WADD TECHNICAL REPORT 60-591 (I)

MEASURES OF REMOTE MANIPULATOR FEEDBACK: DIFFERENTIAL SENSITIVITY FOR WEIGHT

BILLY M. CRAWFORD

BEHAVIORAL SCIENCES LABORATORY
AEROSPACE MEDICAL LABORATORY

MARCH 1961

PROJECT No. 7184
TASK No. 71586

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

McGregor & Werner, Inc., Dayton, O.
900 - October 1961 - 4-69 & 70

FOREWORD

This report was prepared by the Maintenance Design Section, Human Engineering Branch, Behavioral Sciences Laboratory, Aerospace Medical Laboratory. The investigation was conducted from November 1959 to February 1960 under Project No. 7184, "Human Factors in Advanced Flight," Task No. 71586, "Design Criteria for Ease of Maintenance," with Billy M. Crawford acting as project engineer. The author is indebted to Major Leroy D. Pigg, Chief, Maintenance Design Section, and M. J. Warrick, Assistant Chief, Human Engineering Branch, for advice concerning the preparation of this report.

ABSTRACT

The psychophysical Method of Constant Stimulus Differences was used to determine difference thresholds and Weber ratios for both direct and remote lifting of two standard weight stimuli. A Model 8 Master-Slave Manipulator was used for remote lifting. For a 1000-gram weight, difference thresholds were 65.42 and 110.45 grams for direct and remote lifting, respectively. Corresponding difference thresholds for a 3000-gram standard were 149.33 and 195.69 grams. The difference threshold indicates the fineness of weight discrimination which can be expected of a worker. Increases in difference thresholds as a function of remote lifting reflect the loss of "feel" associated with remote handling. The difference threshold is proposed as a criterion of the fidelity of cues reflected to the operator by the remote-handling system.

PUBLICATION REVIEW

Walter F. Grether

WALTER F. GRETHER
Technical Director
Behavioral Sciences Laboratory
Aerospace Medical Laboratory

MEASURES OF REMOTE MANIPULATOR FEEDBACK: DIFFERENTIAL SENSITIVITY FOR WEIGHT

INTRODUCTION

The most common, general-purpose, remote-handling device in use today is the master-slave manipulator which provides for the reciprocal transfer of motions and forces between the master control and the effector or slave section (ref. 3). The primary purpose of the reciprocal force reflection feature is to provide the manipulator operator "feel feedback" in the form of tactual and kinesthetic cues. Differential sensitivity for weight, i.e., the ability to distinguish between weights, is regarded as an approoriate indicator of man's sensitivity to such cues.

Differential sensitivity is measured in terms of the smallest discernible change in in a physical characteristic of a stimulus (in this instance, weight). The smallest discernible change in a stimulus is operationally defined as the increment of change which can be detected 50 percent of the time. This increment is called a difference threshold, or difference limen (DL).

The particular value for which the DL is determined is called the standard stimulus (St). The determination of a DL usually involves the use of a number of other stimuli which vary from the St by different amounts in terms of the physical characteristic being studied. These stimuli are called comparison stimuli (Co's) because the subject is required to compare each of them with the St on numerous occasions. The subject must differentiate between each Co and the St by indicating which seems greater. This procedure is known as the Method of Constant Stimulus Differences.

The DL expressed as a proportion of the St is known as the Weber ratio, and is often used to compare differential sensitivity for the various sensory modes. This particular study was designed to determine and compare differential sensitivity for directly lifted weights with differential sensitivity for remotely lifted weights. This comparison should provide a valid indication of the fidelity of kinesthetic and tactual feedback of the manipulator. The technique could be used in the development and evaluation of different remote manipulator designs. It could also be used to determine the fineness of weight discrimination which can be expected of a remote manipulator operator.

APPARATUS AND SUBJECTS

Central Research Laboratories' version of the Argonne National Laboratory Model 8 Master-Slave Manipulator (ref. 4) was used for the remote-lifting phase of this study. This manipulator incorporates both reciprocal force reflection and conformity of the control and effector with respect to spatial orientation and movement. It can be described generally as consisting of two vertical telescoping tubes connected by a horizontal overhead through-tube. One vertical tube is the effector or slave section, which operates in the irradiated or other remote environment. The other vertical tube is the control or master section, which is protected from the radiation source by a shielding wall through which the horizontal through-tube passes. A reciprocal coupling mechanism connects the master and slave sections. The slave is equipped with a parallel-jaw type hand, controlled from the lower extremity of the master section by a "squeeze-type" assembly which accommodates the thumb and first two fingers of the operator's hand.

The system provides for the reciprocal transfer of motions and forces between the master and slave at a ratio of approximately 1:1 with seven degrees of freedom in movement and force application: three for translation, three for rotation, and one for opening and closing the jaws of the slave hand. Forces required to overcome friction in the remote manipulator are 12 ounces and 1 ounce for the vertical and horizontal motions, respectively. According to manufacturer's specifications, within the load capacity of the manipulator (10 pounds) and over a limited range from the normal rest position, the forces are independent of the weight being lifted. The entire system is counterbalanced against gravitational forces.

A table was placed beneath the slave section of the manipulator to serve as a surface upon which to place the stimulus weights which were presented to the subject. A piece of acoustic tile was used as a cushion for the weights. The top of the table was 41 inches from the floor. A second table was used by the experimenter as a surface upon which to store and assemble the stimulus materials. This table was obscured from the subject's view by the larger first table and the simulated shielding wall. A diagram of the remote-lifting setup is shown in figure 1.

For direct lifting, the cabinet shown in figure 2 was used. The top shelf, 41 inches from the floor, was padded with acoustic tile and used as a surface upon which to place the weights to be lifted by the subject. The lower shelf, obscured from the subject's view by the hood mounted on the top shelf, served the same purpose as the small table used in the remote-lifting situation.

Two St's were used in the experiment: a 1000-gram weight (St_1) and a 3000-gram weight (St_3). For each St there were 9 Co's. Four Co's were less than, four greater than, and one equal to the St. Co's for St_1 were separated by step intervals of 50 grams. They covered a weight range from 800 to 1200 grams. Co's for St_3, separated by step intervals of 1000 grams, ranged from 2600 to 3400 grams. These weights were used for deriving DL's. Each subject also made absolute judgments of 900-, 2700-, and 4600-gram weights during the experiment. These are referred to hereafter as 2-, 6-, and 10-pound weights, respectively.

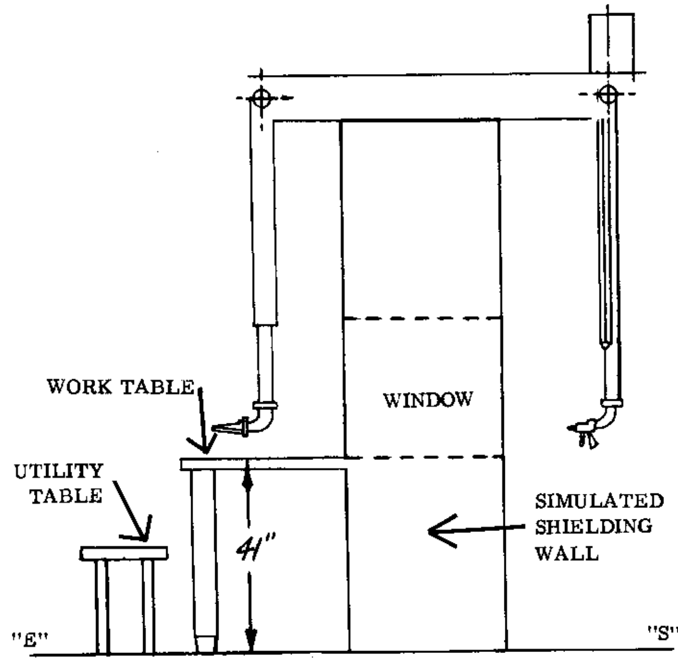

Figure 1. Schematic of Master-Slave Manipulator Used for Remote Lifting, Mounted Over Simulated Shielding Wall, Work Table, and Utility Table. Positions at which Experimenter and Subject Stood are Designated by "E" and "S."

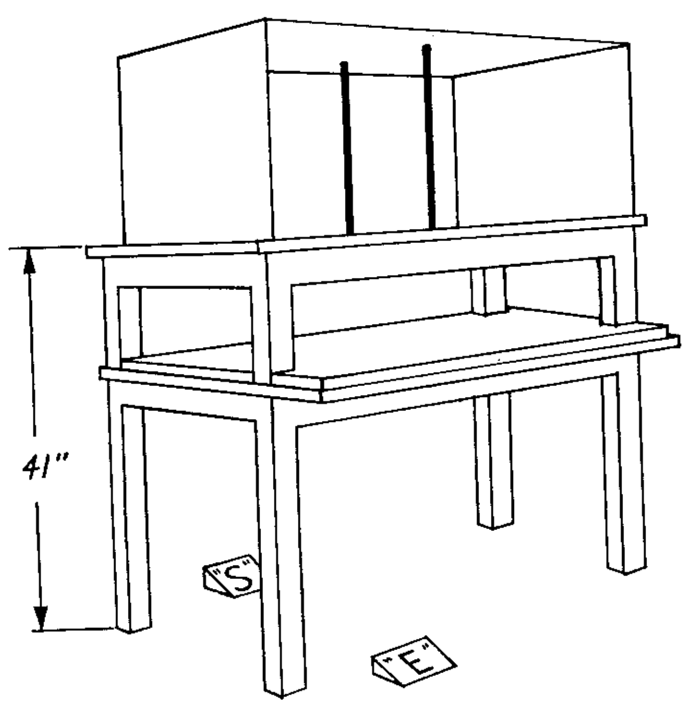

Figure 2. Cabinet Used to Support Weights for Direct Lifting. Wedges "E" and "S" Designate Experimenter and Subject.

Each stimulus weight was formed by placing a metal disk of the appropriate supplemental weight in either of two identical metal capsules. The capsules were cylindrical in shape and weighed 750 grams each. The lids for the capsules were easily opened or closed by pressing and turning the handle or knob. Interchangeable knobs, having identical weights but different configurations, permitted adaptation of the capsules for either direct or remote lifting. A round knob was used for direct lifting; a T-shaped knob, for remote lifting. When the vertical bar of the "T" was grasped between the jaws of the manipulator slave hand, the crossbar rested on the upper surface of the jaws. This reduced the amount of grip force required to prevent the knob from slipping between the jaws of the slave hand, a hazard which rendered the round knob impractical for use with the heavier weights. The pattern of tactual stimulation was not affected further by variation of the capsule knobs since, for direct lifting, the subject gripped the capsule knob while, for remote lifting, he gripped the manipulator control. Components used in forming the stimulus weights are shown in figures 3 and 4.

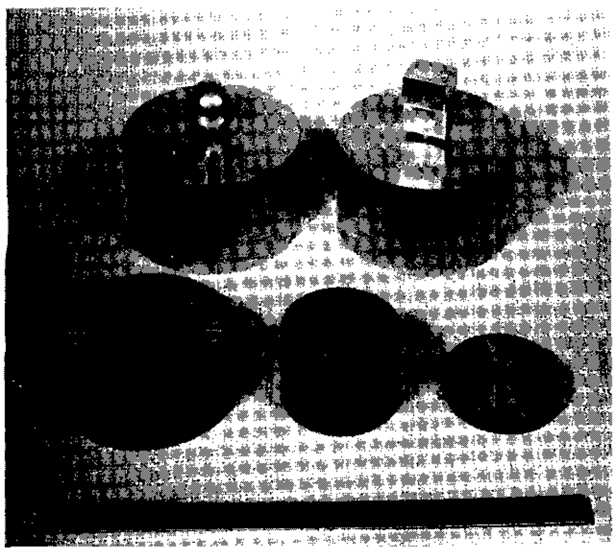

Figure 3. Components of the 2-, 6-, and 10-Pound Stimuli

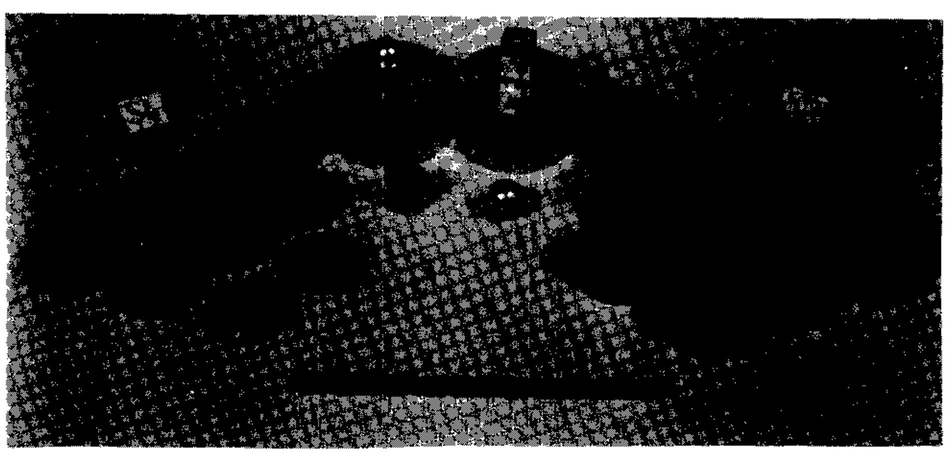

Figure 4. Components of the 1000-Gram (St_1) and 3000-Gram (St_3) Series of Weights

Twenty male university students served as subjects. Their ages ranged from 17 to 23 years. Subjects were randomly assigned to two groups: one to determine DL's for St_1, the other for St_3.

PROCEDURE

All subjects were required to use both lifting techniques. Each subject completed all of the experimental procedure for one lifting condition before going to the other. To control for practice effects, half the subjects of each group began with direct lifting and the other half, with remote lifting. The general procedure is outlined below:

SESSION I. Direct (or Remote) Lifting

Orientation of subject with respect to lifting technique
Absolute judgments of 2-, 6-, and 10-pound weights
Method of Constant Stimulus Differences using either the St_1 or St_3 series of weights (5- to 10-minute rest period at midpoint)
Absolute judgments of 2-, 6-, and 10-pound weights

REST PERIOD (5-10 minutes between sessions)

SESSION II. Remote (or Direct) Lifting

Orientation of subject with respect to lifting technique
Absolute judgments of 2-, 6-, and 10-pound weights
Method of Constant Stimulus Differences using either the St_1 or St_3 series of weights (5- to 10-minute rest period at midpoint)
Absolute judgments of 2-, 6-, and 10-pound weights

Absolute judgments were included in the experimental design to gain information concerning (a) the effect of remote handling upon estimates of weight and (b) the effects of interpolated experience upon these estimates. The results of this phase are presented and discussed in another report (ref. 1).

The orientation periods included a general description of the study and specific instructions concerning the apparatus and lifting techniques to be used. Subjects were told to grasp the knob of the capsule between the thumb and fingers of the preferred hand when lifting the weights directly. Prior to the remote-lifting sessions the experimenter briefly described the development and uses of the remote-handling device. Each subject was allowed two or three minutes to become familiar with the remote manipulator and demonstrate his ability to lift the capsules. All subjects stood throughout the experiment except during the rest periods.

At the beginning of each session, after becoming familiar with the lifting technique to be used, each subject was told that three weights would now be placed one at a time on the table before him, and that he should lift each weight 2 or 3 inches off the table, set it down, and make a verbal estimate of its weight in pounds and fractions of a pound. At no time during the experiment was the actual weight lifted by a subject identified to him. The weights were presented in random order. The experimenter recorded each subject's responses on a record sheet. After he had made these absolute judgments, the subject was told that his task would now be changed somewhat but that later on, from time to time, he would be asked to estimate the actual values of certain weights in the same manner.

At this point the Method of Constant Stimulus Differences was introduced to present either the St_1 or St_3 series of stimuli and the subject was instructed as follows:

"Now a series of pairs of weights will be presented to you one at a time. Again you are to lift each weight 2 or 3 inches off the table and set it down. But now, instead of estimating weights, you are to indicate which of each is heavier by saying 'the first' or 'the second.' Sometimes the difference between the weights will be so small that no one could judge correctly every time. But don't be afraid to make quick judgments even when you're uncertain. If you always give good attention, you'll be correct most of the time. Are there any questions?"

When there were questions, the instructions were clarified to the subject's satisfaction.

Each pair of stimuli consisted of the St and one of the nine Co's. The subject compared the St with each of the Co's on 20 separate occasions for each lifting condition, a total of 180 comparisons or trials per lifting session. The trials occurred in random order. The order in which the St was presented, i.e., first or second, was also random.

Approximately two seconds elapsed between the presentation of the first and second stimulus of each pair. This was the time required for the experimenter to remove the first capsule and replace it with the second. An additional three or four seconds elapsed between pairs of stimuli while the experimenter altered the value of the Co by removing and replacing the disk contained in the capsule. Responses were recorded on the subject's record sheet by the experimenter after each trial.

At the close of each lifting session, the subject made three more absolute judgments.

RESULTS

The frequency of responses indicating the Co to be heavier than the St is presented in tables I and II for each subject, lifting condition, and Co value. The rows labeled "p" represent the total number of "heavier" responses as a proportion of the total (200) responses made for each Co value.

Theory and empirical evidence indicate that the best fitting regular curves for frequency distributions derived by this method are normal ogives (ref. 9). The method of least squares (ref. 5) was applied to the experimental data to derive means and standard deviations (SD's) which were used to obtain the best fitting normal ogives for each experimental condition. Curves derived for St_1 are shown in figure 5. Those for St_3 are shown in figure 6.

The chi square technique described by Guilford (ref. 5) was used to test for significance of discrepancies between the empirical data and the theoretical curves. None of the chi squares was significant ($p < .05$). Chi squares obtained could have occurred by chance with probabilities greater than .35 and .45 for direct and remote lifting with St_1 and .05 and .50 for direct and remote lifting with St_3.

TABLE I

FREQUENCY OF "HEAVIER" RESPONSES FOR EACH Co AND LIFTING CONDITION IN THE St_1 SERIES

DIRECT LIFTING

	COMPARISON STIMULUS								
SUBJECT	800	850	900	950	1000	1050	1100	1150	1200
A	0	1	1	5	7	17	17	20	20
B	0	0	0	7	8	18	19	17	19
C	0	1	0	6	9	11	15	19	20
D	0	1	2	8	9	14	19	19	20
E	0	1	2	4	10	13	19	17	20
F	1	3	1	3	10	14	18	20	20
G	1	1	8	10	16	17	18	19	20
H	1	4	4	7	8	13	16	20	19
I	0	1	4	9	8	11	16	17	18
J	1	1	5	6	7	13	15	19	19
TOTAL	4	14	27	65	92	141	172	187	195
p*	.020	.070	.135	.325	.460	.705	.860	.935	.975

REMOTE LIFTING

	COMPARISON STIMULUS								
SUBJECT	800	850	900	950	1000	1050	1100	1150	1200
A	3	4	4	7	7	14	14	16	19
B	1	3	5	11	12	15	15	20	18
C	2	4	2	7	10	13	14	14	18
D	2	5	8	7	10	12	16	18	18
E	2	5	5	8	11	12	13	16	16
F	6	0	4	6	10	10	11	17	18
G	3	1	2	5	11	9	8	15	16
H	1	9	5	2	12	15	15	14	17
I	2	4	4	10	14	11	17	17	18
J	0	5	7	9	11	14	15	17	19
TOTAL	22	40	46	72	108	125	138	164	177
p*	.110	.200	.230	.360	.540	.625	.690	.820	.885

*p - proportion of "heavier" responses

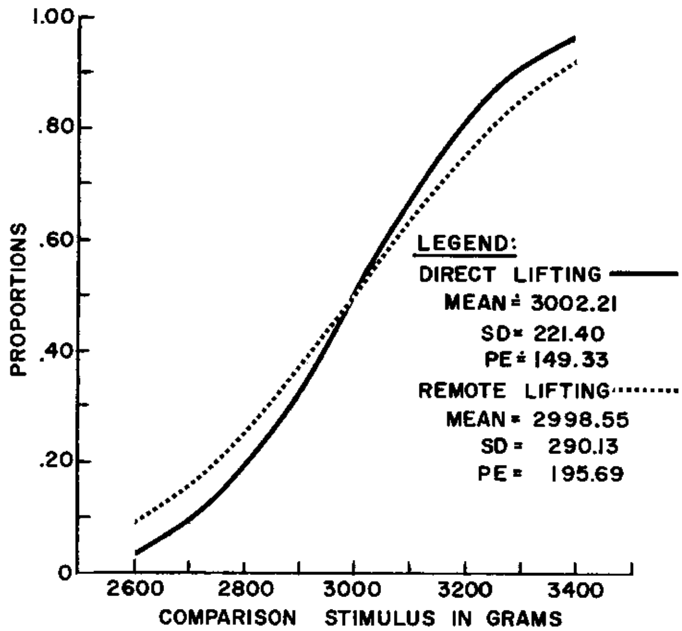

Figure 5. Proportion of "Heavier" Responses as a Function of Comparison Stimulus and Lifting Condition for St_1 Series

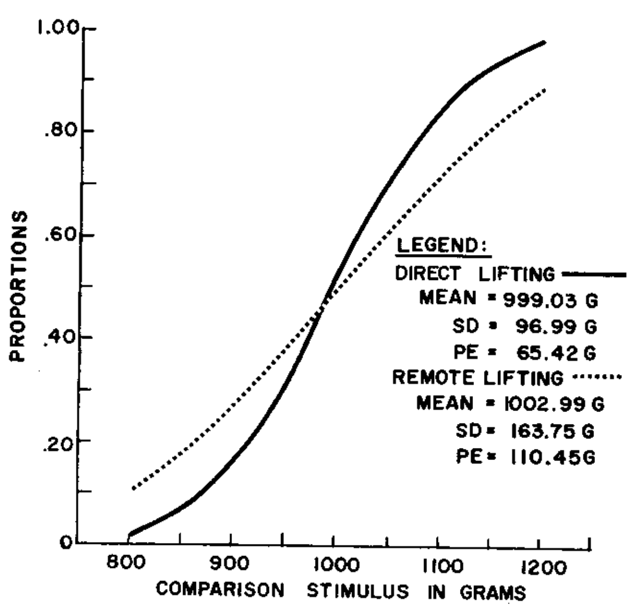

Figure 6. Proportion of "Heavier" Responses as a Function of Comparison Stimulus and Lifting Condition for St_3 Series

TABLE II

FREQUENCY OF "HEAVIER" RESPONSES FOR EACH Co AND LIFTING CONDITION IN THE St_3 SERIES

DIRECT LIFTING

SUBJECT	COMPARISON STIMULUS								
	2600	2700	2800	2900	3000	3100	3200	3300	3400
K	0	0	3	3	11	17	17	19	19
L	0	0	0	5	5	13	13	17	19
M	1	0	2	6	9	13	16	19	19
N	0	2	7	6	10	14	13	17	20
O	0	5	4	7	13	11	14	18	20
P	0	1	2	7	8	13	12	18	19
Q	0	1	3	7	11	14	14	19	18
R	1	5	2	6	8	15	15	19	20
S	1	1	3	5	6	11	16	19	19
T	3	11	4	10	14	19	19	19	20
TOTAL	6	26	30	62	95	140	149	184	193
p*	.030	.130	.150	.310	.475	.700	.745	.920	.965

REMOTE LIFTING

SUBJECT	COMPARISON STIMULUS								
	2600	2700	2800	2900	3000	3100	3200	3300	3400
K	2	2	5	10	11*	16	14	15	16
L	2	2	5	11	6	14	20	18	18
M	2	3	4	4	10	12	12	18	18
N	2	2	3	9	10	12	17	16	18
O	1	3	5	9	13	13	13	18	20
P	3	3	3	5	11	12	15	17	17
Q	3	0	6	10	8	10	19	18	18
R	2	5	4	6	10	14	13	19	18
S	0	6	6	8	12	16	15	18	19
T	1	5	10	7	10	12	18	18	20
TOTAL	18	31	51	79	101	131	156	175	182
p*	.090	.155	.255	.395	.505	.655	.780	.875	.910

*p - proportion of "heavier" responses

The mean for each frequency distribution represents the Co value which shows an equal probability ($p = .50$) of being judged heavier or lighter than the St. This value of the Co is known as the point of subjective equality (PSE). Under certain experimental conditions, the PSE may differ from the point of objective equality, which is, of course, the St value (ref. 9). However, no such tendency was observed in this study. PSE's for direct lifting were 999.03 and 3002.21 grams for St_1 and St_3, respectively. Corresponding values for remote lifting were 1002.99 and 2998.55 grams. These variations from the points of objective equality are not statistically significant.

Since the mean, or PSE, at .50 represents no discriminable difference, it follows that, at $p = .00$ and $p = 1.00$, discrimination between the Co and St is perfect. Similarly, the difference between the St and the Co at $p = .25$ or $p = .75$ can be taken as a difference noted half the time. This difference conforms to our definition of a DL. The increment is also known as the probable error (PE) of the distribution and is equivalent to .6745 SD. Although the PE is not strictly the same as the DL obtained by other psychophysical methods, it is valid for comparison of differential sensitivities found with the different experimental conditions of this study (ref. 8).

The DL for St_1 lifted directly was 65.42 grams. For remote lifting, the DL was 110.45 grams. For St_3, DL's were 149.33 and 195.69 grams for direct and remote lifting, respectively. These DL's are based on the pooled responses of ten subjects for each condition. They are equivalent to the PE's of the distributions represented by the curves shown in figures 5 and 6. With respect to lifting condition, direct versus remote, each subject served as his own control.

DL's and Weber ratios are presented in table III. The Weber ratios vary from St to St as well as from one lifting condition to the other. The variation between ratios is incongrous with Weber's law which states that such ratios are constant. Since separate groups worked with the two St's, part of the discrepancy could be due to sampling error. However, Weber's law is known to hold only over the middle range of St values and exceptions such as this are not uncommon. The Weber ratios for direct lifting are comparable with those obtained by other investigators (refs. 7, 9).

The loss in differential sensitivity as a function of remote lifting is a different matter. The extra force required to operate the remote manipulator itself is equivalent to an increase in the value of the St. As previously stated, manufacturer's specifications indicate that this force is relatively constant and amounts to approximately 340 grams (12 ounces). Assuming that this value is accurate and that no additional loss in differential sensitivity occurs as a function of remote lifting, the products of the adjusted St's (1340 and 3340 grams) and the Weber ratios for direct lifting (.065 and .050) should reasonably approximate the empirically derived DL's for remote lifting. However, such is not the case. Instead of 340 grams, about 700 grams must be added to St_1 and 915 grams to St_3 to produce the obtained DL's.

Differences between expected and empirically derived DL's for remote lifting of St_1 and St_3 were statistically significant at the .01 and .05 levels, respectively. These significance levels were obtained in the following manner: DL's and Weber ratios were derived for each subject just as they were for the pooled data. Each subject's Weber ratio for direct lifting was used to derive an expected DL on the basis of the St adjusted to include the 340 grams of force required by the manipulator itself. Then paired observation-type t-tests (ref. 2) were used to test for significant differences between means for empirical and expected DL's. The raw data required for this exercise are included in tables I and II.

TABLE III

DL AND WEBER RATIOS ($\frac{DL}{St}$) FOR EACH St AND LIFTING CONDITION

LIFTING CONDITION	St (GRAMS)	DL	WEBER RATIO
DIRECT	1000	65.42	.065
REMOTE	1000	110.45	.110
DIRECT	3000	149.33	.050
REMOTE	3000	195.69	.065

DISCUSSION

Differences between empirical and expected DL's for remote lifting point to either one or both of two possible explanations: (a) the amount of force required to operate the manipulator used in the study was greater than manufacturer's specifications; (b) factors other than the additional force required to operate the remote-handling device produce a decrement in differential sensitivity for weight. One other experimental finding requires explanation. Since the increment which must be added to the St to resolve the differences between empirical and expected DL's is greater for St_3 than St_1, the loss in differential sensitivity appears to be directly proportional to the magnitude of the St. This cannot be attributed to the force required to operate the manipulator if that force is constant and independent of the lifted weight.

Therefore, to determine if manufacturer's claims concerning the force required to operate the Model 8 Master-Slave Manipulator held for the manipulator used in this study, Hunter Force Indicators were used to measure the force required to lift weights of various magnitudes. The capacity of force indicators available to the experimenter was less than 6 pounds. The precision of force measures made by these indicators was also restricted by both the measurement technique and the measuring instruments. However, a series of measurements taken at various weight intervals between loads of 0 and 2600 grams showed the force required to operate the manipulator itself to be between 302 and 347 grams. Variation of these measurements showed no systematic relationship between the amount of this force and the magnitude of the load. Hence, manufacturer's specifications concerning the amount and constancy of the force required to overcome friction in the manipulator are probably valid.

In seeking factors to account for the loss in differential sensitivity as a function of remote lifting, one cannot overlook the fact that the pattern of cutaneous and pressure stimulation varies from one lifting condition to the other because of differences in the objects of direct contact, i.e., the capsule knob versus the remote manipulator control. Certainly, this could affect differential sensitivity for weight. The extent and direction of any effect which might be attributed to this variation in the stimulus pattern is not readily apparent.

However, a still greater, and probably more important, variation in the pattern of receptor stimulation results from the fact that the master-slave remote manipulator is designed so that a large amount of the reflected force is concentrated upon the hand and wrist of the operator. As a result, the manipulator operator is more dependent upon wrist action than is the person who uses direct manual lifting. There are three ways by which this added stress upon the hand and wrist could be detrimental to differential sensitivity for weight: (a) it produces fatigue which can be distracting to the subject; (b) it may cause adaptation of the kinesthetic receptors and consequent decrease in sensitivity to stimulation; (c) the wrist is known to be naturally less sensitive to kinesthetic stimulation than the elbow or shoulder. In the direct-lifting situation, the subject is able to minimize these effects by distributing the effort more evenly over the entire arm and shoulder.

CONCLUSIONS

The decrease in differential sensitivity as a function of remote lifting is a reflection of the loss of "feel" associated with remote lifting. This loss as well as increased fatigue is probably a result of increased stress upon the operator's hand and wrist. In practice, a hook can be mounted above the wrist joint of the slave of the ANL Model 8 Master-Slave Manipulator. Using this hook eliminates most of the wrist action required for lifting objects. However, many objects are not readily lifted by means of a hook. Therefore, modification of the master-slave manipulator to include an easily operated wrist-action lock, similar to the finger-grip lock already incorporated, might prove desirable for lifting and holding objects of considerable weight. If differential sensitivity for weight should ever be identified as critical to successful performance of a particular remote-handling task, the master-slave manipulator might be modified to take advantage of the more sensitive elbow and shoulder regions of the operator.

BIBLIOGRAPHY

1. Crawford, B.M., Measures of Remote Manipulator Feedback: Absolute Judgments of Weight, WADD Technical Report 60-591 (II), Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, March 1961.

2. Edwards, A. L., Statistical Methods for the Behavioral Sciences, Rinehart and Co., Inc., New York, 1954.

3. Goertz, R.C., "Fundamentals of General-Purpose Manipulators," Nucleonics, Vol 46, pp 36-42, November 1952.

4. Goertz, R.C., "Mechanical Master-Slave Manipulator," Nucleonics, Vol 12, pp 45-46, November 1954.

5. Guilford, J. P., Psychometric Methods, McGraw-Hill Book Co., Inc., New York, 1954.

6. Holway, A.H., and C.C. Pratt, "The Weber-Ratio for Intensity Discrimination," Psychol. Review, Vol 43, pp 322-340, 1936.

7. Rees, D.W., and N.K. Copeland, Discrimination of Differences in Mass of Weightless Objects, WADD Technical Report 60-601, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, December 1960.

8. Wenger, M.A., F.N. Jones, and M.H. Jones, Physiological Psychology, Henry Holt and Co., New York, 1956.

9. Woodworth, R.S., and H. Schlosberg, Experimental Psychology, Henry Holt and Co., New York, 1954.