WADD TECHNICAL REPORT 60-591 (II)

MEASURES OF REMOTE MANIPULATOR FEEDBACK: ABSOLUTE JUDGMENTS OF 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 - 4-71 & 72

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, for advice concerning the preparation of this report.

ABSTRACT

Man's ability to estimate weights was determined for two lifting conditions: direct manual lifting and remote lifting by means of an Argonne National Laboratory Model 8 Master-Slave Manipulator. The effect of interpolated weight-lifting experience upon absolute judgments of weight was also examined. Results show that: (a) means of estimates made by subjects who lift weights remotely are greater than means of estimates made by subjects who lift the same weights directly; (b) subjects tend to underestimate weights lifted directly; (c) estimates for the remote-lifting condition, even though more accurate on the average, are more variable; and (d) the tendency for subjects to underestimate weights which follow heavier weights and overestimate those which follow lighter weights is more pronounced for direct lifting than for remote lifting.

PUBLICATION REVIEW

Walter F. Grether

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

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INTRODUCTION

WADD TR 60-591 (I) (ref. 1) pointed out that the "feel feedback" of a master-slave manipulator depends on the kinesthetic and tactual cues provided by its operation. Differential sensitivity for remotely lifted weights was compared with differential sensitivity for weights lifted directly. It was proposed that measures of differential sensitivity might be used to compare the effectiveness with which different remote manipulator designs take advantage of the operator's sensory capacities. These measures also indicate the fineness of weight discrimination which can be expected of a manipulator operator.

Weight discrimination is only one aspect of manipulator operator performance. Situations may occur in which remote manipulator operators will need to estimate weights of objects with reasonable accuracy. In these instances, operators and others should know the effect of the remote-handling system upon such judgments. Accordingly, this investigation was conducted to determine and compare: (a) the ability of subjects to judge the magnitudes of various weights lifted both directly and remotely and (b) the effects of interpolated weight-lifting experience upon such judgments.

APPARATUS AND SUBJECTS

The remote-handling device used in this study was the Central Research Laboratories' version of the Argonne National Laboratory Model 8 Master-Slave Manipulator (ref. 3). See figure 1. The construction of this manipulator is based primarily upon the concepts of: (a) conformity of the control and effector with respect to spatial orientation and movement and (b) continuous reciprocal force reflection between the control and effector.

The manipulator may 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 of movement: three for translation, three for rotation, and one for opening and closing the jaws of the slave hand.

In this experiment, a table, 41 inches high, was placed beneath the slave section of the manipulator to serve as a surface for placement of stimulus weights to be lifted by subjects using the remote manipulator. A piece of acoustic tile served as a pad upon which the weights were set. A second table, obscured from the subjects' view by the larger first table and the simulated shielding wall, was used for storing disks used in forming the stimulus weights and as a work area upon which the experimenter performed the operations required for varying the stimuli between trials. A diagram of the remote-lifting setup is shown in figure 1.

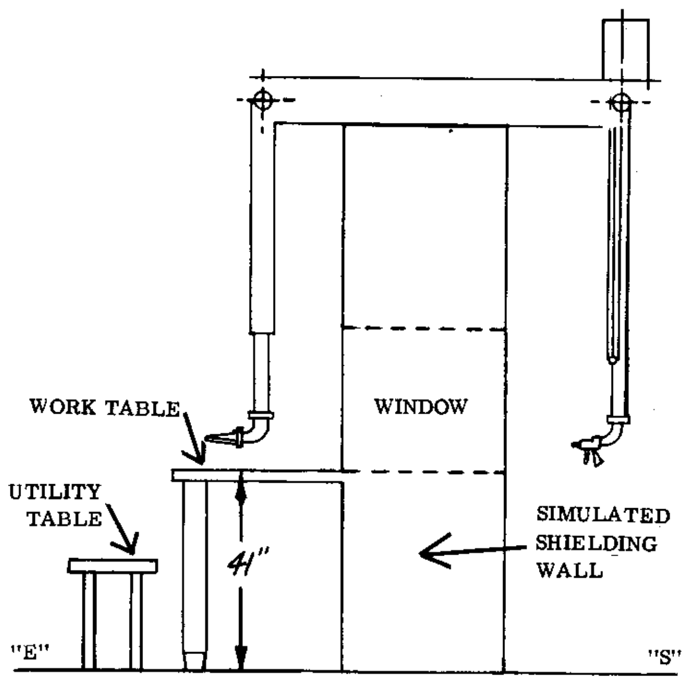

Figure 1. Schematic of Master-Slave Manipulator Used for Remote Lifting, Mounted Over Simulated Shielding Wall, Work Table, and Utility Table. Positions at which Experimenter and Subject Stood are Designated by "E" and "S."

The cabinet, shown in figure 2, was used during the direct-lifting sessions. The upper shelf, padded by the acoustic tile, served as the surface from which the weights were lifted by the subjects. The lower shelf, obscured from the subject by the hood over the top shelf, served the same purpose as the small table used with the remote manipulator.

Twenty-three different weights were used as stimuli. Three of them weighed 900, 2700, and 4600 grams each. These are referred to hereafter as the 2-, 6-, and 10-pound weights, respectively (figure 3). Two separate weight series, each consisting of a Standard stimulus (St) and nine Comparison stimuli (Co's), comprised the remaining 20 weights. One St weighed 1000 (St_1); the other, 3000 grams (St_3). In each series, four Co's were less than, four greater than, and one equal to the St. The step interval between the various Co's was 50 grams for the St_1 series and 100 grams for the St_3 series. The weight ranges covered by the two series of stimuli were from 800 to 1200 grams and from 2600 to 3400 grams, respectively.

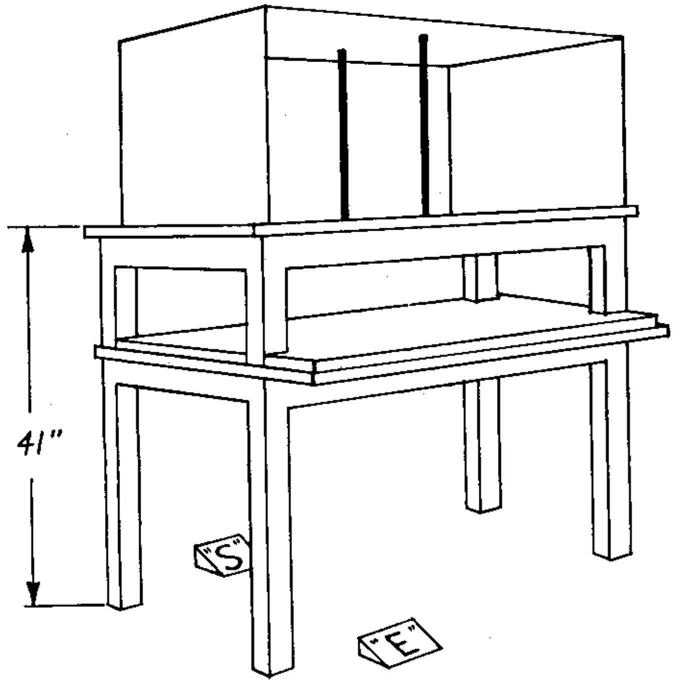

Figure 2. Cabinet Used to Support Weights for Direct Lifting. Wedges "E" and "S" Designate Experimenter and Subject.

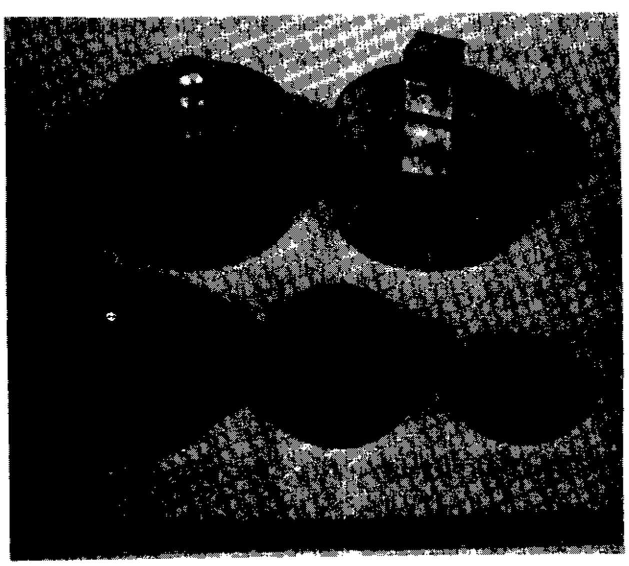

Figure 3. Components of the 2-, 6-, and 10-Pound Stimuli

Each stimulus weight was formed by placing a metal disk of the appropriate supplemental weight in either of two identical metal capsules. These capsules were cylindrical in shape and, when empty, weighed 750 grams each. 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 was used 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 capsule from slipping between the jaws of the slave hand, a hazard making the round knob impractical for use with the heavier weights. Figure 4 shows the components of the St_1 and St_3 series of weights.

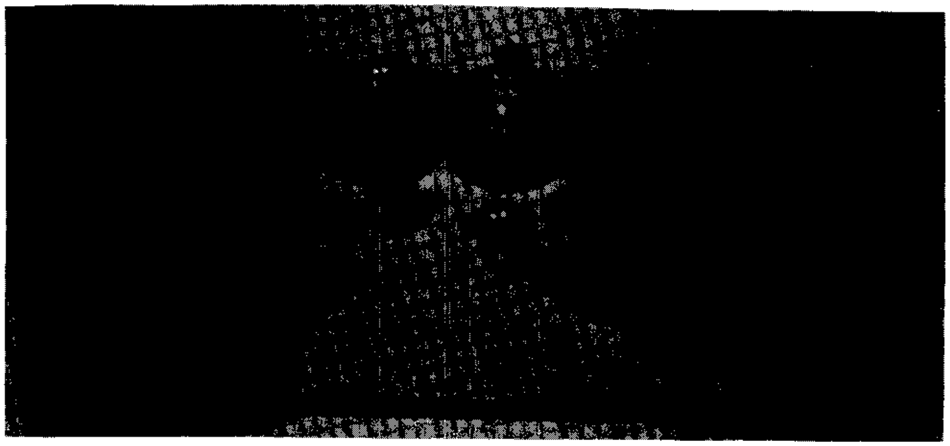

Figure 4. Components of the 1000-Gram (St_1) and 3000-Gram (St_3) Series of Weights

Twenty male university students were randomly assigned to four groups (D_1, D_3, R_1, R_3) of five subjects each. Groups D_1 and D_3 used direct manual lifting during the experiment described in this report. Groups R_1 and R_3 used the remote manipulator. The subscripts indicate which series, St_1 or St_3, was lifted by the subjects during the second step of the procedure described below.

PROCEDURE

The experimental procedure consisted of three main steps:

Step 1: Absolute judgments of the 2-, 6-, and 10-pound stimuli

Step 2: Method of Constant Stimulus Differences, using either the St_1 or St_3 series (5- to 10-minute rest period at midpoint)

Step 3: Absolute judgments of the 2-, 6-, and 10-pound stimuli

The total time required to accomplish the experimental procedure was approximately 90 minutes per subject. Most of this time was devoted to step 2 which involved the Method of Constant Stimulus Differences (ref. 8). Each subject was given a 5- to 10-minute rest period at the midpoint of step 2.

At the beginning, each subject was instructed concerning the lifting technique he was to use during the experiment. Those assigned to the direct-lifting groups, D_1 and D_3, were required to grasp the knob of the capsule between the thumb and fingers of the preferred hand when lifting the weights. Subjects assigned to remote-lifting groups, R_1 and R_3, were first given a brief description of remote-manipulator development. They were allowed two or three minutes to become familiar with the remote-handling device. They were given specific instructions concerning the technique to be used when grasping the T-shaped handle of the capsules.

All subjects stood throughout the experiment. Whether lifting directly or remotely, each subject stood so that his forearm was approximately parallel to the floor when he lifted the weights.

After each subject had become familiar with the experimental apparatus and lifting technique, he was told that three weights would be presented to him one at a time and that he should lift each weight 2 or 3 inches off the table and then set it down. Each weight was lifted only once. The subject was asked to estimate the actual weight and to report this estimate verbally in pounds and fractions of a pound upon setting the weight down. The responses were recorded by the experimenter. At no time, during practice or the experiment, was the actual value of any weight reported to the subject. The weights were presented in random order. At the end of step 1, the subjects were informed that their task would be changed somewhat, but that later on, from time to time, they would be asked to estimate the actual values of certain weights in this same manner.

Step 2 consisted of the Method of Constant Stimulus Differences—a psychophysical procedure used to determine differential sensitivity for weight. Difference thresholds and Weber ratios were derived for each standard weight and lifting condition. These results are presented and discussed in Part I (ref. 1). This step is considered in this report only with respect to effects of the interpolated lifting experience on absolute judgments of weight.

The Method of Constant Stimulus Differences was applied in the following manner: Each subject was required to lift and compare pairs of weights taken from either the St_1 or St_3 series as determined by his assigned group. Each pair was comprised of the appropriate St and one of the nine Co's in the series. Each Co was compared with the St on twenty separate trials by each subject. When comparing weights, the subject lifted each of them from 2 to 3 inches off the table just as he did when making absolute judgments. However, instead of estimating weights, he indicated which seemed heavier.

Following step 2, each subject was asked to make absolute judgments again. The 2-, 6-, and 10-pound weights were presented in random order as before. The subjects were not told that the weights judged in step 3 were the same ones judged in step 1. When questioned after the experiment, subjects indicated that they did not suspect that the weights were identical.

RESULTS

Direct versus Remote Lifting

The results obtained from step 1 of the procedure were used to examine the effects of remote lifting upon absolute judgments of weight. Estimates made by the ten subjects who lifted the weights directly were compared with those of the ten subjects who lifted the same weights remotely, for each of the three stimulus weights. In each instance, the mean absolute judgment was greater for remote lifting than for direct lifting. The difference between mean absolute judgments for direct and remote lifting was not constant but, instead, increased directly with weight. Statistical tests, both student's t-test and a rank test (ref. 2), show the difference between absolute judgments for the two lifting conditions to be significant ($p < .05$) for the 10-pound weight only.

Mean absolute judgments, SD's, and t-test results for data collected during step 1 are shown in table I. The means are depicted graphically in figure 5. Note the marked tendency toward underestimation of weights lifted directly. Mean absolute judgments for remote lifting were closer to the actual values of the weights, although the subject-to-subject variability of remote judgments was greater.

TABLE I

ANALYSIS OF EFFECT OF REMOTE LIFTING UPON ABSOLUTE JUDGMENTS OF WEIGHT
(df* = 18)

STIMULUS WEIGHT (Pounds)	ESTIMATED WEIGHT BY LIFTING CONDITION			t-RATIO	p
		DIRECT	REMOTE		
2.00	MEAN: SD:	0.93 0.76	1.45 0.96	1.33	NS
6.00	MEAN: SD:	4.15 2.60	6.70 4.62	1.51	NS
10.00	MEAN: SD:	7.10 3.49	10.60 3.72	2.17	<.05

*df = degrees of freedom

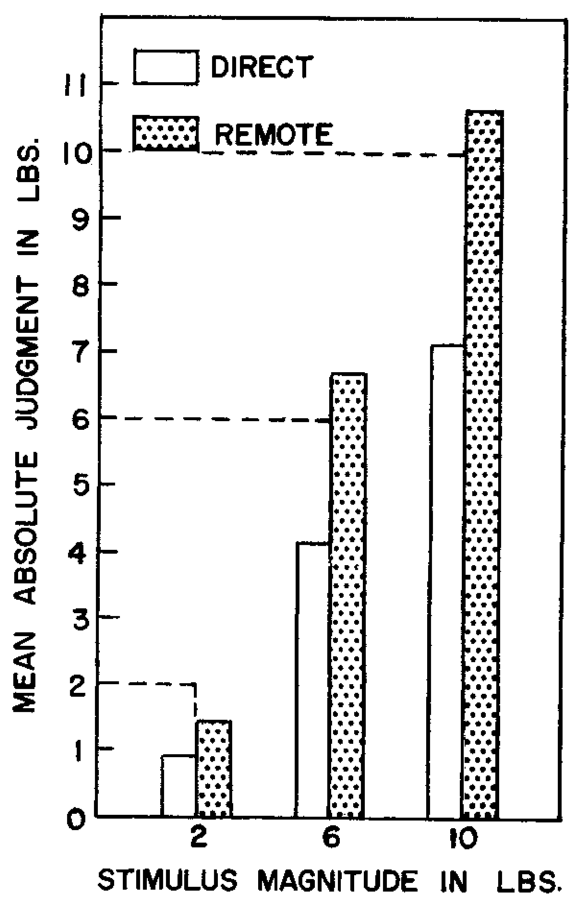

Figure 5. Mean Absolute Judgments of Three Weights for Direct and Remote Lifting

Effects of Experience

Means for absolute judgments made after the lifting experience required by the Method of Constant Stimulus Differences were compared with those made before for each of the four groups.

When the interpolated experience involved the St_1 series, the means of the second absolute judgments were greater than the means of the first absolute judgments for each weight and lifting condition. The differences were less for the remote-lifting condition. Paired observation-type t-tests (ref. 2) produced significant t-ratios for the direct-lifting condition only. These results are shown in table II.

TABLE II

ANALYSIS OF EFFECT OF INTERPOLATED EXPERIENCE IN St_1 SERIES (df = 4)

LIFTING CONDITION	STIMULUS WEIGHT (Pounds)		ABSOLUTE JUDGMENTS		t-RATIO	p
			BEFORE	AFTER		
DIRECT	2.00	MEAN:	0.85	2.60	2.92	$<.05$
		SD:	0.22	1.47		
	6.00	MEAN:	4.40	17.20	5.57	$<.01$
		SD:	2.61	5.63		
	10.00	MEAN:	8.50	27.00	5.23	$<.01$
		SD:	4.53	7.58		
REMOTE	2.00	MEAN:	1.75	3.10	1.53	NS
		SD:	0.83	2.41		
	6.00	MEAN:	9.00	13.00	2.13	NS
		SD:	5.57	5.34		
	10.00	MEAN:	13.00	16.20	1.54	NS
		SD:	2.74	7.09		

When the interpolated experience involved the St_3 series, means of the second absolute judgments were less than those of the first absolute judgments for the 2- and 6-pound weights. For the 10-pound weight, means of the second absolute judgments were greater than the means of the first. These effects were in the same direction for both direct and remote lifting. None of the effects of interpolated experience with the St_3 series was statistically significant. See table III.

In general, the results demonstrate a tendency to overestimate stimuli preceded by stimuli having a mean of lesser magnitude and underestimate those preceded by stimuli having a mean of greater magnitude. With respect to the method of lifting, the evidence indicates that subjects using the remote manipulator are less susceptible to this effect than those using the direct-lifting technique.

TABLE III

ANALYSIS OF EFFECT OF INTERPOLATED EXPERIENCE
IN St_3 SERIES
(df = 4)

LIFTING CONDITION	STIMULUS WEIGHT (Pounds)		ABSOLUTE JUDGMENTS BEFORE	ABSOLUTE JUDGMENTS AFTER	t-RATIO	p
DIRECT	2.00	MEAN:	1.00	0.80	1.00	NS
		SD:	1.12	0.67		
	6.00	MEAN:	3.90	3.80	0.09	NS
		SD:	2.88	1.30		
	10.00	MEAN:	5.70	9.30	1.79	NS
		SD:	1.40	5.17		
REMOTE	2.00	MEAN:	1.15	0.43	1.57	NS
		SD:	1.08	0.17		
	6.00	MEAN:	4.40	3.90	0.41	NS
		SD:	1.95	1.60		
	10.00	MEAN:	8.20	11.40	1.25	NS
		SD:	2.86	4.88		

Effects of the interpolated experiences as a function of the lifting condition are depicted graphically in figures 6, 7, and 8 for the 2-, 6-, and 10-pound stimuli, respectively. Straight lines connect means of initial judgments with means of second judgments, not to imply continuity of the variable represented on the abscissa but to emphasize the extent and direction of the effect. Note especially the contrast between the slopes of the lines for direct and remote lifting of the 6- and 10-pound weights when the interpolated experience involved the St_1 series (figures 7 and 8).

Increases in mean absolute judgments of the 2-pound weight following experience with the St_1 series are an exception to the tendency to underestimate stimuli which follow stimuli that are, on the average, heavier. See table II and figure 6.

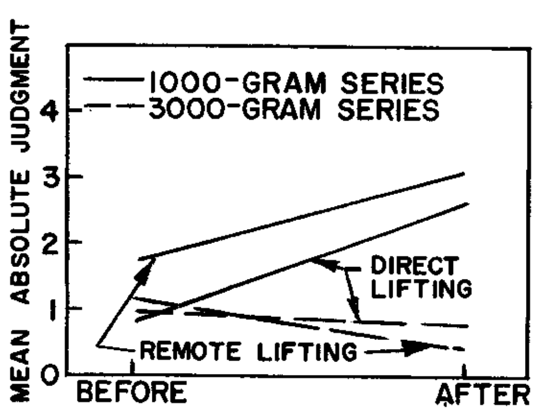

Figure 6. Mean Absolute Judgments of 2-Pound Weight before and after Interpolated Experience with St_1 and St_3 Series

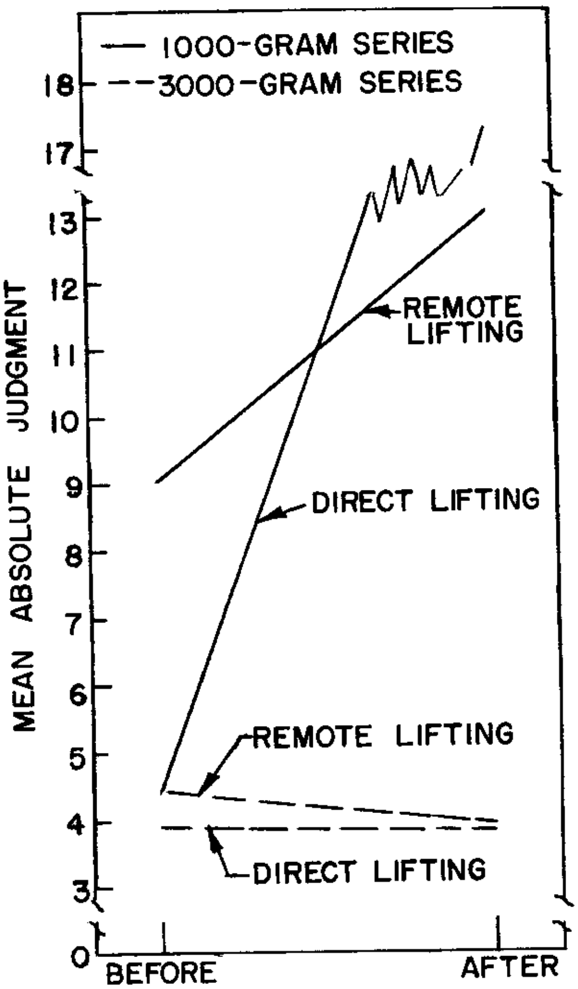

Figure 7. Mean Absolute Judgments of 6-Pound Weight before and after Interpolated Experience with St_1 and St_3 Series

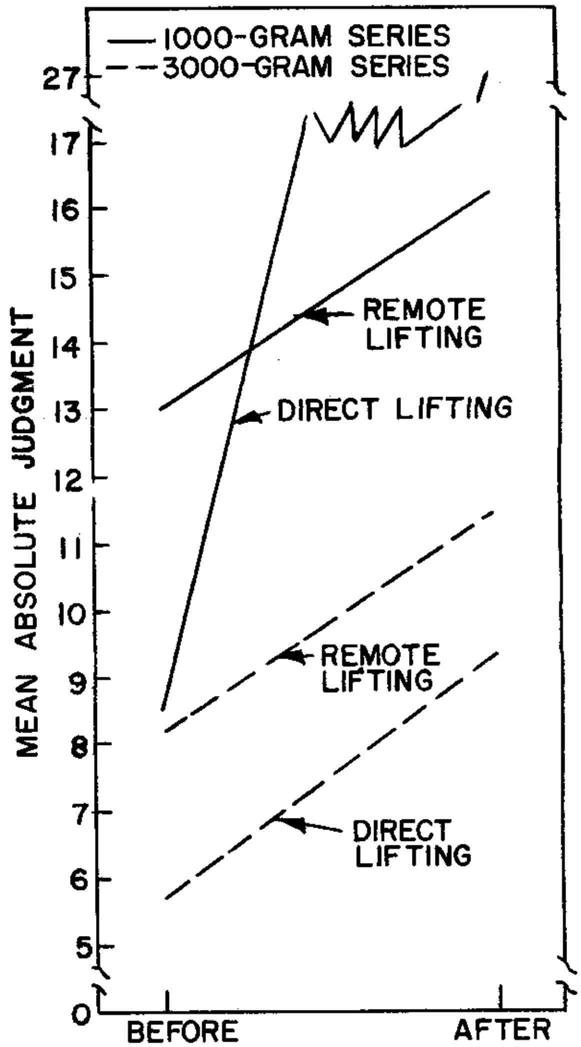

Figure 8. Mean Absolute Judgments of 10-Pound Weight before and after Interpolated Experience with St_1 and St_3 Series

DISCUSSION

Direct versus Remote Lifting

Within the normal load capacity of the Model 8 Master-Slave Manipulator (10 pounds), the force required to overcome friction in the system is independent of the weight being lifted and equal to approximately 12 ounces for vertical movement. Therefore, the observed differences between mean absolute judgments for direct and remote lifting and the fact that these differences vary with the magnitude of the weights require some other explanation.

At least part of the discrepancy between estimates of weight for the two lifting conditions is attributable to the design of the manipulator. The construction of the manipulator is such that the operation involved in lifting weights requires a considerable amount of wrist action. Consequently, the reflected force is concentrated primarily upon the operator's hand and wrist joint. For light weights, normally lifted directly by wrist and finger action without excessive strain or discomfort, sensations may be perceived as essentially the same for the two lifting conditions. But when heavier weights are lifted directly, the effort is usually distributed over a larger number of muscles and joints. The severity of the stress on the hand and wrist joint area for these same weights lifted remotely probably distorts the subject's perception of the amount of force required to lift them. Concentration of the force upon the hand and wrist also increases the effect of fatigue.

This stress might be reduced by relatively minor modifications in control design; e.g., provision for a wrist joint lock or other device for distributing the reflected force along the forearm. Other possible solutions which necessitate more extensive design changes are: (a) reduction in the amount of force reflected to the operator and (b) redesign of the master control section so that it will accommodate the entire forearm as well as the thumb and fingers.

The tendency for subjects to underestimate stimuli following stronger stimuli and to overestimate those following weaker stimuli has been observed experimentally in various sensory fields (refs. 5, 6). Woodrow (ref. 7) attributed this tendency, known as the "contrast effect," to "a set or readiness for a stimulus of a particular character." The value of the stimulus for which the "set" exists is determined by the average intensity of all preceding stimuli.

In general, the results of this study demonstrate the contrast effect, although exceptions occurred for both direct and remote lifting of the 2-pound weight when the interpolated experience involved the St_1 series. In these instances the contrast between the mean of the interpolated series (approximately 2.2 pounds) and the weight judged was small. Nevertheless, to be consistent with the constrast effect, judgments of the 2-pound weight following experience with the St_1 series should have been in the direction of underestimation. Although defense of the contrast effect may not be justified, this inconsistency can be tentatively explained, if we hypothesize that the sensory system is constituted so that the experimental procedure results in a perceived mean for the St_1 series which is actually less than the perceived value of the 2-pound weight.

That subjects lifting weights remotely should be less susceptible to the contrast effect than those lifting them directly is congruous with other experimental results which show difference thresholds for weight to be greater for remote lifting than for direct lifting (ref. 1). The difference threshold for weight is a measure of the smallest detectable change in a weight. Thus, if we use the difference threshold as the unit of measure, the perceived difference between two remotely lifted weights would be less than the perceived difference between the same weights lifted directly. Accordingly, a reduction of the contrast effect for remote lifting should result. This also reflects the loss of "feel" which accompanies remote handling with the Model 8 Master-Slave Manipulator.

SUMMARY

Mean estimates of weights lifted remotely by means of a Model 8 Master-Slave Manipulator are greater than mean estimates of the same weights lifted directly. Redesign of the master-control unit to alleviate the stress placed upon the hand and wrist of the operator should reduce the size of these discrepancies as well as the fatigue effects which accompany the use of the manipulator.

Subjects tend to underestimate weights lifted directly. Estimates of remotely lifted weights are closer, on the average, to the actual weights, but they are also more variable.

Subjects tend to underestimate weights which follow heavier weights and overestimate those which follow lighter weights. Subjects lifting weights directly are more susceptible to this effect than those using the remote manipulator.

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