FACTORIAL STUDY OF REMOTE MANIPULATION
WITH
TRANSMISSION TIME DELAY

by

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In partial fulfillment of the requirement for the degree of Master of Science

The effect of a transmission time delay on the performance of manipulation tasks with a six-degree of freedom master-slave manipulator was studied. Task completion time was the measure of operator performance.

A feedback delay of 3.5 seconds was generated by video tape. Three subjects were tested on three manipulation tasks, each having a large and small scale. For purposes of analysis the tasks were segmented into three components: "get," "transport," and "position." Completion times for the total task and for the segments were measured and in the case of delay, the observed number of waits for feedback was recorded.

The study confirmed that six degree of freedom manipulation was possible and effective with a "move and wait" strategy. Analysis of the data showed that delay most affects the portions of the task requiring greatest precision; feedback delay consistently increased the fraction of the total task time required by the "position" segment.

Ferrell's conclusion that completion time with delay was linearly proportional to the number of waits for feedback was confirmed and extended to conventional manipulators.

The study also permitted several recommendations for manipulator system design.

Thesis Supervisor: Thomas B. Sheridan
Title: Professor of Mechanical Engineering

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INTRODUCTION

Current and future explorations of the hostile environments of outer space emphasize the need for remote mechanical devices which extend man's reach without endangering his health. These remote manipulators would permit man to assemble or repair equipment and perform experiments or collect samples through protective barriers of matter and distance (see Figure 1).

However, remote manipulation at great distances is handicapped by feedback time delays due to limited signal transmission speed (in addition to dynamic lags, processing delays, etc.). The operator's control action and the indication on his display of the manipulator's response are separated by a time delay equal to the round trip signal transmission time plus any processing delays. For example the round trip signal time between earth and moon via synchronous relay satellite is five to six seconds.[1]

Ferrell[2] performed several experiments which indicated that a human operator using a position-controlled "minimal manipulator" could perform simple tasks, requiring considerable accuracy, when there was a transmission delay. The operators adopted a "move and wait" strategy; that is, they sequentially moved open loop and waited a delay time for feedback. Ferrell found that the operators used move and wait so consistently that the completion time for both a simple or complex task was predictable knowing the amount of time delay, completion time without delay and number of open loop moves required when there was no delay. He also showed that task completion time was proportional to the information index of difficulty (log of movement time over terminal tolerance distance).

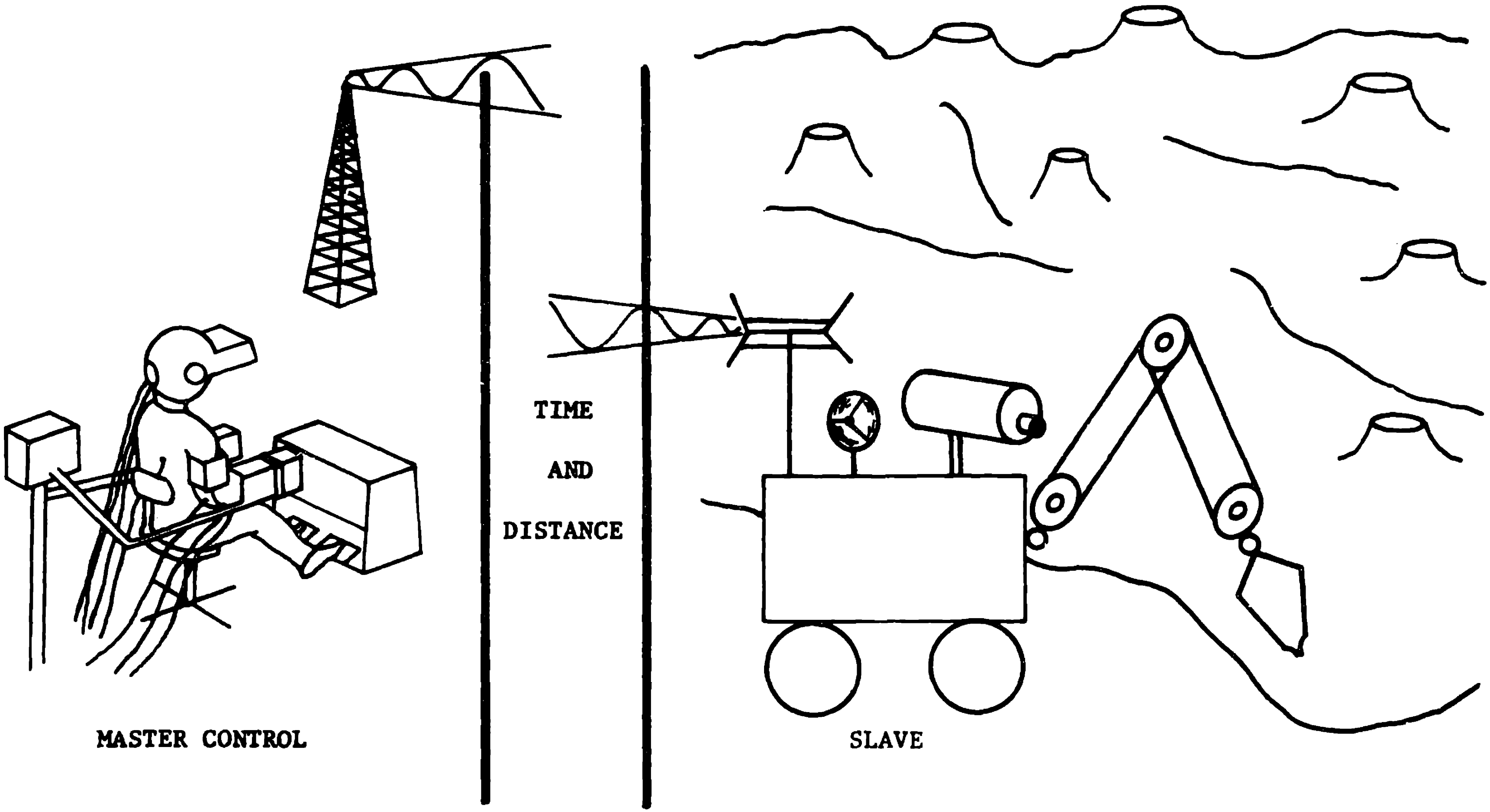


FIGURE 1: CONCEPTUAL DESIGN OF MASTER-SLAVE MANIPULATOR FOR SPACE EXPLORATION

Though Ferrell's results were clear and conclusive, they were based on experiments with his "minimal manipulator," a rudimentary three-degree-of-freedom (X,Y and grasp) device.

This study attempted to extend Ferrell's results to more conventional six-degree-of-freedom manipulators. Video tape recorders were used to generate a 3.5 second feedback delay. Three subjects performed three tasks, with two scales, by controlling a master-slave manipulator. Figure 2 is a schematic of the experimental setup.

For a thorough analysis of delay's affect on manipulation, each task was segmented into three components: "get," "transport," and "position."[3] The study attempted to determine the relation of the task segments to total task time and to determine how this relation changed with delayed feedback.

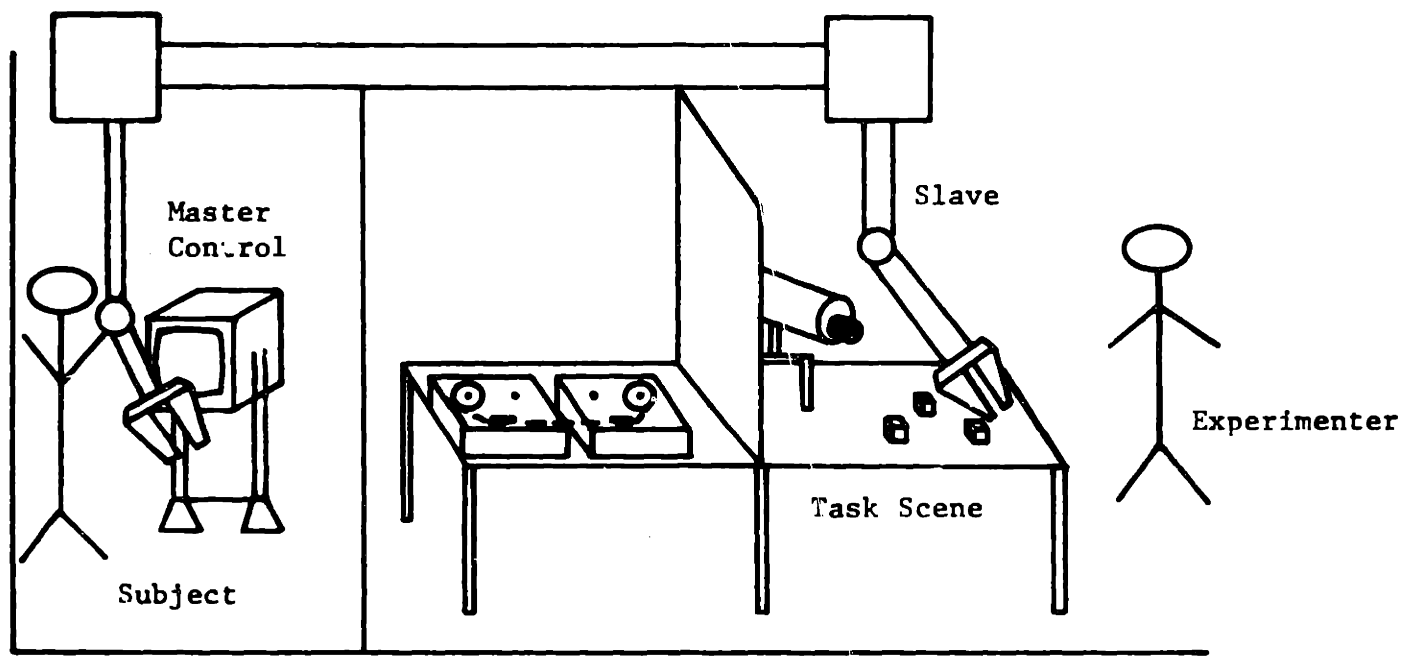


FIGURE 2: SCHEMATIC OF LABORATORY SIMULATION OF REMOTE MANIPULATION WITH TRANSMISSION TIME DELAY

DESIGN OF THE EXPERIMENT

A. SIMULATION EQUIPMENT:

The subjects performed the assigned remote manipulation tasks by controlling a right-hand, six-degree of freedom, Argonne E-2 master-slave manipulator. (See Figures 3 and 4.) This manipulator, an electro-mechanical servo mechanism is kinematically isomorphic to the operator's arm and hand. The device is well balanced and responds to the human operator's arm and hand motions with sufficient speed and accuracy that tracking errors can be considered negligible for this study. Thus, complex tasks could be accomplished easily and accurately (except the effect of delay when imposed) with nearly natural articulation.

Normally, the E-2 manipulator is bilateral: A force or motion applied at the slave hands will produce a similar force or motion at the master (force feedback). However, for the experiments in this study, the force feedback capability was suppressed, so that the E-2 functioned only as a unilateral manipulator.

Viewing of the task scene was via a conventional closed-circuit video system with 250 lines nominal resolution. The chief components were a Craig vidicon camera with 12.5 mm lens, two Sony CV-2600 0.5 inch video recorders, and a Setchell 19 inch monitor.

The camera was mounted two feet above the plane of the task objects (as shown in Figure 5) and focused on the task operating area (approximately twenty-four square inches). Intense lighting allowed a small lens aperture (f22) to provide sufficient depth of field. Camera angle was controlled by a joystick at the subject's fingertips (left hand).

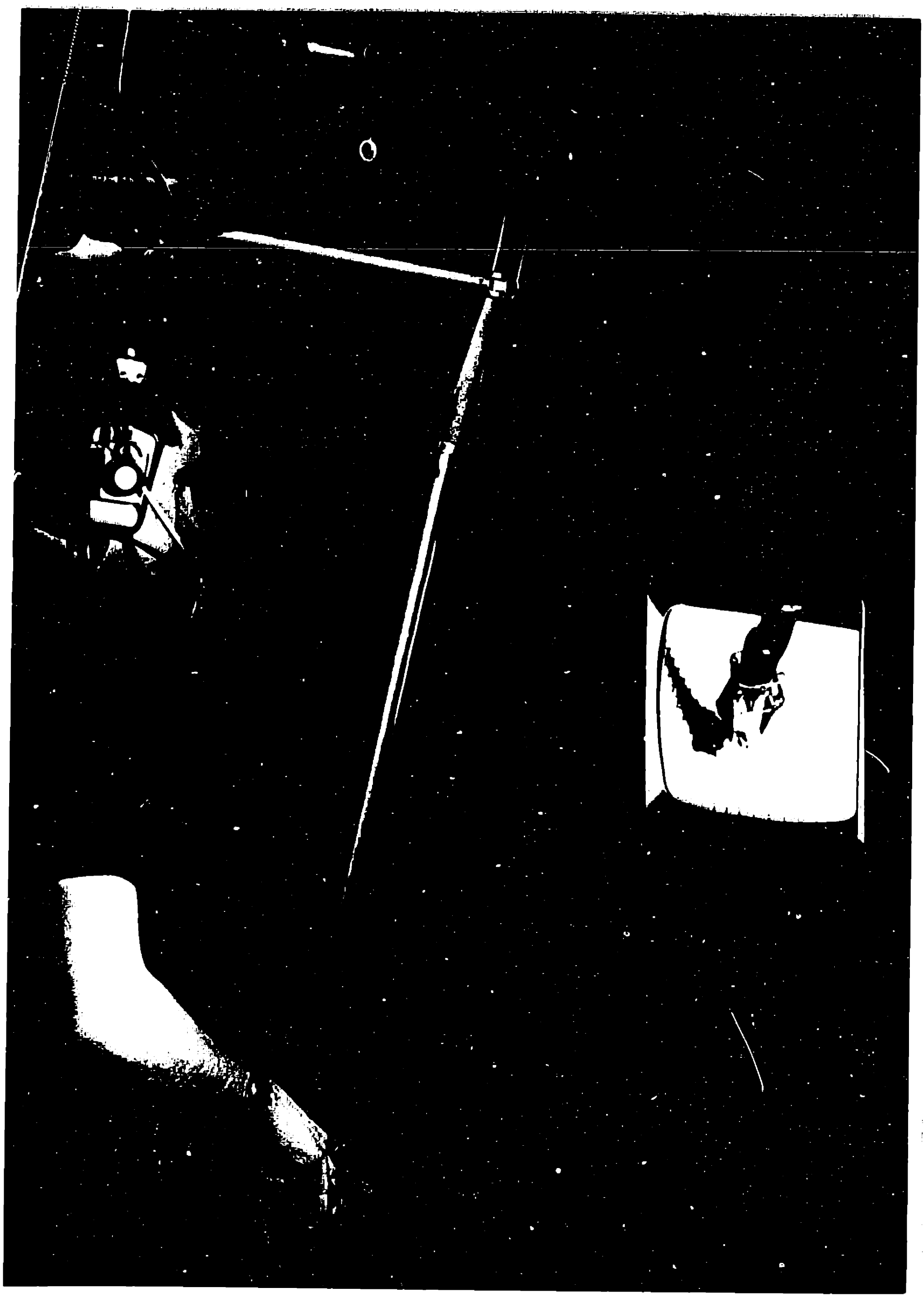
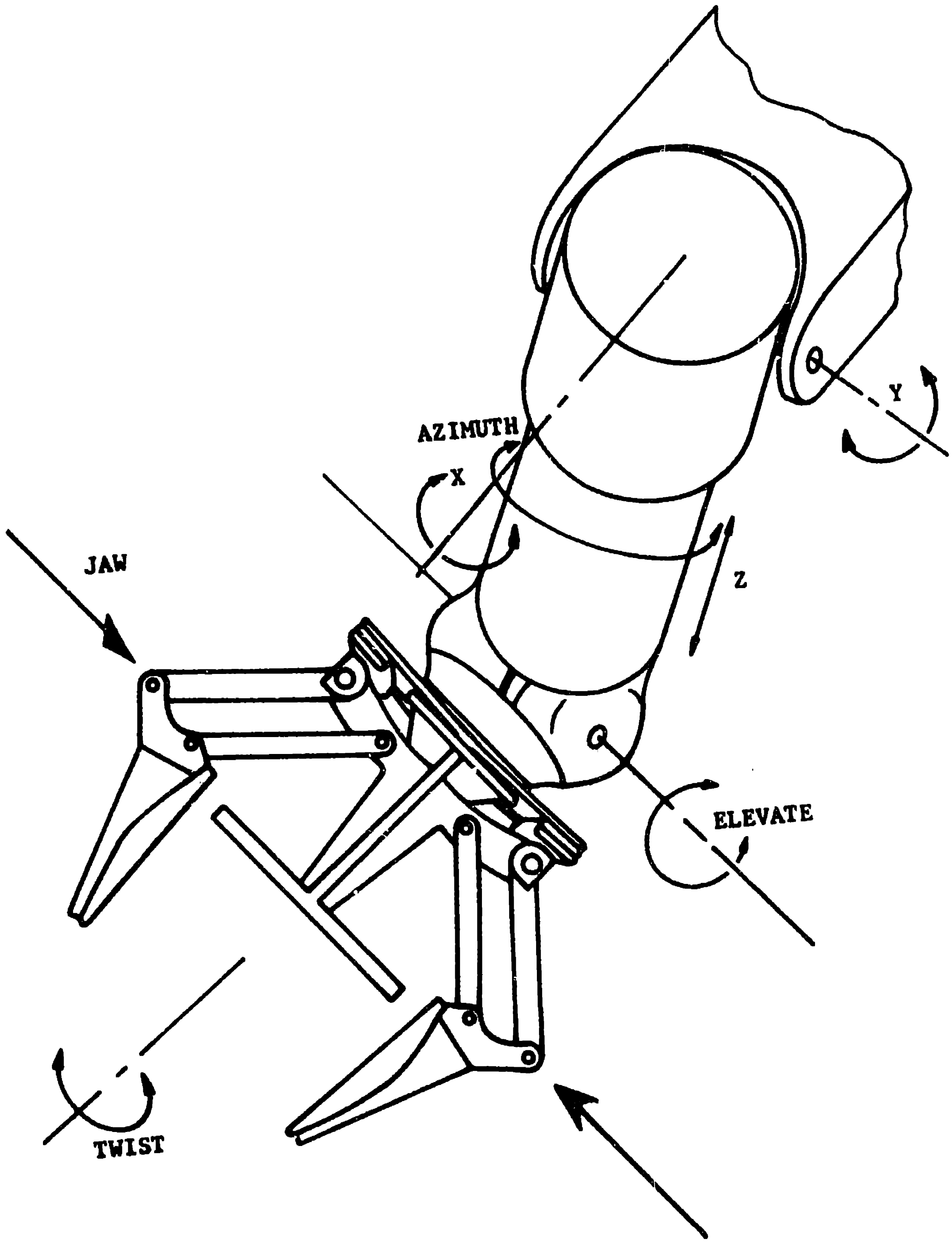


FIGURE 3: MASTER CONTROL AREA

FIGURE 4: E-2 MANIPULATOR DEGREES OF FREEDOM



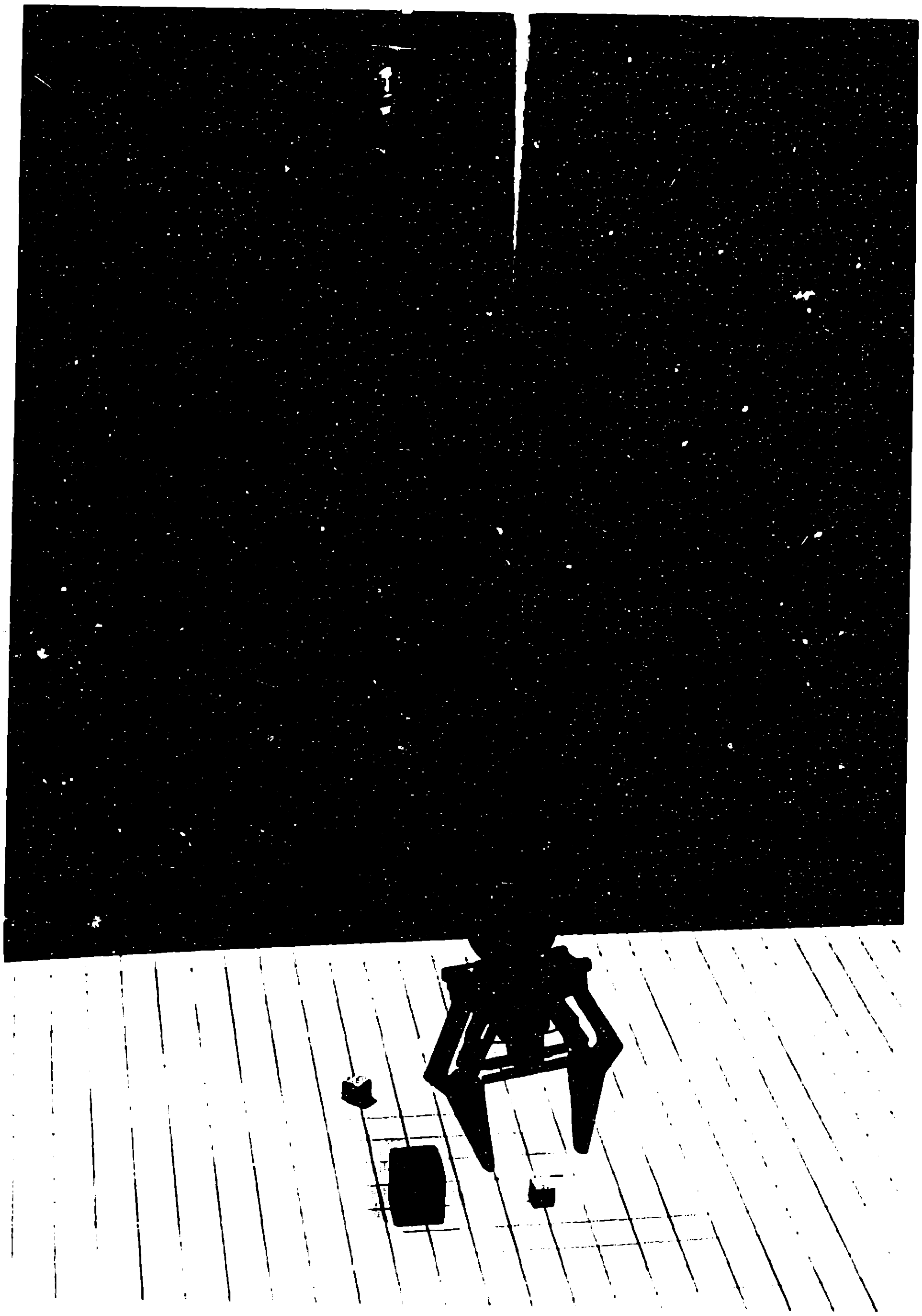


FIGURE 5: MANIPULATOR SLAVE OVER TASK SCENE

The two video recorders were used to generate a transmission time delay simulation. Their mechanical and electronic compatibility permitted video tape to be threaded from the supply reel, around the head and through the transport of the first recorder, then to the head, transport and takeup reel of the second recorder. Figure 6 illustrates this configuration. By simultaneously recording the camera's video signal with the first recorder and playing back with the second, the television image was delayed, simulating a transmission time delay. The length of the simulated delay was equal to the distance between the record and playback heads divided by the tape speed.

FIGURE 6: VIDEO RECORDER SETUP TO GENERATE 3.5 SECOND DELAY

During the manipulation experiments the recorders were positioned so that their heads were 26.25 inches apart which produced a 3.5 second delay at a tape speed of 7.5 inches per second. With a pushbutton selector the subjects could view the video signal without delay (output of the camera) or the signal with 3.5 second delay (output of the second recorder).

In addition to the simplicity of this method of delay simulation, it also produced a video recording of every test. These video recordings were especially useful in reducing the experimenter's variability in data taking. Playbacks of the tapes permitted the experimenter to review each test and to compile thorough, consistent observations.

As shown in Figure 3 , the television monitor was mounted on an instrument rack at approximately eye level. Brightness, contrast, focus, horizontal and vertical control knobs were located on a panel below the monitor screen within operator's easy reach. Also mounted on the instrument rack were the joystick for pan-tilt and the pushbutton selector.

To prevent glare or reflections on the television screen, the rest of the rack was covered in black. Similarly, the whole master control area was enclosed with black drapes so that the subjects could not view the tasks directly nor be distracted by ambient light and motion. The master control "booth" thus formed, provided adequate room for the operator to move around, stand, or sit while performing the tasks. Figure 3 is a photograph of the master control area.

Possible audio cues (i.e. servo whine, objects falling, etc.) during the tests were masked by white noise. Both subject and experimenter wore headsets with microphone and earphones. White noise produced by a random noise generator was continuously played into the earphones. The noise volume was kept low so that subject and experimenter could easily communicate by microphone.

B. PRELIMINARY TESTS:

Several months before the tasks and procedures for the investigation were finalized various preliminary experiments were conducted. A variety of tasks, scales, and subjects were tested. Only the task completion time was recorded. Some of the results are presented in Appendix A.

The tasks ranged from simple block stacking to joining nuts and bolts. Subject fatigue was the most problematic effect of long, complicated tasks performed with delayed feedback. Simpler tasks seemed best suited for the experimental analysis.

During the early tests, the television camera was fitted with a turret of three lens (12.5, 25 and 50 mm). By pushbutton control, the operator could index the turret to select any one of the three lens.

Various light intensities and lighting angles were compared. Different size television monitors (10, 17, 19, and 23 inch models) were also evaluated by subjects and experimenter.

The primary purpose of these preliminary tests was to determine suitable experimental conditions (i.e. lighting, camera angle, lens, etc.) and to select representative tasks for a more thorough factorial study of remote manipulation.

Several of the preliminary tests were filmed and the films edited into a 16 mm movie which vividly demonstrates the difficulties of manipulation with feedback delay.*

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*This movie and a portion of the preliminary results were included in a presentation by T. B. Sheridan and J. L. Nevins at the NASA Teleoperator Conference, 12 March 1970, Houston, Texas.

C. DESCRIPTION OF TASKS AND TASK SEGMENTS

Based on the background and experience gained during the preliminary tests, three representative tasks, each with a large and small scale, were chosen for the factorial study. The tasks were: 1.) block stacking, 2.) transferring a cylindrical peg from one hole to another, 3.) positioning a plate with a center hole over a vertical peg (See Figures 7 a,b,c). These tasks were considered basic to almost all common manipulations, and they are not so prolonged or complicated as to cause the subject fatigue or frustration.

For convenience, in the remaining sections of this report the tasks have been referred to as Task #1, Task #2, and Task #3.

Task #1: Task #1 required stacking two identical, cubical blocks (Figure 7 a). On the command, "go," the subject moved the slave from a fixed starting position to grasp the first block and then placed it on the second block. To compare the effects of scale, one pair of blocks used were 1.5 inches on a side, and a second pair were only 0.5 inches on a side, the large and small scales respectively.

Task #2: The objective in Task #2 (Figure 7 b) was to transfer a cylindrical peg from one vertical hole to another. The peg was four inches long and 0.5 inches in diameter. For this task large and small scale was dependent on the diameter of the final hole. The small scale version required that the operator position the 0.5 inch peg into a hole 0.625 inches in diameter. The large scale was the same peg into a hole 1.0 inch in diameter.

Scale may also be thought of in terms of a task precision index. The precision index is the clearance between the peg and the hole into which the peg is being inserted. In Task #2, large scale corresponds to a

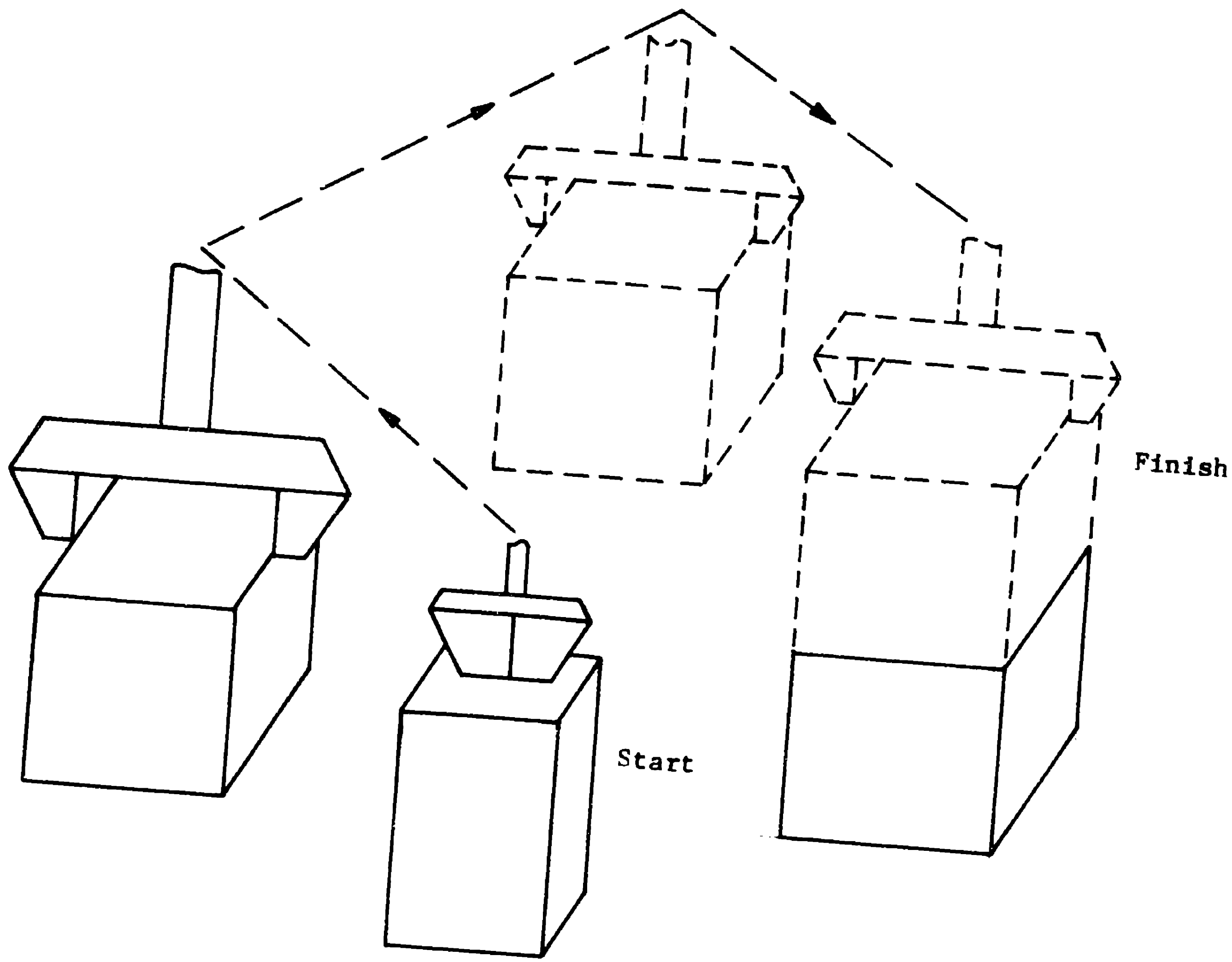


FIGURE 7a: TASK #1 - block stacking

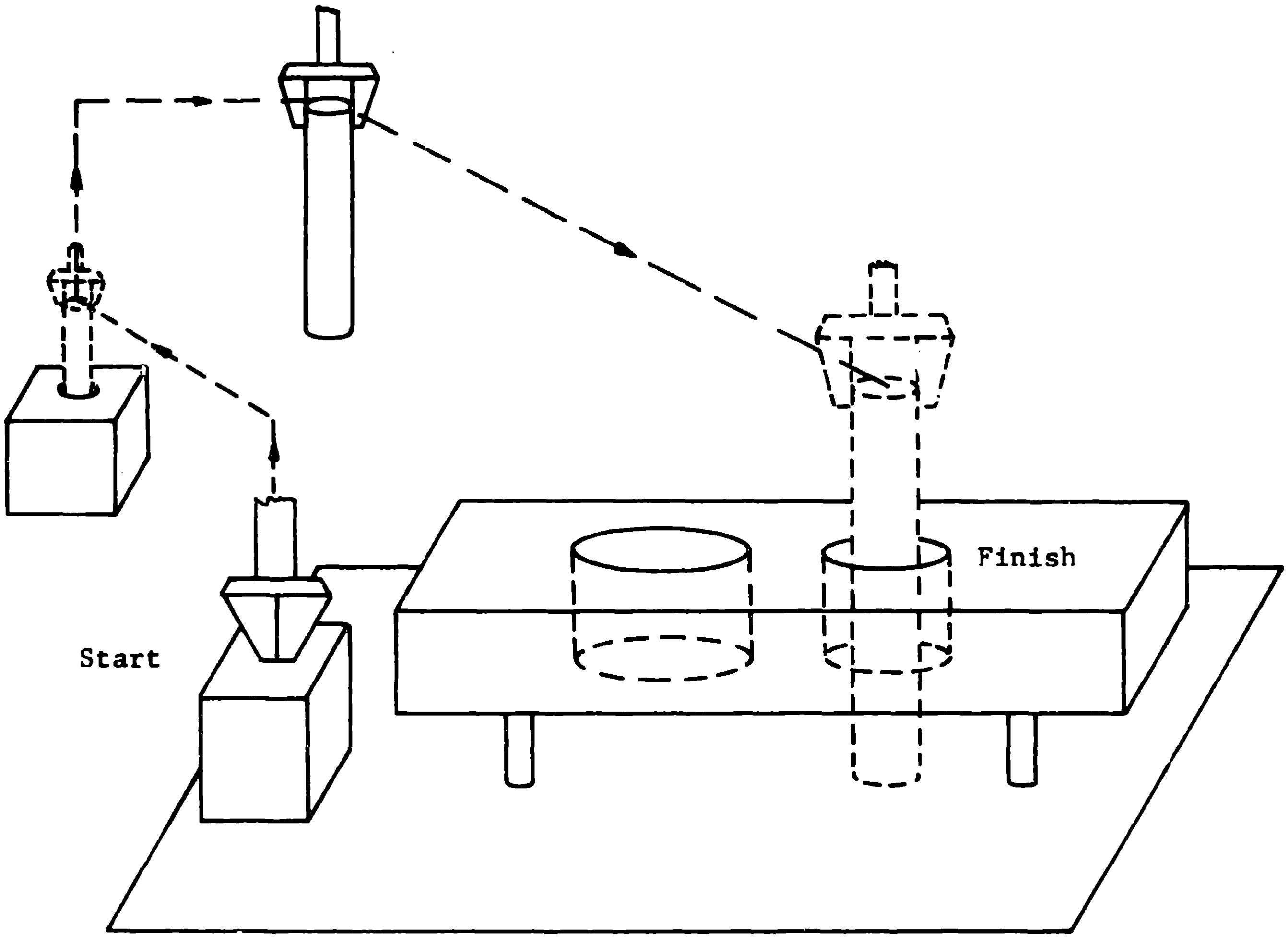


FIGURE 7b: TASK #2 - peg transfer

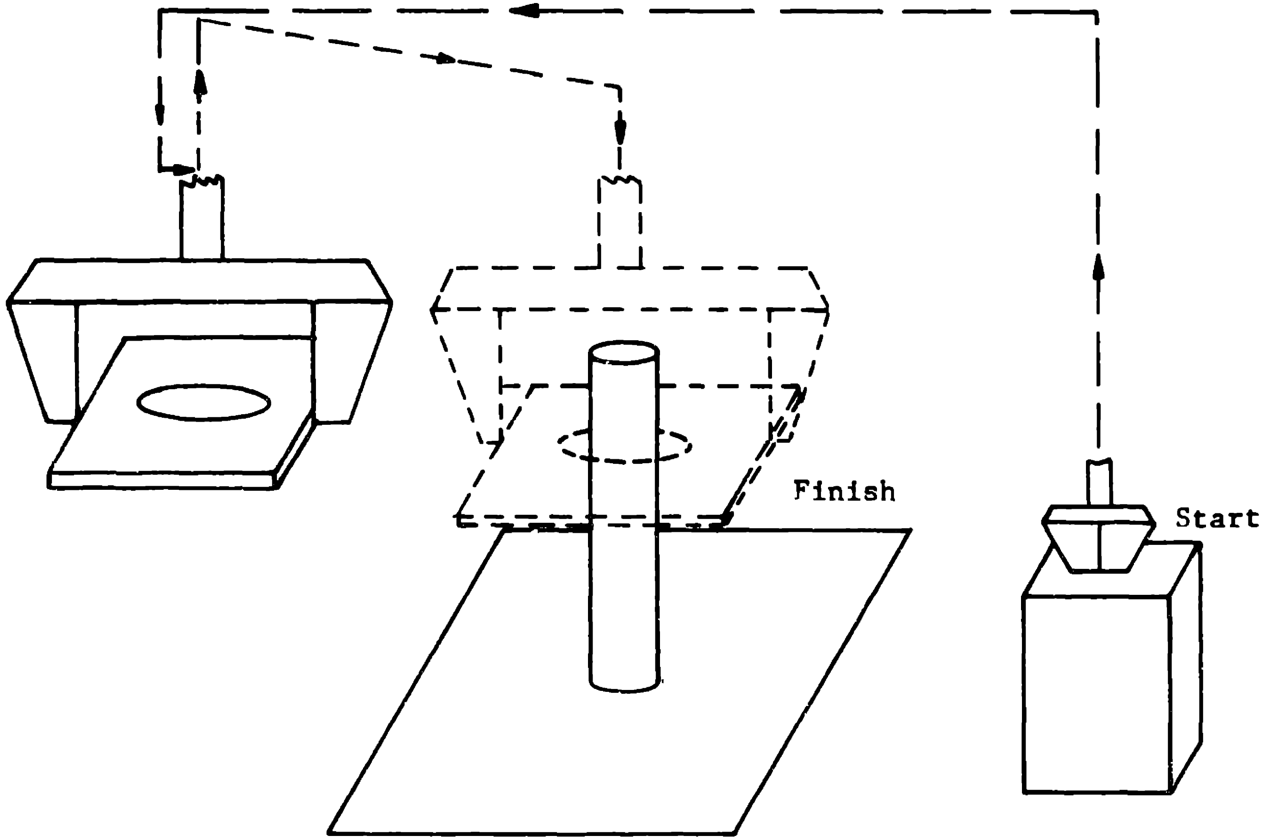


FIGURE 7c: TASK #3 - plate positioned over peg

precision index (1.0 - 0.5 = 0.5) of 0.5, and a small scale to an index (0.625 - 0.5 = 0.125) of 0.125.

Task #3: A thin plate with one hole at its center was positioned over a vertical peg for Task #3 (Figure 7 c). The plate was 1.625 inches square, 0.25 inches thick and the center hole was either 0.625 inches diameter for small scale or 1.0 inch diameter for large scale. The peg's diameter, 0.5 inches, was the same in all the tests. Again as in Task #2, large scale equals a precision index of 0.5 and small scale an index of 0.125.

All the task objects were made from wood. To accentuate certain important areas and edges, portions of the objects were painted flat black or white. For example, the inside surfaces of holes were made black and the surrounding area white. The ends of pegs were black and the cylindrical surfaces white. These colorings assisted the subjects in adapting to the poor depth perception and limited resolution of video viewing.

Task Segment: In order to analyze more thoroughly the effects of transmission delays, all of the tasks were segmented into three basic components (thirbligs): "get," "transport," and "position" (or "place"). During the experiments, completion time for each of the segments as well as a total completion time for the entire task was recorded.

"Get": The first movements of a manipulatory task constituted the "get" segment. The "get" was the task portion spent getting the object to be stacked, transferred, positioned, etc. The "get" began when the task began and ended when the target object was securely grasped.

"Transport": The "transport" segment was more difficult to define in specific terms. Obviously, transport began after the target object had been grasped, and as soon as movement started toward the task's final state. However, there existed a much less definite boundary between the end of the "transport" segment and the beginning of positioning. Very often coarse positioning moves overlapped with transporting, and it was difficult to differentiate the two.

Rather than specify an arbitrary distance or boundary at which transporting would end and positioning begin, the experimenter chose to judge the change independently during each performance of the tasks. The judgment was based on his observation of coarse movement ending and fine movements beginning. This usually occurred when the edge of the object being transported was within one or two object widths of its final position.

Since the experimenter was always able to adequately anticipate the segment's boundary, his reaction time should not have contributed significantly to the experimental error. Also, the experimenter's judging consistancy was easily checked using the video tapes produced during each test session. By video playback, the tasks segments could be repeatedly timed and the times compared. This technique for checking and comparing data reduced the effects of the experimenter's judgment error.

"Position": The "position" segment was the aligning, placing, and releasing of the transported object. Since "position" began when the "transport" ended, difficulties in determining its boundary were exactly the same as those previously discussed for "transport." The end of the "position" segment corresponded to the end of the task.

D. TEST PROCEDURE

A "treatment by subject"[4] experimental design was used to study the manipulations performed with and without feedback delay. Ten observations (replications) were recorded for each combination of variables (3 subjects; 2 treatments - delay, no delay; 3 tasks; 2 scales): i.e. 360 trials produced the data compiled in this study. The experiment was divided into eighteen test sessions with twenty trials per session. Each subject operated the manipulator during six such sessions.

The subjects were three male students, two undergraduate and one graduate. Prior to this investigation, they had not operated a remote manipulator. To familiarize themselves with the tasks and manipulator, each subject practiced 1.5 hours per day on three consecutive days. Based on the preliminary tests and completion times recorded during the practice sessions, 4.5 hours of manipulator experience (delay and no delay) was sufficient to reach a plateau in operator's learning.

Test sessions began the fourth day; each subject was scheduled for one session per day for six consecutive days. Unfortunately, equipment failures continually interrupted the scheduled tests. After an interruption, subjects were given a practice session to regain their skill before data taking resumed.

Task completion time was the measure of operator performance. The subjects were instructed to complete the tasks as quickly as possible without making errors.

An error was any incorrect move or series of moves which disoriented the task configuration so as to change the basic objective of the task. When an error occurred the trial was terminated and repeated at a later time during the test session.

The subjects were paid $2.00 per test session, regardless of the time required to complete twenty task trials. This form of remuneration was incentive for improved performance and minimized errors, since these factors directly influenced the test session length and hence the subject's nominal hourly wage. Early test sessions were nearly one hour in length. By concentrating on being quick and precise, twenty acceptable trials were possible in less than thirty minutes; all subjects quickly achieved this standard of performance. As additional incentive the experimenter attempted to stimulate competition among the subjects by comparing their completion times.

As with all experiments involving human subjects, this study was influenced by boredom, fatigue, learning, etc. To minimize any systematic bias from these effects, the tasks sequence was randomized. The test sessions (i.e. the order) in which the subjects performed specific tasks and scales are shown in Table 1.

TABLE 1: RANDOMIZED SEQUENCE FOR PERFORMING TASKS

TASKS		SUBJECTS		
		P.V.	D.L.	B.J.
TASK #1	Large	1 & 4	3 & 6	2 & 5
	Small	1 & 4	2 & 5	1 & 4
TASK #2	Large	3 & 6	1 & 4	3 & 6
	Small	2 & 5	3 & 6	1 & 4
TASK #3	Large	3 & 6	1 & 4	2 & 5
	Small	2 & 5	2 & 5	3 & 6

For example, subject B.J. completed five trials of Task #1, small scale, with delay and five trials without delay during test sessions 1 and 4.

Though desirable for the subjects to be on a learning plateau in manipulator operation, rote memory of the tasks would have been extremely detrimental to this study. If the tasks had become so routine that they could have been performed "blindfolded" the test data (particularly for delay) would have been valueless.

The twenty trials constituting a test session consisted of two tasks (possibly of different scale; see Table 1) performed five times with delay and five times with no delay. To avoid memorized movements, successive test trials involved different initial locations for the task objects. There were four possible initial arrays, though the "get" and "transport" distances did not vary. These configurations are best described by Cartesian coordinates.

Assuming the center of the task scene to be the origin of an X, Y, Z coordinate system with a unit on the coordinate axes corresponding to one inch, the four possible locations of the "target" object were: (3, 4, 0), (-3, 4, 0), (-3, -4, 0) and (3, -4, 0). The corresponding locations of the jaws (i.e. their starting position) were: (2, -1, 1.5), (-2, -1, 1.5), (-2, 1, 1.5) and (2, 1, 1.5). Respectively, the final position took on coordinate locations: (-1, -1, 0), (1, -1, 0), (1, 1, 0) and (-1, 1, 0). Two of these configurations are illustrated in Figure 8.

In addition the target objects in Task #1 and #3 (block and plate, respectively) were given one of two orientations: a face perpendicular to the camera line of sight or rotated by 90 degrees so that an edge was toward

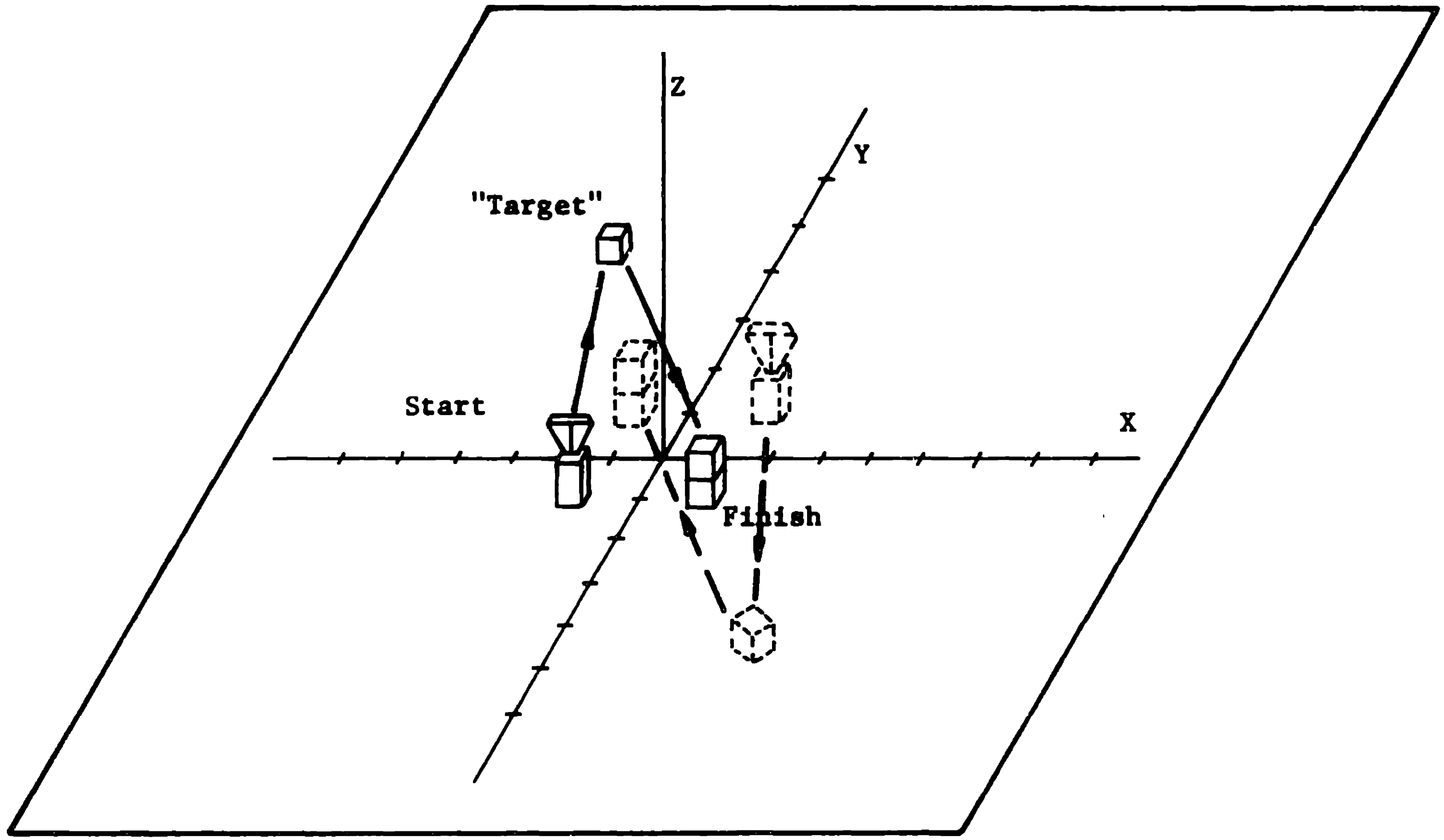


FIGURE 8: TWO OF THE FOUR POSSIBLE INITIAL LOCATIONS FOR THE TASK OBJECTS

the camera. Figure 8 also illustrates these orientations. Because of the peg's symmetry in Task #2, rotation of the "target" object would have been meaningless.

The possible tasks configurations were randomized (by random number table) for each test session. A modified randomization technique was used so that no two successive trials were identical.

Before a trial began the subjects were allowed to adjust the camera angle for optimum viewing of the task configuration. However, no adjustments were permitted during the manipulation, since this uncontrolled variable would have contributed to the task completion time.

After the objects were properly arranged and a suitable camera angle set, the operator positioned the jaws on the starting block. He then selected the proper manipulation mode, delay or no delay, as specified by the experimenter. With everything in a "ready" state, the experimenter started a trial with the verbal command: 1-2-3-GO.

Simultaneously, he started two electronic timers by pressing a hand-held microswitch. The microswitch pulsed a stepping relay, which in turn controlled the timers. One timer recorded total elapsed time and the other recorded "get" completion time. At the end of the "get" segment the experimenter pulsed the relay again, stopping the "get" clock and starting the "transport" timer. This procedure continued until the task was completed; then both the "position" and total elapsed time clocks were stopped simultaneously. The times ("get," "transport," "position," and "total") were recorded to the nearest .05 seconds.

After each test session, all the experimental data was checked by viewing video playbacks. Every trial was observed and the segments retimed repeatedly. Also, from viewing the video tapes the experimenter counted and recorded the number of waits for feedback when the manipulation was with delay.

ANALYSIS AND DISCUSSION OF RESULTS

A. MEANS AND STANDARD DEVIATIONS OF COMPLETION TIMES AND NUMBER OF WAITS:

Data recorded during this study were the total task completion times, the task segment completion times and the number of waits for feedback during tasks with delay. The first step in the data analysis was to calculate means and standard deviations averaged over various margins of the array of experimental conditions. Appendix B contains tables of values resulting from these calculations.

The means and standard deviations averaged over the three subjects and presented here in Tables 2 and 3 are the most commonly used in further analyzing and discussing the experimental results. Also listed in these tables are values for the percent of the total time required by the various task segments and a consistency index, I_c. The significance of these parameters will be discussed in later paragraphs of this section.

The tables show, as was expected, that the completion times for manipulations with delay are very much longer than completion times on the same tasks (or task segments) without delay. The tables also present more subtle results: the effects of scale on task completion times and segment completion times; the effect of delay on the task segments and their relative proportion of the task time; the effect of delay on the relative variability of completion times. These and other factors are more thoroughly analyzed in paragraphs B through F of this section.

As the tables indicate, all the task times, with delay or no delay, have relatively high standard deviations. Yet the writer contends that the subjects reached a learning plateau before test data was recorded. Differences in the way the task was performed, the sequence of actions

TABLE 2: MEANS AND STANDARD DEVIATIONS OF COMPLETION TIMES - NO DELAY (Average of 3 Subjects)

			"GET"	NUMBER "GET" WAITS	"TRANS"	NUMBER "TRANS" WAITS	"POSIT"	NUMBER "POSIT" WAITS	"TOTAL"	NUMBER "TOTAL" WAITS
TASK #1	LARGE	MEAN	1.966		0.894		1.249		4.111	
		S.D.	0.539		0.327		0.525		0.969	
		% of "TOTAL"	47.8%	—	21.7%	—	30.4%	—		—
		I_c	.274		.365		.420		.236	
	SMALL	MEAN	3.129		1.239		3.314		7.684	
		S.D.	1.789		0.441		1.713		2.627	
		% of "TOTAL"	40.7%	—	16.1%	—	43.1%	—		—
		I_c	.571		.356		.517		.341	
TASK #2	LARGE	MEAN	1.909		0.991		1.259		4.161	
		S.D.	0.535		0.307		0.641		0.890	
		% of "TOTAL"	45.9%	—	23.8%	—	30.3%	—		—
		I_c	.280		.310		.509		.214	
	SMALL	MEAN	1.978		1.099		2.201		5.279	
		S.D.	0.366		0.287		0.958		1.204	
		% of "TOTAL"	37.5%	—	20.8%	—	41.7%	—		—
		I_c	.185		.261		.435		.228	
TASK #3	LARGE	MEAN	2.413		0.996		1.251		4.663	
		S.D.	0.950		0.289		0.539		1.148	
		% of "TOTAL"	51.7%	—	21.4%	—	26.8%	—		—
		I_c	.394		.290		.430		.246	
	SMALL	MEAN	2.399		1.158		1.931		5.489	
		S.D.	0.793		0.424		1.293		1.623	
		% of "TOTAL"	43.7%	—	21.1%	—	35.2%	—		—
		I_c	.330		.366		.670		.295	

"GET," "TRANSPORT," "POSITION," "TOTAL" = TIME IN SEC.

TABLE 3: MEANS AND STANDARD DEVIATIONS OF COMPLETION TIMES AND WAITS WITH 3.5 SECOND DELAY (Average of 3 subjects)

			"GET"	NUMBER "GET" WAITS	"TRANS"	NUMBER "TRANS" WAITS	"POSIT"	NUMBER "POSIT" WAITS	"TOTAL"	NUMBER TOTAL "WAITS"
TASK #1	LARGE	MEAN	17.544	3.566	4.523	0.733	14.723	3.333	36.791	7.666
		S.D.	8.996	1.961	1.606	0.442	7.517	1.813	11.506	2.624
		% of "TOTAL"	47.7%		12.3%		40%			72.9%
		I_c	.512	.550	.355	.603	.511	.544	.313	.342
	SMALL	MEAN	26.766	5.233	7.619	1.333	36.064	7.433	70.454	13.966
		S.D.	12.384	2.304	2.868	0.471	19.548	3.809	25.729	4.757
		% of "TOTAL"	38%		10.8%		51.2%			69.4%
		I_c	.463	.440	.376	.353	.542	.512	.365	.341
TASK #2	LARGE	MEAN	18.183	3.666	5.964	1.166	17.411	3.766	41.559	8.600
		S.D.	7.814	1.719	2.925	0.521	9.541	1.891	15.164	2.984
		% of "TOTAL"	43.8%		14.3%		41.9%			72.4%
		I_c	.430	.469	.490	.447	.548	.502	.365	.346
	SMALL	MEAN	19.519	4.000	7.828	1.466	35.641	7.366	62.989	12.833
		S.D.	7.931	1.591	3.578	0.669	19.679	3.619	27.274	4.919
		% of "TOTAL"	31%		12.4%		56.6%			71.3%
		I_c	.406	.398	.457	.456	.552	.491	.433	.383
TASK #3	LARGE	MEAN	21.974	4.600	5.581	1.000	18.748	4.033	46.304	9.633
		S.D.	8.937	1.800	2.099	0.577	6.447	1.353	13.937	2.762
		% of "TOTAL"	47.5%		12.1%		40.4%			72.8%
		I_c	.407	.391	.376	.577	.344	.335	.301	.287
	SMALL	MEAN	22.913	4.766	6.936	1.266	47.806	9.100	77.589	15.133
		S.D.	14.163	3.073	3.122	0.573	50.751	7.077	52.958	7.855
		% of "TOTAL"	29.5%		8.9%		61.5%			68.3%
		I_c	.618	.645	.450	.453	1.06	.778	.683	.519

"GET," "TRANSPORT," "POSITION," "TOTAL" = TIME IN SEC.

and subgoals, different paths and distances moved all contribute to the variability. There was no attempt to study or quantify many of these effects other than to let them enter into the analysis of variance (to follow) as random variability. In the analyses which follow the data has been assumed normally distributed without a learning bias.

B. TECHNIQUES AND STRATEGIES OF MANIPULATION:

Without exception, all the subjects tested (including those during the preliminary experiments) adopted a move-and-wait strategy to cope with the delayed feedback. Prior to testing they were not instructed in possible techniques, nor were they familiar with previous delayed feedback studies; to move "open loop," then wait for feedback was their natural tendency. At first the motions were too large in every direction, but this overshoot diminished with practice and experience.

Gross movements, not restricted by close tolerance (i.e. "transport," parts of "get," etc.), were accomplished with large moves and little regard for precision. More precise movements (aligning, positioning, placing) required many small amplitude moves, each followed by a wait for feedback. The more precision involved, the greater the number of moves, hence a greater number of waits and a longer completion time.

Movements were most often across manipulator degrees of freedom rather than in one degree at a time. The subjects used this technique comfortably and naturally. In fact, training the operator to align the slave first in one degree, then in another would have been difficult.

A major problem for the operator was physical "drifting" while waiting 3.5 seconds for feedback. Even though they were allowed to use their left hand to help stabilize the master control (itself a right-handed control), they always had difficulty maintaining the end position during a move-and-wait sequence. Just respiration causes body motions capable of significant master control drift, particularly during tasks requiring very accurate alignments. With operator fatigue, drift becomes a more serious problem. Similarly, longer delays require longer "holds" increasing the probability of drift.

Six-degrees of freedom manipulation without force feedback was also problematic. Subjects accidentally wasted time by pressing the jaws down hard enough against the task plane (or task objects) to prevent other movement of the manipulator. For example, if an operator positioned the master control jaws lower than the task plane permitted the slave jaws, the servo-mechanisms forced the slave tightly against the task plane making slave movements in any direction but "Z" (up) impossible. With no force feedback the operator had no way of determining how tightly he was "trapping" the slave. The situation sometimes went uncorrected for several cycles, particularly if the operator thought there was danger of losing an otherwise good position.

C. ANALYSIS OF VARIANCE RESULTS

To study the effect of scale and to compare the subject's performance, a two-way analysis of variance has been performed.[5] Data from different tasks were treated separately. For each task segment and for each condition, delay or no delay, a sum of squares table was computed from which the appropriate F ratios were calculated.[6] The results of the F ratio tests, consulting a Table of Snedecor's F,[7] are given in Table 4.

Subject differences: For all cases of manipulation without delay and for most cases of manipulation with delay, the F test for subject differences was not statistically significant. Thus, for the remainder of this report, the subjects will be considered independent, unbiased performers of the assigned tasks. Results and conclusions will be based on experimental data averaged over all three subjects.

Scale effects: The two-way variance analysis also produced helpful insight into the effect of scale on remote manipulation, with and without delay. Table 4 lists the F-tests results for scale effects.

Task #1: Block stacking was the most influenced by scale. In both the delay and no delay case, the scales tested significantly different at very high confidence levels. This was not a surprising result considering that the large scale was stacking blocks 1.5 inches on a side; and, the small scale required stacking blocks only 0.5 inches on a side. The precision necessary to perform tasks of these two scales is obviously very different. However, this stacking precision only accounts for the scale effect during the "position" segment. Explanation of scale effect on the "get" and "transport" segments was not as obvious; it was necessary to examine more closely the relationship of the physical dimensions of the task manipulator jaws, and block's edge.

TABLE 4

RESULTS OF TWO-WAY ANALYSIS OF VARIANCE

TASKS AND CONDITIONS		"GET"	"TRANSPORT"	"POSITION"	"TOTAL"
TASK #1	Without Delay	Scales: >97.5% * Subjects: N.S.	Scales: >95.% * Subjects: N.S.	Scales: >99.95% * Subjects: N.S.	Scales: >99.95% * Subjects: N.S.
	With 3.5sec Delay	Scales: >99.% * Subjects: >90.%	Scales: >99.95% * Subjects: N.S.	Scales: >99.95% * Subjects: N.S.	Scales: >99.95% * Subjects: >70.%
TASK #2	Without Delay	Scales: N.S. Subjects: N.S.	Scales: N.S. Subjects: N.S.	Scales: >99.95% * Subjects: >70.%	Scales: >99.5% * Subjects: >70.%
	With 3.5sec Delay	Scales: N.S. Subjects: >99.9% *	Scales: >90.% Subjects: >97.5% *	Scales: >70.% Subjects: >70.%	Scales: >97.5% * Subjects: >97.5% *
TASK #3	Without Delay	Scales: N.S. Subjects: N.S.	Scales: N.S. Subjects: >70.%	Scales: >70.% Subjects: N.S.	Scales: N.S. Subjects: N.S.
	With 3.5sec Delay	Scales: N.S. Subjects: >70.%	Scales: >70.% Subjects: N.S.	Scales: >97.5% * Subjects: >70.%	Scales: >90.% Subjects: >70.%

* - levels greater than 95.% are considered significant

N.S. - Not Significant; levels less than 70.%.

Task #1, "get.": The "get" segment requires a movement and positioning of the jaws in order to grasp the block. Positioning jaws 0.5 inches wide along the sides of a 1.5 inch block was much less difficult than positioning the same jaws along the sides of a 0.5 inch block. This difference in difficulty transforms into significantly different (>97.5% level with no delay and >99.% level with delay) mean "get" times.

Task #1, "transport": A similarly subtle effect of scale was noted for the "transport" segment of Task #1. The "transport" completion time was increased when greater precision was required to stack blocks of differing scale. Although the distance between block centers was the same in each case, the nominal distance a block was moved before fine positioning began, varied with scale. As previously noted, in "Design of the Experiment," transporting and coarse positioning usually changed to fine positioning when the edge of the object being transported was within one to two object widths of its final position. Thus, in the specific case of block stacking, a large block 1.5 inches wide, reduced the "transport" distance (6.4 inches) by from 1.5 to 3.0 inches. Whereas a small block, only 0.5 inches wide, reduced the "transport" distance by from 0.5 to 1.0 inches. These differences in nominal "transport" distances resulted in different mean "transport" times.

Only for the block stacking task did the width of the transported object change with scale; hence, no scale effects of this nature are expected for "transport" segments of Task #2 and Task #3. The validity of this expectation was tested and reported in a succeeding paragraph.

Tasks #2 and #3, "get": Scale did not affect the "get" time of Tasks #2 or #3; though the scales differed, the object the operator grasp did not change in a way that could influence the "get" completion time. In the peg transfer, Task #2, the hole's dimension (the final position of the peg) and not the peg, was changed to produce large and small scales. Similarly, the center hole of the plate in Task #3 varied with scale variations, but the outside physical dimensions of the plate (the dimensions important to grasping) did not change. Therefore getting the large or small scale plate (or peg) required exactly the same movements and precision. The analysis of variance agrees with the obviously predictable result: The get segment of manipulation, with or without delay, is not affected by scale (hole size) if the outside dimensions of the object to be grasped do not change.

Tasks #2 and #3, "transport": In the case of manipulation without delay, the variance analyses for Tasks #2 and #3 concurred with the previously predicted results: varying the scale did not affect the "transport" segment if the outside dimensions of the object being transported were independent of scale (hole size).

However, the same tasks with delay have produced results seemingly (Task #2, scale effect >90.% level; Task #3, scale effect >70.% level) contrary to the expected outcomes. These scale effects on "transport" with delay were most easily understood as follows: when the subjects were confronted with a small scale task, they tended to move more cautiously near the end of the transport segment (i.e. coarse positioning). This coarse positioning consisted of making slow movements and occasionally stopping to wait for feedback. Every wait for feedback increased the completion time by an amount slightly greater than the delay. For this study the delay was 3.5 seconds, so a single wait near the end of the transport segment would increase the transport completion time by more than

3.5 seconds. Table 4 shows the large and small scale "transport" segments of Task #2 have means differing by only 1.9 seconds. One wait for coarse positioning feedback during every other performance of the task would account for this difference. The preceding argument also applies to the influence of scale on transport times with delay in Task #3.

Task #2, "position": The most surprising results of the analysis of variance are the significance levels for scale effects on the positioning segment of Tasks #2 and #3.

For Task #2, without delay, scale effects are significant at a very high level (>99.95%). A similar confidence level would be expected for the effect of scale on the same manipulation with delay. The variance analysis seems to contradict this expectation by registering a scale effect significant at only the >70.% level. The following are plausible statistical and quantitative reasons for this phenomenon.

First, the analysis of variance indicated a significant subject-scale "interaction" (at >95.% level). Testing for an interaction is the first F test of the variance analysis. If the interaction tests significant at a meaningful level, then the formats of the remaining F tests change. (An example is outlined in Appendix C). To show only those significant differences in means which are not a function of interaction, the data must be treated as if there were only single observations (rather than the 10 performed in this study) for each combination of subject and scale. Thus the analysis was obtained by disregarding the within groups and total sum of squares, thereby tremendously reducing the degrees of freedom in the F ratios.

For example, if the significance of the interaction effect in Task #2 had been rejected, the scale effect F ratio would equal 5.9 with 1 and 56 degrees of freedom in numerator and denominator respectively. This F ratio, according to the Table of Snedecor's F, suggests the scale effect for positioning with delay in Task #2 is significant at >97.5% level. However, for the same case, but acknowledging a significant interaction, the F ratio equaled 7.7 with only 1 and 2 degrees of freedom in numerator and denominator respectively. The loss of degrees of freedom imposed a much more stringent test on the scale effect F ratio. It tested significant at only the >70.% level. Thus, subject-scale interaction has blurred the effect of large and small scales.

Statistically, the interaction was: those differences among means which can not be accounted for by constant shifts in row (subject) means and column (scale) means; i.e. the columns and rows have an effect in combination different from the sum of their separate effects. Several factors may have caused a significant interaction:[8]

1. There was no interaction but we have obtained a value which we declare significant. This will happen only 5.% of the time at a 95.% level of significance.

2. The two variables of classification (subjects and scales) were interacting to produce effects together which would not be produced separately.

3. Another uncontrolled factor was of significant importance to be included in the experiments.

The effect of television viewed manipulation during this study may easily have been the uncontrolled factor which caused a significant interaction. Camera angle, resolution and lighting all had an indeterminant effect on subject's performance. Most important was the loss of a sense of three dimensions when viewing a task via television monitor. The limited depth perception of a television image was problematic for all the subjects, yet a quantitative study of the effect was impossible since a video image was essential to the delay simulation technique.

Early in the practice sessions, the subjects concentrated on adapting to the television feedback. As depth clues, they first used the shadows cast by the jaws and task objects, then progressed to a higher frequency trial-and-error method of oscillating about the final position until they perceived an accurate orientation. The second method was very successful with no delay in the feedback, but oscillating (a high frequency trial-and-error) was impossible with a 3.5 second delay. Manipulation with feedback delay is by necessity move and wait.

In Task #2 with delay, the subjects found that perceiving exactly when the peg was accurately positioned was very difficult. They often lowered the peg, thinking it was on-line with the hole, but in fact the peg was in front or behind the correct position. This common error, caused by limited depth perception, occurred in both the large and small scale cases. Similar errors were not as frequent in block stacking, since the shadows could be more effectively used in making final position movements. However in Task #2 shadows were often cast into, in front or behind the hole in such a way as to be out of view.

In addition to the uncontrolled video feedback factors, there may have also been a subject-scale interaction of a psychological nature. To the subjects, positioning a peg into a hole twice the peg's diameter (large scale) appeared very simple. The final position was a much larger "target," so their psychological attitude allowed them to be more careless in fine positioning. Careless positioning during the large scale experiment coupled with the depth perception factor could have produced the interaction effect.

Task #3, "position": The most interesting variance analysis results were those for the positioning segments of Task #3. Without delay the scale effect was significant at only >70.% level. Whereas, with delay the large and small scale completion times were significantly different at >97.5% level. This important result means varying the task scale did not significantly change the difficulty of the task when manipulating without delay. However, for the same task performed with delay the small scale was significantly more difficult than the large scale. I think this is one indication that scale (i.e. clearance) had a greater effect on manipulation with delay. Task scale variations going essentially unnoticed in the no delay condition, were amplified by delayed feedback: small task variations became grossly more difficult with delayed manipulation.

D. TASK SEGMENTS WITH AND WITHOUT DELAY

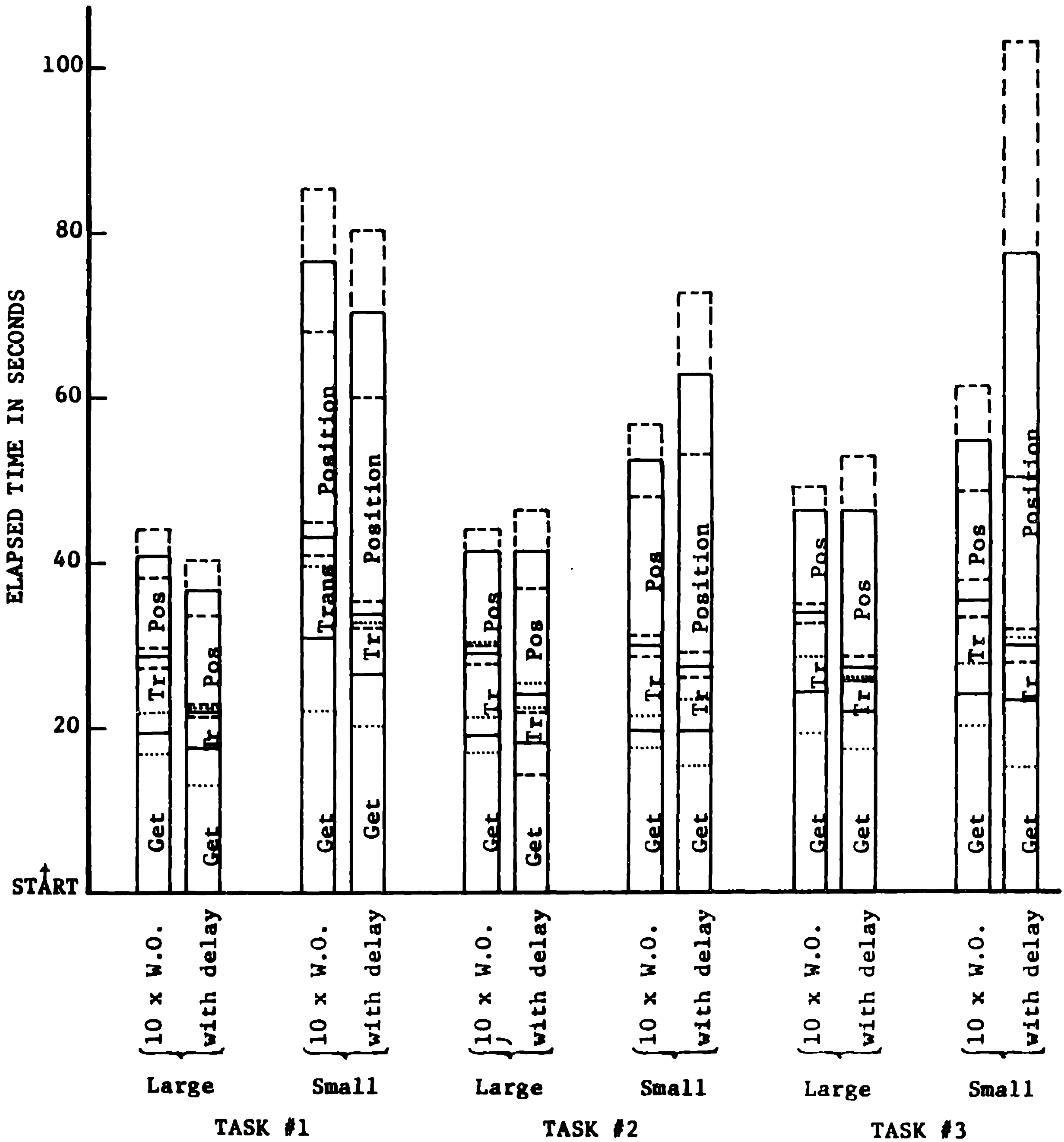
A major portion of this study concerned segmenting the tasks and recording completion times for each segment. Figure 9 is an interesting illustration of these results. The bar graphs compare the mean completion times with delay to scaled (by a factor of ten) mean completion times without delay. The solid horizontal lines indicate the elapsed-time transitions (a mean value) between the various segments. The dotted lines either side of the mean values correspond to one standard deviation. As with the mean completion times, the standard deviations for the no delay condition have been scaled up by a factor of ten. The bar graphs illustrate how the different task segments contributed to the "total" elapsed-time (i.e. the task completion time). The sum of the segment mean completion times equals the mean task completion time.

By coincidence in each of the six task and scale cases approximately, ten times the no delay task time, equals the task time with a 3.5 second feedback delay. Obviously, a different delay time would not have produced this factor of ten relationship, which consistently applies with less than 10% error in four out of the six cases and was particularly accurate for large scale. Scaling up the no delay times by a factor of ten was convenient for graphically displaying the effects of delay on the proportions of the "total" time contributed by the task segments.

In general, the graphs show:

1) "Transport" is a smaller fraction of the total time with delay than without.
2) "Position" with delay took a significantly greater proportion of the total time than "position" without delay.

FIGURE 9: SEGMENT CONTRIBUTIONS TO TOTAL COMPLETION TIME



3) With or without delay, "get" was nearly a constant fraction of the total time.

Similarly, the effects of scale on the task segments previously discussed in the "ANALYSIS OF VARIANCE RESULTS" are illustrated in the bar graphs of Figure 9 . "Get" and "transport" in Task #2 and #3 were not affected by scale, since the outside dimensions of the object to grasp did not change with scale. However, small scale increased the precision necessary for positioning, and hence significantly increased the "position" time in all tasks.

Figures 10, 11 and 12 present the relative time proportions in another way. When task segment time is expressed as a percentage of the total completion time, several very consistent patterns appear. The figures show both the effects of scale and the effects of delay on the distribution of time among the task segments.

With scale changes, "position," the task component most affected by the increased precision, required an increased amount of time while the other segments remained more or less constant. Hence, the small scale "position" segment took an increasingly larger percentage of the total time at the expense of "transport" and "get." This was a consistent trend for all three tasks.

The effects of manipulation with delay cause a similar, significant change in the distribution of task completion time. Again, the "position" segment, the component requiring the most precision, is most sensitive to delay. Its increased percentage of the task time results in "get" and "transport" taking a proportionately smaller fraction of the total time.

FIGURE 10: TASK #1 - PROPORTION OF TOTAL TASK TIME ALLOCATED TO TASK SEGMENTS

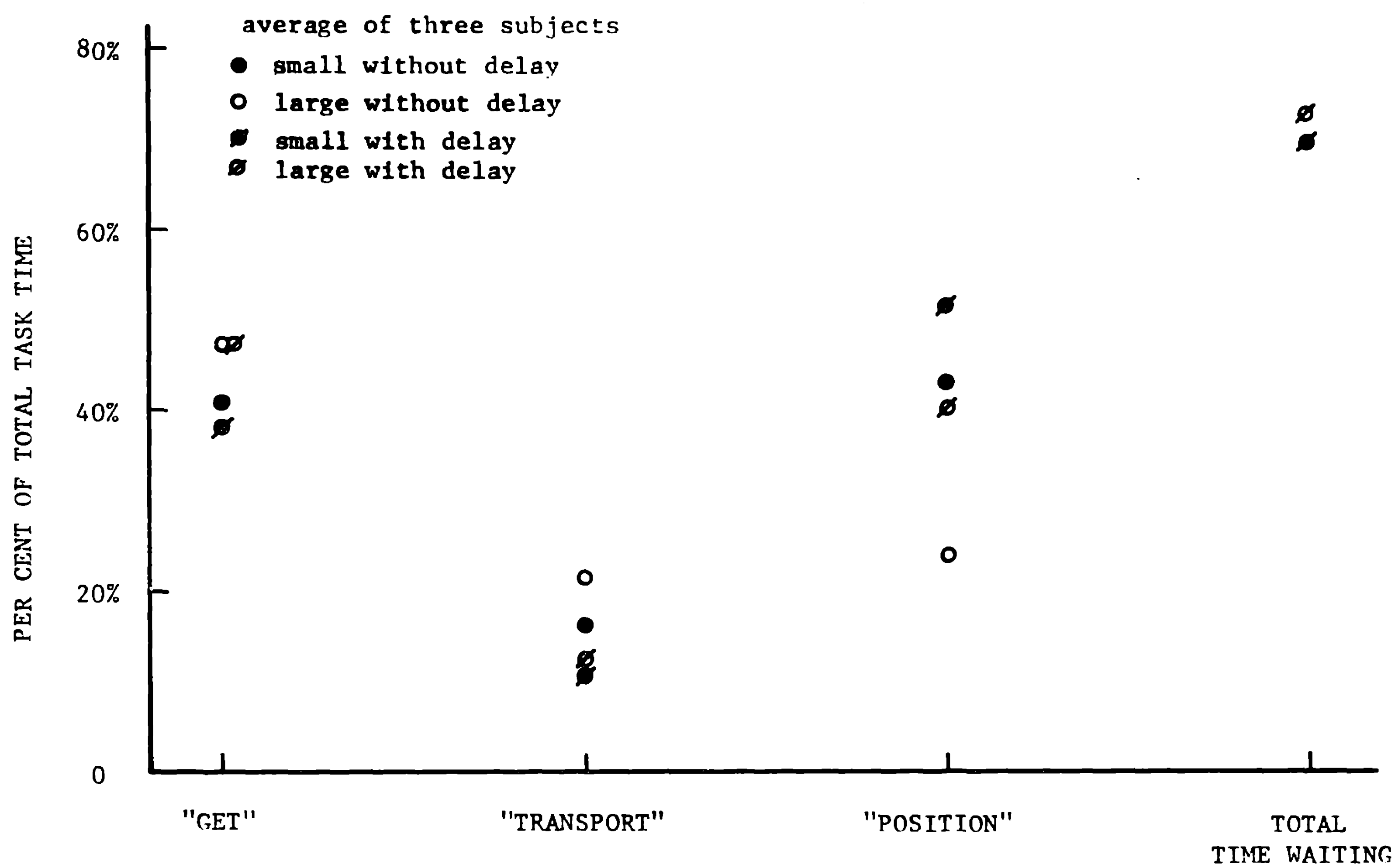


FIGURE 11: TASK #2 - PROPORTION OF TOTAL TASK TIME ALLOCATED TO TASK SEGMENTS

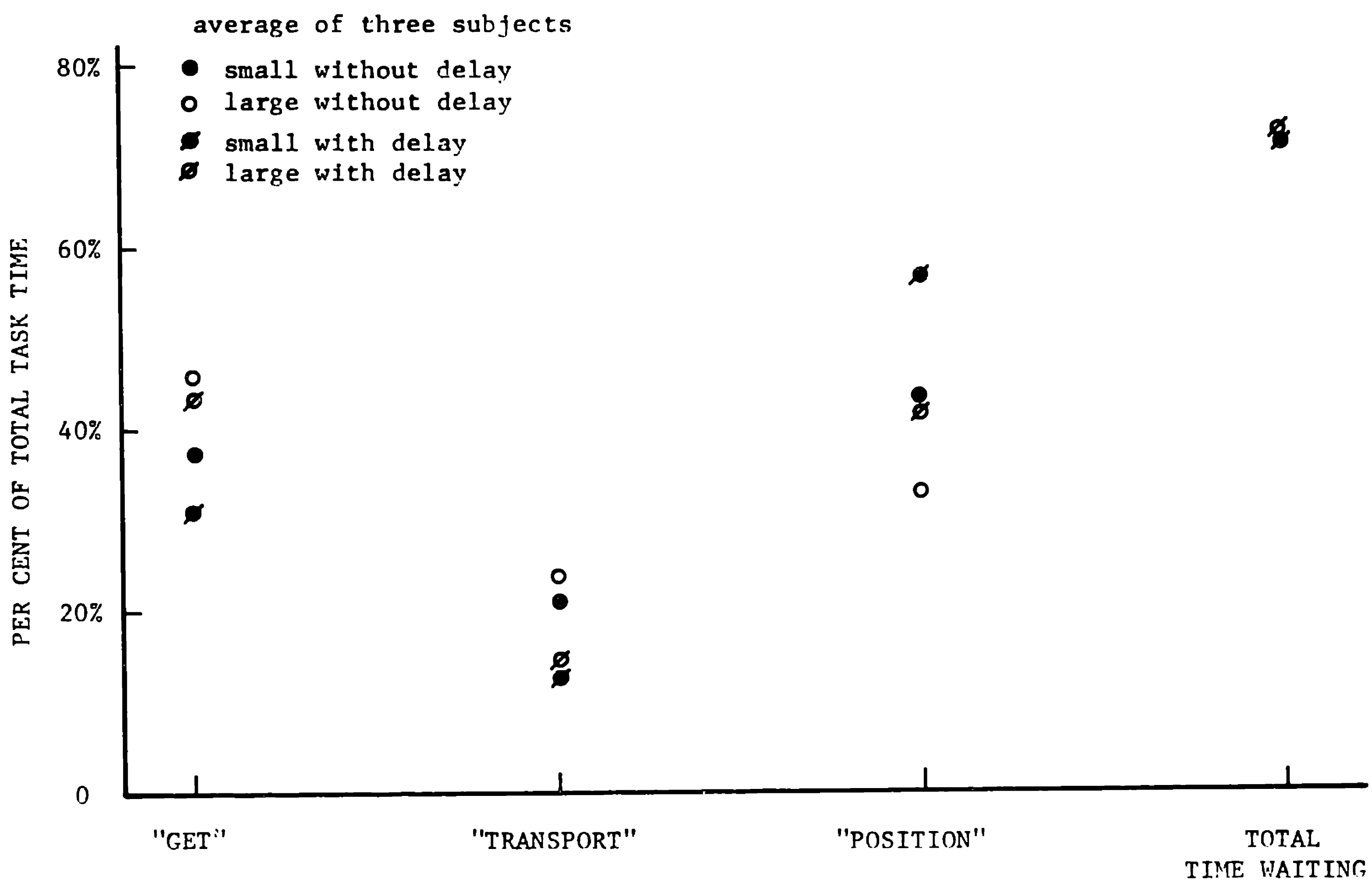
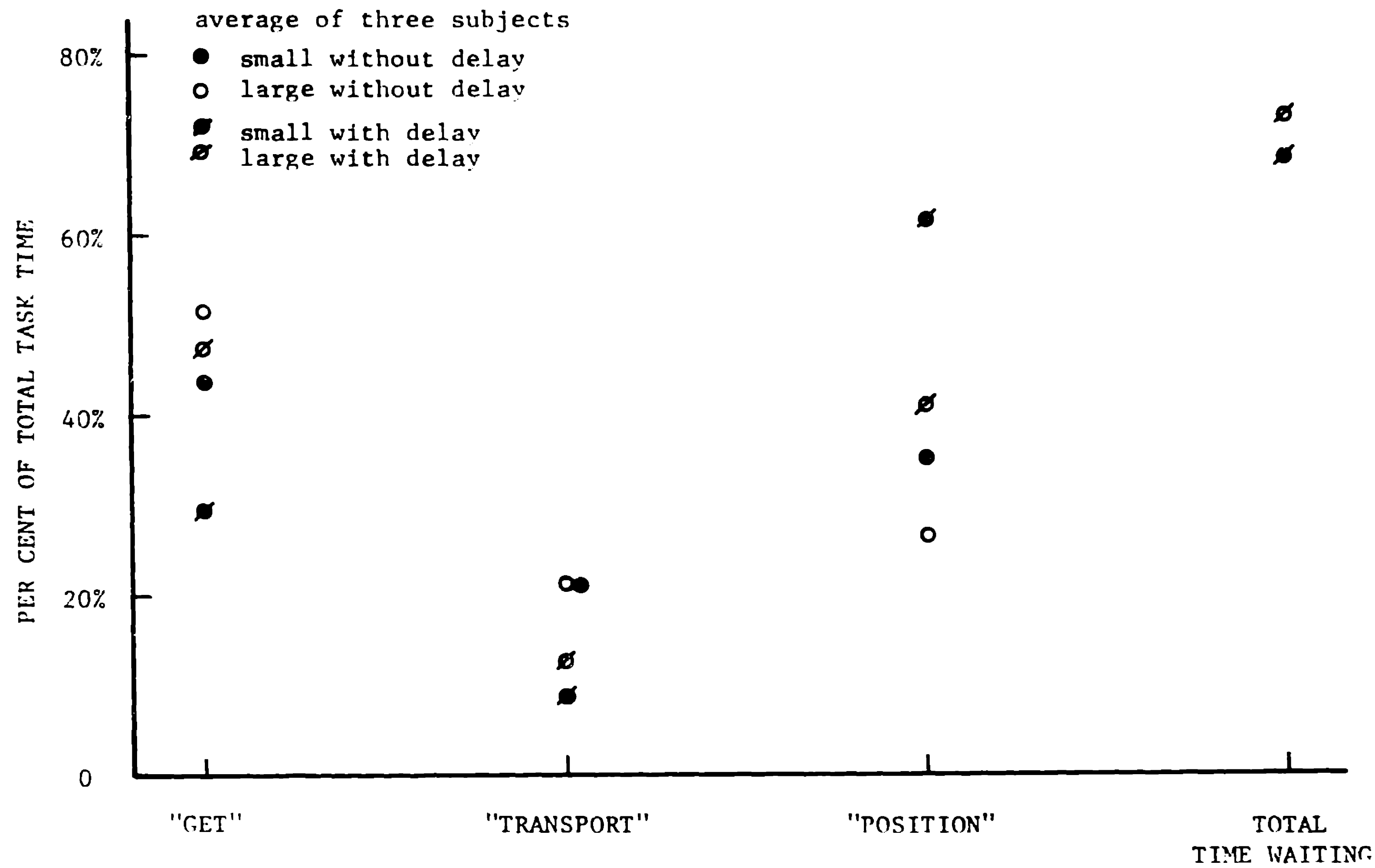


FIGURE 12: TASK #3 - PROPORTION OF TOTAL TASK TIME ALLOCATED TO TASK SEGMENTS



Also plotted in Figures 10, 11 and 12 are the percentages of the total time spent waiting during each task. [The waiting time was determined from the mean number of waits, recorded in Table 3, multiplied by the length of the delay (3.5 seconds).] The graph illustrates a significant result: total time waiting is nearly a constant fraction of the total task time for all three tasks, regardless of scale.

E. RELATIVE CONSISTENCY OF COMPLETION TIMES

For comparing the variability of completion times with and without delay a consistency index has been defined as follows:

$$I_c = \sigma/\text{MEAN}$$

where MEAN = mean completion time
σ = standard deviation of completion time

I_c ranges from 0, for an absolutely predictable completion time, to approximately 1, indicating extreme variance. I_c, a dimensionless number, and its formula are also applicable for studying the consistency of the number of waits for feedback.

The index (for time and for the number of waits) has been computed (see Tables 2 and 3) for each combination of variables (task, scale, delay-no delay) and the results plotted in Figure 13 a, b, and c. A general trend apparent from the graphs is that the completion time for a particular segment, task, and scale with delay was more variable than the corresponding completion time without delay (i.e. I_c with delay > I_c without delay).

Plots also show that the I_c for waits are approximately equal to the I_c values of the associated segment completion times, indicating the source of the increased variability in I_c for time with delay probably resulted from variability in the number of waits for feedback.

More specific trends are illustrated in two additional figures. In Figure 14 an I_c based on the mean completion time averaged over subjects and scale, is plotted for each task, with and without delay. The graph shows that "position" was the most variable segment and "transport" was generally the most consistent. The plotted values also show that with but

FIGURES 13 a, b, c: INDEX OF CONSISTENCY, I_c

FIGURE 13a: TASK #1

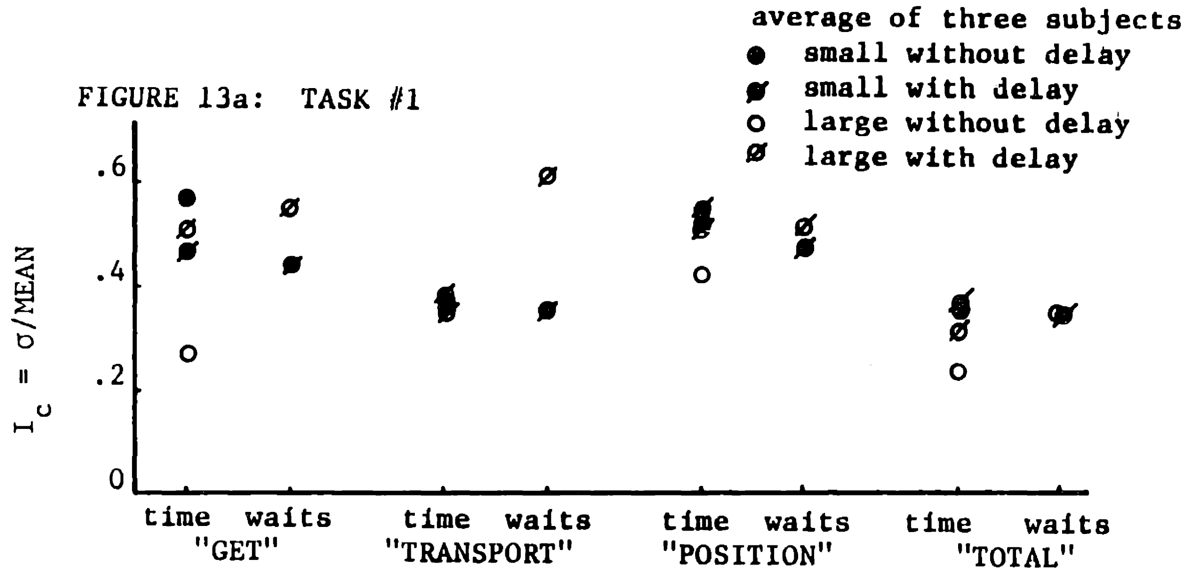


FIGURE 13b: TASK #2

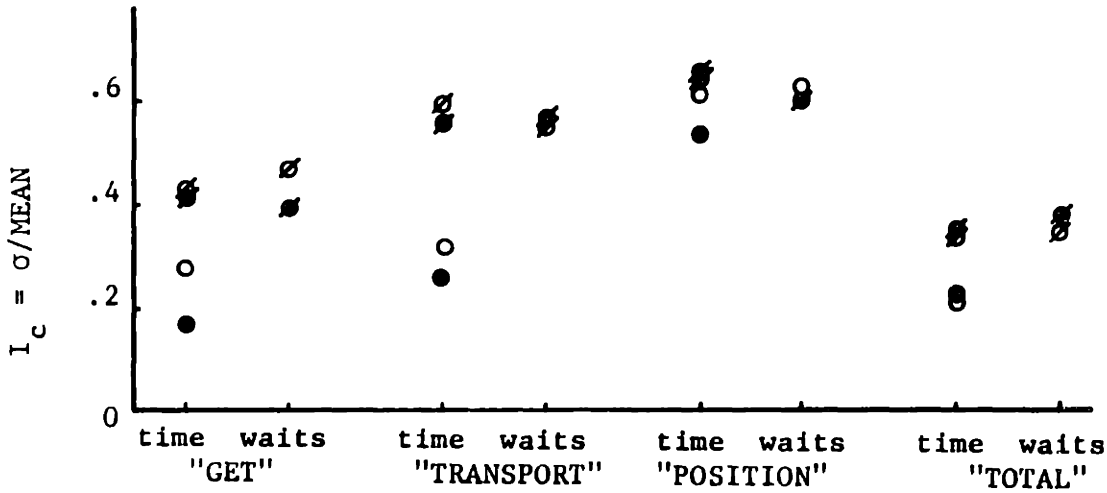
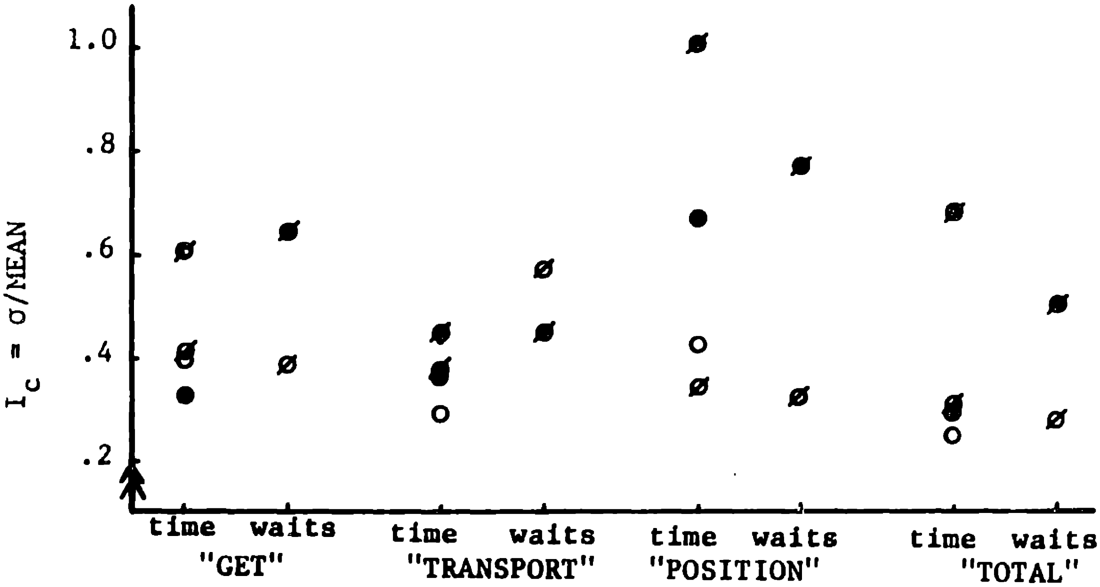


FIGURE 13c: TASK #3



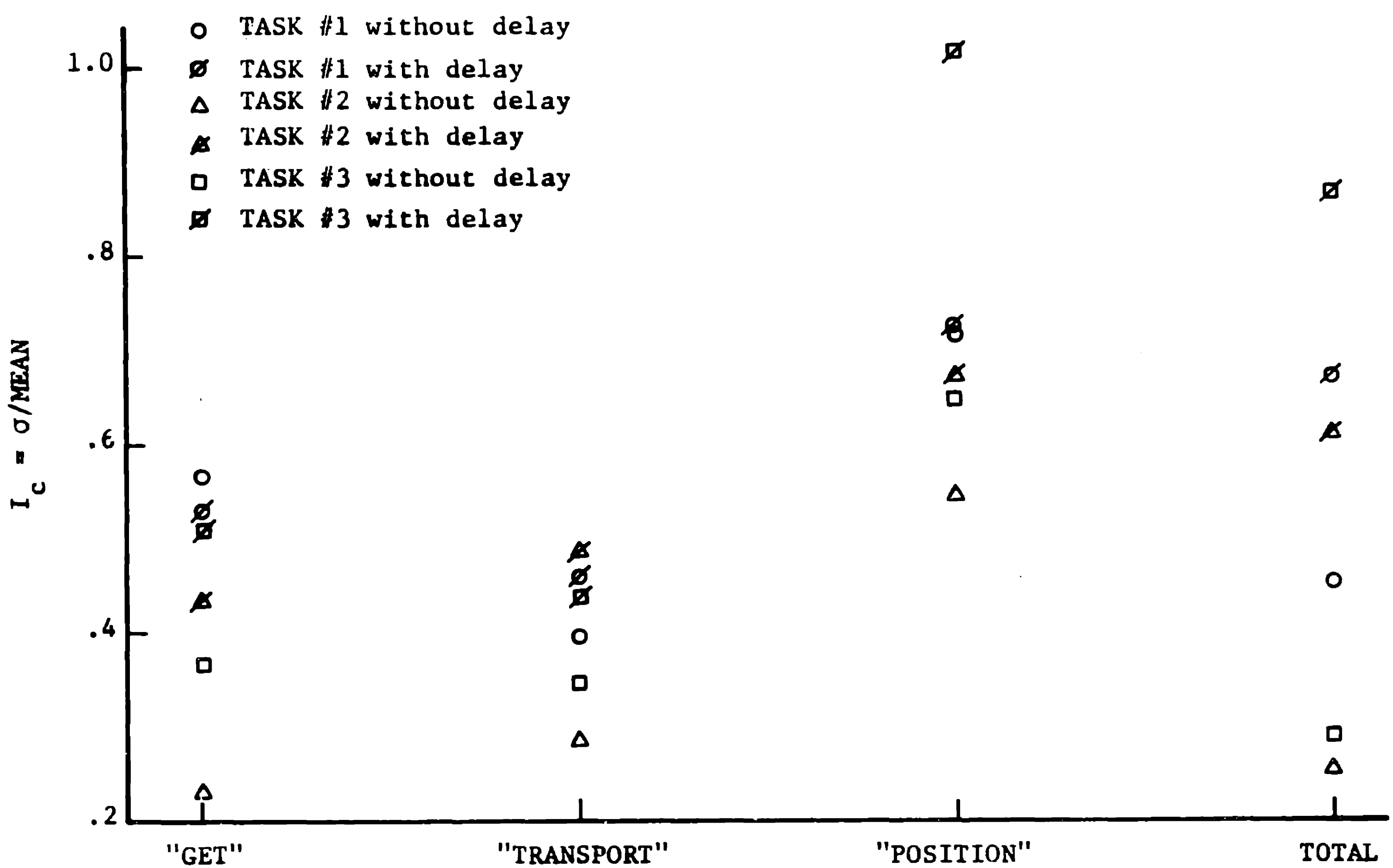


FIGURE 14: CONSISTENCY INDEX, I_c, COMPARING TASKS
(average of 3 subjects and 2 scales)

one exception, delayed manipulation was more variable than the same manipulation without delay. The degree which delay increased the variability is the ratio of $\frac{I_c \text{ with delay}}{I_c \text{ without delay}}$. Values of this ratio for the three tasks averaged over scale and subjects appear in Table 5 a.

Finally, the consistency index was computed for the completion times averaged over tasks and subjects. The results, presented in Figure 15 , compare the completion time variability of the large and small scales, with and without delay.

Without exception, small scale was more variable than large scale; this result is true for each task segment and for manipulation with delay or no delay. As also noted in the Figure 14 , "position" was consistently the most variable segment and "transport" the least variable regardless of the manipulation condition, delay or no delay.

An important result in Figure 14 is that the completion time for manipulation with delay was always more variable than the completion time of the same scale and segment without delay. The extent delay increased the variability is again determined by the ratio $\frac{I_c \text{ with delay}}{I_c \text{ without delay}}$, and the values are listed in Table 15 b.

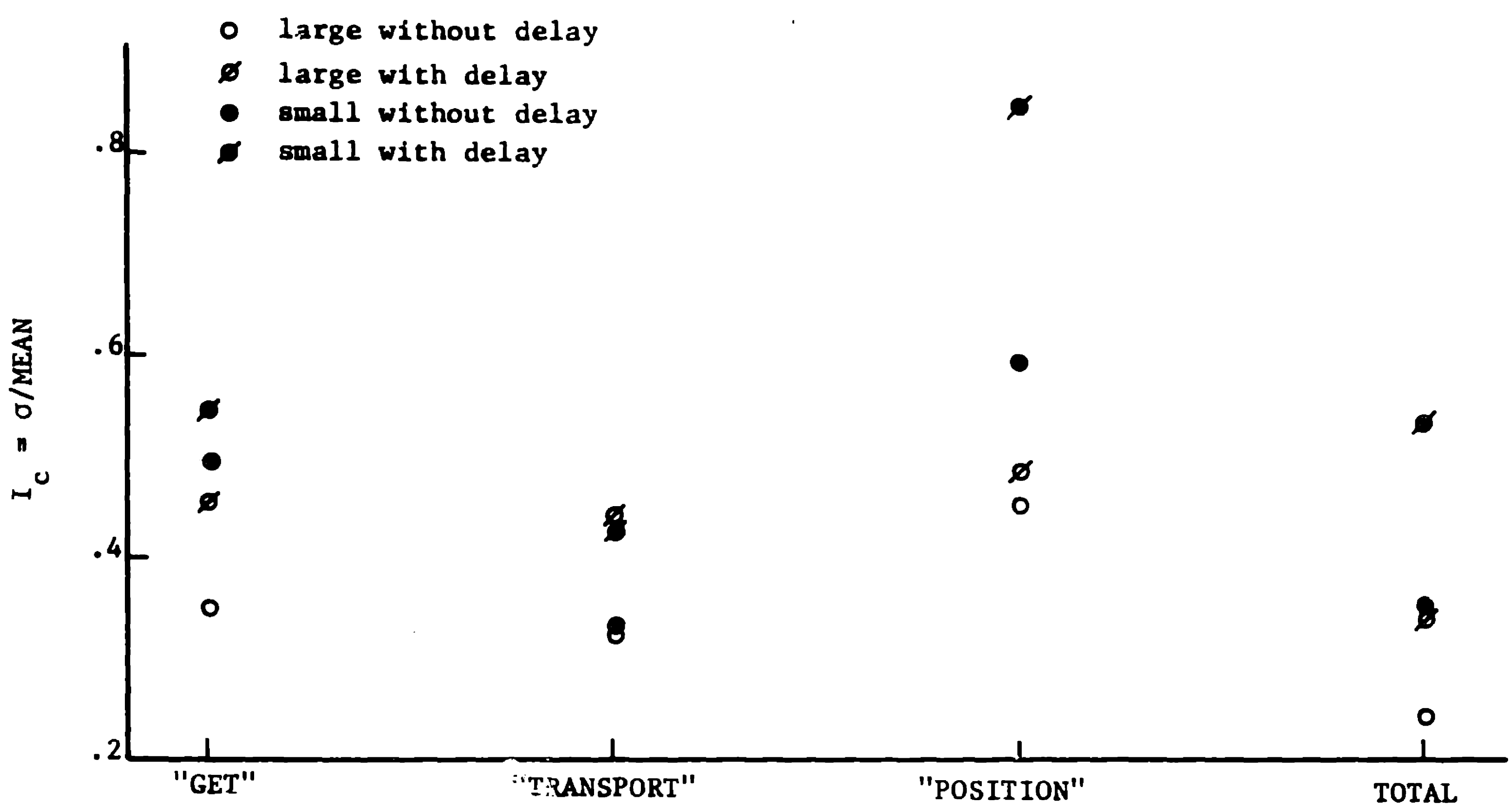


FIGURE 15: CONSISTENCY INDEX, I_c, COMPARING SCALES
(average of 3 subjects and 3 tasks)

TABLE 5 a and b: FACTOR BY WHICH DELAY INCREASED COMPLETION TIME VARIABILITY

a. Tabular value = $\frac{\sigma/\text{MEAN with delay}}{\sigma/\text{MEAN without delay}}$ for tasks, average of 3 subjects and 2 scales.

	"GET"	"TRANSPORT"	"POSITION"	TOTAL
TASK #1	.936	1.16	1.01	1.08
TASK #2	1.77	1.7	1.2	1.85
TASK #3	1.45	1.27	1.78	2.32

b. Tabular value = $\frac{\sigma/\text{MEAN with delay}}{\sigma/\text{MEAN without delay}}$ for scales, average of 3 subjects and 3 tasks.

	"GET"	"TRANSPORT"	"POSITION"	TOTAL
LARGE	1.3	1.35	1.05	1.4
SMALL	1.06	1.28	1.42	1.5

F. APPLICABILITY OF FERRELL'S RESULTS

A primary goal of this study was to determine if Ferrell's conclusions about remote manipulation with delay in three degrees of freedom (2 translate and grasp using minimal manipulator previously described) were also applicable to a six-degree-of-freedom manipulator. One of his most significant conclusions was that task completion time with delay was linearly dependent on an informational index of difficulty, the log of movement distance over terminal tolerance distance. Unfortunately this index is not easily determined for complex tasks.

However, Ferrell also reported that the number of waits for feedback during a task with delay was also a consistent linear function of the information index. Hence task completion time was linearly proportional to the number of waits for feedback.

Figure 16 is a graph of the average completion time versus the average number of waits for the six-degree of freedom manipulations in this study. The "total" and segment mean completion times and corresponding mean number of waits are plotted for the three tasks and both scales. The result is remarkably linear, corroborating Ferrell's conclusion, and extending its generality to a conventional master-slave manipulator.

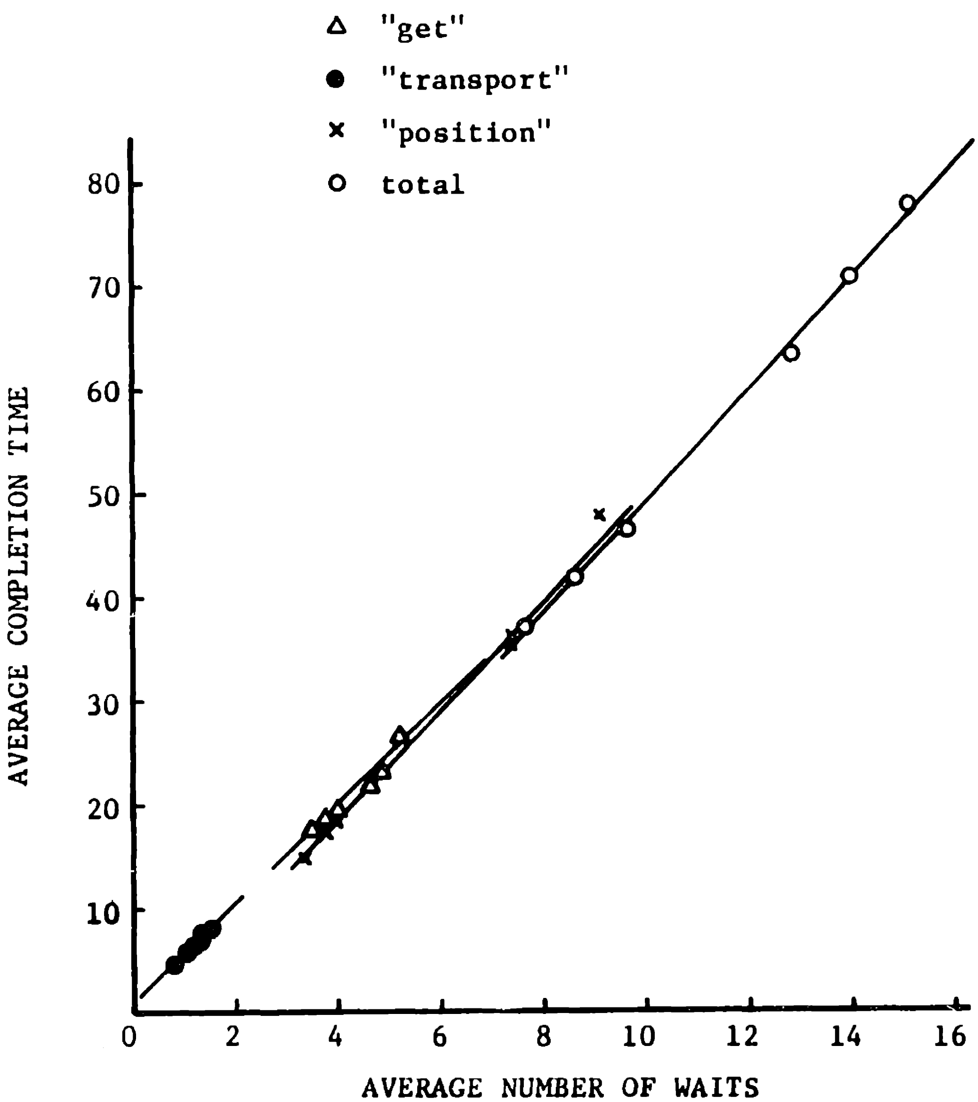


FIGURE 16: AVERAGE COMPLETION TIME WITH DELAY AS A FUNCTION OF AVERAGE NUMBER OF WAITS

CONCLUSIONS

Six degrees of freedom remote manipulation is possible with transmission time delay. The technique of making "open loop" moves and waiting for feedback is exactly analogous to the strategies Ferrell observed with his two degree of freedom minimal manipulator. Operators also found it convenient and natural to move across manipulator degrees of freedom and wait for feedback rather than move in one degree at a time.

Results of study with three manipulation tasks of both small and large scale (i.e. high and low precision indices) and with measures of task segment completion times, permit the following conclusions:

1. The commonly held conjecture that delay most affects the portions of the tasks requiring greatest precision is confirmed.
2. The "position" segment of tasks with delay consistently required an increased percentage of the total time at the expense of "get" and "transport."
3. Similarly, feedback delay consistently increased the variability of manipulation completion times.
4. Analysis of variance results for the "position" segment for placing a plate with a hole into a peg (Task #3) shows that with delay small variations in scale (i.e. the precision required): had a much greater effect than with no delay.

Counting the number of waits for feedback and raising these values in the analysis (preceding section) has produced several conclusions:

1. The fraction of the total task time spent waiting is nearly equal for all three tasks, regardless of scale.
2. The variability in the mean number of waits for a task segment correlates with and may account for the variability of the segment's mean completion time.
3. Mean completion time with delay is a linear function

of the average number of waits for feedback. This result concurs with and extends Ferrell's conclusion.

Design recommendations: Operator fatigue, physical drifting and lack of force feedback, all coupled with limited depth perception due to television viewing, were detrimental to subject's performance. These factors should be significant when devising design criteria for master-slave manipulators to be operated with transmission time delay.

Physical "drifting" is influenced by operator fatigue and delay length. If operators are to perform complicated or prolonged tasks the master control area must be as comfortable as possible. Also a lock or brake mechanism is needed to "hold" the operator's position while he waits for feedback. "Locking" the manipulator means immobilizing its six degrees of freedom; this function probably should be controlled at the master control fingertips. The longer the delay time, the more essential the brake becomes.

There were also instances when selective braking of various degrees of freedom would have assisted the operator. For example, a long positioning task could be more comfortably performed if the jaws were locked so that the operator might relax his grip without fear of dropping the grasped object. Similarly, an operator may want to hold a good position in several degrees of freedom while making final corrections in one or more degrees.

In addition, the tests showed that some form of force feedback is needed with a six-degree of freedom manipulator. Otherwise it is possible to "trap" the slave by accidentally forcing it against an immovable object in the task area. When this happens the only possible slave movement is

"Z" (up); but the operator may waste several moves and wait cycles before he discovers and corrects this situation. A very simple, visually displayed force feedback could help prevent the problem, yet avoid the instabilities (shown by Ferrell[9]) resulting in bilateral manipulators.

These studies emphasize the operator's need for good depth perception in viewing, which would be likely to improve his performance and help reduce his fatigue and the difficulties associated with no force feedback.

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APPENDIX A: PRELIMINARY TEST RESULTS

A portion of the tasks and subjects tested during the preliminary experiments are reported in the following table.

TABLE A1: Partial Summary of Preliminary Results

TASK	DIMENSIONS	SUBJECT	BEST TIME, SECONDS	
			NO DELAY	$3\frac{1}{2}$ SECOND DELAY
Plate with one hole placed onto peg	0.75" hole,0.25" peg	LS	8.2	56.5
	0.75" hole,0.5" peg	EL	8.3	103.9
	0.38" hole,0.25" peg	EL	11.9	119.2
Peg transferred from one hole to another	0.75" hole,0.5" peg	LS	4.8	85.4
	0.75" hole,0.5" peg	MS	7.9	111.7
	1.0" hole,0.75" peg	MS	5.6	49.2
Three blocks stacked	1.25" edge	WV	10.8	128.5
	1.25" edge	MS	11.0	129.6
	1.75" edge	WV	15.3	132.4

APPENDIX B: MEANS AND STANDARD DEVIATIONS

The following tables are means and standard deviations of the completion times and number of waits averaged over various margins of the array of experimental conditions. There are two tables for each margin, one for manipulation with delay and one for manipulation without delay.

SUBJECT P.V. -NO DELAY

MEANS AND STANDARD DEVIATIONS

	SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	LARGE	MEAN	2.164	0.000	1.049	0.000	1.364	0.000	4.579	0.000
		S.D.	0.530	0.000	0.288	0.000	0.375	0.000	0.941	0.000
	SMALL	MEAN	3.119	0.000	1.144	0.000	3.069	0.000	7.334	0.000
		S.D.	0.929	0.000	0.450	0.000	1.613	0.000	2.645	0.000
TASK=2	LARGE	MEAN	1.709	0.000	0.899	0.000	1.464	0.000	4.074	0.000
		S.D.	0.323	0.000	0.234	0.000	0.424	0.000	0.682	0.000
	SMALL	MEAN	2.109	0.000	1.064	0.000	2.379	0.000	5.554	0.000
		S.D.	0.406	0.000	0.294	0.000	1.118	0.000	1.553	0.000
TASK=3	LARGE	MEAN	1.994	0.000	0.844	0.000	1.144	0.000	3.989	0.000
		S.D.	0.621	0.000	0.224	0.000	0.462	0.000	0.741	0.000
	SMALL	MEAN	2.584	0.000	1.239	0.000	2.754	0.000	6.579	0.000
		S.D.	0.789	0.000	0.414	0.000	1.633	0.000	1.717	0.000

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

SUBJECT P.V. -WITH 3.5 SEC DELAY

MEANS AND STANDARD DEVIATIONS

TASK	SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	LARGE	MEAN	23.084	4.800	4.304	0.600	17.974	4.200	45.364	9.600
		S.D.	12.374	2.712	2.243	0.489	8.490	2.271	13.593	3.168
	SMALL	MEAN	32.899	6.400	7.994	1.500	36.434	7.300	77.329	15.200
		S.D.	13.006	2.289	2.624	0.500	22.494	4.450	33.028	6.193
TASK=2	LARGE	MEAN	18.639	4.000	4.679	1.000	14.049	3.100	37.369	8.100
		S.D.	6.222	1.414	0.465	0.000	5.885	1.299	8.476	1.813
	SMALL	MEAN	18.699	3.800	7.644	1.600	44.339	9.100	70.684	14.500
		S.D.	6.072	1.469	4.671	0.916	24.053	4.592	32.315	6.053
TASK=3	LARGE	MEAN	20.244	4.200	5.904	1.200	16.929	3.700	43.079	9.100
		S.D.	7.388	1.536	1.638	0.400	5.971	1.486	11.559	2.624
	SMALL	MEAN	23.374	5.100	8.564	1.600	51.199	10.700	82.939	17.400
		S.D.	6.644	1.577	4.543	0.800	23.358	5.330	24.307	5.834

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

SUBJECT D.L. -NO DELAY

MEANS AND STANDARD DEVIATIONS

TASK	SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	LARGE	MEAN	1.724	0.000	0.839	0.000	0.929	0.000	3.494	0.000
		S.D.	0.399	0.000	0.386	0.000	0.236	0.000	0.515	0.000
	SMALL	MEAN	2.539	0.000	1.389	0.000	3.429	0.000	7.359	0.000
		S.D.	0.501	0.000	0.517	0.000	1.770	0.000	2.165	0.000
TASK=2	LARGE	MEAN	2.164	0.000	1.229	0.000	1.324	0.000	4.719	0.000
		S.D.	0.582	0.000	0.349	0.000	0.937	0.000	0.927	0.000
	SMALL	MEAN	1.874	0.000	1.034	0.000	2.500	0.000	5.409	0.000
		S.D.	0.413	0.000	0.313	0.000	0.929	0.000	1.099	0.000
TASK=3	LARGE	MEAN	2.609	0.000	1.234	0.000	1.274	0.000	5.119	0.000
		S.D.	0.788	0.000	0.229	0.000	0.417	0.000	0.980	0.000
	SMALL	MEAN	2.279	0.000	1.309	0.000	1.384	0.000	4.974	0.000
		S.D.	0.680	0.000	0.505	0.000	0.634	0.000	1.114	0.000

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

SUBJECT D.L. -WITH 3.5 SEC DELAY

MEANS AND STANDARD DEVIATIONS

TASK	SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	LARGE	MEAN	15.789	3.000	4.574	0.700	12.749	2.700	33.114	6.500
		S.D.	5.304	1.000	1.346	0.458	7.291	1.345	7.858	1.627
	SMALL	MEAN	28.564	5.300	7.764	1.200	40.464	8.400	76.794	14.800
		S.D.	11.200	2.238	3.270	0.400	19.603	3.322	18.301	3.026
TASK=2	LARGE	MEAN	22.924	4.400	8.309	1.500	24.624	5.100	55.859	11.000
		S.D.	8.993	2.107	3.599	0.670	10.492	1.972	14.525	3.130
	SMALL	MEAN	24.694	4.800	9.439	1.500	41.334	8.100	75.469	14.400
		S.D.	9.247	1.886	2.827	0.500	15.282	2.773	22.665	4.340
TASK=3	LARGE	MEAN	24.949	5.100	5.369	0.800	22.824	4.500	53.144	10.400
		S.D.	11.471	2.211	2.248	0.600	5.788	1.118	16.288	3.104
	SMALL	MEAN	28.989	5.700	6.804	1.200	66.219	10.800	102.014	17.700
		S.D.	21.156	4.670	1.845	0.400	79.074	10.017	78.357	10.421

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

SUBJECT B.J. -NO DELAY

MEANS AND STANDARD DEVIATIONS

	SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	LARGE	MEAN	2.009	0.000	0.794	0.000	1.454	0.000	4.259	0.000
		S.D.	0.575	0.000	0.228	0.000	0.689	0.000	1.021	0.000
	SMALL	MEAN	3.729	0.000	1.184	0.000	3.444	0.000	8.359	0.000
		S.D.	2.789	0.000	0.280	0.000	1.725	0.000	2.886	0.000
TASK=2	LARGE	MEAN	1.854	0.000	0.844	0.000	0.989	0.000	3.689	0.000
		S.D.	0.556	0.000	0.143	0.000	0.242	0.000	0.713	0.000
	SMALL	MEAN	1.949	0.000	1.199	0.000	1.724	0.000	4.874	0.000
		S.D.	0.196	0.000	0.215	0.000	0.539	0.000	0.688	0.000
TASK=3	LARGE	MEAN	2.634	0.000	0.909	0.000	1.334	0.000	4.879	0.000
		S.D.	1.199	0.000	0.247	0.000	0.682	0.000	1.316	0.000
	SMALL	MEAN	2.334	0.000	0.924	0.000	1.654	0.000	4.914	0.000
		S.D.	0.864	0.000	0.170	0.000	0.946	0.000	1.388	0.000

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

SUBJECT B.J. -WITH 3.5 SEC DELAY

MEANS AND STANDARD DEVIATIONS

TASK	SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	LARGE	MEAN	13.759	2.900	4.689	0.900	13.444	3.100	31.894	6.900
		S.D.	3.664	0.943	0.901	0.300	5.306	1.299	6.297	1.513
	SMALL	MEAN	18.834	4.000	7.099	1.300	31.294	6.600	57.239	11.900
		S.D.	7.856	1.673	2.582	0.458	14.625	3.322	17.265	3.726
TASK=2	LARGE	MEAN	12.984	2.600	4.904	1.000	13.559	3.100	31.449	6.700
		S.D.	3.726	0.800	2.057	0.447	7.087	1.577	9.097	2.002
	SMALL	MEAN	15.164	3.400	6.399	1.300	21.249	4.900	42.814	9.600
		S.D.	4.461	0.916	1.982	0.458	5.878	0.943	7.184	1.200
TASK=3	LARGE	MEAN	20.729	4.500	5.469	1.000	16.489	3.900	42.689	9.400
		S.D.	6.328	1.431	2.307	0.632	5.524	1.300	10.657	2.332
	SMALL	MEAN	16.374	3.500	5.439	1.000	25.999	5.800	47.814	10.300
		S.D.	5.489	1.204	0.537	0.000	10.127	2.271	13.088	2.722

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

AVE. OVER SCALE + SUBJECTS -NO DELAY
MEANS AND STANDARD DEVIATIONS

		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	MEAN	2.548	0.000	1.067	0.000	2.282	0.000	5.898	0.000
	S.D.	1.443	0.000	0.425	0.000	1.634	0.000	2.666	0.000
TASK=2	MEAN	1.944	0.000	1.045	0.000	1.730	0.000	4.720	0.000
	S.D.	0.460	0.000	0.302	0.000	0.941	0.000	1.197	0.000
TASK=3	MEAN	2.406	0.000	1.077	0.000	1.591	0.000	5.076	0.000
	S.D.	0.875	0.000	0.372	0.000	1.047	0.000	1.465	0.000

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

AVE. OVER SCALE + SUBJECTS -WITH 3.5 SEC DELAY
MEANS AND STANDARD DEVIATIONS

		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
TASK=1	MEAN	22.155	4.400	6.071	1.033	25.394	5.383	53.623	10.816
	S.D.	11.764	2.296	2.793	0.546	18.253	3.619	26.086	4.968
TASK=2	MEAN	18.851	3.833	6.896	1.316	26.526	5.566	52.274	10.716
	S.D.	7.901	1.664	3.398	0.618	17.951	3.402	24.530	4.586
TASK=3	MEAN	22.444	4.683	6.259	1.133	33.277	6.566	61.947	12.383
	S.D.	11.851	2.519	2.745	0.590	38.983	5.690	41.762	6.498

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

AVE. OVER TASKS + SCALES -NO DELAY
MEANS AND STANDARD DEVIATIONS

		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
SUBJECT=1	MEAN	2.280	0.000	1.040	0.000	2.029	0.000	5.352	0.000
	S.D.	0.782	0.000	0.355	0.000	1.312	0.000	1.992	0.000
SUBJECT=2	MEAN	2.199	0.000	1.173	0.000	1.807	0.000	5.179	0.000
	S.D.	0.661	0.000	0.437	0.000	1.296	0.000	1.689	0.000
SUBJECT=3	MEAN	2.419	0.000	0.976	0.000	1.767	0.000	5.163	0.000
	S.D.	1.478	0.000	0.270	0.000	1.216	0.000	2.139	0.000

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

AVE. OVER TASKS + SCALES -WITH 3.5 SEC DELAY
MEANS AND STANDARD DEVIATIONS

		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
SUBJECT=1	MEAN	22.824	4.716	6.515	1.250	30.154	6.350	59.461	12.316
	S.D.	10.325	2.090	3.501	0.698	22.504	4.618	29.062	5.826
SUBJECT=2	MEAN	24.319	4.716	7.044	1.150	34.703	6.600	66.066	12.466
	S.D.	13.001	2.745	3.128	0.600	38.433	5.339	41.592	6.288
SUBJECT=3	MEAN	16.308	3.483	5.667	1.083	20.339	4.566	42.317	9.133
	S.D.	6.108	1.360	2.060	0.457	10.963	2.361	14.358	3.019

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

AVE. OVER TASKS + SUBJECTS -NO DELAY
MEANS AND STANDARD DEVIATIONS

SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
LARGE	MEAN	2.096	0.000	0.961	0.000	1.253	0.000	4.312	0.000
	S.D.	0.737	0.000	0.312	0.000	0.571	0.000	1.038	0.000
SMALL	MEAN	2.502	0.000	1.166	0.000	2.482	0.000	6.151	0.000
	S.D.	1.244	0.000	0.394	0.000	1.483	0.000	2.201	0.000

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

AVE. OVER TASKS + SUBJECTS -WITH 3.5 SEC DELAY
MEANS AND STANDARD DEVIATIONS

SCALE		GET	GWAIT	TRANS	TWAIT	POSIT	PWAIT	TOTAL	TOWAIT
LARGE	MEAN	19.234	3.944	5.356	0.966	16.961	3.711	41.552	8.633
	S.D.	8.819	1.887	2.356	0.546	8.114	1.727	14.164	2.907
SMALL	MEAN	23.066	4.666	7.461	1.355	39.837	7.966	70.344	13.977
	S.D.	12.154	2.454	3.225	0.583	33.865	5.152	37.934	6.088

GET,TRANS,POSIT,TOTAL = TIME IN SEC.

GWAIT,TWAIT,PWAIT,TOWAIT = NUMBER OF WAITS

APPENDIX C: ANALYSIS OF VARIANCE EXAMPLE

The following is a summary of the analysis of variance format used in this study.[10] The numerical values shown were calculated from data (completion times) recorded for the "position" segment of Task #2 with delay.

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	$\hat{\sigma}^2$
Between Scales	$V_2 = 4985$	1	$S_2 = V_2/1 = 4985$
Between Subjects	$V_3 = 2640$	2	$S_3 = V_3/2 = 1320$
Interaction	$V_5 = V_4 - V_3 - V_2 = 1294$	2	$S_5 = V_5/2 = 647$
Subtotal	$V_4 = 8919$	5	——
Within groups	$V_6 = V_1 - V_4 = 10416$	54	$S_6 = V_6/54 = 193$
Total	$V_1 = 19335$	59	——

$F_{Interaction} = F_I = S_5/S_6 = 3.35$ Consulting F tables: > 95%

Assuming F_I was <u>significant</u>:

F scales $= S_2/S_5 = \frac{4985}{647} = 7.7$ Consulting F tables: > 70%

F subjects $= S_3/S_5 = \frac{1320}{647} = 2.1$ " " " : > 70%

Assuming F_I was <u>not significant</u>:

$F_{scales} = S_2/S_5+S_6 = \frac{4985}{840} = 5.93$ Consulting F tables: > 97.5%

$F_{subjects} = S_3/S_5+S_6 = \frac{1320}{840} = 1.57$ " " " : > 70%