TORQUE SENSITIVITY AS A FUNCTION OF RADIUS AND LOAD ON HAND-OPERATED KNOBS

by

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INTRODUCTION

In a previous study Woodruff and Helson (1965) measured sensitivity to torque by introducing a rotatory as well as a translatory component in a lifted-weight situation, thus adding a new dimension to the tactile-kinesthetic modality never before investigated by psychophysicists. In the previous study Ss lifted a rod with attached weight by grasping one end of the rod. They compared the force exerted by the horizontally held rod and weight with a standard rod and weight. The torque component was varied by moving the weight different distances from the point where the rod was held. Thus although the weight of the stimulus was constant the torque exerted on the fingers varied with the distance of the weight from the end of the rod. It was thus established that when a rotatory component is introduced a new dimension of sensitivity enters which can be measured independently of classical lifted-weight sensitivity. In the experiment reported here, sensitivity to torque was measured in a different way, i.e., by requiring Ss to turn knobs of various sizes against various loads.

There are several reasons why a knob-turning task was chosen over the lifted-rod task for this investigation. First, knobs are commonly used as control and regulatory devices and torque enters into their manipulation since they must be turned or rotated against various loads. A second reason for this choice is that some variables are more easily studied when knobs are used instead of rods or levers. When lifted rods are used it is much less convenient to assess the effect and importance of variables such as radius, inertia, design, mechanical advantage, and loading of manipulanda. Finally, knob turning was employed in this study because it simulates both design of manipulanda and brings into play muscles and motion more commonly found in everyday life than does the lifted rod situation previously employed.

Surprisingly little work has been done to investigate the sensitivity of individuals in a situation where torque sensitivity is in question. Hoisington (1920) conducted an investigation using stimuli very similar to those used by Woodruff and Helson (1965), but he was interested in the nonvisual perception of length in lifted rods rather than in sensitivity to torque.

If torque discrimination in a knob turning task can be reliably determined, then the possible use of torque as a feedback mechanism can be investigated. The only studies that concern themselves with torque sensitivity deal with terminal thresholds. For example, Sharp (1962) studied the maximum amount of torque that could be exerted on a knob of given radius and surface design. He found that as knob radius increased from .25 inches to 2.50 inches, maximum exertable torque also increased. He also verified the intuitively obvious fact that more torque can be exerted on knurled knobs than on smooth knobs.

This paper presents the results of an experiment designed to measure changes in torque sensitivity as a function of knob diameter and the load moved in turning knobs of varying sizes.

METHOD

Apparatus. The apparatus consisted of a 45 cm. steel rod (1.27 cm. diameter) mounted on 2 ball-bearing assemblies so that it could be rotated freely. Knobs were attached to the rod by means of a drill chuck on one end of the rod. A string was attached to the middle of the rod and a hook tied to the end. Series weights, hereafter called loads, were compared with a standard load by varying the load hung from the hook.

Round knobs were cut from 0.25 inch plywood, sanded, and painted flat black. The knobs were 1.27, 2.54, and 3.81 cm. in radius (1, 2, and 3 inches in diameter).

In a pilot study stimulus series of 5 loads were determined using standard (Std) loads of 50, 100, or 200 gm. at the center of each series. The step interval between adjacent series stimuli was adjusted so that the lightest series stimulus produced approximately 15% heavier than standard judgments and the heaviest series stimulus, 85% heavier than standard judgments using the method of constant stimulus differences. Because knob radius affected the proportion of heavier judgments, 3 different series were developed for each knob size. Table 1 gives the values of series and standards used with each knob radius.

Subjects. Twelve Ss were recruited from general psychology classes at Kansas State University and paid $1.25 an hour for participation. The average age of the 6 male Ss was 18.0 and of the 6 female Ss, 18.8. All Ss were right-handed. Each S participated in one fifty-minute session a day for three days a week until the experiment was completed.

Design. The experiment was set up as a complete factorial arrangement of treatments giving 9 conditions (3 knob radii X 3 load series). The conditions were presented in a random order with all Ss receiving the same order. Because this procedure might lead to changes in threshold with practice, a spot check was made by rerunning the first condition after all the data had been collected. The following is the order in which the conditions were presented: 2.54 cm. knob with 100 gm. Std; 1.27 cm. knob with 100 gm. Std, 2.54 cm. knob with 200 gm. Std, 3.81 cm. knob with 200 gm. Std, 1.27 cm. knob with 50 gm. Std, 2.54 cm. knob with 50 gm. Std, 3.81 cm. knob with 50 gm. Std, 1.27 cm. knob with 200 gm. Std, 3.81 cm. knob with 100 gm. Std, and finally a repetition of the first condition--the 2.54 cm. knob with 100 gm. Std. No differences due to practice were found between the original and rerun observations with the first condition.

Table 1

Standard and Series Loads in Gm.
Used with Each Knob Size

Knob Radius (cm.)	Standard Load (gm.)	Series Loads (gm.)				
1.27	50	35.0	42.5	50.0	57.5	65.0
	100	65.0	82.5	100.0	117.5	135.0
	200	160.0	180.0	200.0	220.0	240.0
2.54	50	26.0	38.0	50.0	62.0	74.0
	100	65.0	82.5	100.0	117.5	135.0
	200	140.0	170.0	200.0	230.0	260.0
3.81	50	26.0	38.0	50.0	62.0	74.0
	100	60.0	80.0	100.0	120.0	140.0
	200	140.0	170.0	200.0	230.0	260.0

PROCEDURE

The method of constant stimulus differences was used to measure difference thresholds under the 9 conditons. Each S made 150 judgments under each condition--30 judgments for each standard-variable combination. Both time-order presentations were used in a single session; i.e., S was presented the Std stimulus first and then the series stimulus (S_1V_2) or the series stimulus was presented first, then the Std stimulus (V_1S_2). One-half of the Ss randomly received each time-order for the first 75 trials on any given day.

To minimize any effects of order of presentation, 10 different sequences were used. Each sequence was constructed by randomly choosing 4 of the 120 ways 5 stimuli can be ordered. The entire set of 150 trials for a session was derived by repeating these 4 randomly chosen orderings. Sequences were randomly assigned to the 10 experimental conditions so that all 10 sequences were used in each condition. The same sequence was not repeated with any S.

When S entered the experimental room he saw a large black plywood shield with the chuck protuding from it. The chuck was 94 cm. from the floor. The shield was large enough to completely hide E when the stimuli were presented. S was seated in a straight-backed chair so that he could grasp the knob with his right hand without bending his elbow. The S was positioned so that his right shoulder was directly in front of the knob. In this position, the arm was not displaced to the left or right while data were being collected. When S had been properly seated the following instructions were read:

> This study investigates torque discrimination. Your task is to turn the knob in front of you. Each trial will consist of two knob turns. You are to judge if the second turn required more, less, or an equal amount of force when compared to the first turn. Use the equal judgment very sparingly.
>
> This is the procedure we will follow. When I say ready, you are to grasp the knob with your right hand, turn it 90° to the right, then

> release the knob. When I say ready for the second time, you should once again grasp the knob, turn, and release. You should make your judgment after you have released the knob for the second time.
>
> Grasp the knob so that your fingers are near the top and your thumb is near the bottom. Turn the knob to the right with a wrist motion until the thumb and index finger are in the horizontal plane. Do not return the knob to the start position. Release it while it is turned the 90°. Remember, after you have released the knob for the second time you should make your judgment. Do not touch the knob after you have made your judgment until I once more say ready. There are several rest breaks scattered throughout the session. When I say stop, you are to rest your forearm in your lap until I again say ready.

E then demonstrated the proper way to grasp and turn the knob and let *S* practice two or three times. Then *E* continued reading:

> There are several things I want to emphasize. First, do not turn the knob more than 90°. There is a stop that prevents it from turning further. If you hit the stop, the feel of the stimulus will be changed. Second, keep your hand near the knob at all times. Do not try to rest your elbow on the table. Please do not move your forearm from your lap during the rest breaks.
>
> Remember, you are to tell me if it takes more, less, or an equal amount of force to turn the knob the second time than the first. There is no right or wrong answer except that in order to obtain a true measure of your powers of discrimination, careful observation on your part is required.
>
> We will try a few practice trials now to acquaint you with the range of stimulation and to make sure that you understand the instructions. Do you have any questions?

E then answered any questions that *S* had and gave *S* 10 practice trials--2 for each standard-variable combination. Then *E* read:

> Stop. Those were the practice trials. Do you have any questions before we begin the regular series?

The experimental session consisted of 10 blocks of 15 trials with a 30 second rest between blocks. *S* was asked not to discuss the experiment with anyone. At the beginning of the second session, the same instructions were read; in all other succeeding sessions, the instructions were condensed but the same procedure was followed.

When *S* used more than 5 equal judgments in any block of 15 trials, then during the next rest break he was cautioned to use the equal judgment sparingly.

After S released the knob, E stopped the rod before it could return to the start position. In this way, S received no cue as to the size of the stimulus from the speed or rebound of the knob.

The interval between stimuli within a trial was approximately 3 seconds. The length of the intertrial interval depended upon the amount of time S took to make his judgment. The next trial was started about 2 seconds after S's judgment.

When a session was completed, E totaled the number of more, less, and equal judgments. If S showed a reversal greater than 2 judgments between adjacent stimuli, that condition was repeated in the next session. Six of the Ss never showed a reversal large enough to warrant repeating any condition. In the case of the other 6 Ss, at least one experimental condition was repeated.

Prior to the development of the technique finally adopted, two knobs were employed so that S had to turn one knob, then reach over six inches and turn the other. This procedure would have allowed more observations per unit of time by using the technique described by Shaad and Helson (1931). Unfortunately, the two-knob procedure led to an extremely large space-error that completely masked any differences in conditions; therefore, the single-knob procedure was adopted.

DATA

Before the data can be interpreted, the actual stimulus values must be determined. The stimuli cannot be defined in terms of loading alone for the mechanical advantage in the apparatus must not be ignored. Stimulation must be defined in terms of the components of the knob-turning situation. When S turns the knob, the force he exerts depends upon three variables--the mass of the load, the radius of the rod, and the radius of the knob. Changing any one of these values changes the amount of force S exerts due to differences in torque.

If the apparatus is considered to be a lever, stimulus values more appropriate than mass can be defined. The radius of the rod, k, and the radius of the knob, r, may be regarded as the two arms of a lever. Then when a load of mass m is suspended from the rod, a moment of inertia, mk, is produced. To bring the system into balance, S must apply to the knob another force, F, so that the resulting moment, Fr, equals the first:

$$Fr = mk \tag{1}$$

The amount of force is determined quite simply by dividing formula (1) by r:

$$F = \frac{mk}{r} \tag{2}$$

Dimensional analysis of formula (2) shows that the appropriate units for F is grams. The S must apply to the knob a force equivalent to a weight of F gm. in order to bring the lever into balance. The stimuli in this study are thereby defined as equivalent to weights in grams equal to mk/r.

For any combination of knob radius and load it is easy to determine the value of stimulation, F. First, multiply the mass of the load in grams by the radius of the rod, then divide this product by the radius of the knob. If S is lifting a 200 gm. load by turning the 3.81 cm. knob, the stimulus value, F, is 33.34 gm. (200 gm. X 0.635 cm./3.81 cm.); if the load is 50 gm. and the knob has a radius of 1.27 cm., then F has a value of 25.00 gm. (50 gm. X 0.635 cm./1.27 cm.).

Because a load and its equivalent stimulus are both in units of grams, two different specifications will be used in presenting results. The mass of a load will always be specified in terms of grams (gm.) while the value mk/r, indicating the force, F, required to bring the lever system into equibrium, will be specified, for convenience, in terms of equivalent-grams (e-gm.). Table 2 lists the values of the standard stimuli in terms of e-gm. This table also presents the results of suspending weights from the knob to balance each of the stimuli under actual conditions of operation thus checking the theoretical stimulus values against the actual values of the stimuli. The obtained values for stimuli are rounded to the nearest whole e-gm. It is important to note the close correspondence between the calculated and actual values. The small differences in the two sets of values are indicative of the small amount of friction in the apparatus.

The entire experimental results rest upon 16,200 judgments (12 Ss X 9 conditions X 150 trials). After the collection of data had been completed, a greater (L_g) and a lesser (L_l) limen was calculated for each of the Ss for each condition. The limen is defined as the stimulus value that elicits a judgment category (greater or less) 50% of the time. The value of the liminal stimulus was determined by fitting ogives, the integral of the normal curve, to each set of data. Separate ogives were required for the greater and lesser judgments for when equal judgments are permitted the proportions of greater and less judgments do not sum to unity for all values of the series stimuli. The ogives were fitted to the data using Urban's method which is a variation of the least-squares procedure. Urban's method weights the observed percentages in proportion to their reliabilities and produces the best fitting ogive consistent with this criterion.

Table 2

Calculated and Measured Values of Standard Stimuli in Equivalent-grams (e-gm.)[1]

Standard Loading (gm.)	Knob Radius (cm.) 1.27	2.54	3.81
50			
Calc.	25.00	12.50	8.35
Obser.	25	13	9
100			
Calc.	50.00	25.00	16.67
Obser.	51	26	18
200			
Calc.	100.00	50.00	33.34
Obser.	101	51	34

[1]See text for explanation

The actual computations were programmed by the writer for an IBM 1410-1401 computer and the correctness of the programming was checked by manual calculation of a limen from a representative set of values.

The point of subjective equality (PSE) had to be calculated before difference limens could be determined. PSE is the stimulus value judged to be equal to the standard according to some criterion. For the benefit of readers who are not versed in classical psychophysics, it should be noted that when the standard is compared with itself, it is not judged to be equal to itself 100% or even 50% of the trials. In the majority of the trials, the standard will be judged to be either greater or less than itself. The PSE is the stimulus that would have been judged equal to the standard. In some psychophysical methods, the PSE can be determined by asking S to choose a stimulus that equals the standard. The stimulus S selects is the PSE. In the method of constant stimulus differences, a statistical criterion is used to determine the value of the PSE that was operative during the time S was judging the set of stimuli. The criterion chosen in this study was the stimulus value that elicited an equal percentage of greater or less judgments (Guilford, 1954, p. 138):

$$PSE = L_l + \frac{s_l(L_g - L_l)}{s_l + s_g} \tag{3}$$

where s_l is the sample standard deviation for the lesser limen and s_g is the sample standard deviation for the greater limen. The two sample standard deviations were obtained from the precision factor, h, ($h = 1/s\ 2$) when the ogive curves were fitted to the data.

The criterion expressed for PSE in formula (3) is also the point at which the fitted ogive for the less than standard judgments crosses the fitted curve for the greater than standard judgments. When PSE is interpreted in this manner it is seen to be an indifference point separating stimuli judged greater than the standard from stimuli judged less than the standard.

Finally, when s_l equals s_g, formula (3) yields a PSE that is the point one-half the distance between the two limens. Guilford (1954, p. 138) uses this criterion as an alternative procedure for calculating the PSE.

Time-order-effects (TOE), which will be discussed below, were also calculated. TOE is defined as the signed difference between PSE and the standard stimulus:

$$TOE = PSE - Std \tag{4}$$

Difference limens (DL), also referred to as absolute difference limens, can now be calculated. The absolute DL is the amount of stimulation that must be added to or subtracted from a stimulus that results in a change in the sensation noticed 50% of the time. The absolute DL differs from the limen in that the limen is the stimulus per se that is judged greater or less than the standard 50% of the time. The absolute DL can be calculated to be the difference between the limen and the standard. However, a better method of calculating the DLs is given below:

$$DL_g = L_g - PSE \tag{5a}$$

and

$$DL_l = PSE - L_l \tag{5b}$$

This method of computing DLs is very similar to that suggested by Guilford (1954, p. 137) who defines the DL as one-half of the interval of uncertainty (IU); i.e., one-half the difference between the upper and lower limens. Formulae (5a) and (5b) give the same result as one-half the IU when the sample standard deviations are equal.

What purpose is served by using the PSE instead of the standard stimulus as the point from which the absolute DLs are calculated? The PSE is the stimulus value judged to be equal to the standard; as such, it is the standard stimulus from which <u>S</u> made his judgments of greater or less. Therefore the PSE serves as a better dividing point between judgments of greater and less than does the objective standard stimulus. There are several advantages in using the PSE instead of the standard stimulus. First, we are measuring the DL, a psychological concept, in terms of two other psychological concepts--

the limen and the PSE. When the standard stimulus is used, then the absolute DL is defined in terms of a physical and a psychological variable. A second advantage in using PSE instead of the standard stimulus is, unless the sample standard deviations of the two fitted ogives are very different, the upper and lower DLs will be approximately the same size. When large TOEs occur, the method of calculating DLs from the standard stimulus leads to asymmetry--one of the DLs will be considerably larger than the other. This problem does not occur when the PSE is used instead of the standard stimulus. Finally, a third advantage of taking DLs from PSE is that PSE can be related to other psychophysical data in a quantitatively meaningful way (Michels & Helson, 1954) for PSE is a measure of prevailing adaptation level (Helson, 1964).

Weber fractions, also referred to as relative DLs, were calculated from PSE and absolute DLs. Only one Weber fraction was calculated for each condition since the greater and lesser DLs were approximately equal. The Weber fraction was taken as the unweighted algebraic mean of the greater and less Weber fractions as follows:

$$\frac{\Delta S}{S} = \frac{DL_g + DL_l}{2(PSE)} \qquad (6)$$

RESULTS AND DISCUSSION

There are two completely different ways in which the results of this investigation can be presented. Both are equally valid and useful.

The first procedure calls for the presentation of the results in terms of grams with parameters of knob radius and loading. This technique answers the question, "When S turns a knob of given size and loading, what is his sensitivity to load changes?" The answer provides useful industrial engineering information. Unfortunately, when the results are presented in terms of grams, there is no way to order the 9 conditions along a stimulus dimension. This limitation makes it impossible to directly compare the results of this study with sensitivity studies in other tactile-kinesthetic modalities.

The second way of presenting the results is in terms of equivalent-grams and provides an answer to the question, "How sensitive is S to changes in the level of stimulation in a knob-turning task?" Answering this question provides information on sensitivity of a more general nature because the 9 conditions can now be ordered on a stimulus continuum and are directly comparable to sensitivity studies in other modalities.

Neither method of data presentation and interpretation by itself gives the complete picture of sensitivity in a knob-turning task, therefore both methods will be used.

When the results are presented in terms of gram units, then changing the value of either knob radius or loading produces concomitant changes in the size of the absolute DLs and Weber fractions. However, the effect of increasing either independent variable depends upon the dependent variable being measured. Qualitatively, the results of this study may be generalized as follows: as knob radius is increased, absolute DL decreases and relative DL increases; but as loading increases, absolute DL increases and relative DL decreases. These generalizations are presented in Table 3.

Table 3

Effect of Increasing Knob Radius, Loading and E-Gm. on Absolute DL and Weber Fraction

Condition	Absolute DL	Weber Fraction
Increase in Knob Radius	DECREASES	INCREASES
Increase in Loading	INCREASES	DECREASES
Increase in E-Gm.	INCREASES	DECREASES

As is readily apparent, the independent variables are both directly and inversely related to sensitivity measures depending on which measure of sensitivity is employed. However, if the stimulus is specified in terms of e-gm., the results can be generalized more simply: as the number of e-gm. required for turning the knob increases, the absolute DL increases and the Weber fraction decreases within the limits of this study.

Let us consider the results of this experiment in detail by first examining the effect of changes in knob radius and loading upon relative and absolute DLs.

The average absolute DLs are given in Table 4 and are graphically shown in Figs. 1 and 2. Without exception, when loading increases, the absolute DL increases, as seen in the curves of Fig. 1 and by the reading down the columns of Table 4. When Fig. 2 is inspected and Table 4 read across any row, absolute DL is seen to be inversely related to knob radius. Whenever larger knobs are used the size of the absolute DL decreases.

Statistical analysis confirms this interpretation of the results. A four-way AOV (sex X knob radius X loading X DL type) on the data of Table 4 shows that only knob radius and loading had any effect on the size of the absolute

DL. There were no significant interactions. Table 5 presents the summary table of this analysis. Trend tests (Edwards, 1960; Fryer, 1966; and Snedecor, 1956) performed on the two significant sources of variance indicated that the linear component accounted for the largest portion of the sums of squares in both cases. Table 5 includes the results of the trend test.

Table 4

Average Absolute DLs in E-Gm. as a Function of Knob Radius and Load

Standard Load (gm.)	1.27		2.54		3.81		Average
	DL_l	DL_g	DL_l	DL_g	DL_l	DL_g	
50							
Women	2.00	1.70	1.28	1.22	1.10	1.02	1.40
Men	1.79	1.70	1.57	1.28	0.95	1.15	
100							
Women	3.51	3.42	1.93	1.92	1.46	1.35	2.43
Men	3.35	4.65	2.25	2.24	1.54	1.59	
200							
Women	5.18	5.32	3.16	3.12	2.29	2.34	3.32
Men	3.40	3.79	3.04	2.89	2.71	2.55	
Average	3.32		2.16		1.67		2.38

Table 5

Summary Table for AOV of Greater and Lesser Absolute DLs

Source	DF	Mean Square	Error Term	F Ratio
Sex (A)	1	.126	(1)	.060
Knob Radius (B)	2	51.572	(2)	45.115 ***
Linear	1	97.713	(2)	85.479 ***
Residual	1	5.432	(2)	4.752 *
Loading (C)	2	66.404	(3)	37.401 ***
Linear	1	125.494	(3)	70.683 ***
Residual	1	7.315	(3)	4.120
DL Type (D)	1	.095	(4)	.037
AXB	2	1.751	(2)	1.532
AXC	2	3.258	(3)	1.835
AXD	1	.493	(4)	1.926
BXC	4	4.197	(5)	2.043
BXD	2	.495	(6)	2.575
CXD	2	.391	(7)	1.340
AXBXC	4	2.431	(5)	1.183
AXBXD	2	.627	(6)	3.264
AXCXD	2	.377	(7)	1.291
BXCXD	4	.318	(8)	1.428
AXBXCXD	4	.214	(8)	.960
(1). S(A)	10	2.108		
(2). S(A)XB	20	1.143		
(3). S(A)XC	20	1.775		
(4). S(A)XD	10	.256		
(5). S(A)XBXC	40	2.055		
(6). S(A)XBXD	20	.192		
(7). S(A)XCXD	20	.292		
(8). S(A)XBXCXD	40	.223		
TOTAL	215			

$^{*}p < .05$

$^{***}p < .001$

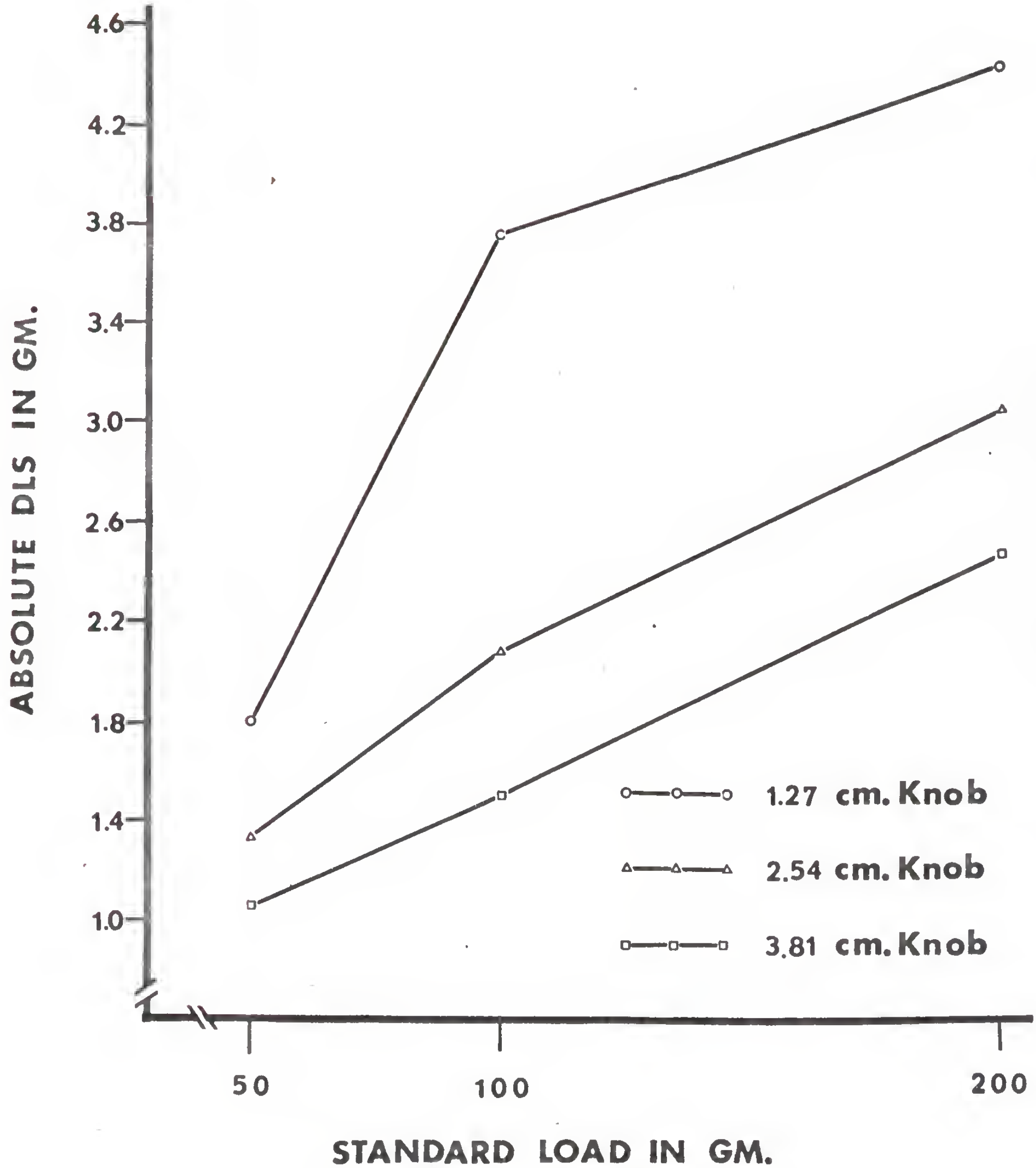

Fig. 1. Effect of load size on absolute DL.

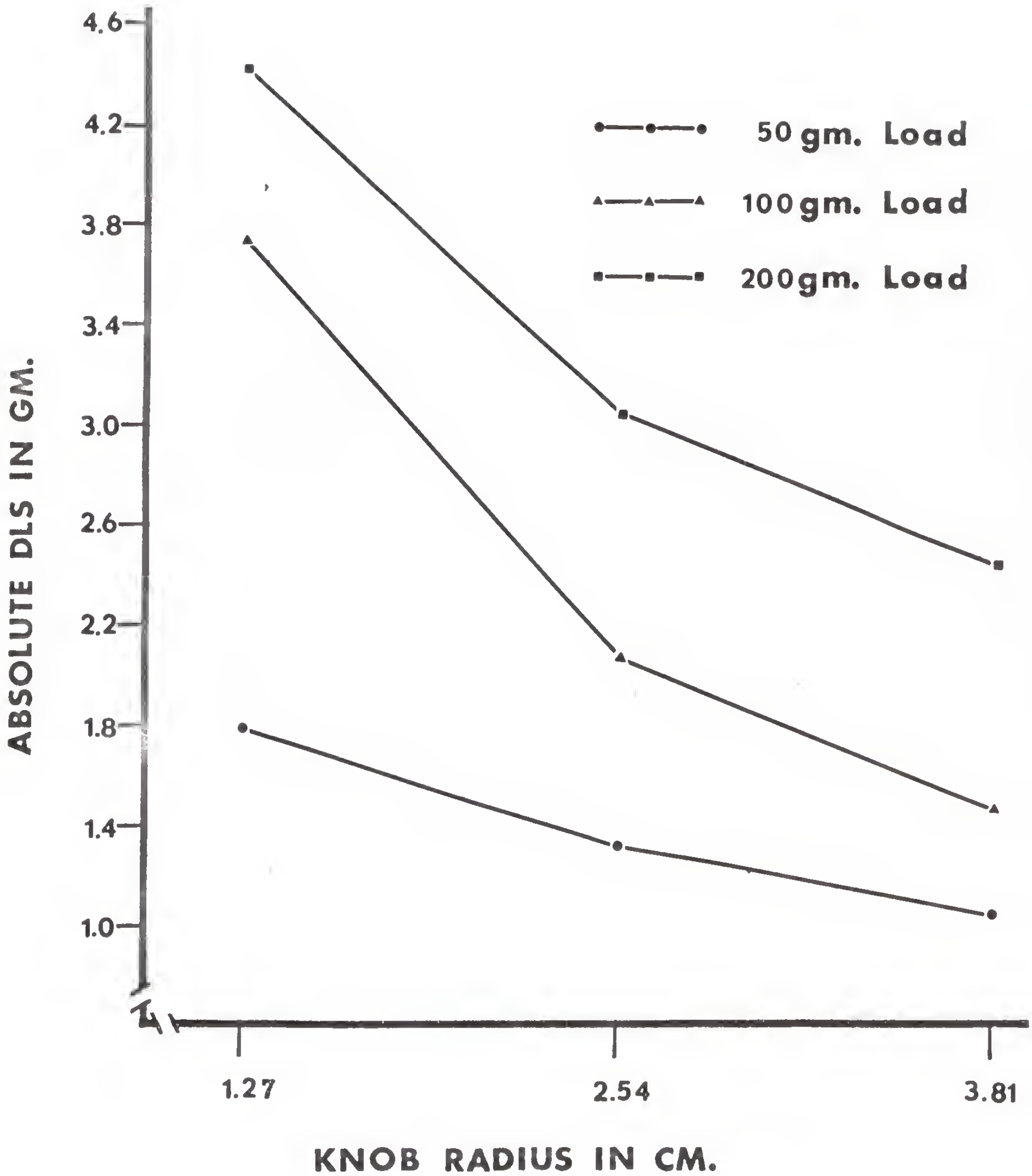

Fig. 2. Effect of knob radius on absolute DL.

Nonsignificant differences in the absolute DLs between the sexes may be surprising. This result may be due to the fact that the men and women Ss in this study did not have significantly different amounts of practice in turning knobs.

The lack of differences between DL_l and DL_g (DL type in Table 5) is not surprising since using the PSE in their calculation almost assured equality. This finding indicates that the sample standard deviations of the greater and lesser absolute DLs were not different. If the sample standard deviations had been different, then the two absolute DLs would also have been significantly different. However, the method of calculation may have been the reason for the extremely small F ratio (0.037) in the AOV. This ratio and all other F statistics of less than one were tested against the lower tail of the F distribution using the procedure given by Bennett and Franklin (1954).

The changes in the size of the absolute DL caused by manipulating knob radius and loading can be simplified if the results are presented in terms of e-gm. stimulation. From formula (2), $F = mk/r$, it is known that increasing the load (m) or decreasing knob radius (r) will increase the force that S has to exert to turn the knob. Therefore, the results given in terms of knob radius and loading (Table 4 and Figs. 1 and 2) can be reinterpreted in terms of e-gm. stimulation (Table 6 and Fig. 3): when e-gm. stimulation is increased by using smaller knobs or larger loads, the absolute DL is also increased.

Fisher's LSD was determined for the 9 absolute DLs by calculating the appropriate error term in a completely randomized AOV ($s_{\bar{X}} = 0.271$, 80 DF). Because of the effect of a prior test on the alpha level of the LSD, the .001 level of significance was chosen (Federer, 1955). In using this extreme level of significance, the actual alpha level, though unknown but definitely larger than .001, will (hopefully) remain fairly small. Table 6 shows the results of the LSD test. The means that are underlined by a single bracket do not differ from one another significantly. Inspection of Table 6 shows that there is a progressive increase in the size of the absolute DL as stimulation increases. Most importantly Table 6 shows that any one stimulus value in e-gm. has the same absolute DL regardless of knob size and loading. Thus a stimulus of 25 e-gm. may be produced with a 1.27 cm. knob and a 50 gm. load or with a 2.54 cm. knob and a 100 gm. load: these yield absolute DLs of 1.80 and 2.08 e-gm., respectively, which are not significantly different. Similarly, the two 50 e-gm. conditions do not differ significantly from one another. If the LSD for a 95% confidence level is calculated instead of for the 99.9% confidence level, more means will be significantly different and the brackets will be shorter. However, the duplicated stimulus values of 25 and 50 e-gm. still do not differ significantly from each other (LSD = 0.761, α = .05). Thus the important variable is stimulus magnitude measured in e-gm. The significance of knob size and loading must be evaluated together; i.e., in terms of actual use.

Table 6

Results of LSD Performed on Absolute DLs (LSD = 1.307, α = .001)

Loading	(gm.)	50	50	100	50	100	200	200	100	200
Knob Radius	(cm.)	3.81	2.54	3.81	1.27	2.54	3.81	2.54	1.27	1.27
Force	(e-gm.)	8.35	12.50	16.67	25.00	25.00	33.34	50.00	50.00	100.00
Absolute DL	(e-gm.)	1.06	1.34	1.49	1.80	2.08	2.47	3.05	3.73	4.42

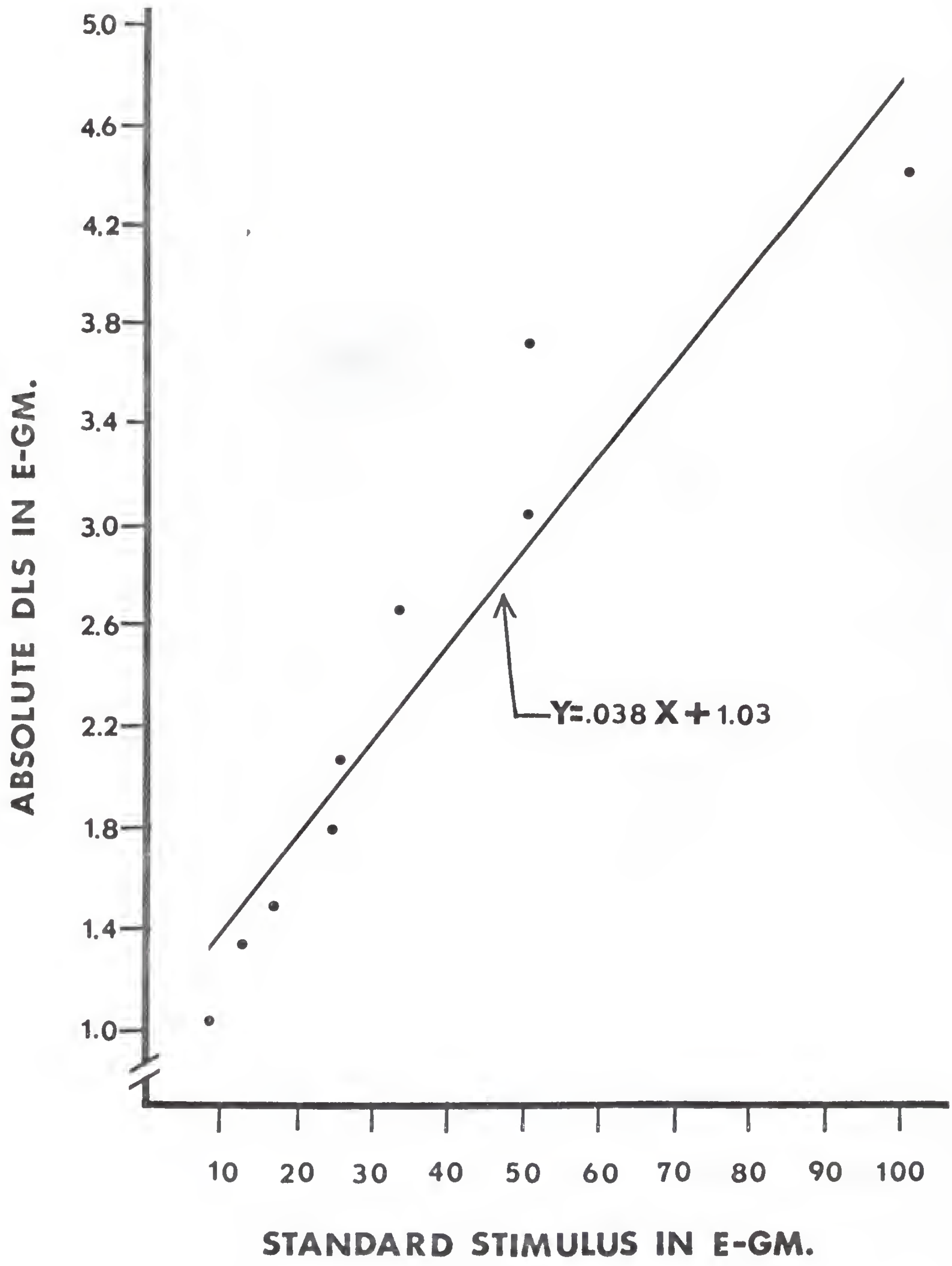

Fig. 3. Effect of stimulus magnitude on absolute DL.

Weber fractions for each condition, with parameters of knob radius and loading, are given in Table 7 and Figs. 4 and 5. The relative DLs show, with one exception, a decrease with increased loads, as seen by reading down the columns of Table 7. When read across by rows, Table 7 shows that the relative DL increases with increases in knob radius as is to be expected since sensitivity is less with larger knobs as the hand must turn a greater amount to get the same feedback from any given load. If relative DL decreases with increased load then it should increase with knob radius since larger knob radius is equivalent to decreased load due to the greater lever action of the larger radius knob.

Table 7

Average Weber Fractions for 3 Knob Radii
and 3 Standard Loads

Standard Load (gm.)	Knob Radius (cm.) 1.27	2.54	3.81	Average
	Weber Fraction			
50				
Women	.074	.100	.127	.102
Men	.070	.114	.126	
100				
Women	.069	.077	.084	.082
Men	.080	.090	.094	
200				
Women	.052	.063	.069	.060
Men	.036	.059	.078	
Average	.063	.084	.096	.081

The AOV (sex X knob radius X loading) of the Weber fractions gives the same results as the AOV for the absolute DLs. The summary table of the AOV (Table 8) shows that only knob size and load were important sources of variation. Trend tests performed on the two sources show the linear component to be much larger than the residual in both cases.

Table 8

Summary Table for AOV Using Weber Fractions

Source	DF	Mean Squares[1]	Error Term	F Ratio
Sex (A)	1	334.260	(1)	.1814
Knob Size (B)	2	9,954.510	(2)	23.8369***
Linear	1	19,569.014	(2)	46.8596***
Residual	1	340.005	(2)	.8142
Loading (C)	2	16,067.593	(3)	13.6534***
Linear	1	31,396.892	(3)	26.6794***
Residual	1	738.294	(3)	.6274
AXB	2	331.954	(2)	.7949
AXC	2	473.148	(3)	.4021
BXC	4	1,290.120	(4)	1.5628
AXBXC	4	230.760	(4)	.2795
(1). S(A)	10	1,842.182		
(2). S(A)XB	20	417.609		
(3). S(A)XC	20	1,176.820		
(4). S(A)XBXC	40	825.598		
TOTAL	107			

[1]The AOV was performed on the Weber Fraction X 1,000.

***$p < .001$

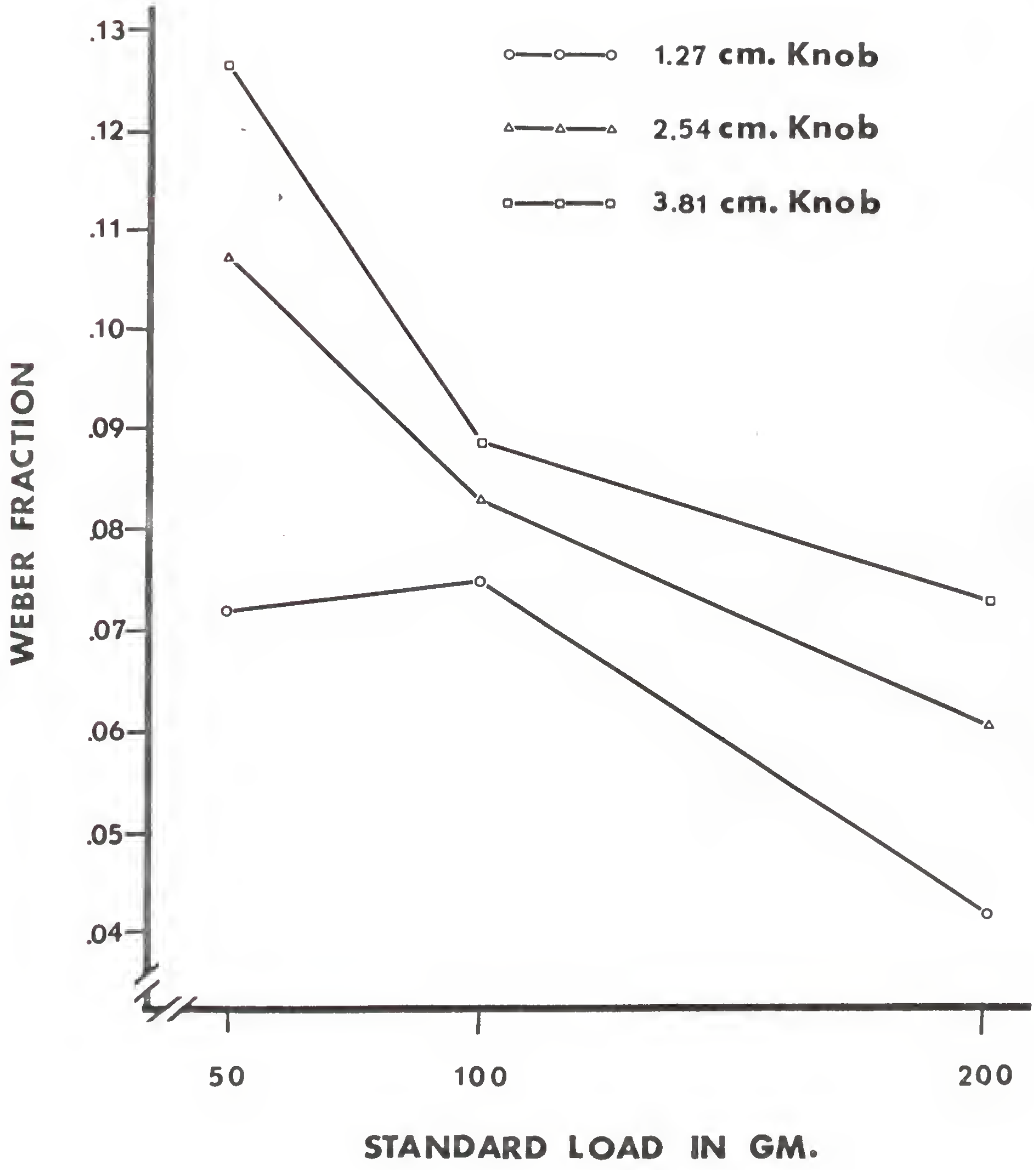

Fig. 4. Effect of load size on the Weber fraction.

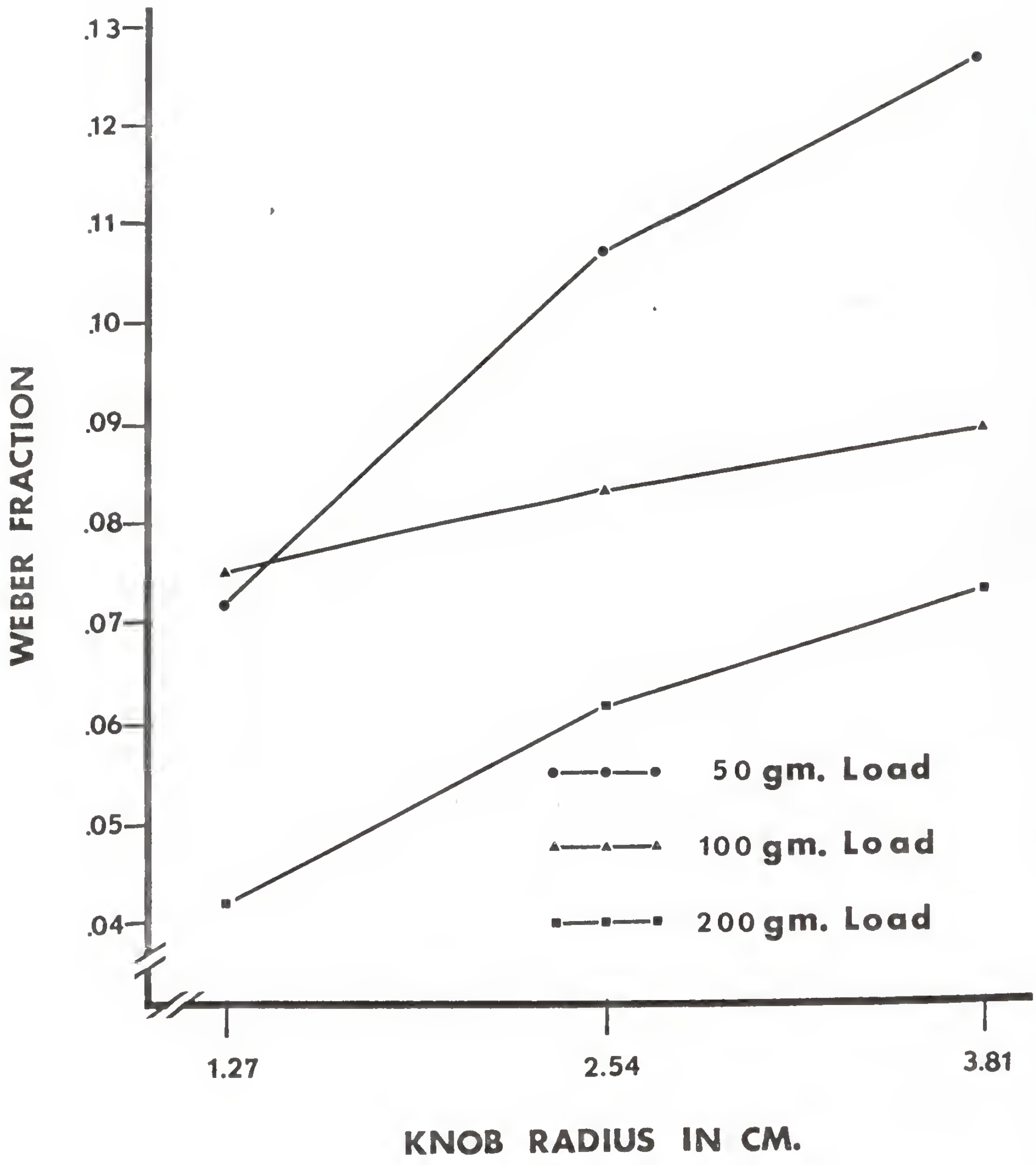

Fig. 5. Effect of knob radius on the Weber fraction.

The effect of changing knob size and load upon the relative DL can immediately be interpreted in terms of e-gm. stimuli by using formula (2), $F = mk/r$. Weber fractions are plotted against stimulus magnitude in e-gm. in Table 9 and Fig. 6. The data show more irregularities than do the data on the absolute DLs (Table 6 and Fig. 3). Still, the underlying trend in Table 9 is very apparent--as e-gm. values increase, the Weber fraction decreases. From Table 9 it is seen that there is an almost three-fold range in Weber fractions (0.126 : 0.044) as the stimulus increases twelve-fold (8.35 : 100 e-gm.). This result is in keeping with the finding that absolute DL increases with increase in stimulation.

Table 9

Results of LSD Performed on Weber Fractions (LSD = 0.040, α = .001)

Loading (gm.)	50	50	100	100	100	200	50	200	200
Knob Radius (cm.)	3.81	2.54	3.81	2.54	1.27	3.81	1.27	2.54	1.27
Force (e-gm.)	8.35	12.50	16.67	25.00	50.00	33.34	25.00	50.00	100.00
Weber Fraction	.126	.107	.089	.083	.075	.073	.072	.061	.044

LSD was determined for the 9 Weber fractions by calculating the appropriate error term in a completely randomized design ($s_{\bar{x}}$ = 0.008, 80 DF). The results of the LSD are in Table 9. The means that are underlined by a single bracket do not differ from one another significantly.

Inspection of Table 9 shows, once again, that stimulus magnitude in e-gm. is the important variable because the two 25 and 50 e-gm. treatments are not significantly different from each other. Nor do these conditions differ from each other significantly at an alpha level of .05 (LSD = 0.023, α = .05).

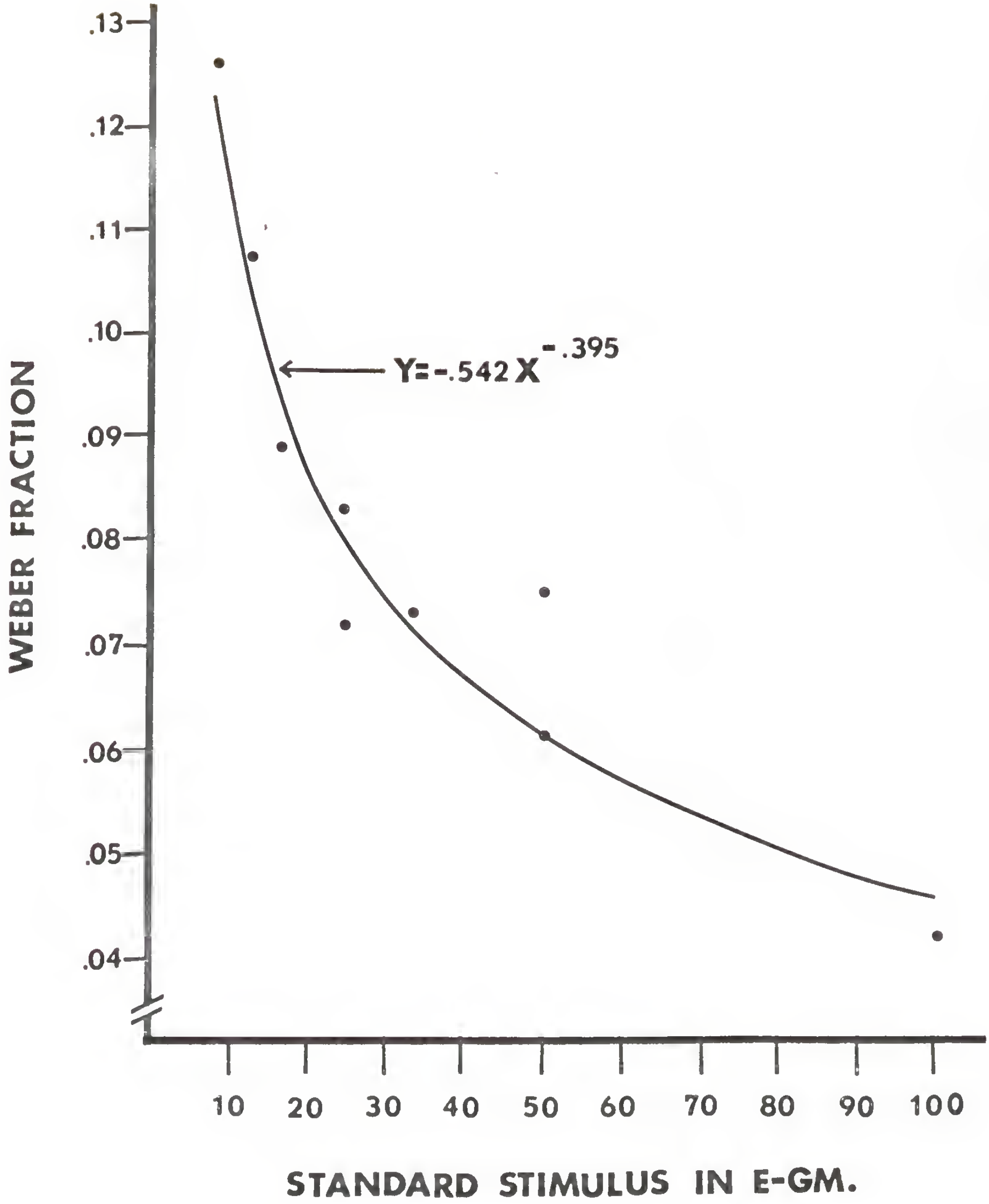

Fig. 6. Effect of stimulus magnitude on the Weber fraction.

Within the limits of this study, the Weber fraction is inversely related to stimulus magnitude--a result that runs counter to the complete generality of Weber's law according to which the relative DL should be constant. But, it is well known that Weber's law does not hold except for midrange values of stimulation (Geldard, 1953). Holway and Pratt (1936) reviewed sensitivity studies that had been conducted in such diverse sensory modalities as vision, audition, somesthesis, olfaction, and gustation. They found that the Weber fraction decreases to asymptotic values as stimulation increases from zero and then rises sharply as stimulus values increase beyond a certain point. Woodworth and Scholsberg (1954) report that the Weber fraction decreases rapidly as stimulation increases from 0 to 500 gm. Between 500 and 3,000 gm. there is a comparatively small change (the asymptotic region of maximum sensitivity). If data had been presented from stimuli beyond 3,000 gm., then at some stimulus value the relative DL would have once more begun to increase. Since the largest stimulus in the present investigation was 100 e-gm., it is not surprising that the data show a progressive and regular decrease in the relative DL as the stimulus values increase from 8.35 to 100 e-gm.

The relative DLs of this study (Fig. 6) show the progressive decrease reported by Holway and Pratt (1936). The stimulus range was not extended far enough to show the typical sharp increase in relative DLs when very large stimuli are employed. Inspection of Fig. 6 shows that maximum sensitivity is approached with stimuli as small as 100 e-gm. This maximum sensitivity is reached when the curve asymptotes yielding Weber fractions of approximately 0.04. The stimulus values of maximum sensitivity will probably extend from 100 e-gm. to at least 1,000 e-gm. depending upon the exact stimulus value at which the relative DL begins to become larger. It is safe to predict from this curve that a stimulus of 500 or 1,000 e-gm. will have a relative DL of approximately 0.04 so that it would not be inefficient to design equipment with much greater stimulus loads than the maximum employed in this study.

The Weber fraction is a dimensionless measure of sensitivity that lends itself to the direct comparison of relative sensitivity in different modalities. The smaller the asymptotic fraction, the greater the sensitivity of that modality. Woodworth and Schlosberg (1954) report that the value of the relative DL for lifted weights of 3,000 gm. is approximately 0.05. Compare this fraction with the fraction obtained with the 100 e-gm. stimulus (.044) and the fraction reported by Woodruff and Helson (1965) for a torque stimulus of 2,146 gm.-cm. (0.46). Evidently sensitivity to torque stimuli in either the lifted-rod or knob-turning task produces an asymptotic fraction of approximately .04 which is comparable to the asymptotic fraction for lifted weights. Furthermore, the possibility arises, in the knob-turning task, that maximum sensitivity occurs at a lower stimulus level than does asymptotic sensitivity in lifted-weight tasks. This greater sensitivity may be the result of larger kinesthetic involvement when S turns a knob as opposed to lifting a weight. Certainly finger and wrist joints and muscles, used when knobs are turned, are more highly innervated and therefore capable of producing finer discriminations than are the larger elbow and shoulder joints and muscles which are usually used in lifting weights.

The TOEs (Table 10) present a means of determing if the PSEs of the 9 conditions were shifted differentially. Inspection of Table 10 does not reveal any trends in the TOEs. A three-way AOV (sex X knob radius X loading) yields no significant F ratios. However, a t test shows that the average TOE (0.38) is significantly different from zero ($t_{107\ DF} = 2.91$, $p<.01$).

Table 10

Average TOEs in E-Gm.

Standard Load (gm.)	Knob Radius (cm.) 1.27	2.54	3.81	Average
	TOE			
50				
Women	.12	.44	-.23	.23
Men	.28	.89	-.10	
100				
Women	1.07	-.60	.14	.17
Men	.56	-.29	.14	
200				
Women	1.71	.33	.57	.75
Men	1.03	.77	.07	
Average	.80	.26	.10	.38

The final area of interest was to determine if thresholds change with practice. Therefore an analysis was performed on the data collected from the two sensitivity determinations on the 2.54 cm. knob with a load series having a 100 gm. standard. These identical determinations were the first and last conditions under which data were collected. If a threshold change, caused by practice, occurs, then these two conditions should show it most distinctly.

A three-way AOV (sex X time X type of DL) was made of the greater and lesser absolute DLs of these two determinations. No condition or interaction yielded an F ratio that reached the .05 alpha level. Next a two-way AOV (sex X time) was performed on the TOEs of the two determinations. The result of this analysis was the same as the first--no effect reached the .05 level of significance. Finally, another two-way AOV was performed on the Weber fractions--with the same result. Therefore, it is safe to assume that the data presented in this study do not show a systematic practice effect. If the procedure used in measuring torque sensitivity had had a practice component, it would have shown up in the comparison between the first and last data collected under the same conditions.

CONCLUSIONS

When small knobs are turned against various loads the problem of determining actual stimulus values becomes critical. Measures of sensitivity lose much of their meaning if the stimulus magnitude is unknown or misrepresented. For this and other reasons the stimuli must be presented in terms other than that of a load of X gm. being lifted by turning a knob of Y cm. radius. Though under actual conditions of use, this mode of specifying stimulation can be very informative. A better method of specifying stimulus magnitude is in terms of the force S must exert to turn the knob. This procedure allows all combinations of knob size and loading to be ordered along one continuum. It is easy to show that the force S must exert to turn the knob increases with larger loads and smaller knobs.

Using this procedure of ordering stimulation it can be stated, for stimuli of 100 e-gm. or less, that torque sensitivity is inversely related to stimulus magnitude. As stimulation increases from 8.35 to 100 e-gm. the Weber fraction decreases from .126 to .044.

When different knob sizes and loads produce the same stimulus value in e-gm., the absolute and relative DLs reflect only stimulus magnitude and not the way in which the stimulus was produced. Thus knob radius and loading are not important determiners of sensitivity per se. Their importance lies in the manner in which they produce changes in stimulus magnitude as measured in e-gm. This conclusion does not minimize the importance of knob size because large knobs will permit loadings, much larger than investigated, to be handled easily. Furthermore, situational variables may increase the importance of both load and knob radius.

In the region of stimulation investigated (8.35 to 100 e-gm.) the Weber fraction decreases rapidly in accordance with the findings of Holway and Pratt (1936). Further increases in stimulation will not serve to further reduce the Weber fraction as it has already approached its asymptotic value.

Torque sensitivity did not show improvement with practice nor was the sensitivity of the two sexes found to be different.

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TORQUE SENSITIVITY AS A FUNCTION OF RADIUS AND LOAD ON HAND-OPERATED KNOBS

by

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This study is concerned with sensitivity to torque in a knob-turning situation. Torque enters into operations of twisting and turning knobs, dials, handwheels, and all manipulanda in which the applied force is tangential to the line of motion. Previously, torque sensitivity had been measured when the end of a rod was held between the thumb and forefinger. Moving a weight along the rod varied the torque. However, the lifted-rod technique is limited because it is difficult to assess the effect and importance of variables such as radius, inertia, design, mechanical advantage, and loading of manipulanda. But a knob-turning task simulates both design of manipulanda and the play of muscles and motion commonly found in everyday tasks. In the present study, S turned a round knob which was attached to a steel rod. Weights were suspended from the rod to vary the load. Differential thresholds were determined for 3 standard loads (50, 100, and 200 gm.) and 3 knob radii (1.27, 2.54, and 3.81 cm.) making a total of 9 conditions.

The method of constant stimulus differences was used. Series stimuli were constructed for each of the 9 conditions with the proviso that (1) the standard load was in the center of the series and (2) the 4 series stimuli were equally spaced around the standard. The step interval of each of the series was adjusted for every knob size to produce "greater" judgments of from 15% to 85% when series stimuli were compared with the standard.

During each fifty-minute session, 6 men and 6 women Ss made 150 judgments on one of the 9 conditions--75 judgments in each time order. All Ss received the 9 conditions in the same random order. The first condition was repeated at the end of the design as a tenth condition to investigate the effect of practice upon sensitivity. Different sequences of stimulus pairings were used to minimize presentation-order artifacts.

There are two ways of viewing stimulus intensity. The first is in terms of a load of X gm. being lifted by turning a knob of Y cm. radius. The second presents stimulus intensity in terms of the force S must exert to turn the knob. In this measure the ratio of rod to knob diameter enters and hence stimulus values are denoted in terms of equivalent-grams (e-gm.). Measuring stimulation in e-gm. allows all combinations of knob size and loading to be ordered along one continuum. The first procedure does not permit this ordering. Both ways of presenting the data are given.

Ogives were fitted to the greater and less judgments by Urban's method. Limens, absolute difference limens (DLs), points of subjective equality (PSE), time order effects (TOE), and Weber fractions were calculated for each S for each condition from the fitted ogives.

The experimental data show that absolute DL is increased with increased loading or decreased knob size. When knob size is reduced or load is increased, e-gm. stimulation is increased; therefore, the absolute DL is increased with increased e-gm. stimulation. The Weber fraction, however, is decreased with increased e-gm. stimulation which may be achieved either by decreased knob radius or increased load. The decrease in the Weber fraction (.126 to .044) as stimulation is increased (8.35 to 100 e-gm.) is typical when a low range of stimulation is used. With the 100 e-gm. stimulus, the Weber fraction has already approached its asymptotic value which is approximately the same as its asymptotic value for lifted weights.

Torque sensitivity did not show improvement with practice nor was the sensitivity of the two sexes found to be different.