each half of the array. The testing schedule consisted of a series of 12 test sessions, of which the first three, the 5th through 7th, and 9th through 11th, required a partial report of the patterns and the 4th, 8th, and 12th required a whole report of the patterns. Each of the testing sessions consisted of 36 trials.

Both the whole-and partial-reporting methods are the same as those described in Experiment P1 except that in the partial-report experiment the tone frequency was either 4000, 1000, or 250 Hz, designating respectively the top, middle, or bottom row, and was from either the left or right earphone, designating respectively the left or right half of the row. Subjects were asked to report the positions of the marked half-row using the alphanumeric report alphabet. A typical verbal response would be 2AC.

d. Analysis

Two different methods were used to analyze the data of the experiments. The first is the number of correctly reported two-position patterns in the training experiment and the number of correctly reported two-position half-rows in the whole- and partial-report testing experiments. These two-position patterns are counted correct only if both positions are reported in their correct locations. The chance of a successful guess is only 1/6 in the testing experiments since there are 6 possible two-position patterns in each half-row.

The second method used is the number of positions perceived, which has been described in Hill and Bliss (1968). The number of positions perceived is the number of positions correctly located, corrected for guessing. Since the change of a correct guess with the 12-position patterns is 1/2, the need for the guessing correction is obvious.

2. Results

The visual experiment was completed first and the tactile experiment second for both of the test subjects. The results of the visual and tactile training sessions for both subjects are shown in Figure 7. The main differences between the two modalities are the lower initial reporting accuracy and the longer time necessary to reach the required 90 percent correct response level with the tactile presentations. The greater learning in the tactile training experiment is very similar to that previously obtained by Bliss (1966) and attributed to inexperience using the tactile modality to perceive patterns.

The results of the main experiments are shown in Figure 8.

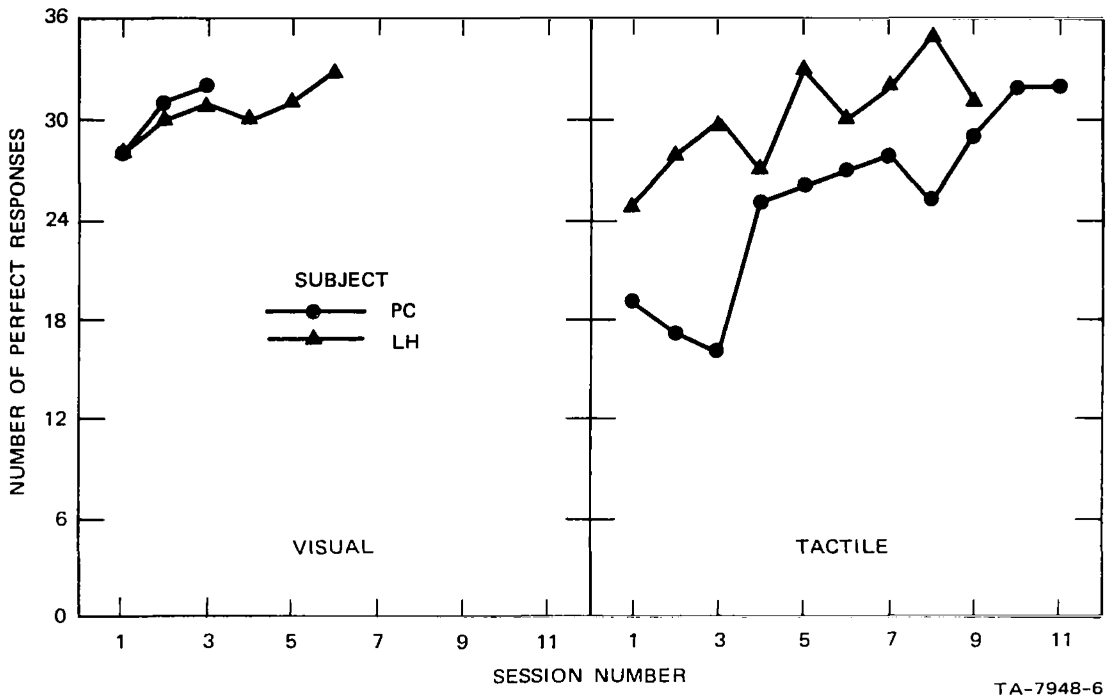

FIGURE 7 RESULTS OF THE TRAINING EXPERIMENTS

Here the two methods of measuring subject performance are shown side-by-side for comparison. These two measures are similar, except when performance is near the guessing level. In this case the guessing level is the lower limit of the number of perfectly reported patterns, and performance grows with the height above the guessing level rather than above zero. The data of the partial-report experiments is the information available to the subjects; that of the whole-report experiments is the information correct. This difference between these two measures as explained by Sperling (1960) is that the information available is obtained by multiplying the number of positions (or patterns) correctly reported in the partial report experiments by the number of simultaneously presented patterns. Since there were six subpatterns that could have been designated by the marker tone after the stimulus pattern terminated, the multiplication factor in this case is six.

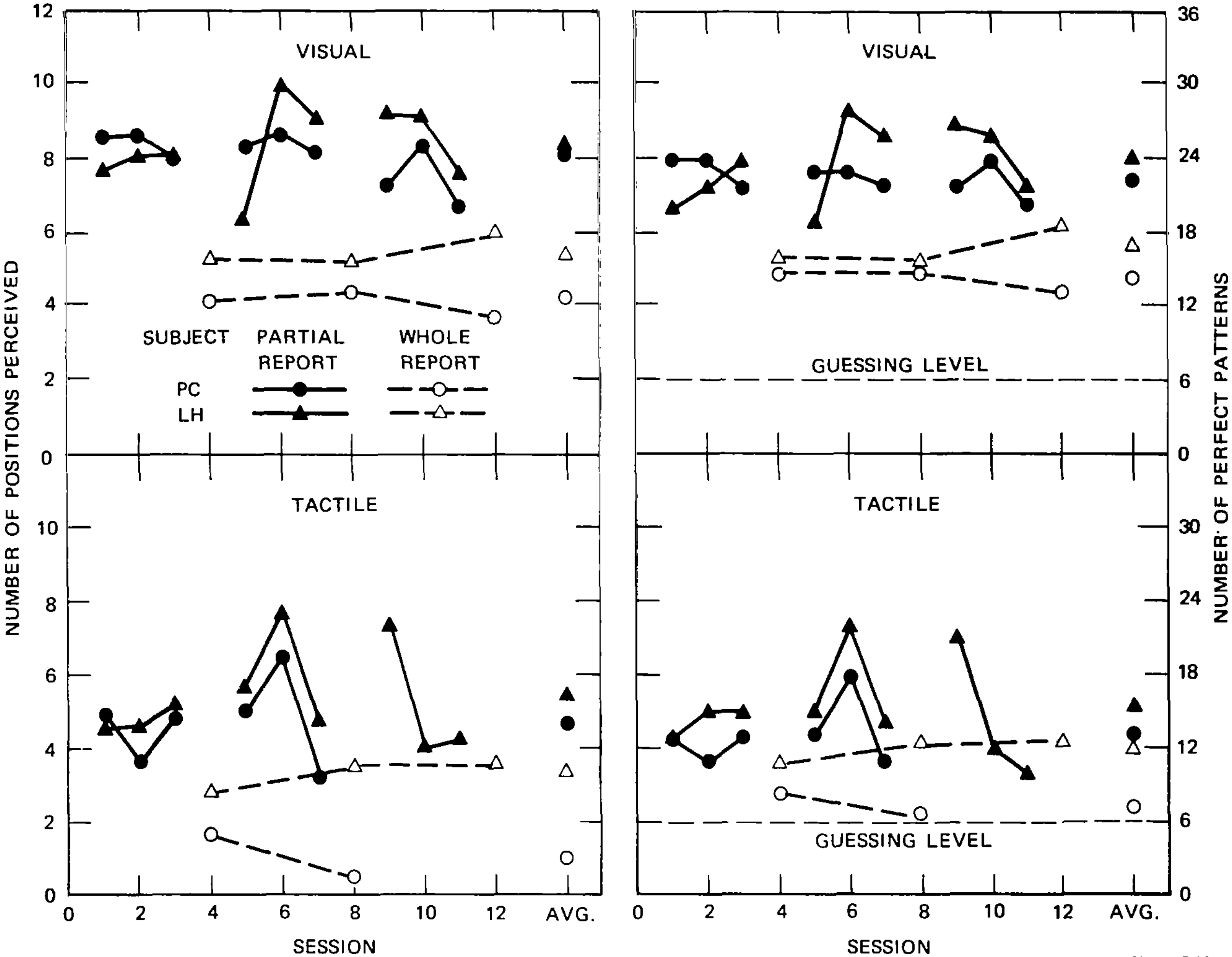

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FIGURE 8 COMPARISON OF WHOLE AND PARTIAL REPORT DATA USING TWO PERFORMANCE MEASUREMENTS

The relationship between the two measures is better shown in Figure 9, which shows the results of each partial-report session plotted in terms of the two measures obtained from it. The theoretical curves in Figure 9 represent predictions based on equal probabilities of perceiving the two positions of each subpattern and a constant correlation coefficient $\rho = \sigma_{12}/\sigma_1\sigma_2$ between the two probabilities. Noise in the

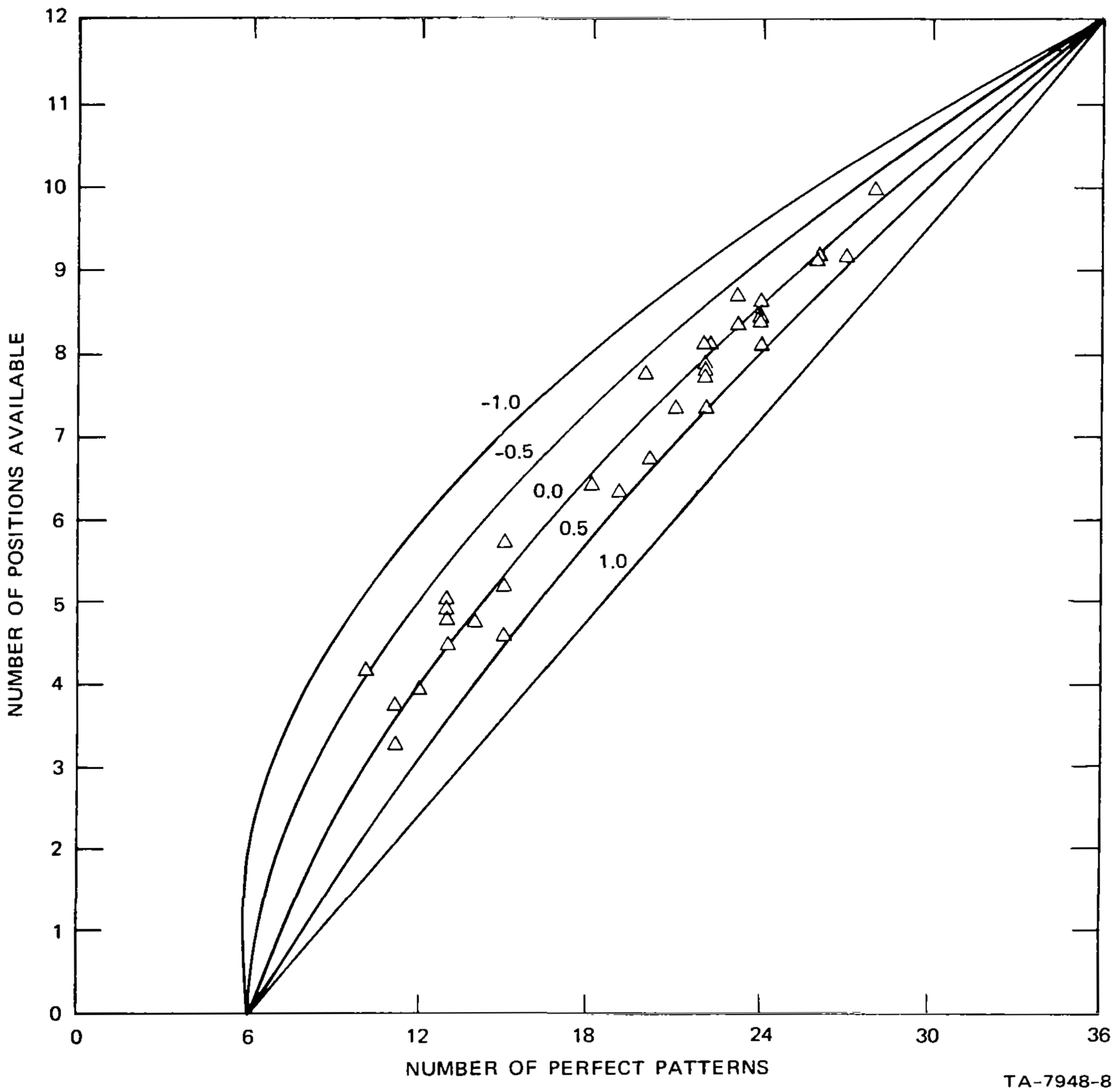

FIGURE 9 RELATIONSHIP BETWEEN THE TWO PERFORMANCE MEASUREMENTS

data is due to averaging the results of all six subpatterns, some of which are consistently reported more accurately, and some less accurately. The data fit the independent case ($\rho = 0$) fairly well, but are better fitted by a slightly positive correlation, $\rho = 0.1$. A positive correlation between the two positions indicates that more patterns are either totally correct or totally wrong than predicted from independently perceived points.

One of the main reasons for conducting this experiment was to compare tactile and visual short-term memory, and another reason was to compare short-term memory obtained with both two- and four-point subpatterns. The data necessary to make these comparisons have been gathered in Table II. All of the data are in terms of positions perceived instead of the number of perfect subpatterns. The whole- and partial-report capacities of the present experiments shown in the upper portion of Table II are significantly different ($p < .001$), indicating the presence of a short-term memory for both modalities. These results also hold when the number of perfect patterns is used as the performance measure.

Using Table II, the previous experiments with 4-point subpatterns and the current experiments with 2-point subpatterns can also be compared. Table II shows that with each modality, the whole-report capacities for both two- and four-point subpatterns are about the same. The partial-report capacities for the two-position subpatterns are both higher than the corresponding capacities for the four-position subpatterns. This increase in partial-report capacity with the smaller subpatterns accounts for the larger percentagewise increases for these patterns shown in Table II. This change in short-term memory capacity with number of positions is different from that noted for visual letter presentations by Sperling (1960), who found that short-term memory

Table II

SUMMARY OF SHORT-TERM MEMORY DATA

Modality	Points in Subpattern	Whole-Report Capacity	Partial-Report Capacity	Percentage Increase
Tactile*	2	3.36	5.35	59
Visual	2	4.84	8.24	70
Tactile†	4	3.3	4.9	49
Tactile§	4	3.4	5.0	47
Visual**	4	5.9		
Visual††	4	4.38	5.61	28
Visual§§	4		7.7	

*Data from Subject LH only, since subject PC did not finish experiment.

†Hill and Bliss (1968).

§Bliss, Hill, and Wilber (1968), page 92.

**Bliss, Hill, and Wilber (1968), page 97.

††Bliss (1969).

§§Bliss, Hill, and Wilber (1969).

estimates did not depend on this number. This dependence is similar to the whole-report result of Hill and Bliss (1968), who showed that the span of apprehension for these patterns was not fixed, but was directly proportional to the number of positions presented.

To find the statistically significant portions of the experiments, analyses of variance were performed on the number of perfect patterns from both the whole- and partial-report results. Since one subject did not finish the last third of the tactile experiment, only the results of the first two thirds (first eight sessions) are included in the analyses that are summarized in Tables III and IV. Besides the

Table III

SUMMARY OF ANALYSIS OF VARIANCE OF THE NUMBER OF PERFECT PATTERNS IN THE PARTIAL REPORT

Source of Variation	DF	Mean Square	F Ratio
Subjects (S)	1	1.778	-
Modality (M)	1	75.111	42.9†
Row (R)	2	15.396	8.79†
Half (H)	1	4.000	2.28
S x M	1	1.361	-
S x R	2	9.382	5.35*
S x H	1	4.694	2.68
M x R	2	3.840	2.19
M x H	1	1.361	-
R x H	2	.271	-
S x M x R	2	.632	-
S x M x H	1	11.111	6.35*
S x R x H	2	4.007	2.28
M x R x H	2	4.215	2.41
S x M x R x H	2	4.257	2.43
Within Replications	120	1.755	

*Significant at the .05 level.

†Significant at the .005 level.

modality differences that have already been discussed, the other most significant variable in the experiment is the row of the response. The dependence between row and subject, which is significant in both whole- and partial-report parts of the experiment, is shown in Figure 10. The primary difference between the subjects is (1) that in the partial report Subject PC performs best on the middle row, while

Table IV

SUMMARY OF ANALYSIS OF VARIANCE OF THE NUMBER OF PERFECT PATTERNS IN THE WHOLE REPORT

Source of Variation	DF	Mean Square Patterns Correct	F Ratio
Subjects (S)	1	17.18	3.76
Modality (M)	1	38.02	8.32*
Row (R)	2	97.76	21.4†
Half (H)	1	75.51	16.6†
S × M	1	28.52	6.24*
S × R	2	71.68	15.7†
S × H	1	1.68	-
M × R	2	52.64	11.5†
M × H	1	5.02	1.10
R × H	2	5.39	1.18
S × M × R	2	4.14	-
S × M × H	1	31.68	6.94*
S × R × H	2	12.56	2.74
M × R × H	2	6.27	1.37
S × M × R × H	2	26.68	5.85*
Within Replications	24	4.57	

*Significant at the .05 level.

†Significant at the .005 level.

Subject LH does best on the top row and (2) that in the whole report Subject LH performs better on the top row. The dependence between response row and modality, which is only significant in the whole report, is shown in Figure 11. The figure shows that tactile performance is near chance on the bottom two rows for Subject PC.

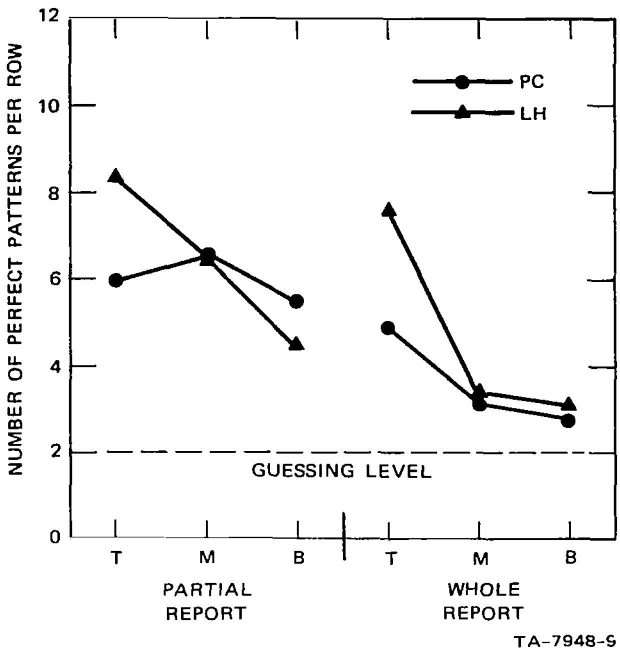

FIGURE 10 AVERAGE VISUAL AND TACTILE PERFORMANCE OF THE TWO SUBJECTS AS A FUNCTION OF ROW

D. Conclusions

Three experiments are described that measure the perception of visual and tactile dot patterns presented with a 3 x 8 matrix of visual or tactile stimulators. By providing an auditory, instead of visual, marker for the partial report in Experiment P1, a small but significant short-term memory was found comparable in size with previously measured tactile short-term memory. Experiment P2 shows that this visual memory is relatively independent of stimulus brightness, background brightness, and pattern size, but depends on stimulus duration in the same way that tactile memory does. These results of Experiment P2 suggest that visual short-term memory is a central, rather than a peripheral (or retinal) limitation. Comparison of the results of Experiment P2 with the similar, previous tactile results suggests that the short-term memory

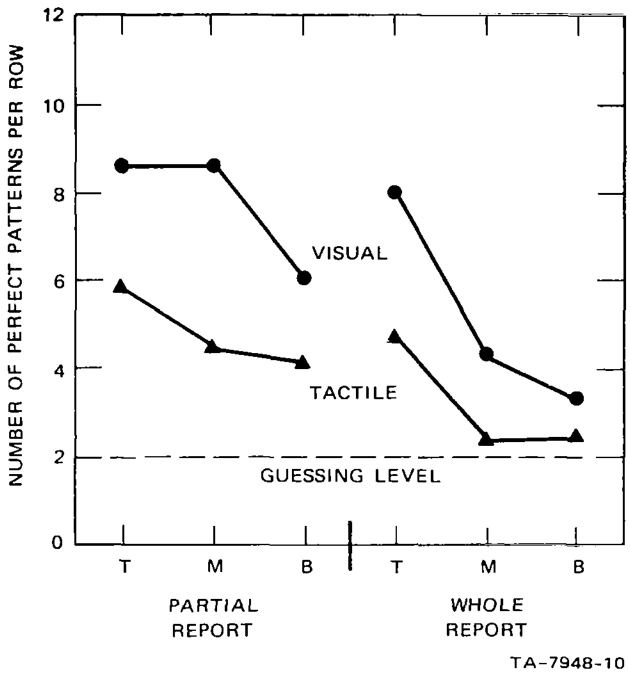

FIGURE 11 AVERAGE PERFORMANCE OF THE TWO SUBJECTS AS A FUNCTION OF RESPONSE ROW AND MODALITY

being measured resides in an area common to both visual and tactile modalities.

Experiment P3 measures short-term memory and the span of apprehension for 12-position patterns divided into six subpatterns instead of three. This change reduces the size of the partial-report response from four to two positions, but leaves the whole-report response unchanged at 12 positions. The span of attention measured with 12-position patterns is the same as previously measured, but the short-term memory capacity with two-position patterns is larger than previously measured. This is different from Sperling's (1960) result with letters and indicates that dot-pattern memory capacities depend on the size of the response for both modalities.

III TELEOPERATOR STUDIES

The information conveyed by tactile feedback can be of two basic types. One is kinesthetic, or overall force feedback, where the force on the operator's hand is proportional to the overall force on the corresponding part of the manipulator. The other type is force-distribution feedback. Here the distribution of force on the operator is proportional to the distribution of force on the manipulator. This distribution type of feedback could tell the operator the shape of an object in the manipulator jaws, where in the jaws he is holding the object, and the force he is exerting at any point on the object. Many manipulators presently have force feedback, but none have force-distribution feedback. It is expected, but as yet unproven, that this additional information should greatly enhance manipulation performance.

The main variables influencing remote manipulation were studied and are presented in outline form in Table V. An experimental study of all the tactile feedback parameters discussed in the outline would obviously take a much longer time than we had available to us in this project, so we chose to explore the following uses of tactile displays.

(1) Force-distribution feedback versus no such feedback, by adding a 48-element force-distribution feedback system to a manipulator.

(2) The kind of tasks most improved with tactile feedback, by trying a number of conceptually different tasks both with and without this tactile display.

(3) Direct viewing, television, and noisy television viewing of the arm in combination with force-distribution feedback.

Table V

VARIABLES INFLUENCING REMOTE MANIPULATION

WITH TACTILE INFORMATION DISPLAYS

(1) Conditions Involving Overall Force Feedback

- (a) None, only visual observation permitted
- (b) For hand or tong only
- (c) For all joints

(2) Conditions Involving Spatial Force Feedback (may be on-off or proportional)

- (a) None
- (b) Single contact only--as vibrators on the fingertips, wrist, elbow, or other extremities, indicating contact at the corresponding manipulator locations
- (c) Center of gravity of force distribution on the tongs transmitted to the finger pad
- (d) Distribution of force on tongs transmitted to the finger pad

(3) Type of Communication Link

- (a) Quality of the visual signal
  - Direct viewing
  - Television viewing system
  - Noisy television viewing
- (b) Amount of Time Delay
  - No delay other than manipulator servo lags
  - Additional time delay up to several seconds

(4) Type of Task (compare speed and accuracy)

- (a) Remote operations--knob adjusting, switch throwing, or oiling machinery
- (b) Assembly and disassembly--alignment, inserting bolts, tightening nut or Allen screw, or replacing parts
- (c) Inspection--sorting, picking things up, or stacking blocks

(5) Use of Automatic Operation

- (a) Automatic gripping (with a specified force)
- (b) Automatic centering of object in gripping tong
- (c) Automatic touching (reach until first contact).

A. Remote Manipulator

The facility used for performing these evaluation experiments is the Model 8A Rancho Arm,* shown in Figures 12 and 13. The members of the control brace and arm correspond in size and in relative position to each other and to the operator's arm. Seven closed-loop servomechanisms position the arm in the same orientation as the control brace, allowing the operator to move the arm in a fairly natural manner. After receipt of the arm, we carried out several modifications to make it operational. These included (1) constructing a sturdy mounting pedestal for it, (2) mechanically reworking and stiffening a number of arm joints, (3) strengthening the joint-angle pickup potentiometer mountings, and (4) installing variable gain controls in the seven servo channels to damp oscillations.

B. Design of a Force-Distribution Feedback System

After considering possible switch and strain gauge force sensors, we constructed a simple and reliable array of sensors using a conductive rubber sheet. The conductive rubber was mounted so that contact was made when an external object pushed the flexible rubber against conductors imbedded in an insulating plate. The 48 contact points are on 0.1-inch centers in a uniformly spaced 4 × 12 matrix. The whole unit, mounted in a rubber sleeve and fastened to the manipulator tong shown in Figure 14(a), has proved very rugged, requiring no maintenance or modifications throughout our experimentation.

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*The Model 8A Rancho Arm is a seven-degree-of-freedom manipulator, anthropomorphic with the human arm, manufactured by R.&D. Engineering, Downey, California.

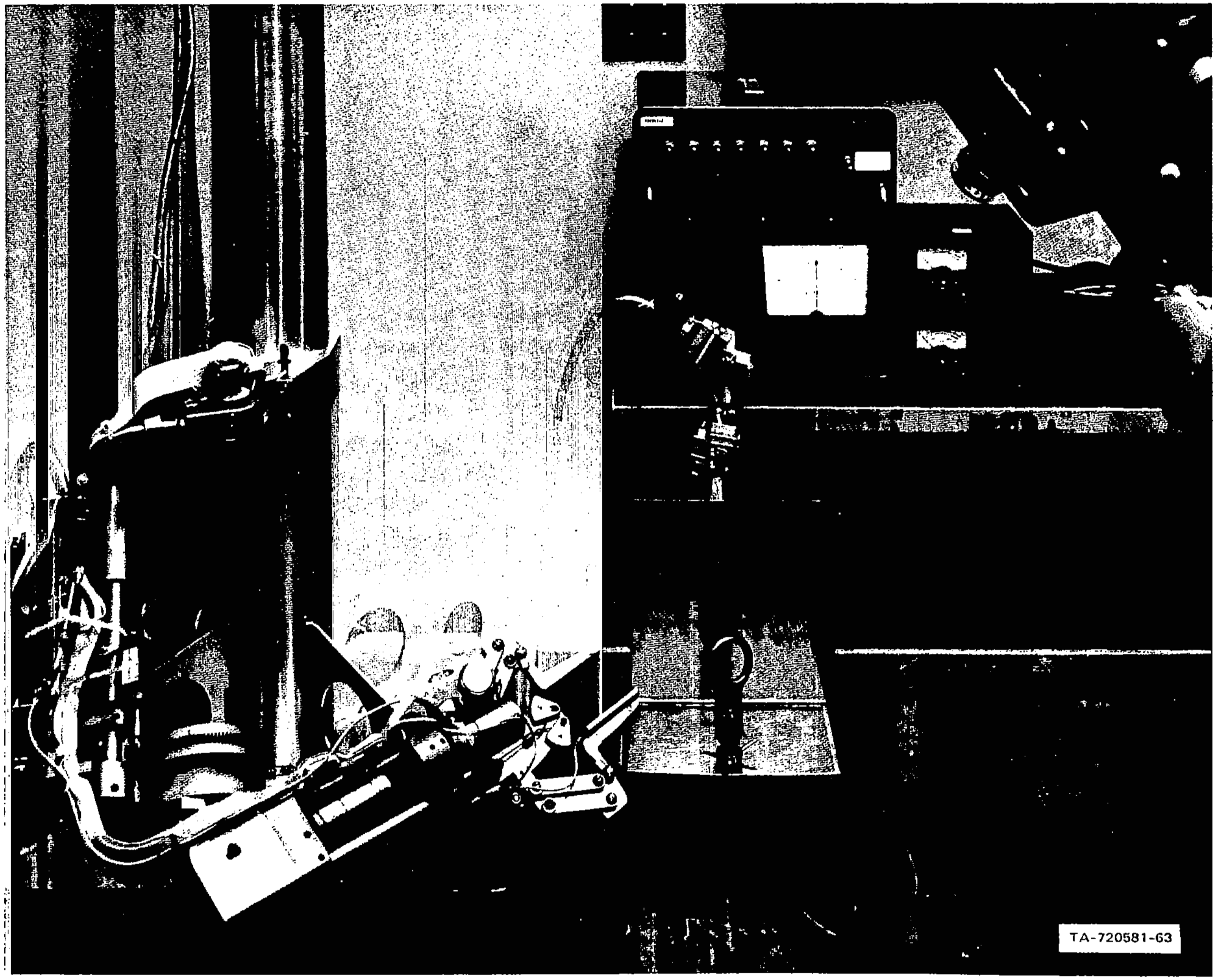
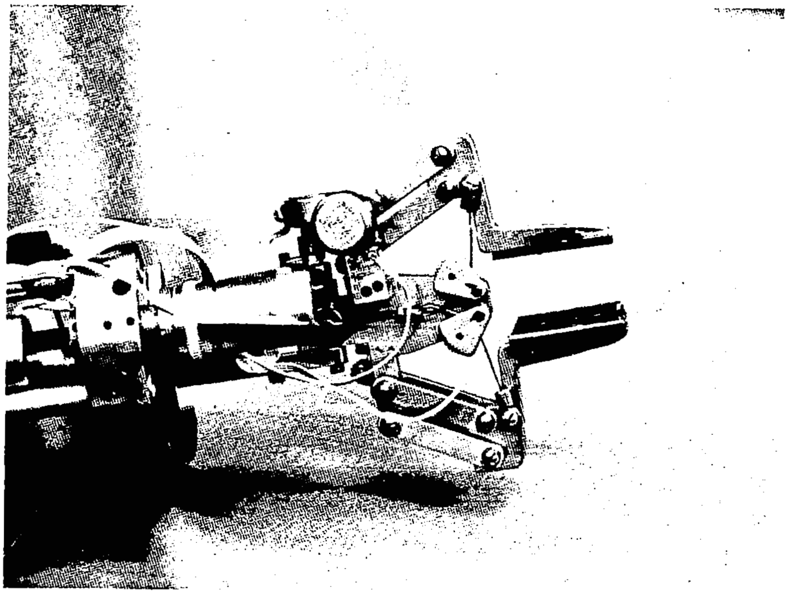
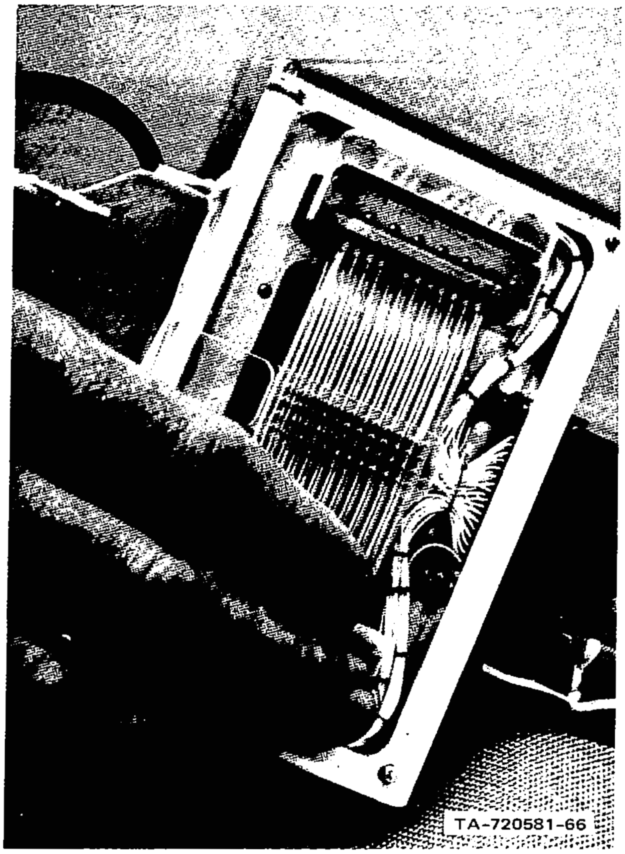


FIGURE 12 THE RANCHO MANIPULATOR IN THE EXPERIMENTAL SITUATION

FIGURE 13 USE OF THE CONTROL BASE



(a) FORCE DISTRIBUTION SENSOR ATTACHED TO BOTTOM TONG



(b) FORCE DISTRIBUTION DISPLAY FOR OPERATOR'S FINGER

FIGURE 14 THE TWO TRANSDUCERS OF THE TACTILE FEEDBACK SYSTEM

The tactile stimulator for the operator's finger is shown in Figure 14(b). It consists of a corresponding 4 X 12 array of vibrators uniformly spaced on 0.1-inch centers. Each vibrator is a piezoelectric Bimorph* transducer tipped with a metal pin protruding through holes in a recessed plastic sensing plate. The vibrators are either off or are connected to a 250-Hz square wave generator through individual conductive rubber switches. They produce a pattern of vibration identical to the patterns of switch closures on the manipulator tongs.

The use of this feedback system is illustrated in Figure 15, which shows the tongs gripping a triangular block. The force sensing pad, which is mounted on the near tong, has been connected to a 4 X 12 light box in such a manner that each of its switches actuates one lamp. The triangular group of illuminated lamps presents the same force pattern visually that the operator would feel tactually.

In actual manipulations with the arm, the operator's fingers are positioned as shown in Figure 16, with the index finger centered on the vibrators. The control brace has been modified for this application so that the tong position, which was originally governed by the fingers, is now governed by the thumb. The fingers remain stationary on top of the display unit and are sometimes held in place by a rubber strap.

C. Evaluation Experiments

After reworking the arm to achieve fairly reliable operation, some exploratory manipulations were carried out. Various kinds of children's building blocks, peg-in-hole arrangements, nut and bolt fasteners, and a

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*Bimorph is the trade name for piezoelectric transducers manufactured by Clevite Corp., Bedford, Ohio.

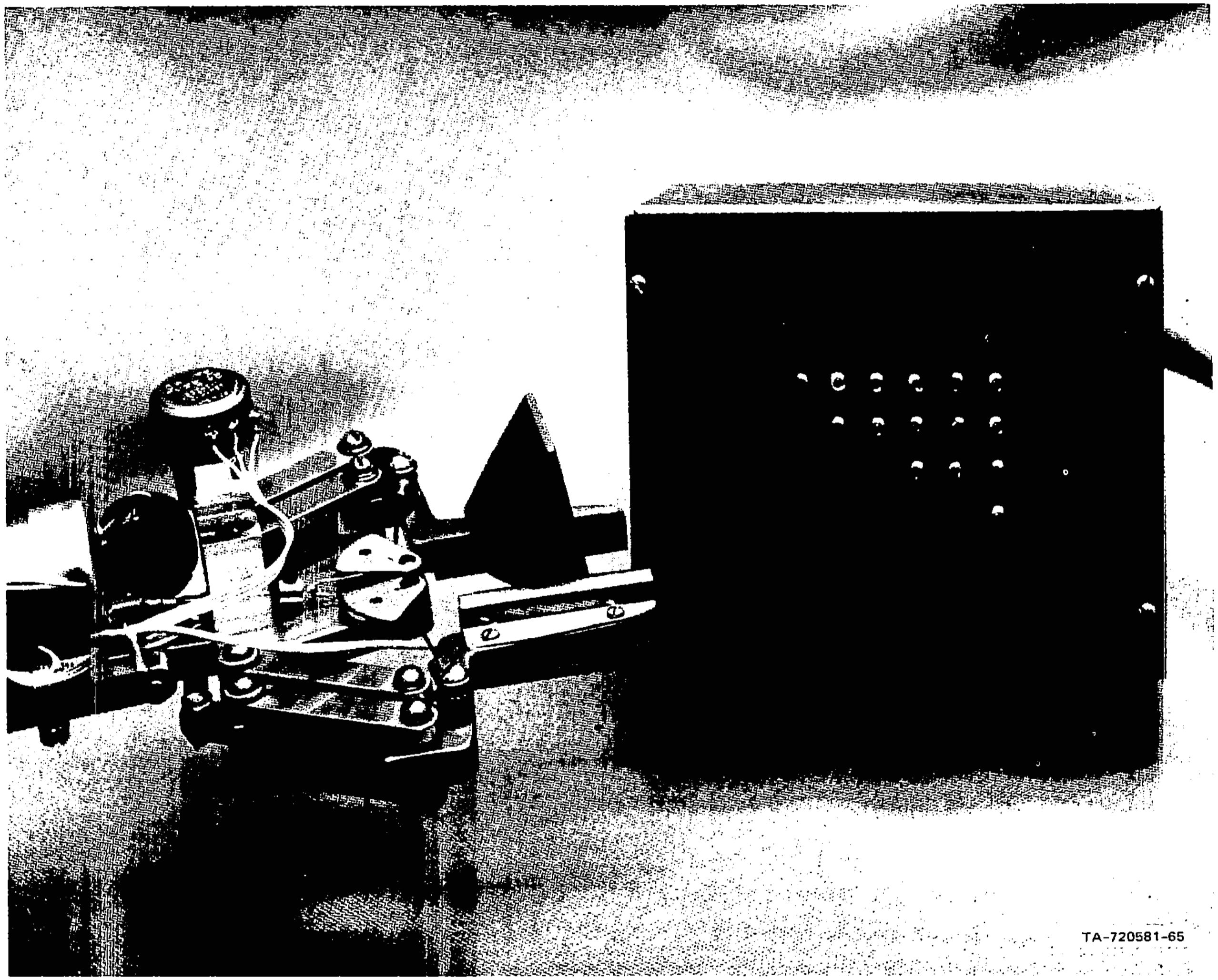

FIGURE 15 GRIP OF A TRIANGULAR BLOCK WITH A LIGHT BOX DISPLAY OF THE FORCE DISTRIBUTION PERSENTED TO THE OPERATOR

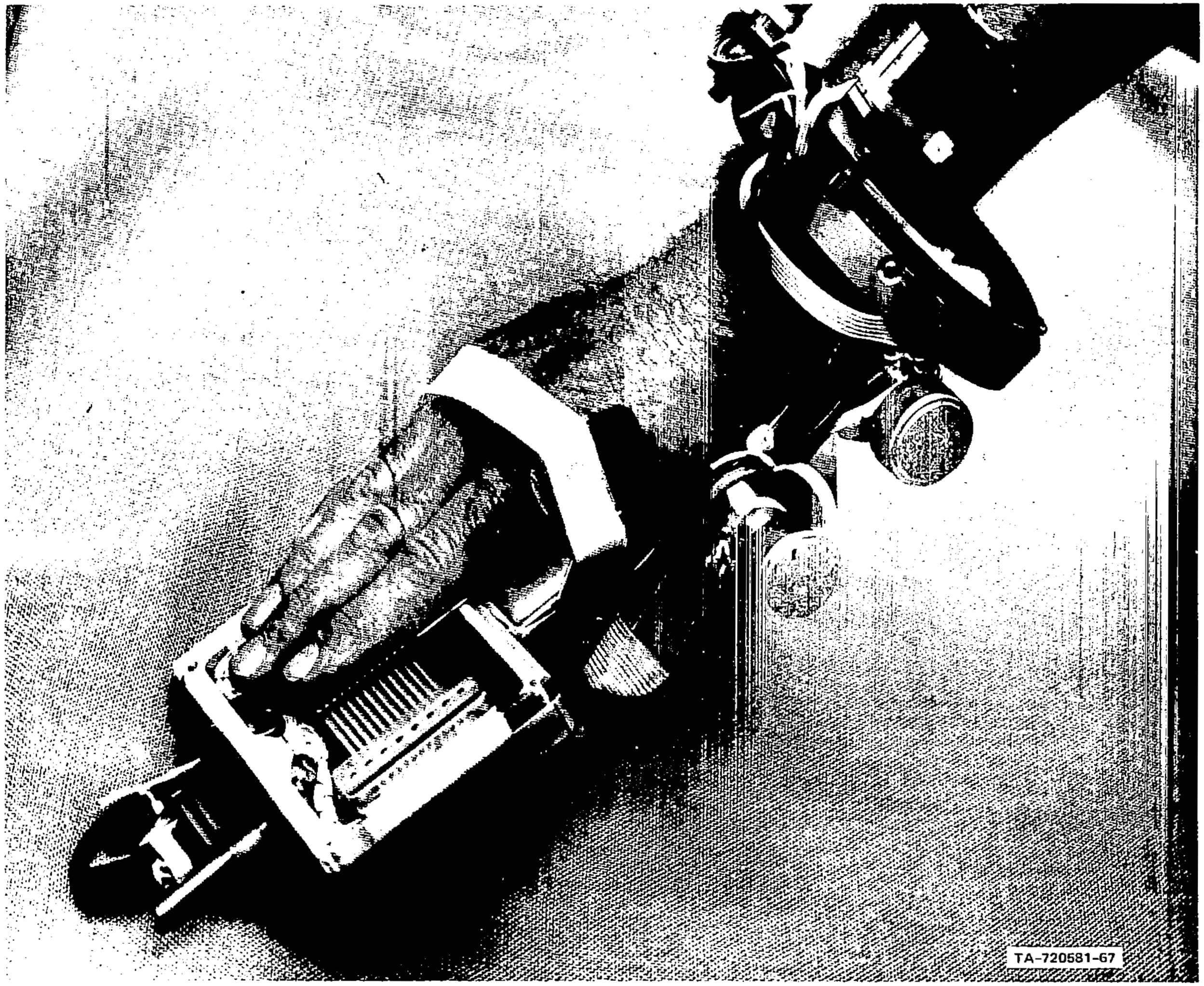

FIGURE 16 OPERATOR'S HAND POSITIONED IN THE BRACE WITH FINGER OVER FORCE-DISTRIBUTION DISPLAY

special latch (a Kupu latch*) were considered for evaluation experiments. The tasks chosen for the preliminary experiments were (1) picking up and removing a cylindrical block, and (2) retrieving a Kupu latch from a metal panel.

In all, five different experiments were carried out: the first two involved block pickups and the last three used the Kupu latch. In the block experiments, the time for complete pickup was measured with a photoelectrically activated counter. When the first part of the arm passed through the beam of light, which defined a plane about one foot from the block, the counter was automatically started, and when the arm finally moved back through the light beam with the block, the counter automatically stopped, indicating the elapsed time. In the latch pickup experiments the experimenter started a stopwatch when the first part of the arm crossed a plane about one foot from the block defined by two vertical posts and stopped the watch when the latch first cleared the chassis it was mounted on.

Descriptions of the five experiments carried out are given below. The experiments, which consisted of either 40 or 80 pickups each, were performed by the one subject (JH) to whom the arm was fitted.

Experiment M1--Picking Up a Round Block

The time required to pick up a block was measured both with and without tactile feedback and with both local and remote viewing. The operator's view of the task is shown in Figure 17(a). In different parts of the experiment the operator either observed the arm's operation

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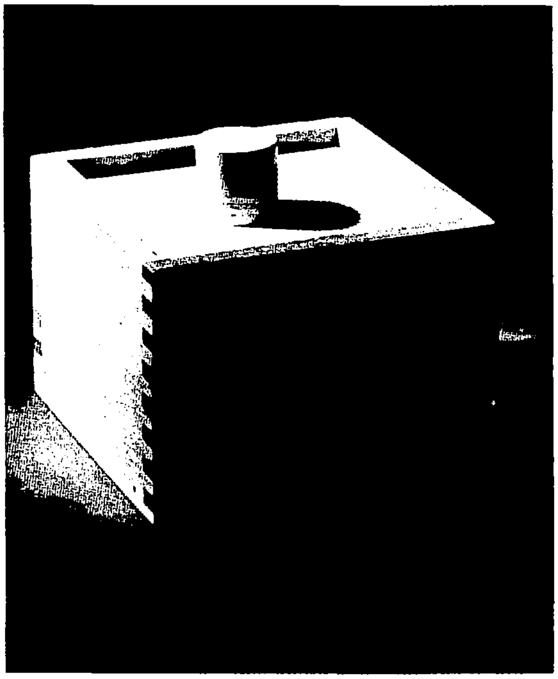
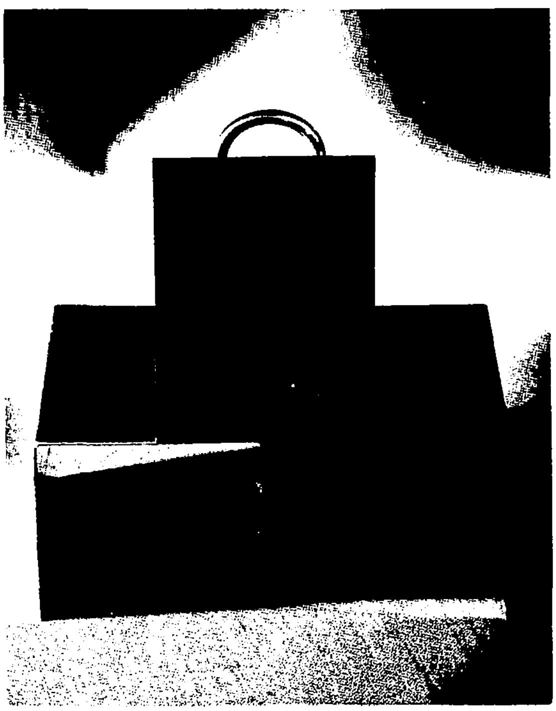
*The Kupu latch was developed by the National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California.

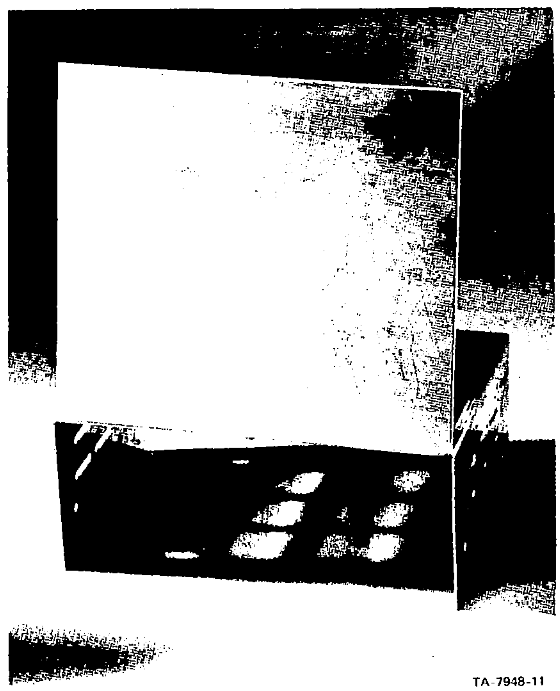


(a) ROUND BLOCK

(b) KUPU LATCH



(c) PARTIALLY OBSCURED LATCH



(d) COMPLETELY OBSCURED LATCH

FIGURE 17 OPERATOR'S VIEW OF THE REMOTE RETRIEVAL TASKS THAT WERE PERFORMED directly from a position a few feet away, or observed the operation remotely via a closed circuit TV system located in a separate room isolated from audible clues. In two other parts of the experiment the tactile feedback system was either turned on, providing force-distribution feedback, or turned off, providing no feedback. The testing schedule for the experiment (shown in Table VI) consisted of eight test sessions

Table VI

TEST SCHEDULE OF EXPERIMENT M1

<table>
<tr><th>Session</th><th>Visual Condition</th><th>Tactile Condition</th></tr>
<tr><td>Practice</td><td rowspan="2">Direct Viewing</td><td>Tactile Feedback</td></tr>
<tr><td>1</td><td rowspan="2">No Tactile Feedback</td></tr>
<tr><td>2</td><td rowspan="2">Remote TV</td></tr>
<tr><td>3</td><td rowspan="4">Tactile Feedback</td></tr>
<tr><td>4</td><td rowspan="2">Direct Viewing</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td><td rowspan="2">Remote TV</td></tr>
<tr><td>7</td><td rowspan="2">No Tactile Feedback</td></tr>
<tr><td>8</td><td>Direct</td></tr>
</table>

divided into two visual feedback and two tactile feedback conditions balanced so that linear learning trends during the experiment would not bias the results. Each of the eight sessions was continued until ten tasks were completed. If a drop or knockdown occurred, the task was aborted and a new pickup attempt was started.

Experiment M2--Picking Up a Round Block

This experiment is identical to experiment M1 except that only remote viewing was used. The operator, located in the adjacent room, either viewed the manipulator and block with standard, broadcast-quality TV or with the same TV system with white noise added. When noise was used, the RMS values of noise and video signals were approximately equal.

Experiment M3--Retrieving a Kupu Latch

This experiment is designed identically to experiment M2 except that the task is different. Instead of picking up a block, the modified Kupu latch shown in Figure 18 was removed from a metal chassis in which it was inserted. The latch has four spring-loaded prongs that protrude from its lower cylindrical body. Once the latch has been inserted into a hole, these prongs must be retracted by squeezing across its midportion in order to remove it. The task presented the operator is shown in Figure 17(b).

Experiment M4--Retrieving a Partially Obscured Latch

The time required to remove the Kupu latch partially obscured from view was measured in an abbreviated experiment similar to the previous three. The experimental situation as seen by the operator [shown in Figure 17(c)] permits only the top portion of the latch to be seen. In this case only four sessions with ten tests each were undertaken, using the remote, noiseless TV viewing condition. The four balanced sessions (feedback off, feedback on, feedback on, feedback off) varied the tactile feedback condition to measure its effectiveness. This task was more difficult than the simple removal of Experiment M3, having a completion rate of 85 percent.

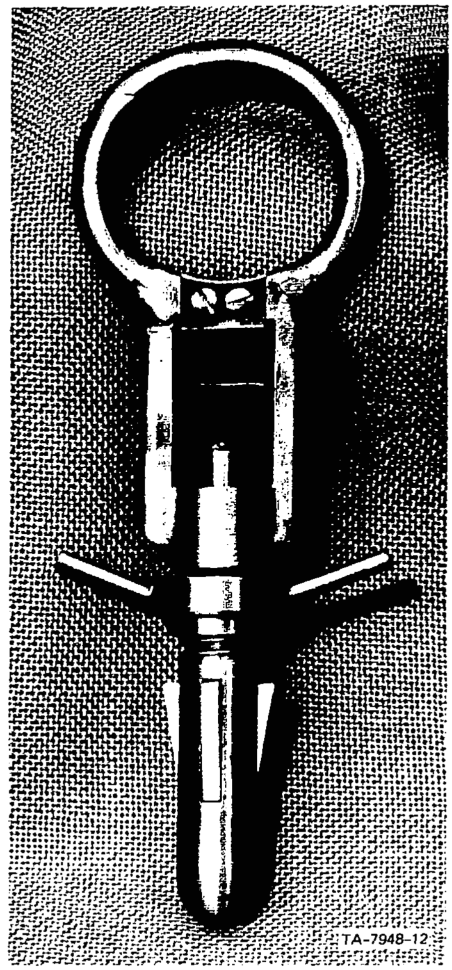


FIGURE 18 MODIFIED VERSION OF THE KUPU LATCH USED IN THE EXPERIMENTS

Experiment M5--Retrieving a Completely Obscured Latch

The time to remove a Kupu latch obscured from view by a metal screen was measured with an experimental design identical to that of Experiment M4. The operator used the remote TV station to control the arm and had the view of the task shown in Figure 17(d). Because of the low task completion rate (20 percent), this task was not repeated to obtain ten complete retrievals as in the previous experiments, but stopped after ten pickup attempts. Instead of the time to complete the task, other measures were used such as the completion rate and the number of false attempts and fumbles.

D. Results

For the first four experiments the task completion times were given analyses of variance to determine the significant variables. These analyses are shown in Tables VII through X. In all of the analyses the "Replications" refer to the first and second halves of the experiments.

Table VII

SUMMARY OF ANALYSIS OF VARIANCE OF THE TASK COMPLETION TIMES OF EXPERIMENT M1

Source	df	Mean Square	F Ratio
Tactile Feedback (T)	1	57.8	2.00
Visual Feedback (V)	1	858.0	29.7*
Replications (R)	1	44.7	1.55
T X V	1	12.8	--
T X R	1	108.1	3.74
V X R	1	28.1	--
T X V X R	1	37.3	1.29
Within Sessions	72	28.9	

*Significant at the .005 level.

Where different viewing conditions were used in the experiments, their effects were all significant (see analyses for Experiments M1, M2, and M3). The changes in task completion time for these experiments are shown in Figure 19 along with some other pickup times plotted for

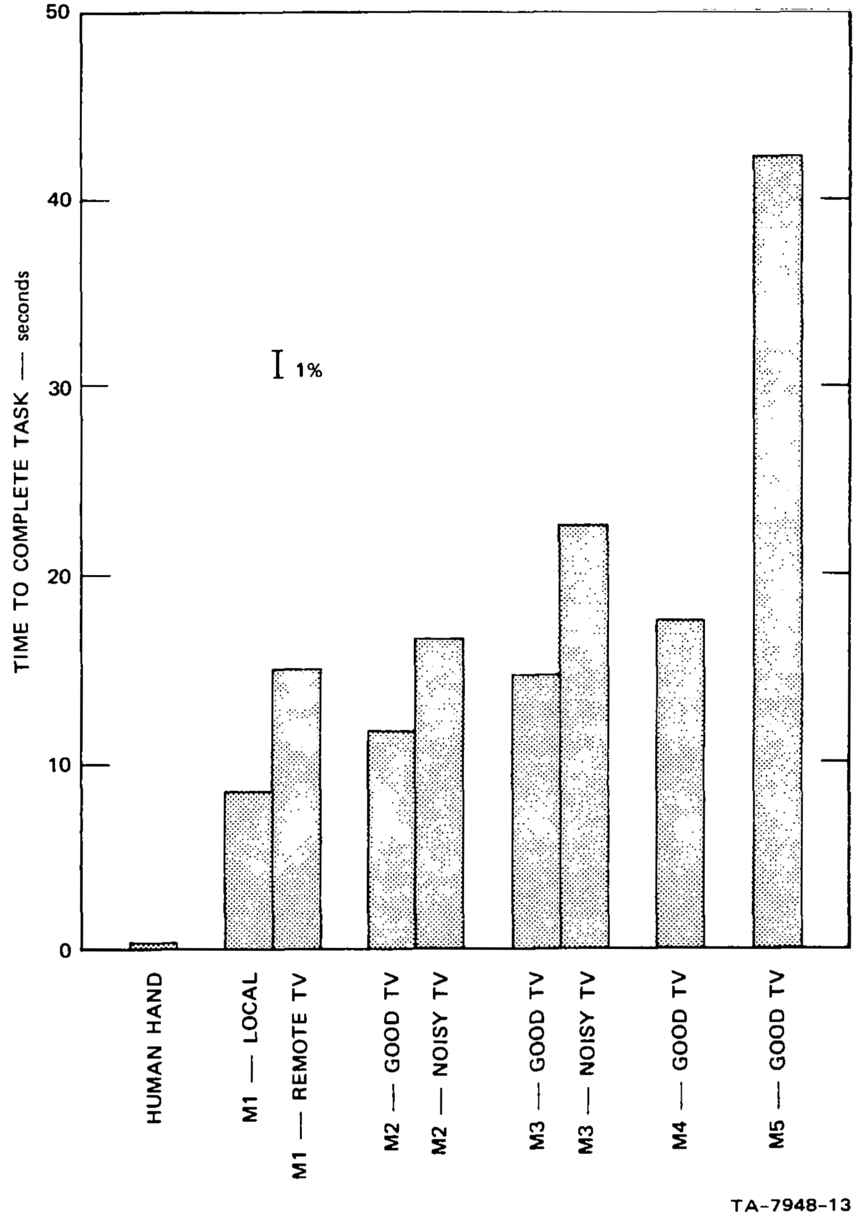


FIGURE 19 DEPENDENCE OF COMPLETION TIME ON TASK

Table VIII

SUMMARY OF ANALYSIS OF VARIANCE OF THE TASK COMPLETION TIMES OF EXPERIMENT M2

Source	df	Mean Square	F Ratio
Tactile Feedback (T)	1	18.6	--
Visual Feedback (V)	1	505.0	12.1*
Replications (R)	1	38.9	--
T × V	1	8.1	--
T × R	1	354.5	8.49*
V × R	1	53.7	1.29
T × V × R	1	7.3	--
Within Sessions	72	41.7	

*Significant at the .005 level.

Table IX

SUMMARY OF ANALYSIS OF VARIANCE OF THE TASK COMPLETION TIMES OF EXPERIMENT M3

Source	df	Mean Square	F Ratio
Tactile Feedback (T)	1	42.2	--
Visual Feedback (V)	1	1329.3	28.8†
Replications (R)	1	6.2	--
T × V	1	15.7	--
T × R	1	97.9	2.12
V × R	1	1.8	--
T × V × R	1	387.6	8.40§
Within Sessions	72	46.1	

†Significant at the .005 level.

§Significant at the .05 level.

Table X

SUMMARY OF ANALYSIS OF VARIANCE OF THE

TASK COMPLETION TIMES FOR EXPERIMENT M4

Source	df	Mean Square	F Ratio
Tactile Feedback (T)	1	0.60	--
Replications (R)	1	31.86	--
T X R	1	0.87	--
Within Sessions		76.45	

comparison. The time for picking up a block with a human hand (0.4 s) represents a lower time limit for these tasks. In addition, the average completion times for Experiments M4 and M5 (retrieving the obscured or partly obscured latch) are shown.

None of the task completion times significantly depended on the tactile feedback conditions, even though the task completion times for all of the four experiments were shorter with the tactile feedback system on. This small, but regular, time reduction averaged 7 percent for experiments M1 through M4. To investigate the influence of tactile feedback further, two other variables that were tabulated in the experiments are given in Tables XI and XII as a function of the tactile feedback.

Table XI

PERCENTAGE OF TASKS COMPLETED

FOR EXPERIMENTS M3, M4, and M5

Condition	M3	M4	M5
Tactile Feedback On	100%	95%	80%
Tactile Feedback Off	83%	75%	40%

Table XII

NUMBER OF PICKUP ATTEMPTS THAT FAILED

FOR EXPERIMENTS M3, M4, AND M5

Condition	M3	M4	M5
Tactile Feedback On	1	9	26
Tactile Feedback Off	7	23	41

Both the percentage of completed tasks and the number of failed pickup attempts depended strongly on tactile feedback condition and on the difficulty of the task.

The main failure in the latch removal experiments (M3, M4, and M5) was due to the manipulator tongs slipping and pushing the spring-loaded release spring off of the release button, rendering the latch unremovable. The number of tasks without this failure was computed from the first 10 attempted tasks of each session to obtain the entries of Table XI. Although the change in completed tasks brought about by the tactile feedback system is small for unobscured removal (Experiment M3) it grows with obscuration and is very large for the completely obscured case (Experiment M5).

Another effect noticed in the experiments (particularly in Experiment M5) was that the value of tactile feedback depended on the novelty of the task. For example, during the first session of Experiment M5, two of the ten trials were successful (20 percent), but during the second session with tactile feedback turned on, eight of the ten trials were successful (80 percent). Thereafter about 65 percent were successful, independent of whether tactile feedback was supplied. These results suggest that tactile feedback is important for exploratory work with remote manipulators where the tasks are highly variable or perhaps unknown ahead of time.

After the operator performed the identical task 20 times in a row, tactile feedback is not nearly as important.

Two strategies for removing the latch developed during the experiment, explaining the data shown in Table XII and probably explaining the insensitivity of the total task time to tactile feedback. With tactile feedback turned off, the method of retrieving the latch was (1) to place the tongs around the latch using only visual feedback, and then (2) to grasp the latch and attempt to lift it out of the metal chassis. If the attempt failed, the procedure was recycled until the latch was either removed or accidently disabled. With tactile feedback turned on, the method of retrieving the latch was (1) to position the tongs similarly using visual feedback and then (2) to grasp the latch and feel its shape. If the crossbars and sheet metal release were felt, then an attempt would be made to lift the latch; otherwise an attempt would be made to reposition the tongs and feel again. After the release button was felt, an attempt to lift the latch was made.

Table XII shows that the number of unsuccessful pickup attempts is considerably higher with the tactile feedback turned off. The reason that the increased number of attempts did not increase the overall task time is probably due to the increased number of feeling attempts with the tactile feedback system on: the operator was apparently trading pickup attempts for sensing attempts. When the object is fragile, or hard to find, or requires accurate positioning to be picked up, then the tactile feedback system increases efficiency, as shown in Table IX.

E. Conclusions and Recommendations

These results indicate that the success and confidence with which the operator could perform the tasks was much greater with tactile feedback than without. Tactile feedback was more beneficial under the poorer visual conditions and provided highly useful information that required a relatively low bandwidth channel.

These results warrant further development of tactile feedback systems for remote manipulation. During the course of this project a number of possible improvements to the current system occurred to us, some of which are described below as recommendations for future work.

1. Distribution of Force on Tongs

Even though our simple spatial relay has aided performance, it has some shortcomings as a display system that can be improved upon to make operations with it more efficient. We recommend making the pick-up pad the same size as the gripping area of the tongs and mounting one pad on each of the contacting tong surfaces. These changes would eliminate some insensitive areas of the current sensing pad and further eliminate some instances where ambiguous information was displayed to the operator. In addition, the system would be more efficient (requiring fewer vibrators and pickups) if a nonuniform distribution of transducers were used. We recommend doubling the density of pickups and of corresponding stimulators on the fingertip area as compared to the rest of the finger, as shown in Figure 20. These different pickup densities would provide the fingertip,

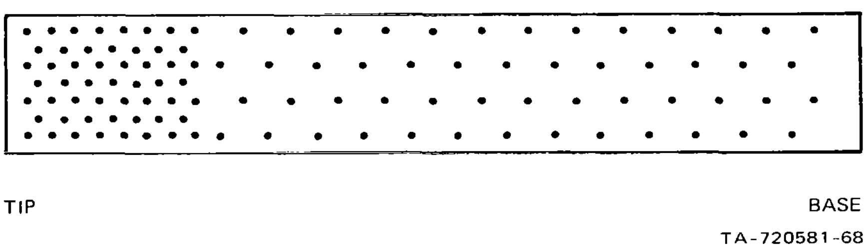


FIGURE 20 NONUNIFORM DISTRIBUTION OF FORCE SENSORS AND STIMULATORS

which has higher spatial resolution than the rest of the finger, with more information and hence could provide increased ability to handle small objects.

The construction of the previous pickup pad, consisting of a sheet of conductive rubber over individual metal pins, has proved very rugged and reliable and could be used in the new pads. Since contact resistance depends on the overall force pushing the pins against the rubber, this pickup can additionally be used in a proportional display where vibration intensity is made proportional to the force on the contacts. The piezoelectric vibration transducers used in the current tactile display have proved to be very reliable and adequate for presenting detailed tactile information in this and several other devices (Bliss, 1969, Linvill and Bliss, 1966, Bliss et al, 1970). Therefore, we recommend construction at two of these tactile displays for presenting spatial information to the operator's index finger and thumb. These displays built into the control arm would present the force-distribution pattern on both gripping surfaces of the tongs to the operators' fingers using the distribution of sampling points shown in Figure 20. This system would provide a unique one-to-one correspondence for touch between the remote arm and operator that has not previously been implemented.

2. Contact Force on Hand

After several preliminary experiments with the Rancho Remote Manipulator, it became apparent that contact between the outside surfaces of the tongs and the object to be gripped, or other nearby objects, would facilitate operation. Contact information very often is unobtainable from the video monitor simply because the remote hand is in a position where it obscures the necessary view of the object. This helpful contact information can be simply obtained by constructing sensing plates on the tongs that produce electrical signals when a small force is applied to them. These signals can be used to turn on tactile stimulators at the corresponding locations on the operator's hand.

Appropriate locations for contact sensors are the tips, sides, top, and bottom of the tongs and the sides, top, and bottom of the "hand," as illustrated in Figure 21. There are several alternative means of constructing these sensors, including strain gauges, conducting rubber, microswitches, and protruding whiskers. These different methods of instrumentation should be compared to determine the most appropriate for evaluation experiments. Tactile stimulators mounted on corresponding parts of the operator's hand (thumb, fingertip, finger, and wrist) would notify him in a straightforward, easy-to-learn manner when and where a contact was made. Although the tactile stimulators used may be either piezoelectric vibrators or airjets, the airjets are easy to position and inexpensive, hence, in an experimental situation, the most versatile. Only a small amount of hardware is necessary to position the jets and their effect is undiminished over stimulator-to-skin spacings of 1/16 to 1/4 inch. The airjets could be mounted on a glove the operator wears or attached directly on the control arm with adjustable mounts.

3. Overall Force Feedback

Force feedback--the transmission to the operator's arm--of the forces of the remote arm acting against objects is beneficial in many applications and essential in others (Flatau, 1969). In addition, force pickups can measure the weight of an object and tell the operator what kind of forces will be necessary to move it, perhaps indicating that the operator must switch to higher power levels, change his strategy, or even risk high forces that will damage the arm. In a time-delay situation, however, such as remote operations on the moon, conventional force feedback is the source of oscillations in the manipulator control loop. As an example, consider picking up a heavy load on the moon using a teleoperator with force feedback: only some time after the lift will the operator feel the reflected force. The reflected force will jerk his arm, inserting yet another transient into the system. In experiments with a time-delay system, Sheridan (1970) found that conventional force feedback had to be turned off for the operator to perform reasonably.

There are several ways of providing equivalent force feedback for the operator that do not interfere with his motions in a time-delay control situation. One is to scale down the force feedback so that it is still perceivable but not strong enough to interfere with the operator's movements. A second method is to present the feedback information via vibrators to different parts of the operator's arm. Two vibrators could be provided for each degree of freedom as used for position feedback in the Boston Arm (Mann and Reimers, 1970); or the total force acting on the arm could be resolved into three coordinates and presented on a display with six vibrators. A third method, similar to the second, uses static feedback forces applied orthogonally to the control motions. An example of such a force is pinching across the arm, a constricting band placed around the arm, or a single force moving up and down the axis of the arm (position display). These orthogonal presentations may give the operator the usual proportional information--thus speeding operation--without its drawback, oscillation, while operating with a time delay.

We recommend constructing simple versions of these orthogonal force feedback systems only on the tong motion of the Rancho Remote Manipulator to study their feasibility and usefulness. If one of these methods proves to be useful, it should be considered for transmitting forces for the two wrist motions.

4. Slippage Sensing

The method used by human beings to pick up fragile objects without breaking them is to apply a minimal gripping force and then attempt to lift the object. If the object begins to slip, the grip is then tightened until slipping ceases. A person can sense slippage both visually and tactually when lifting an object himself; however, when operating through a remote manipulator, he has only a visual display of limited quality from which to deduce this information. Using the proper pickup and tactile display devices, information on slippage can again be provided to the manipulator operator to facilitate his performance.

Slippage can be measured by means of a perpendicular force transducer embedded in one of the tongs of the manipulator (Ring and Welbourn, 1968 and Tomović, 1969). When slippage begins there is a large, high frequency vibrational component in the perpendicular force that can be picked up, amplified, and supplied to the operator on different types of displays. This vibration could be supplied directly to the operator's fingers by a special vibration transducer or possibly supplied on the force-distribution display already on the operator's fingertip. In the latter case, after gripping an object, the operator would switch, or perhaps have automatically switched, the piezoelectric vibrator display from the force-distribution mode to a new vibration mode. The intensity of the vibrators, acting in unison, would reflect the intensity of slippage picked up on the arm.

Still another means of providing slippage information is by signalling the operator only when the force distribution on the tongs changes. This information, essentially the time derivation of the force distribution, could be automatically or manually turned on after a jaw closure. The initial force pattern would be removed from the stimulator array and stored in an array of flip-flops, or a computer memory. If, during the subsequent lifting attempt, the force pattern changed (any closed contact opened or any open contact closed) then only these changes would be presented to the operator on the distribution display. If no slippage resulted from the pickup, then there would be no vibration felt by the operator, but if some slippage resulted, the operator would feel the edges of the object that moved.

IV COMPUTER TECHNIQUES FOR ON-LINE EXPERIMENT CONTROL*

The development of our LINC-8 computer facility for on-line experiment control has concentrated principally on the development of software. Just prior to the beginning of this contract, we had acquired a disk memory unit. Thus one of our tasks was to install into our software the proper interfaces to the disk. The interface at first used a call to the resident different from that used to access files on magnetic tape. The diagnostic program supplied with (and for) the disk was incompatible with our resident and was not specifically oriented to our acceptance criteria, so for those reasons, as well as to debug the resident's interface and to gain some experience with the disk, we wrote a diagnostic program to run under the resident's control. Then, to aid our course of development of the software, we obtained the services of another programmer. The first tasks in this regard were to acquaint her with the philosophy behind the software and its current state so she would be equipped to assist in writing its next generation.

A. Goals of the Software System

The major work on this project was involved with the design and implementation of our new software. There were three major areas of change, the first of which centered about the file structure. Our former software had a rather rigid file structure that was bearable because it

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was not necessary to stay within it. However, we anticipate the accessibility to the computer of data to which we do not wish to give arbitrary programs arbitrary access, and we desire the ability to freely move data about within the computer's storage media without necessitating any programming changes. Moreover, we strongly feel that flexibility should be provided gracefully by the resident instead of painfully building partial flexibility into each program. Thus we wished to give our system a structure of files flexible enough to be used as the sole root of access into the storage media. One of the obvious shortcomings of our previous file system was that it contained only two file directories: one to programs and one to manuscripts (text files); and the only logical subdivisions of a manuscript are the line of text and the character.

1. Subfiles and Pages

Our new filing and text-handling systems contain more levels of accessibility, based on the new concept's subfiles and pages, respectively. Any file can contain a file directory whose entries describe files completely contained in that file. These are called subfiles of that file, and their being files themselves permits them to have subfiles, and the process can go on indefinitly.* Any manuscript, on the other hand, contains some amount of text (usually between 30 and 500 lines) and can have intermediate divisions called pages. With few

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*Subject to restrictions of space. Subfiles of a file each contain at least one record; they are wholly contained in the file of which they are subfiles; they overlap neither each other nor the directory defining them. In any file containing subfiles, the first record of that file is the directory defining the subfiles.

restrictions,* page boundaries can be placed anywhere in the manuscript at the discretion of any person writing (or altering) the manuscript. Thus we have introduced two new kinds of addressing subdivisions into the file structure, and to a large extent, the way they are used depends solely upon the person or persons using them.

Two advantages gained from the concept of pages are the ability of any person modifying a manuscript to guide the listing program in its division of the manuscript into 8-1/2 X 11 inch sheets and his concomitant freedom, by using pages as addressing subdivisions, to enable one to easily find one's way through the manuscript. For example, after changing a page of a manuscript, one can update one's listing thereof by listing only that one page. On the other hand, subfiles as we have implemented them and as we use them give one the capability of restricting the context within which a specific program operates. This can be useful for debugging purposes, and it can enable one to use a given name to mean different things in different contexts. For example, one might wish to have the hypothetical commands "run slime" and "edit slime" refer to a program and a manuscript named "slime," respectively. Both these facilities can be used to several more ends in addition. Both are conducive to the formation (and maintenance) of libraries; the elements of a library could be pages of a manuscript or subfiles of a file. Again, either could be used to subdivide experimental parameters into groups adapted to individual experimental sessions, and these groups would now be easier to maintain in an orderly fashion because they are grouped

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*Those restrictions are:

(1) Each page contains an integral number of lines, at least one but no more than 2047;
(2) The first page begins at the beginning of the manuscript; and
(3) The last page ends at the end of the manuscript.

together on a different level. Finally, both facilities greatly help in utilization of file storage: the subfile organization increases the number of filès that can be kept in a given area allotted to file storage without increasing the number of entries a directory can contain; and by using pages of a manuscript as submanuscripts, one can have the effect of multiple manuscripts without the fixed part of the overhead of the editor's control information--in the case of short manuscripts (where this would be most useful) this storage overhead can be more than 70 percent.

2. Character Set

The second major area of change was that of character sets. The character set formerly used* was very far from universally accepted and was decidedly lacking (by modern standards) in control functions, the most sorely missed of which were a tabulation, a page mark, and marks to show the functional ends of a transmission block (record) and a manuscript. As a suitable alternative, we chose a character set closely derived from USASCII; this gave us those extra control functions (and potential for great expansion), permitted us to use the teletypes attached to the computer without the overhead of memory space and programming time formerly incurred by the needs to transliterate characters, and permitted us to use the formerly inaccessible printing characters on these instruments.

The Six Bit Universal Random Character Set (SBURCS) is a particular six-bit contraction of USASCII. It is a contraction of ASCII

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*The manufacturer-supplied character set was one used with the LINC computer and consisted of the letters and digits, as well as 16 punctuation marks especially tailored to the LINC.

since, because of the widespread acceptance thereof, our character-set-dependent hardware uses it. Thus to use a non-ASCII-derived character set, as was previously the case, we would need even more elaborate (and thus costly of memory space) transliteration routines than that currently used for compatability or would need to contend (as we do now for compatability) with having several different character sets for different purposes, with attendant confusion and waste of time. Because equipment fitted out for ASCII is used here as well as in a widespread community of computer people, it is somewhat desirable to be able to use all the graphic representations available on the equipment. Finally, it was desirable to increase the number of control functions specifiable in a text string, and ASCII is amply provided with useful control functions.

One may ask why ASCII was contracted to SBURCS instead of being carried around with its full 8-bit width--this would have saved 44 words (2 percent) of the resident. However, the six-bit contraction permits characters to be packed two to a word, thus halving the size of text strings in a program and substantially compacting files. Incidentally, the LINC has halfword-oriented instructions, thus causing halfword packing to be attainable at little or no additional overhead. Given the desire to use a six-bit contraction without losing the extra control functions, it was necessary to establish a case-shift convention. Based on expected usefulness, a character (%) was chosen as a case-shift character, and there remained only to decide the usage thereof. Since most characters in our text strings are printing characters, and because of the nuisance (and bugs) surrounding initialization conventions, it was decided that the case-shift character would affect only the character immediately following it. The final convention chosen was the algorithm by which the spacing characters are converted between ASCII and SBURCS, the control characters converting in a computationally expedient way.

On the LINC, it seems easier to generate a zero than any other given bit pattern, and thus considerations of ease of initialization (e.g., of text buffers) lead the character code for a blank (space) to be chosen as zero. This left only computational considerations to form the final configuration of SBURCS.

3. Block Structure

The last major change in the software was the least sweeping of the three; it is concerned solely with the process of formulating programs for translation to machine language. In order to increase flexibility, it is useful to be able to divide a program into units, called blocks, with the property that any name is meaningless (and thus available for contradictory use) outside its block. Blocks can be contained in other blocks, and as long as a block doesn't establish a new (and contradictory) use for a name, all names mean the same within it as they do in the block containing it. The implementation of this concept, called block structure, is conducive to more easily modified programs because more things can be named, and names can be used more freely because one can be less concerned with possible other uses of a given name. At the end of a block then, any names local in scope to that block need no longer be remembered; thus the memory space used to remember them can be recovered to remember other names.

B. The Resident

The software system we have evolved consists of two parts: the resident and the nonresident. The resident is so called because it stays in a specific part of memory for days at a time. It provides general-purpose functions to be used by the programs (called object programs) more properly thought of as running on the computer. Almost all input and output is done by the resident, as called upon by the object programs, and the face presented the object programs of this work is considerably more program-oriented than the face seen by the resident itself. The nonresident, on the other hand, is simply a collection of object programs, each of which is general-purpose in function but no function of which is urgently enough needed to require its inclusion in the resident.

The modifications to the resident can be grouped into two broad classes--functional and technical, the distinction being one of the degree of outward visibility of the modifications. The most important aspect of the functional modifications was the establishment of complete compatibility in the sense that it is now possible (and even easy) to write programs having all the characteristics desired for eventually time-shared programs. Of course the most important part of this is that the resident can use the file system as fully conceptualized and that the file system does in fact give enough capability that no parallel method of access to the storage media need be used. The other principal new functional capability is that the nonresident system can at last move about in the storage media as it wishes. This flexibility will probably not see heavy use, but it is a very important one.

On the more technical side, the resident has been generally cleaned up and made quite coherent and readable, thus enhancing its readiness to accept modifications. Along with this cleanup, the interface software for the teletypes was rethought and generalized, a swapper was installed in the scheduler, and in general the time-sharing capability was provided for and barred only by lack of space for expansion of tables. When we cut off compatibility with our previous system, we will finally be able to expand those tables. Finally, the new resident has functioned admirably well as a test bed for the new methodology.

C. The Nonresident

The nonresident system can be viewed as consisting of three parts: the file-manipulating part (with some general-purpose utility programs), the text-handling part, and the program-handling part. The first of these parts consists of a program called the Iceberg, which manipulates file directories, and several file-copying routines, which will not be further discussed. The principal text-handling program is the editor, and subsidiary to it are a program to easily type out the contents of a manuscript in an appealing format and MUNG, a program to clean up a manuscript. There are two main programs in the program-handling part: KOS, the loader of programs, and the assembler, its link to the text-handling part. The rest of this section will slightly expand on these parts of the nonresident software.

1. File Handling

The Iceberg handles subfile directories. (There is another format of file directory, but directories in this format although important, will not often be altered.) It has the feature that it will make an initialized directory when asked to manipulate entries in a nonexistent directory. It also keeps the subfiles of a file separate from each other--it can in some cases be useful to overlap subfiles, but this capability is not provided by the Iceberg.

2. Text Handling

In the text-handling part, the editor is the principal part, the one permitting alteration of the text. It addresses the text by page number and line number within that page, and it has two commands to manipulate page marks. One of these commands causes insertion of a page mark before the current line, and the other removes the page mark starting the current page. Of course, both of these functions are subject to the aforenoted restrictions (see footnote to Section IV-A-1) and also cause automatic renumbering of all succeeding lines on the current page and of all succeeding pages. Thus flexibility is enhanced as much as possible. The listing program (not part of the editor, solely because of memory space limitations) types a manuscript in 8-1/2 inch X 11 inch sheets, each of which has a heading containing the manuscript's name, the page number, the sheet number of that page, and several dozen characters' worth of information supplied by the person using the lister. Lastly, MUNG can read text in a format easily generated by experiment-running programs, and it writes a manuscript containing control information and blocked for the editor. (At this point it might be noted that the easiest way to make a program read a manuscript will cause it to ignore this blocking and control information.) MUNG also has the capability of merging several manuscripts into one, leaving page boundaries as vestiges of the old manuscript boundaries, thus giving a powerful and flexible grip on the structure of the text. A feature to be added is that MUNG be able to optionally select pages from its source files, thus increasing the utility of the system.

3. Program Handling

In the program-handling part of the nonresident, KOS (the program loader) occupies a very powerful position. By virtue of the subfile facility, it can easily and does draw upon several libraries of programs. Thus the maintenance of libraries of programs is much less cumbersome than was previously the case. Moreover, this effect is further enhanced by the fact that we can now have public and private libraries, where formerly we had at first a system with only a private library (which had to contain <u>all</u> programs) and then a system with a single public library and a single private library (which also contained all manuscripts). In addition to this powerful flexibility, whenever KOS loads a program, it can as it sees fit (and in practice must) designate a file directory (somewhere in its universe of files) as the root of the universe of files for that program. (The selected directory is usually a subfile directory.) Thus not only does KOS select a program from several libraries thereof, but it selects a library of data for that program to operate upon.

The assembler translates manuscripts containing a program in a textual form to programs in "machine language" (a form usable by KOS). As previously mentioned, this involves a capability for the use of block structure in the assembly language version of a program, which simplifies the problems in formulating a program. Another useful property of this assembler is its capability to accept a string of manuscript names for the source of the program, thus permitting a program to be broken as convenient into manuscripts, which can be put together in different ways for different programs. Of course, the division of a program into blocks is independent of its division into lines, pages, and manuscripts. For technical reasons, the assembler is broken into two parts, one translating the manuscripts (assembly language) to an intermediate form, the other translating the intermediate form to machine language. This latter part will soon be able to place the machine language version directly into a KOS library.

D. Conclusions

A system of software for our LINC-8 facility has been described. This system has been especially designed for experiment control. Even though the system is based on a small computer, the addition of a disk memory unit together with this software system removes many of the programming and operating restrictions typically found in small computer installations.

Some further work on the system is still required before we have full use of its major capabilities. This mainly involves cutting off compatibility with our previous system, thus enabling expansion of the resident tables and operation in a time-sharing mode. We hope to complete these steps soon.

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