MINIMUM ALLOWABLE DIMENSIONS FOR CONTROLS MOUNTED ON CONCENTRIC SHAFTS

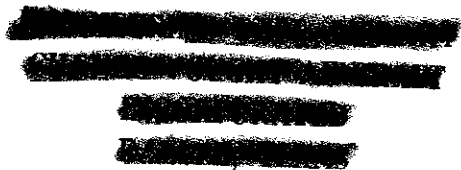*JAMES V. BRADLEY*

NORMAN E. STUMP

AERO MEDICAL LABORATORY

DECEMBER 1955

JUL 1 1 1956

PROJECT No. 7182-71514

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

This report was prepared by the Psychology Branch of the Aero Medical Laboratory, Directorate of Research, Wright Air Development Center under a project identified by Research and Development Task No. 71514, "Control Design and Arrangement." The research program was begun with Norman E. Stump acting as Task Scientist. Later, Mr. Stump accepted employment with private industry, turning the research program over to James V. Bradley. The research effort was greatly facilitated by frequent consultation with the following members of the Controls Section of the Psychology Branch: John W. Senders (electronic circuitry), W. Dean Chiles (statistics) and John P. Hornseth (general experimental methodology).

The experimental data were collected at Antioch College under Contract No. AF 18(600)-50 under the direction of Dr. Virginia L. Senders. The authors are indebted to Dr. Senders for a critical review of the first draft of the report and many excellent suggestions which improved the final form of the report. They are indebted to the entire Human Engineering staff at Antioch College for analysis and presentation of data, particularly so to Alan Lapiner (graphs) and George Norris (analysis of variance).

WADC TR 55-355

ABSTRACT

A series of experiments was performed to determine the minimum allowable dimensions of circular, nondetent knobs mounted upon concentric shafts when frequent inadvertent operation of adjacent coaxial knobs cannot be tolerated. Both unshielded knobs and knobs whose front faces were shielded against inadvertent operation were investigated. A standard setting was used, and measures were taken of reach time, turning time and inadvertent touching of adjacent coaxial knobs. Manipulated variables were thickness, diameter and difference in diameter between the operated knob and the adjacent knobs.
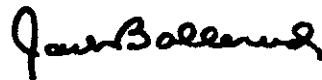
The conclusion was reached that if three knobs are to be concentrically ganged, and if the middle knob is about 2 in. in diameter (1) the diameter of the front knob should be at least 1 in. smaller, and that of the back knob 1 1/4 in. greater, than that of the middle knob, (2) the front and middle knobs should both be 3/4 in. thick but the back knob may be as thin as 1/4 in. These statements apply to both unshielded and shielded knobs. Statistically significant decrements in performance between adjacent experimental conditions were found when dimensions smaller than these were used.

Comparisons between the panel space consumed by nonganged knobs and by concentrically ganged knobs indicated that panel space will seldom be saved by concentrically ganging knobs when the following conditions obtain: (1) the knobs can be operated by application of moderate torque, (2) the difference in diameter between concentrically mounted knobs is large enough to insure that their inadvertent operation will be infrequent, (3) small diameter (1/2 in. to 1 in.) nonganged knobs are acceptable substitutes for the larger diameter concentrically ganged knobs.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

As aircraft and air missions increase in complexity, more and more instruments must be crowded into the limited panel space available. It is desirable, therefore, to find methods of grouping instruments which will permit a greater instrument "density" without seriously impairing the efficiency of operation of the instruments concerned. One technique suggested to meet these requirements is to gang or "stack" several control knobs along the dimension perpendicular to the instrument panel by mounting them on concentric shafts (Fig. 1). It is the purpose of this report: (a) to determine the minimum allowable dimensions for concentrically ganged knobs, (b) to determine under what, if any, conditions panel space is saved by using ganged controls of these minimum dimensions.
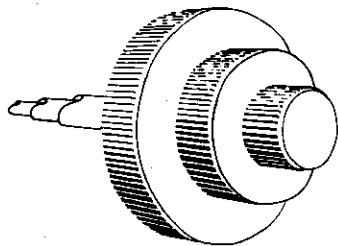
Figure 1: Concentrically ganged knobs.
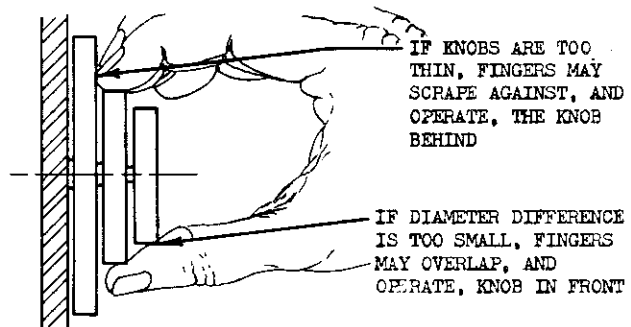
Figure 2: Hazard of inadvertent operation of adjacent knobs.

Ganging control knobs probably increases the chance of inadvertent operation of adjacent knobs. In turning one of the knobs, the operator's finger tips or knuckles may scrape against the face of the knob immediately behind it, or his fingers or palm may scrape against one of the knobs in front of it, thereby invalidating the setting of the knob inadvertently operated. (Fig. 2)

Inadvertent operation of the knob behind the operated knob presumably can be eliminated by shielding the face of each except the foremost knob. Shielding, however, does not prevent inadvertent operation of the knob in front of the operated knob. Since a shield would necessarily be of smaller diameter than the knob it protects (to allow the knob to be grasped and turned), the edge of the knob remains unprotected. Furthermore, shielding itself introduces problems. If the shield is fastened to the chassis, then the support which anchors the shield to the chassis is an obstruction to the fingers in turning any except the foremost knob. (Fig. 3) Where multiple rotation knobs are used, there would be strong objections to this type of shield. Even with single rotation knobs, one would expect speed and ease of operation to suffer. On the other hand, if the shield is fastened to the knob shaft, each shield, in effect, is part of the knob to whose shaft it is attached. Thus, since the diameter of the shield must necessarily be considerably larger than that of the knob mounted on the same shaft, the chance is greatly increased that, when turning the protected knob,

the operator's fingers will overlap the shield and thereby inadvertently turn the knob to which it is attached. (Fig. 4). Finally, there is a method of shielding which would be free from the objections listed above, but which, in all probability, would be unacceptable to design engineers because it would nearly double the number of concentric shafts required for a given number of ganged knobs. This would be to fasten the shields to fixed concentric shafts ("shield" shafts alternating with "knob" shafts) which would not rotate and whose sole purpose would be to anchor the shields.
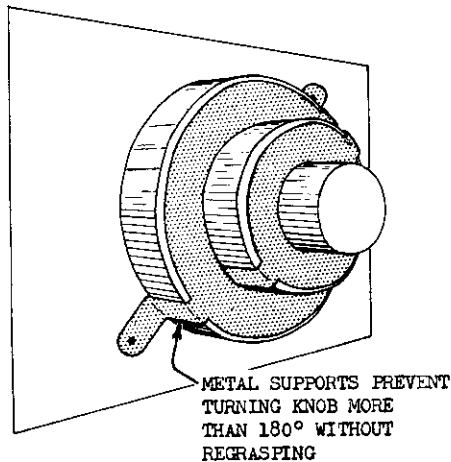
Figure 3: Disadvantage of shielding knobs when shield is attached to the chassis.
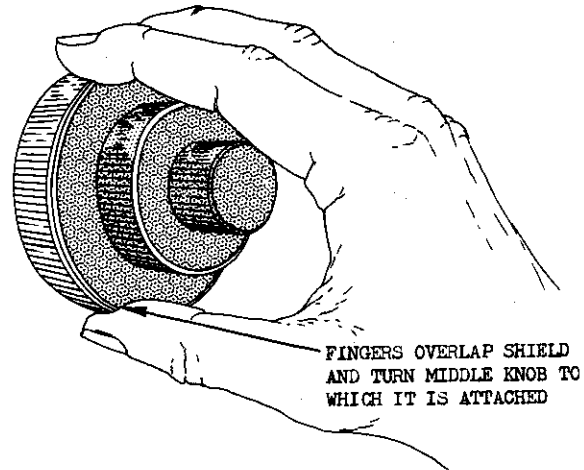
Figure 4: Disadvantage of shielding knobs when shield is attached to the knob shaft.

In the series of experiments to be reported here, the situations in which an operator makes settings with either the front, the middle or the back knob of three concentrically ganged knobs were simulated or reproduced. Because the chance of inadvertent operation is inferred from the frequency of inadvertent touching, the results will apply only to a series of concentrically ganged knobs all of which are capable of being operated by the application of moderate torque. Specifically, the results will not apply to concentrically ganged detent knobs.

Three variables associated with knob dimensions were investigated: thickness, diameter and difference in diameter between the operated knob and the adjacent knobs. Design engineers may set their own criteria for minimum allowable dimensions. The authors took as minimum allowable dimension the largest value tested at which performance was significantly superior to performance at the next smaller value. This was usually the point at which the time or error curve became nearly parallel to the X-axis. Another perfectly reasonable criterion would be dimensions which give rise to an arbitrarily selected percentage of errors, such as errors on 5% of all trials. Designers wishing to use such a criterion will find the necessary figures in the Appendix. Obviously such an

approach can be expected to result in an entirely different set of "minimum allowable dimensions."

APPARATUS AND PROCEDURE

The subject's task was to reach from a fixed position, grasp one of three ganged controls and make a standard setting. When the results were to apply to unshielded controls, he was instructed to avoid touching any of the other knobs in the series. When shielded controls were to be simulated, he was instructed only to avoid touching the knobs in front of the operated knob (since shielding protects the knobs behind the operated knob but not those in front of it). In either case he was instructed to regard the controls to be avoided as being set to an extremely delicate adjustment, the accuracy of which was just as important as that of the adjustment he was to make with the operated control. He was further instructed to consider that the slightest touch of the hand would invalidate the setting of a control inadvertently touched. With this orientation he was instructed to work both for speed and for accuracy as defined by absence of inadvertent touching of the "prohibited" controls. Inadvertent touching, rather than inadvertent operation, of a "wrong" control was selected as the criterion of error because frequency of inadvertent operation would necessarily be a function of the amount of torque required to move the inadvertently operated knob. It is not intended that frequencies of inadvertent touching be interpreted as absolute frequencies of inadvertent operation. It is intended only that they serve as an index of relative "task difficulty" or "error susceptibility" in comparing one experimental condition with another. Finally, the subject was asked always to grasp the operated control with the thumb diametrically opposite the fingers and in contact with the knob.

The apparatus is shown in Figure 5. The sequence of operations was as follows. At the start of a trial the operated knob was in either its extreme counterclockwise or its extreme clockwise position (i.e. with the black radial line on its face pointing at 8 o'clock or at 4 o'clock), and the subject was depressing the telegraph key with his dominant hand. The experimenter then threw a switch to illuminate the amber light. This was a signal to the subject that, whenever he was ready, he might reach up, avoiding the "prohibited" knobs, grasp the "operated" knob and turn it until the black radial line on its face was pointing straight up, at which point the light would go out. When he had turned out the light, the subject was to return his hand to the telegraph key until the experimenter threw a switch disconnecting his time clocks from the subject's apparatus. The throwing of the switch was a signal to the subject to reset the operated knob. He was to alternate the starting position of the black radial line between its extreme clockwise and its extreme counterclockwise positions. There were five clockwise and five counterclockwise settings for each experimental condition.

The experimenter's apparatus recorded: (a) reach time - the time elapsed from the release of the telegraph key until the operated knob begins to turn, (b) turning time - the time, after the operated knob starts to turn, that the knob spends outside of the narrow "adjustment" zone in which the black radial line on its face is vertical and the amber light is extinguished, (c) back knob

AMBER LIGHT
(CAN BE TURNED ON BY A
SWITCH ON EXPERIMENTER'S
PANEL. IT IS TURNED OFF
WHEN THE BLACK RADIAL LINE
ON THE OPERATED KNOB IS
ROTATED TO THE VERTICAL
POSITION. WIDTH OF
"ADJUSTMENT ZONE" IS 2°)

METAL BACK KNOB
(INSULATED FROM SHAFT BY A
PLASTIC SLEEVE)

PLASTIC OPERATED KNOB
(INDICATOR ROTATES 250°, FROM
8 O'CLOCK TO 4 O'CLOCK)

METAL FRONT KNOB

TELEGRAPH KEY

12"

7"

2"

2¼"

12"

2½"

1"

" 'K KNOB'S SHAFT "
(NON-ROTATABLE)

SHAFTS CAN BE LOCKED INTO
PLACE AT ANY LINEAR POSITION

FRONT KNOB'S SHAFT
(NON-ROTATABLE)

OPERATED KNOB'S SHAFT
(SINCE SAME SHAFT IS
ALWAYS USED FOR OPERATED
KNOB, FRICTION IS HELD
CONSTANT)

RECORDS TIME FROM
RELEASE OF
TELEGRAPH KEY
UNTIL OPERATED
KNOB BEGINS
TO TURN

RECORDS TIME FROM
BEGINNING OF TURN
OF OPERATED KNOB
UNTIL AMBER LIGHT
IS FINALLY
EXTINGUISHED

BACK KNOB
THYRATRON
TOUCHPLATE
CIRCUIT

FRONT KNOB
THYRATRON
TOUCHPLATE
CIRCUIT

LIGHTS WHEN
SUBJECT TOUCHES
FRONT KNOB

LIGHTS WHEN
SUBJECT TOUCHES
BACK KNOB

BACK KNOB
LIGHT

FRONT KNOB
LIGHT

EXPERIMENTER'S ERROR PANEL
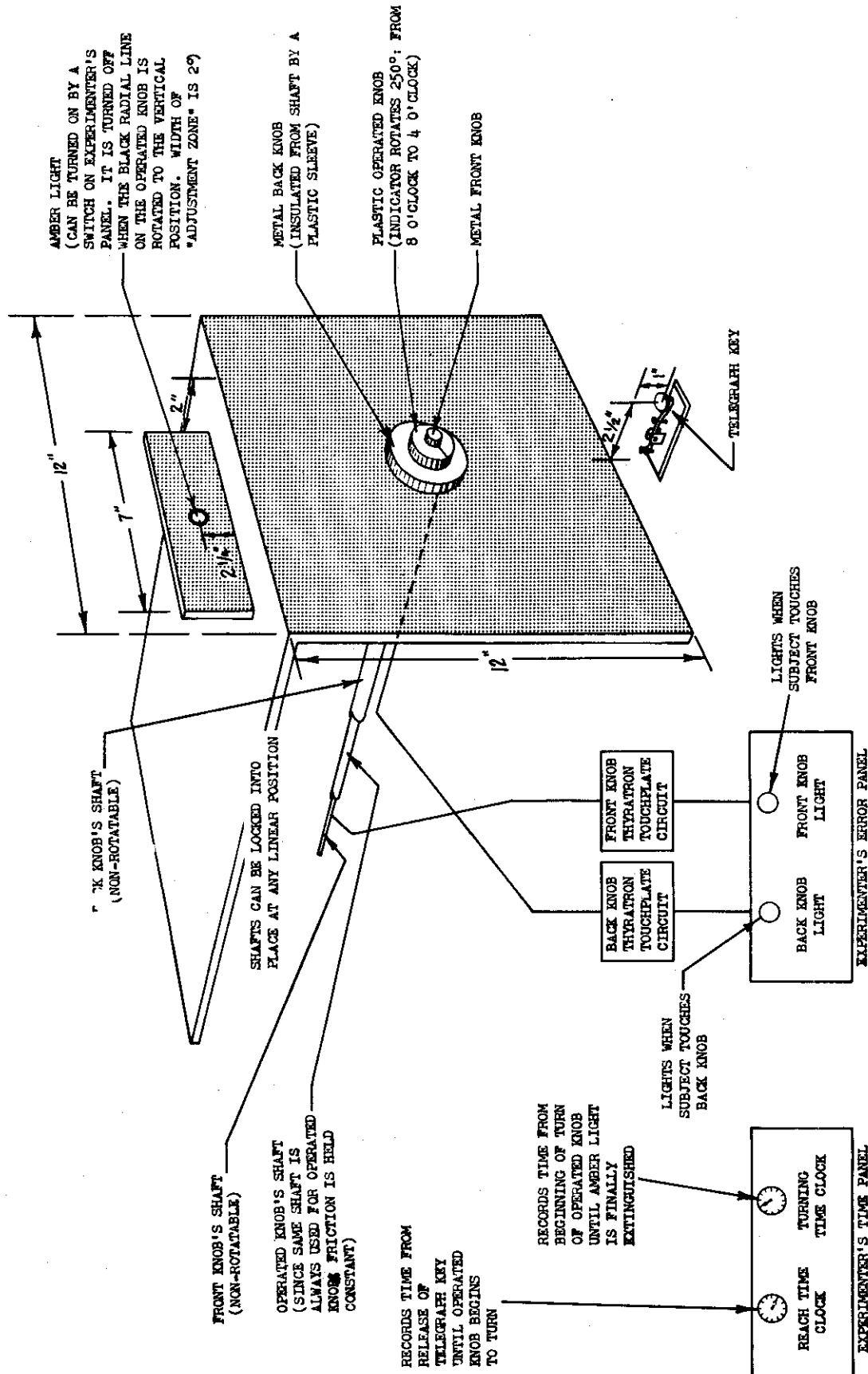
REACH TIME
CLOCK

TURNING
TIME CLOCK

EXPERIMENTER'S TIME PANEL

Figure 5: Apparatus

errors - inadvertent touching of the knob immediately behind the operated knob, (d) front knob errors - inadvertent touching of the knob in front of the operated knob. Any frequency of touching of a particular "prohibited" knob during a single trial was counted as only one error. Only those errors committed during a "trial" proper were recorded; errors in resetting the knob were not counted. Both time and error scores were recorded on the theory that they are complementary measurements: a subject may make few errors because he is willing to spend an inordinate amount of time in meticulous operation of the knob, or he may make low time scores because he does not exercise sufficient care to avoid errors. A difficult condition, therefore, may escape detection by one of these measures, but it is unlikely to escape detection by both.

In order to assure consistent operation of the thyratron circuits, the subject (except in Experiment I-B) was biased with 22½ volts D.C. by means of a clip attached to his dominant forearm. In Experiments I-A and I-B, a very sensitive thyratron circuit was used. In all other experiments, the thyratron circuit recording front-knob errors was quite sensitive. However, the back-knob-error thyratron circuit was appreciably less sensitive to touching. Frequencies of back-knob errors, therefore, should not be compared with frequencies of front knob errors.

Seventy-six male college students served as subjects for these experiments. Since clockwise and counterclockwise settings were alternated under each condition, it was deemed safe to use both right and left-handed subjects. In any given experiment, each subject performed under every experimental condition, thereby acting as his own control. The order of presentation of experimental conditions to the various subjects was balanced in a manner tending to cancel out learning effects. Each condition of each variable was presented the same number of times first, second, third, etc. The subject was not told what measurements the experimenter was recording; however, all of the measurements taken could be inferred from the clicking of relays.

A number of experiments was conducted in which the effect of various parameters was investigated when the front, the middle or the back of three ganged knobs was operated. The variables manipulated as well as the constant values assigned to the nonmanipulated variables for each of the experiments can be found in Table I. The specific values used for the manipulated variables will not be reported in the text but can be obtained from the graphs. Reasons for the choice of the constant values selected for the nonmanipulated variables can be found in the Discussion section of the pilot study.

In three of the experiments, shielded as well as unshielded knobs were investigated, the only changes in experimental procedure when shielded knobs were simulated being that: (a) subjects were instructed to avoid touching only those knobs in front of the operated knob, (b) the back knob was disconnected from its touchplate circuit so that only front knob errors were recorded, (c) a number of new subjects, equal to that used in investigating unshielded knobs, was used. It will be noted that results of experiments in which the middle of three shielded knobs is operated are also applicable to the situation where the second of two ganged knobs is operated, since, in effect, the subject ignores the third knob. Furthermore, the results would be equally applicable to shielded and unshielded knobs, since shielding would serve only to protect the second knob when the front knob was operated.

TABLE I

Apparatus and Procedure Variations for Each of the Separate Experiments

Experiment	No. of Ss	Shielding Condition of Knobs	Errors Recorded	Knob Operated	Dimensions Held Constant	Dimensions Varied
Pilot Study	12	Unshielded	Back Knob Front Knob	Middle	-	Middle Knob Diameter. Diameter Difference between Middle and Adjacent Knobs. Thickness of all three knobs.
I-A	8	Unshielded	Back Knob	Front	Back Knob Diameter (9") Back Knob Thickness	Front Knob Diameter and Thickness
I-B	8	Shielded	None	Front	Back Knob Diameter (9") Back Knob Thickness	Front Knob Diameter and Thickness
II-A	6	Unshielded	Back Knob Front Knob	Middle	Middle Knob Diameter (2") Middle Knob Thickness (½") Back Knob Diameter (5") Back Knob Thickness (1")	Front Knob Thickness Diameter Difference between Middle and Front Knob.
II-B	6	Shielded	Front Knob	Middle	Middle Knob Diameter (2") Middle Knob Thickness (½") Back Knob Diameter (5") Back Knob Thickness (1")	Front Knob Thickness Diameter Difference between Middle and Front Knob.
III-A	12	Unshielded	Back Knob Front Knob	Middle	Front Knob Thickness (½") Middle Knob Diameter (2") Back Knob Diameter (5") Back Knob Thickness (1")	Middle Knob Thickness Diameter Difference between Middle and Front Knob.
III-B	12	Shielded	Front Knob	Middle	Front Knob Thickness (½") Middle Knob Diameter (2") Back Knob Diameter (5") Back Knob Thickness (1")	Middle Knob Thickness Diameter Difference between Middle and Front Knob.
IV	12	Either	Touching either Middle or Front Knob	Back	Front Knob Diameter (1") Front Knob Thickness (3/4") Middle Knob Diameter (2") Middle Knob Thickness (3/4")	Back Knob Thickness Diameter Difference between Middle and Back Knob.
V	12	Unshielded	Back Knob Front Knob	Middle	Middle Knob Diameter (2")	Diameter Difference between Middle and Adjacent Knobs. Thickness of all three.

There were occasional variations in the general apparatus and procedure described above. In Experiment I-A, errors were recorded, not by a light on the experimenter's panel, but by a Veeder counter which operated every time the back knob was touched during a trial (an error, however, was still defined as one or more inadvertent touchings in a single trial). The operation of the counter was far noisier than that of the holding relay used in the succeeding experiments, and the association between its operation and the commission of an error was far more compelling than was the association between errors and relay clicks in the experiments which followed. In Experiment I-B, the subject was given no instructions whatever concerning the avoidance or nonavoidance of adjacent knobs. The "back knob" was a 9 in. diameter metal plate, fastened to the chassis by four screws. In Experiment IV, the subject operated the back knob and a single touchplate circuit was used to record inadvertent touching of either the front or middle knob. Therefore it was impossible to determine which knob had been the cause of the error. In Experiment V, the subject made settings with his eyes closed, and reset the knob with his eyes open. The overhead lights were extinguished and the subject "observed" the amber light through his closed eyelids, using the associated relay clicks as supplementary cues. The subjects used for this experiment were the same subjects who had been used in Experiment IV. They were run immediately after the completion of Experiment IV with no interval between experiments other than that necessary to read a new set of instructions. The reason for this procedure was to provide the subjects with a foreperiod of practice (Experiment IV) in which to learn the location of the operated knob and acquire a kinaesthetic "feel" for the task.

PILOT STUDY

This experiment was an exploratory one. It was intended that its results should indicate the proper direction for more precise and specific experiments.

The task required was the operation of the middle knob of three, unshielded, concentrically mounted knobs. This was presumed to be the most difficult task encountered in the operation of three concentrically mounted knobs. It was selected for investigation on the assumption that a variable found to be weak or insignificant in this situation would probably be negligible in all others. It was hoped in this fashion to reduce the number of variables requiring investigation in the experiments to follow.

AVOIDED

OPERATED

AVOIDED

DIAMETER OF OPERATED KNOB, DIAMETER DIFFERENCE BETWEEN OPERATED AND AVOIDED KNOBS, AND THICKNESS (OF ALL THREE KNOBS) WERE VARIED
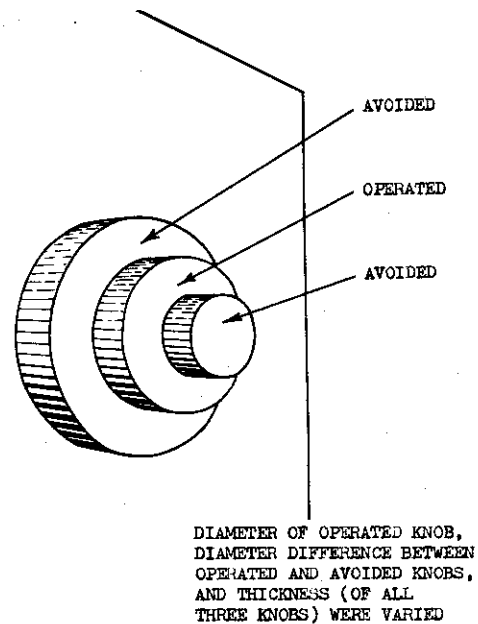
Figure 6: Specific task conditions for pilot study.

The diameter of the operated knob, the diameter difference between the operated knob and both the front knob and the back knob, and the thickness of all three knobs were varied. In any given experimental condition, all three knobs had the same thickness, and the same value was used for both diameter differences. There were four conditions of each variable, making 64 possible combinations. Each of these combinations was tested. The experimental design is described by Lindquist (3). Each subject performed under one fourth of the possible conditions in such a way that each subject performed under all two variable combinations but under only one fourth of the possible three variable combinations.

TABLE II

Results of Statistical Analysis for Pilot Study

Significance Levels from Analysis of Variance

Type of Measure	Thickness	Diameter Difference	Diameter	TxDD	TxD	DDxD	TxDDxD (Within Groups)
Back Knob Errors	.001	.001	NS	.001	NS	NS	.001
Front Knob Errors	.001	.001	.001	.001	NS	.01	.001
Reach Time	.001	.001	.01	NS	NS	.01	.001
Turning Time	.001	.001	.001	NS	.01	.001	.001

Discussion of Results: Because the experiment was intended only as a guide for further research, only those results which strongly influenced the direction taken in subsequent experiments will be discussed, the discussion being based solely upon the graphs and the analysis of variance for errors.

Diameter, as a main effect, influenced only front knob errors. Its only significant interaction was with diameter difference for front knob errors. For both error measurements, thickness and diameter difference were highly significant, both as main effects and in interaction with each other. Diameter, then, is by far the weakest and least important variable of the three. An examination of the graphic data suggests that, when diameter had a significant effect, the significance was probably due to the 3 and 4 inch diameter values, where performance was poor, rather than to the 1 or 2 inch values. In most of the experiments to follow, therefore, the diameter of the operated knob was held constant at 2 in. since this figure seems to be about the optimum, since small changes in diameter around 2 inches apparently have little effect upon performance, and since 2 inches permits reasonable values for front and back knob diameters when a diameter difference is used which the graphic data seem to demand (i.e. about 1¼ in.).
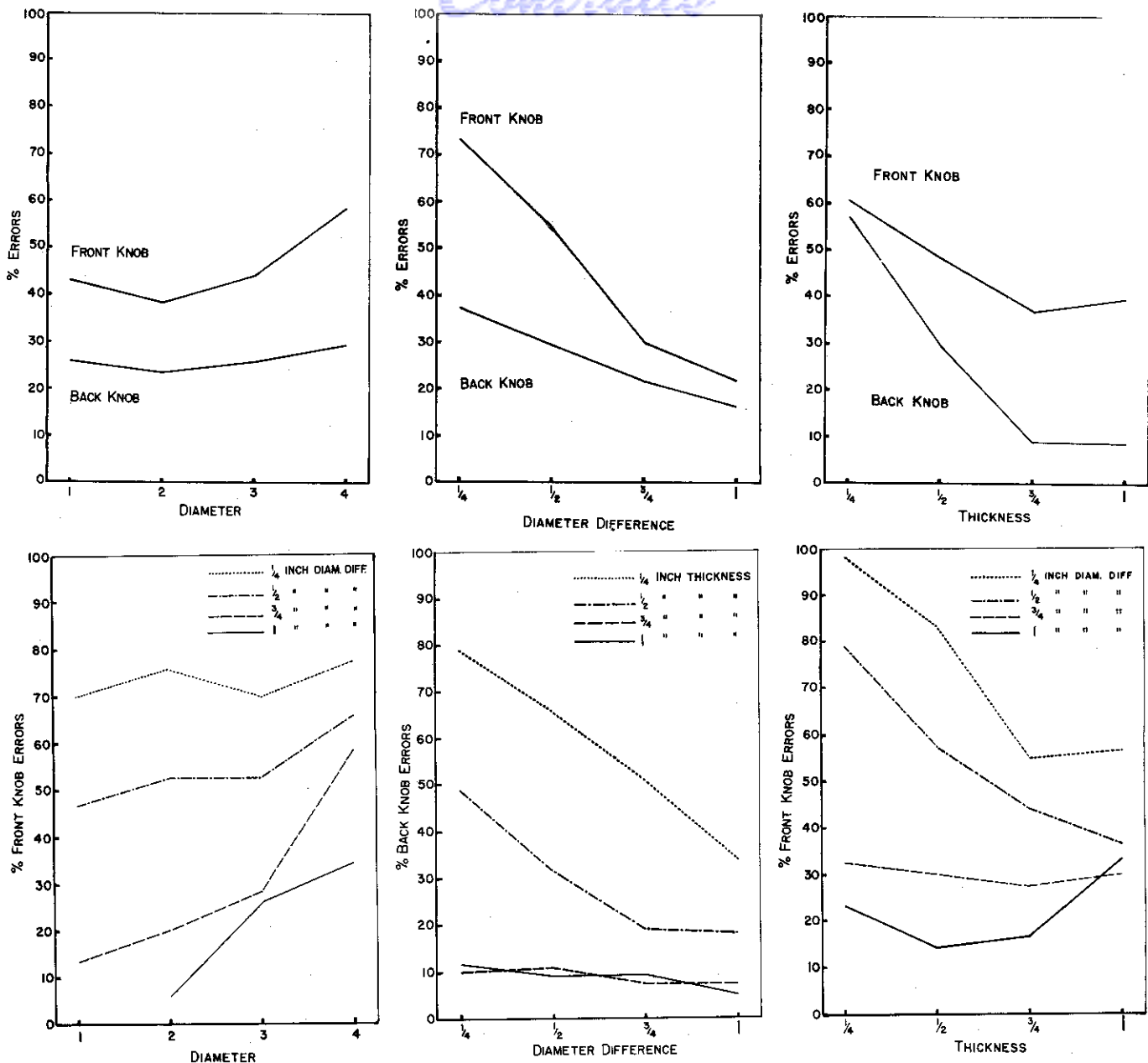
Figure 7: Error scores for the operation of the middle knob of a series
of unshielded, concentrically mounted knobs when thickness, diameter
difference and diameter of the operated knob are varied.

Errors continue to diminish rapidly with increasing diameter difference up
to the end of its range of values. One inch, then, is not a sufficiently large
difference in diameter to reduce errors to a tolerable level. Therefore, in the
experiments to follow, the range of diameter differences was extended.

Diameter difference appears to have its greatest effect upon front knob
errors, although back knob errors are also affected. Since back knob errors

TABLE III

Error Results for Pilot Study

		% Back Knob Errors				% Front Knob Errors			
		Diameter Difference				Diameter Difference			
		1/4	1/2	3/4	1	1/4	1/2	3/4	1
Thickness (All diameters combined)	1/4	79.2	65.8	50.8	34.2	98.3	79.2	32.5	23.3
	1/2	49.2	31.7	19.2	18.3	83.3	57.5	30.0	14.4
	3/4	10.0	10.8	7.5	7.5	55.0	44.2	27.5	16.7
	1	11.7	9.2	9.2	5.0	56.7	36.7	30.0	33.3
Diameter (All thicknesses combined)	1	35.0	38.3	18.3	12.5	70.0	46.7	13.3	----
	2	36.7	24.2	21.7	11.7	75.8	52.5	20.0	5.8
	3	32.5	28.3	24.2	18.3	70.0	52.5	28.3	25.8
	4	45.8	26.7	22.5	22.5	77.5	65.8	58.3	34.2
		Diameter				Diameter			
		1	2	3	4	1	2	3	4
Thickness (All diameter differences combined)	1/4	55.8	50.0	59.2	65.0	67.8	54.2	58.3	64.2
	1/2	27.5	27.5	32.5	30.8	47.8	43.3	41.7	60.8
	3/4	11.7	7.5	5.8	10.8	24.4	28.3	31.7	60.8
	1	9.2	9.2	5.8	10.8	33.3	28.3	45.0	50.0

Percentage of Front Knob Errors When Middle Knob Is 1" in Diameter

		Diameter Difference		
		1/4"	1/2"	3/4"
Thickness	1/4"	100	90	13
	1/2"	83	43	17
	3/4"	40	33	0
	1"	57	20	23

diminish with increasing diameter difference (as more back knob area becomes exposed to the hazard of inadvertent touching) it seems obvious that it is not the diameter difference between the middle and back knob, but rather the diameter difference between the middle and front knob, which influences back knob errors. Presumably, at small diameter differences, the subject, in attempting to avoid touching the front knob, reaches farther back on the middle knob in grasping it, thereby increasing the chance of touching the back knob and recording a back knob error. If this be true, then back knob errors vary with diameter difference only because the subject is trying to avoid touching the front knob. In any event the data suggest that the diameter difference between the middle and back knob is an irrelevant variable. In most of the experiments to follow, therefore, the back knob was assigned a large constant diameter, and only the diameter difference between the middle and front knobs was varied.

Since thickness was varied for all three knobs simultaneously, it is impossible to say with certainty which knob thickness is responsible for a certain effect. It seems entirely reasonable to assume, however, that the influence of thickness upon back knob errors is mainly attributable to the thickness of the middle knob. The knob whose thickness affects front knob errors is more difficult to identify on logical grounds. One might expect front knob errors to increase as front knob thickness increases, since this brings the face of the front knob closer to the palm of the hand. On the other hand, one might expect front knob errors to increase as middle knob thickness decreases, since subjects may grasp the middle knob closer to its face when thickness is small in an attempt to avoid back knob errors. In the present experiment front knob errors increased with decreasing thickness. Therefore the evidence supports the second hypothesis. However, both hypotheses may be true, the second effect being stronger than, and obscuring, the first when thicknesses are varied simultaneously. It would be desirable, then, that these two hypotheses be tested separately in the experiments to follow.

Table III shows that large diameter differences are necessary even with small diameter knobs. Wilcoxon's nonparametric test for paired replicates (4) was applied to the data for front knob errors when the operated knob diameter was 1 inch. Statistically significant improvements in performance were found for each increase in diameter difference from 1/4 in. to 3/4 in. (at which the error frequency was 13.3%). Since at a diameter difference of 3/4 in. the front knob is 1/4 in. in diameter, it is clear that using knobs of small diameter does not relieve one of the necessity to use large diameter differences.

This experiment investigated the effect upon performance of front knob thickness and diameter when the front knob of a series of unshielded ganged knobs is operated.
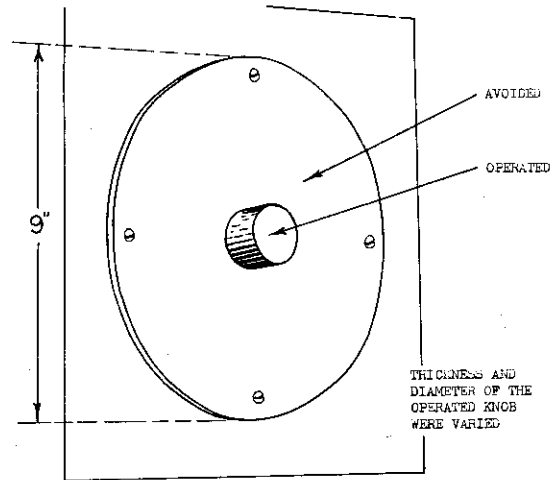
Figure 8: Specific task conditions for Experiment I-A.
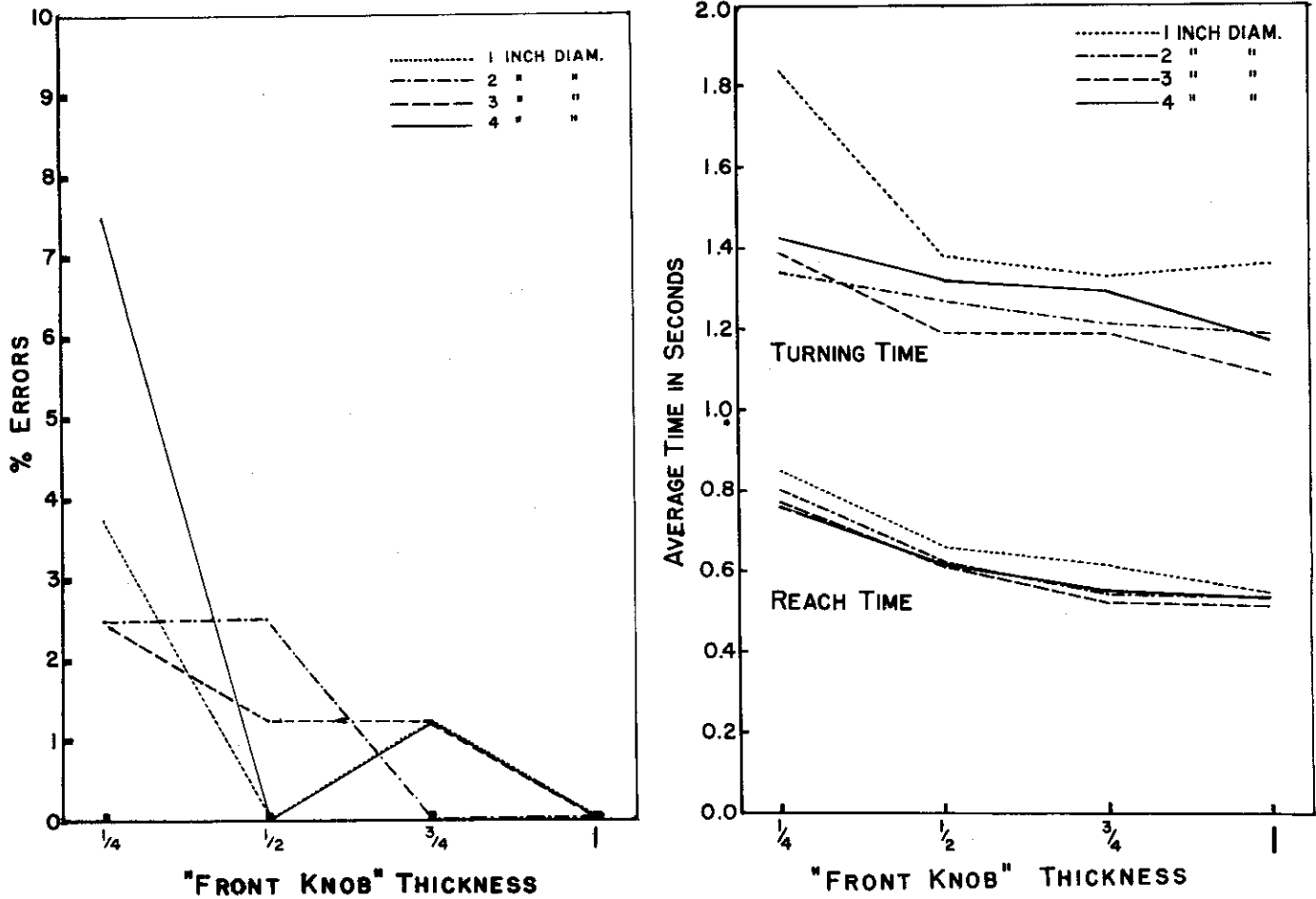
Figure 9: Results for Experiment I-A.

TABLE IV

Statistical Analysis for Experiment I-A

Significance Levels from Analysis of Variance

Type of Measure	Thickness	Diameter	T x D Interaction
Back Knob Errors	.05	NS	NS
Reach Time	.001	.001	NS
Turning Time	.01	.001	.05

Significant (two tailed) t Tests Between Adjacent Conditions

Type of Measure	Thicknesses Compared	At Which Diameter	Sig. Level	Diameters Compared	At Which Thickness	Sig. Level
Back Knob Errors	None Significant	All Combined		Not Tested		
Reach Time	1/4 & 1/2	All Combined	.001	1 & 2	All Combined	.05
	1/2 & 3/4	All Combined	.01			
Turning Time	1/4 & 1/2	1	.05	1 & 2	1/4	.05
	1/4 & 1/2	3	.05	4 & 3	1/2	.05

Conclusions: When the front knob of a series of unshielded, concentrically ganged knobs is to be operated, performance will suffer if the knob is less than 3/4 in. thick. This performance decrement will be confined mainly to operation time, however, since errors are quite infrequent under all thickness conditions tested. While the optimum diameter appears to be in the neighborhood of two or three inches, a diameter as small as one inch may be used without increasing errors but at an additional cost in time.

EXPERIMENT I-B

This experiment repeated Experiment I-A except that _shielded_ knobs were simulated and tested.
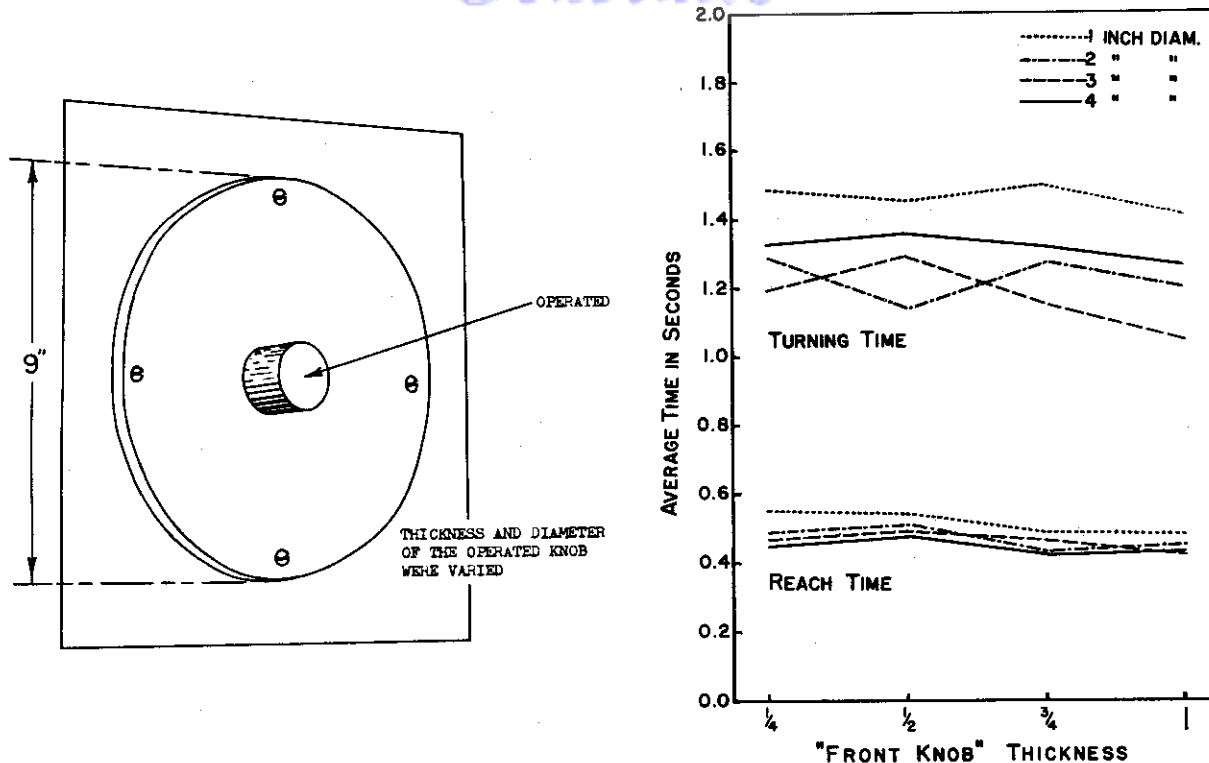
Figure 10:   Specific task conditions and results for Experiment I-B.

TABLE V

Statistical Analysis for Experiment I-B

Significance Levels from Analysis of Variance

Type of Measure	Thickness	Diameter	T x D Interaction
Reach Time	.05	.001	NS
Turning Time	NS	.001	NS

Significant (two tailed) t Tests Between Adjacent Conditions

Type of Measure	Thicknesses Compared	At Which Diameter	Sig. Level	Diameters Compared	At Which Thickness	Sig. Level
Reach Time	1/2 & 3/4	All Combined	.05	1 & 2	All Combined	.001
Turning Time	Not Tested			1 & 2	All Combined	.001
				4 & 3	All Combined	.001

Conclusions: When the front knob of a series of shielded concentrically ganged knobs is to be operated, a 1 in. diameter knob is too small for optimal performance scores. However, since concentric ganging necessarily involves the use of knobs of several different diameters, a diameter of 1 inch for the front knob cannot be rejected simply because it is not the optimum.

EXPERIMENT II-A

This experiment investigated the effect of front knob thickness and the diameter difference between the middle and front knob when the middle of three, unshielded, ganged knobs is operated.

TABLE VI

Statistical Analysis for Experiment II-A

Type of Measure	Significance Levels from Analysis of Variance			Significant (two tailed) t Tests Between Adjacent Conditions		
	Front Knob Thickness	Diameter Difference	T x DD Interaction	Diam. Diffs. Compared	At Which Thickness	Sig. Level
Back Knob Errors	NS	.01	NS	None Significant	All Combined	
Front Knob Errors	NS	.001	NS	1/4 & 1/2	All Combined	.01
				1/2 & 3/4	All Combined	.01
Reach Time	NS	.001	NS	1/4 & 1/2	All Combined	.05
				1/2 & 3/4	All Combined	.001
Turning Time	NS	.01	NS	1/4 & 1/2	All Combined	.05
				1/2 & 3/4	All Combined	.01
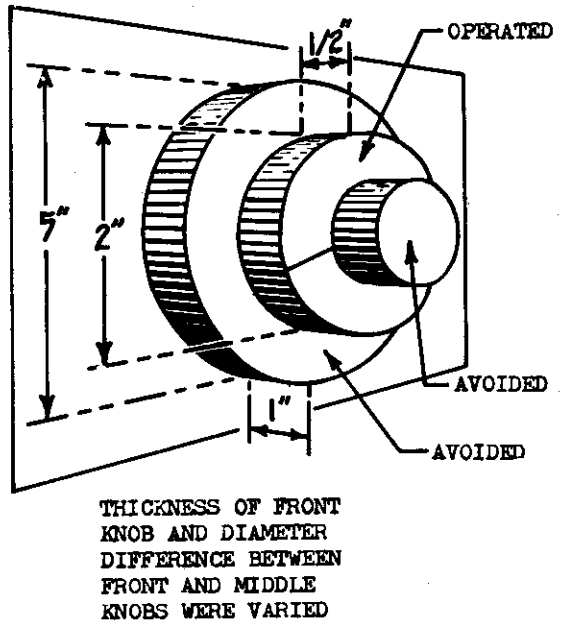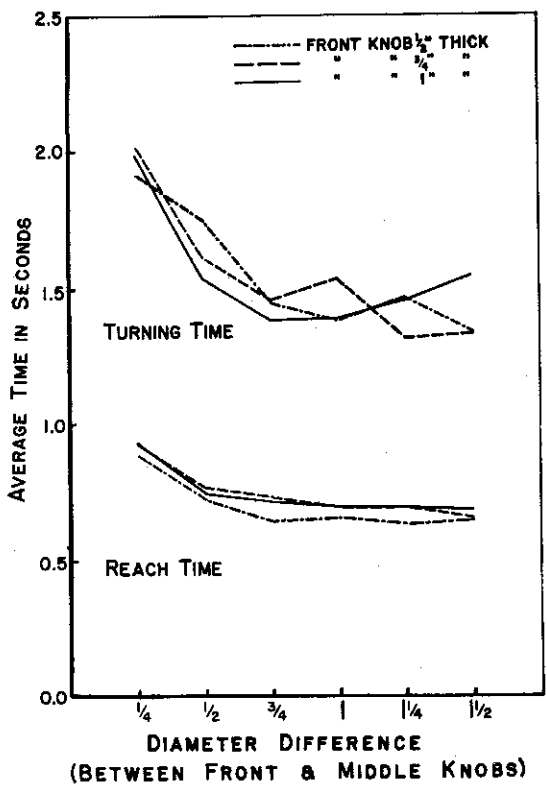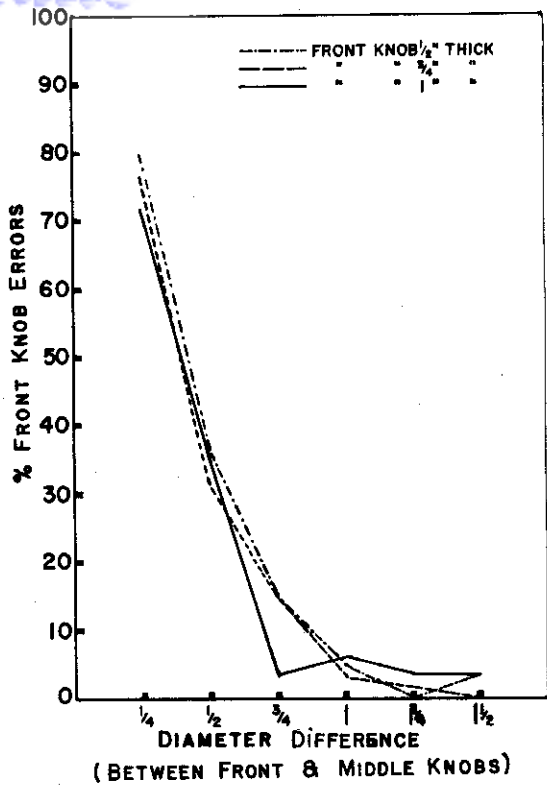
Figure 11: Specific task conditions and results for Experiment II-A.

Conclusions: When the (2 in. diameter, 1/2 in. thick) middle of three unshielded, concentrically ganged knobs is to be operated: (a) performance is independent of the thickness of the front knob (within the range: 1/2 in. to 1 in. front knob thickness), (b) performance in general suffers when a diameter difference of less than 3/4 in. exists between the front and middle knob.

EXPERIMENT II-B

This experiment repeated Experiment II-A except that <u>shielded</u> knobs were simulated and tested.

TABLE VII

Statistical Analysis for Experiment II-B

Type of Measure	Significance Levels from Analysis of Variance			Significant (two tailed) t Tests Between Adjacent Conditions		
	Front Knob Thickness	Diameter Difference	T x DD Interaction	Diam. Diffs. Compared	At Which Thickness	Sig. Level
Front Knob Errors	NS	.001	NS	1/4 & 1/2	All Combined	.01
				1/2 & 3/4	All Combined	.05
				1 & 1 1/4	All Combined	.05
Reach Time	NS	.001	NS	3/4 & 1	All Combined	.05
Turning Time	NS	.01	NS	None Significant	All Combined	
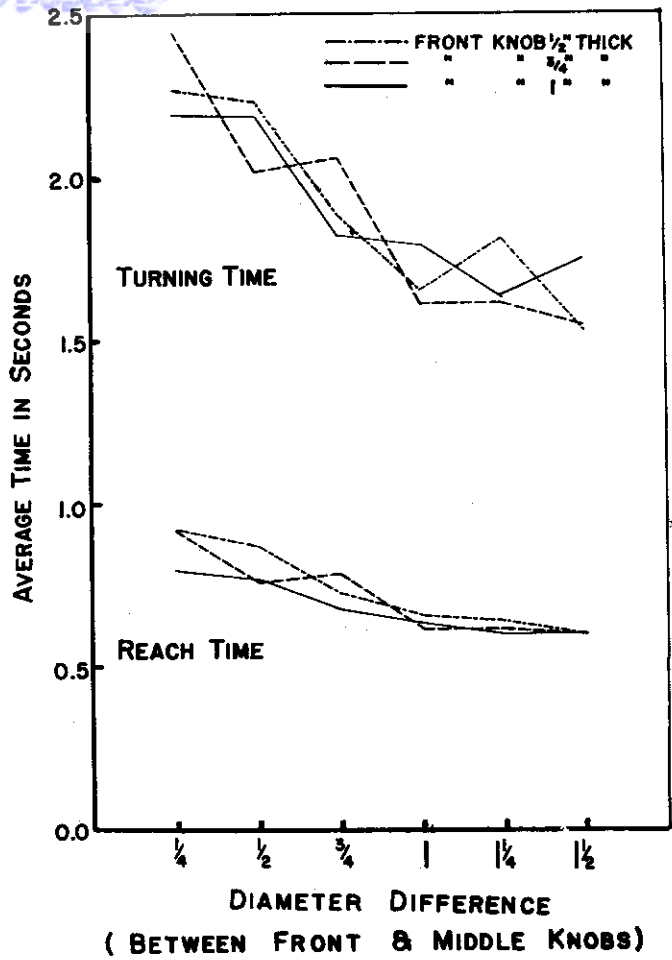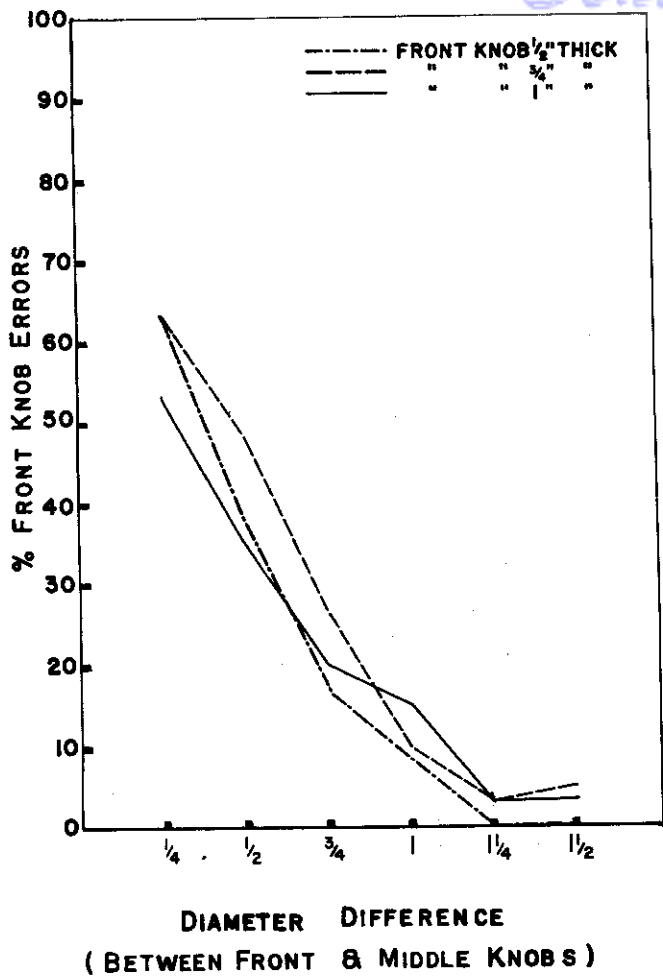
Figure 12: Results for Experiment II-B.
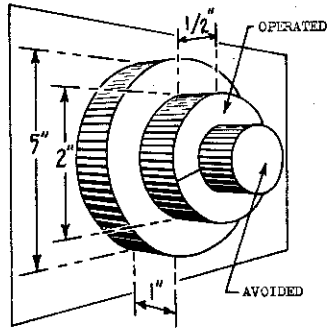
THICKNESS OF FRONT
KNOB AND DIAMETER
DIFFERENCE BETWEEN
FRONT AND MIDDLE
KNOB WERE VARIED

Figure 13: Specific task conditions
for Experiment II-B.

Conclusions: When the (2 in. diameter, 1/2 in. thick) middle of three, shielded concentrically ganged knobs is to be operated: (a) performance is independent of the thickness of the front knob (within the range: 1/2 in. to 1 in. front knob thickness), (b) performance suffers when a difference of diameter of less than 1 1/4 in. exists between the front and middle knob.

This experiment investigated the effect of middle knob thickness, and diameter difference between the middle and front knob, when the middle of three, unshielded, concentrically ganged knobs is operated. One of the "thicknesses" investigated was a 1/2 in. thick knob separated by a 1/2 in. space gap from the face of the knob behind it, so that the distance between middle knob face and back knob face was one inch.

TABLE VIII

Statistical Analysis for Experiment III-A

Significance Levels from Analysis of Variance

Type of Measure	Middle Knob Thickness	Diameter Difference	T x DD Interaction
Back Knob Errors	.001	.05	.05
Front Knob Errors	.001	.001	.001
Reach Time	.001	.001	NS
Turning Time	NS	.001	.05

Significant (two tailed) t Tests Between Adjacent Conditions

Type of Measure	Thicknesses Compared	At Which Diam. Diff.	Sig. Level	Diam. Diffs. Compared	At Which Thickness	Sig. Level
Back Knob Errors	1/2 & 3/4	1/2	.05	None Significant		
	1/2 & 1/2 spaced 1/2	1/2	.01			
	1/2 & 1/2 spaced 1/2	1 1/4	.05			
Front Knob Errors	1/2 & 3/4	1/2	.05	1/2 & 3/4	1/2	.01
	1/2 & 3/4	3/4	.01	1/2 & 3/4	3/4	.001
	1/2 & 3/4	1	.05	1/2 & 3/4	1	.05
	1/2 & 1/2 spaced 1/2	1/2	.001	3/4 & 1	1/2	.05
				1 & 1 1/4	1/2	.001
Reach Time	1/2 & 3/4	All Combined	.01	1/2 & 3/4	All Combined	.001
	1/2 & 1/2 spaced 1/2	All Combined	.001	3/4 & 1	All Combined	.001
Turning Time	Not Tested			1/2 & 3/4	3/4	.01
				1/2 & 3/4	1	.001
				1 & 1 1/4	1/2	.05

The four charts each contain the legend:

MIDDLE KNOB ½" THICK
" " ¾ " "
" " ½ " "
" " ¼ " "
WITH ½ IN. SPACE-GAP

Chart 1 (top left): Y-axis "% BACK KNOB ERRORS" (0 to 25); X-axis "DIAMETER DIFFERENCE (BETWEEN FRONT & MIDDLE KNOBS)" values ½, ¾, 1, 1¼.

Chart 2 (top right): Y-axis "% FRONT KNOB ERRORS" (0 to 100); X-axis "DIAMETER DIFFERENCE (BETWEEN FRONT & MIDDLE KNOBS)" values ½, ¾, 1, 1¼.

Chart 3 (bottom left): Y-axis "AVERAGE TIME IN SECONDS" (0.0 to 2.0); labels "TURNING TIME" and "REACH TIME"; X-axis "DIAMETER DIFFERENCE (BETWEEN FRONT & MIDDLE KNOBS)" values ½, ¾, 1, 1¼.

Chart 4 (bottom right): diagram with labels OPERATED, AVOIDED, AVOIDED; dimensions 5", 2", 1", ½".

MIDDLE KNOB THICKNESS
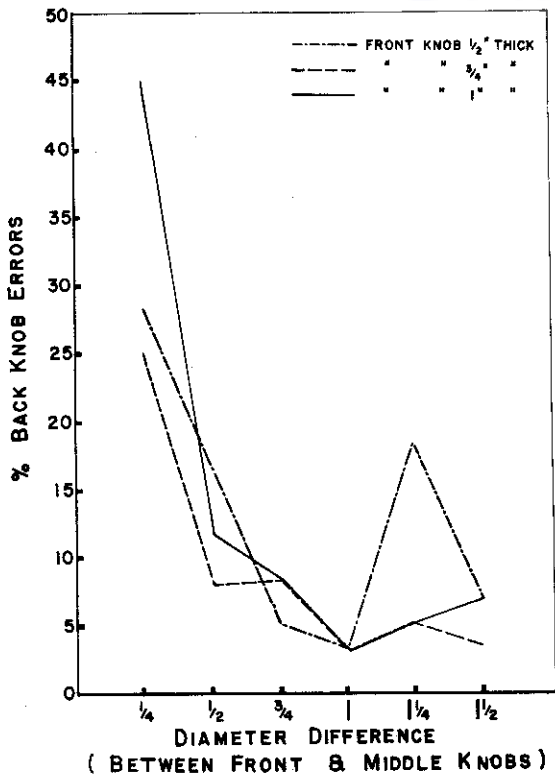AND DIAMETER DIFFERENCE
BETWEEN FRONT AND MIDDLE
KNOBS WERE VARIED

Figure 14: Specific task conditions and results for Experiment III-A.

Conclusions: When the (2 in. diameter) middle of three, unshielded, concentrically ganged knobs is to be operated: (a) performance improves with increasing middle knob thickness up to a thickness of 3/4 in., (b) under certain conditions, spacing between middle and back knobs is equivalent to and interchangeable with middle knob thickness (because performance with the 1/2 in. thick

middle knob separated by a 1/2 in. space gap from the back knob was statistically indistinguishable from performance with a 1 in. thick middle knob with no space gap, but was frequently superior to performance with a 1/2 in. thick middle knob with no space gap), (c) performance improves with increasing diameter difference between front and middle knobs up to a diameter difference of 1 in. for performance in general and up to 1 1/4 in. in certain cases.

EXPERIMENT III-B

This experiment repeated Experiment III-A except that <u>shielded</u> knobs were simulated and tested.

TABLE IX

Statistical Analysis for Experiment III-B

Significance Levels from Analysis of Variance

Type of Measure	Middle Knob Thickness	Diameter Difference	T x DD Interaction
Front Knob Errors	NS	.001	.05
Reach Time	.01	.001	NS
Turning Time	NS	.05	NS

Significant (two tailed) t Tests Between Adjacent Conditions

Type of Measure	Thicknesses Compared	At Which Diam. Diff.	Sig. Level	Diam. Diffs. Compared	At Which Thickness	Sig. Level
Front Knob Errors	Not Tested			1/2 & 3/4	1/2	.05
				1/2 & 3/4	3/4	.001
				1/2 & 3/4	1	.05
				1/2 & 3/4	1/2 spaced 1/2	.001
				3/4 & 1	1/2	.01
				3/4 & 1	3/4	.05
Reach Time	1/2 & 3/4	All Combined	.05	1/2 & 3/4	All Combined	.001
	1/2 & 1/2 spaced 1/2	All Combined	.01			
Turning Time	Not Tested			1/2 & 3/4	All Combined	.05
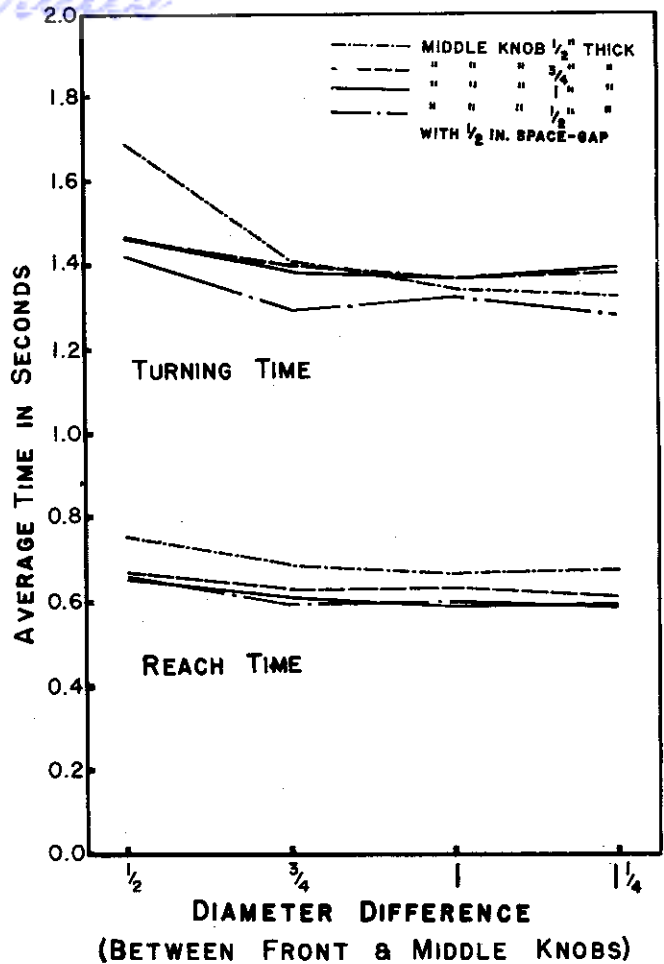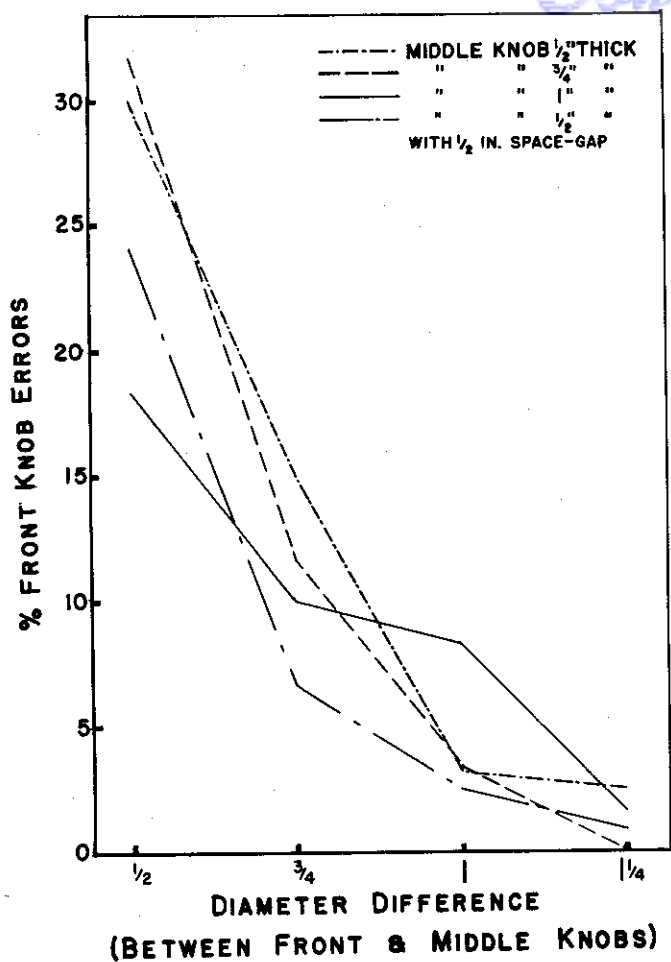
Figure 15: Results for Experiment III-B

Figure 16: Specific task conditions
for Experiment III-B.

Conclusions: When the (2
in. diameter) middle of three,
shielded, concentrically ganged
knobs is to be operated: (a)
under certain conditions spacing
between middle and back knobs is
equivalent to and interchangeable
with middle knob thickness, (b)
performance in general improves
as diameter difference between
front and middle knobs increases
up to 3/4 in. difference in diam-
eter, and in certain cases as
far as 1 in.

WADC TR 55-355

This experiment investigated the effect of back knob thickness and the difference in diameter between the back and middle knobs when the back knob of three concentrically ganged knobs is operated.

Since shielding protects only the knobs <u>behind</u> the operated knob, shielding has no effect when the backmost of a series of knobs is operated as in the present experiment. Results of this experiment are therefore applicable to both shielded and unshielded knobs.

THICKNESS OF OPERATED KNOB AND DIAMETER DIFFERENCE BETWEEN THE OPERATED KNOB AND THE SECOND KNOB WERE VARIED
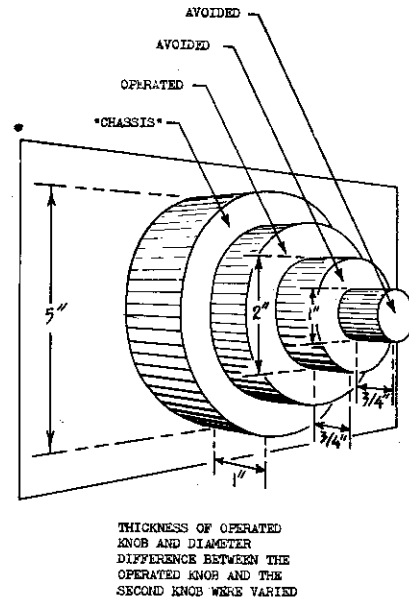
Figure 17: Specific task conditions for Experiment IV.
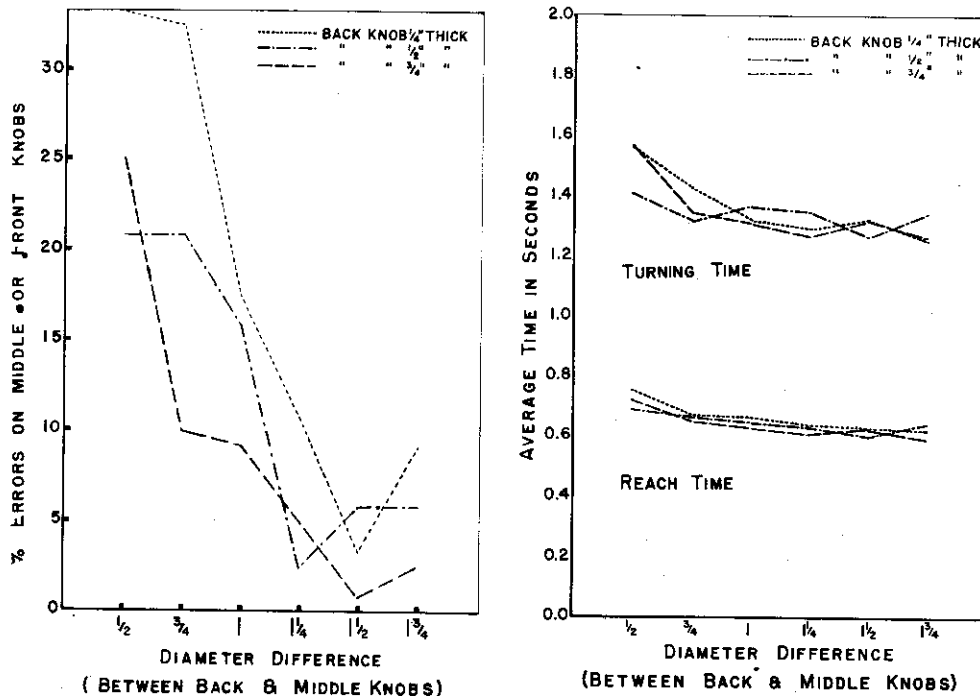
Figure 18: Results for Experiment IV.

TABLE X

Statistical Analysis for Experiment IV

Type of Measure	Operated Knob Thickness	Diameter Difference	T x DD Interaction	Diam. Diffs. Compared	At Which Thickness	Sig. Level
Front Knob Errors	NS	.001	.05	1/2 & 3/4	3/4	.01
				3/4 & 1	1/4	.05
				1 & 1 1/4	1/2	.05
Reach Time	NS	.001	NS	1/2 & 3/4	All Combined	.05
				1 & 1 1/4	All Combined	.05
Turning Time	NS	.01	NS	1/2 & 3/4	All Combined	.05

Conclusions: When the back knob of three concentrically ganged knobs is to be operated, and when the middle knob is 2 in. in diameter: (a) performance improves with increasing differences in diameter between back and middle knob up to a diameter difference of 1 1/4 in., (b) back knob thickness may be as small as 1/4 in. without greatly increasing operation time. The statistical criterion for concluding that errors vary with back knob thickness was almost, but not quite, met. The general appearance of the data suggests that such an effect did exist. Therefore, it is difficult to formulate a concise positive conclusion as to the minimum allowable thickness of the back knob.

EXPERIMENT V

This experiment was designed to determine the effect of "blind reaching" upon performance in the operation of concentrically ganged controls. "Blind" operation of the middle of three, unshielded, ganged knobs, was selected as the task since this represents the most demanding situation to be encountered.

In Experiment III-A, at certain middle knob thicknesses, the task performed was quite similar to that required in the present experiment except that the settings were made with the eyes open. By comparing these two experiments, therefore, the interested reader will obtain a gross indication of the extent to which performance suffers because of the necessity to make settings "blindly".
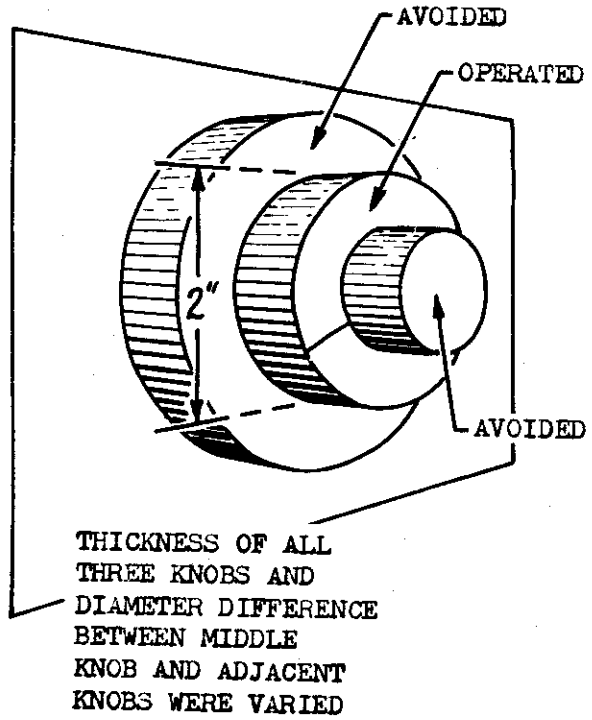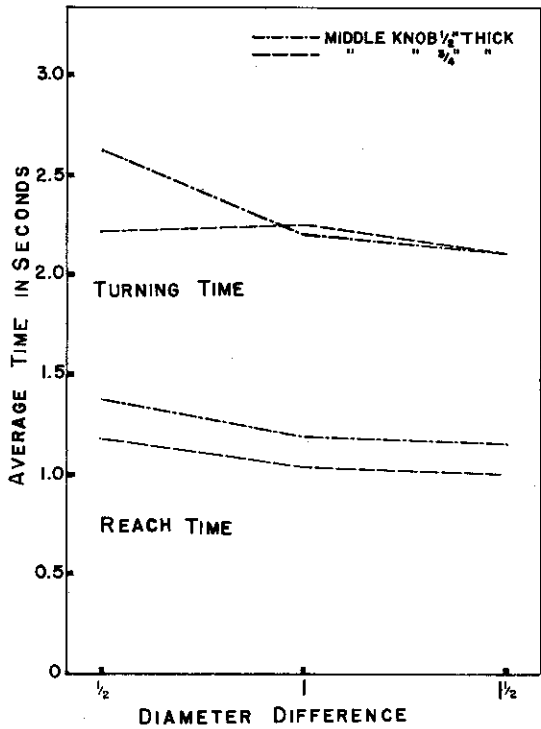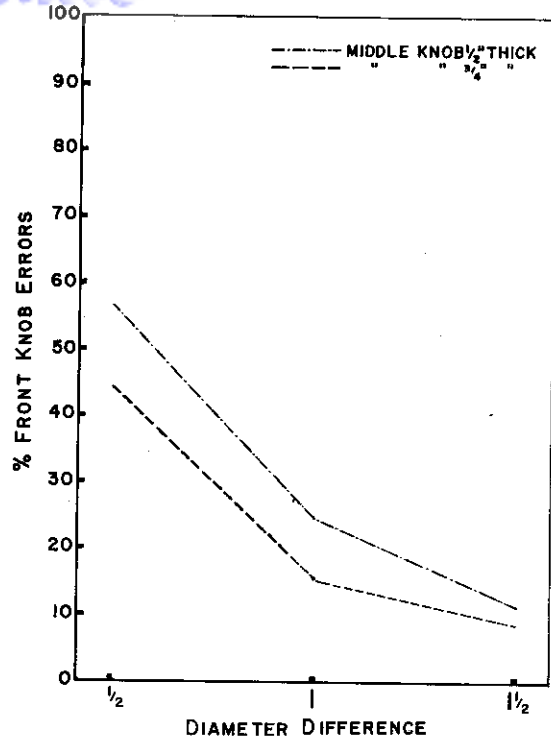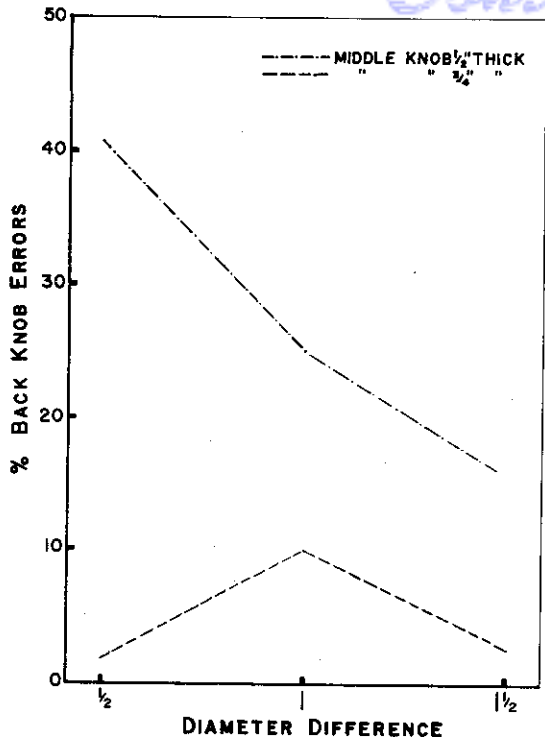
Figure 19: Specific task conditions and results for Experiment V.

TABLE XI

Statistical Analysis for Experiment V

Significance Levels from Analysis of Variance

Type of Measure	Thickness	Diameter Difference	T x DD Interaction
Back Knob Errors	.01	.01	.05
Front Knob Errors	.05	.001	NS
Reach Time	.01	.01	NS
Turning Time	NS	.05	.05

Significant (two tailed) t Tests Between Adjacent Conditions

Type of Measure	Thicknesses Compared	At Which Diameter Diff.	Sig. Level	Diam. Diffs. Compared	At Which Thickness	Sig. Level
Back Knob Errors	1/2 & 3/4	1/2"	.01	1/2 & 1	1/2"	.05
	1/2 & 3/4	1"	.05			
Front Knob Errors	1/2 & 3/4	All Combined	.05	1/2 & 1	All Combined	.001
				1 & 1 1/2	All Combined	.01
Reach Time	1/2 & 3/4	All Combined	.01	1/2 & 1	All Combined	.01
Turning Time	Not Tested			1/2 & 1	1/2"	.01

Conclusions: When the (2 in. diameter) middle of three, unshielded, concentrically ganged knobs is to be operated "blindly": (a) errors can be markedly reduced by using a middle knob thickness of at least 3/4 in., (b) even with a 3/4 in. thick middle knob, a diameter difference at which errors would be negligible would probably be prohibitively large. At "reasonable" knob dimensions (i.e. middle knob 2 in. in diameter, 3/4 in. thick, diameter difference 1 1/4 in.) the number of trials resulting in an error, though appreciable, is fairly low, probably being somewhere around 10 percent.

Of the four measures of performance taken, back knob errors appeared to be sensitive primarily to operated knob thickness. Front knob errors responded most dramatically to diameter differences. Reach time was sensitive to all real effects, although not always so sensitive to diameter differences as were front knob errors. Turning time was virtually insensitive to knob thickness and was generally somewhat inferior to reach time in reflecting changes in the second manipulated variable. Reach time, in a sense, was the best measure of error hazard. The nonoccurrence of an error can in no way reflect the difficulty with which its occurrence was prevented by the operator. A time score, however, can reflect the cost of accurate performance and can do so on every trial. Reach time was particularly well suited to be such an index of error-conduciveness, including as it did, the time necessary to assume a manual, grasping posture which would permit taking hold of the proper knob without touching the adjacent knobs.

A number of logical criteria can be used to arrive at "minimum allowable dimensions". All, however, involve some arbitrary decision as to what degree of performance decrement is intolerable. The authors used a statistical criterion. The largest dimension at which performance was significantly superior to that at the next smaller one was regarded as the minimum dimension allowable. Here, of course, the size of the sample, the level of probability chosen for "significance", and the "distance" between adjacent dimensions tested all imply arbitrary decisions of the type just mentioned. Those who prefer to define minimum dimensions as those resulting in a specified percentage of errors will find Table XIII useful.

Table XII presents minimum dimensions as defined by the statistical criterion. The reader is strongly urged to give due weight to the following considerations in interpreting this summary table of results: (1) Only statistically significant differences between adjacent experimental values of a dimension are reported. Therefore some larger nonadjacent value may be significantly superior to the value entered in the table. (2) Probably because of the small N used, the largest value of a dimension which is significantly superior to the next smaller value is frequently itself appreciably smaller than the value at which the "curve" for the dimension levels off. (3) The value entered in the table is sometimes the largest value tested in the experiment. This is particularly true of the "blind operation" experiment. In such cases, much larger values might have qualified for entry into the table had only they been tested. (4) Statistical significance is based upon the .05 level of significance for a two tailed t-test for matched pairs. This is by far the safest procedure when the possibility of a nonnormal distribution exists.

Referring now to the summary table of results, the thickness data are fairly clear cut. Whether shielded or not, the front and second ganged knobs (of a series of either two or three ganged knobs) should be 3/4 in. thick for good performance. The third knob may be as thin as 1/4 in. if it is the last knob and if its diameter is in the neighborhood of 3 in. Under certain conditions the space between a knob and the knob behind it may have the same effect as knob thickness.

TABLE XII

SUMMARY TABLE OF RESULTS

Largest Value of Each Knob Dimension at Which Performance Was Significantly Superior to That at the Next Smaller Value. (Based upon Two Tailed t Tests for Matched Pairs.)

Dimension (& Experiment in Which Tested)	Unshielded Knobs				Shielded Knobs		
	Back Knob Errors	Front Knob Errors	Reach Time	Turning Time	Front Knob Errors	Reach Time	Turning Time
Front Knob Thickness (Exp. I)	S		3/4	1/2*		3/4	NS
Front Knob Thickness (When middle knob is operated) (Exp. II)	NS	NS	NS	NS	NS	NS	NS
Middle Knob Thickness (Exp. III)	3/4*	3/4*	3/4	NS	NS	3/4	NS
Middle Knob Thickness ("Blind" Operation) (Exp. V)	3/4*	3/4	3/4	NS			
Back Knob Thickness (Diameter Range: 2 1/4" to 3 3/4") (Exp. IV)	NS	NS	NS	NS	NS	NS	NS
Diameter Difference between Front and (1/2" thick, 2" diameter) Middle Knob (Exp. II)	S	3/4	3/4	3/4	1 1/4	1	S
Diameter Difference between (1/2" thick) Front and (2" diameter) Middle Knob (Exp. III)	S	1 1/4*	1	1 1/4*	1*	3/4	3/4
Diameter Difference between Back and (3/4" thick, 2" diameter) Middle Knob (Exp. IV)		1 1/4*	1 1/4	3/4	1 1/4*	1 1/4	3/4
Diameter Difference for "blind" operation of a 2" diameter Middle Knob (Exp. V)	1*	1 1/2	1	1*			
Front Knob Diameter (Exp. I)	NS		2	2*		2	2

NS – As determined by analysis of variance, the dimension is not a significant one.

S – Analysis of variance indicated that the dimension is a significant one, but no significant t's were found between adjacent conditions.

* – Table entry is valid only under certain conditions of the other manipulated variable.

Solid Underline – The table entry is the largest value of the dimension which was tested.

Since the evidence so clearly indicates that a 3/4 in. thick middle knob should be used, only the data on diameter difference for a middle knob 3/4 in. thick or more (or data for all middle knob thicknesses combined, when there is no significant diameter difference by thickness interaction) will be discussed. Diameter difference data, then, indicate that for good performance the diameter difference between a 2 in. diameter, 3/4 in. thick middle knob and the front knob should be at least 1 in. The diameter difference between the same middle knob and the back knob should be at least 1 1/4 in. (and probably should not be greater than 1 1/2 in. - See variation of front knob errors with increasing operated knob diameter in the Pilot Study.). At smaller diameter differences than these, performance will suffer whether shielded or unshielded knobs are used.

Data on knob diameter suggest that the optimum knob diameter is somewhere in the neighborhood of 2 or 3 inches, that both speed and accuracy suffer at a diameter of 4 in. and that speed is reduced at a 1 in. diameter. A front knob diameter as small as 1 in., then, can be used without increase in errors but at an additional cost in operation time.

In general, the minimum allowable dimensions for shielded knobs have been no smaller than those for unshielded knobs, It would appear, therefore, that while shielding is of definite advantage in eliminating back knob errors and in providing a stationary surface upon which to print graduation marks, numbers and labels, it contributes very little, if at all, to the saving of panel space when the statistical criterion for minimum allowable dimension is used.

THICKNESS CAN BE AS
SMALL AS 1/4" IF
DIAMETER IS ABOUT 3"
AND IF THIS IS THE
BACKMOST KNOB

DISTANCE BETWEEN KNOB
FACES SHOULD BE NO
LESS THAN 3/4"

SHOULD BE NO LESS
THAN 1/2"

SHOULD BE NO LESS
THAN 5/8"
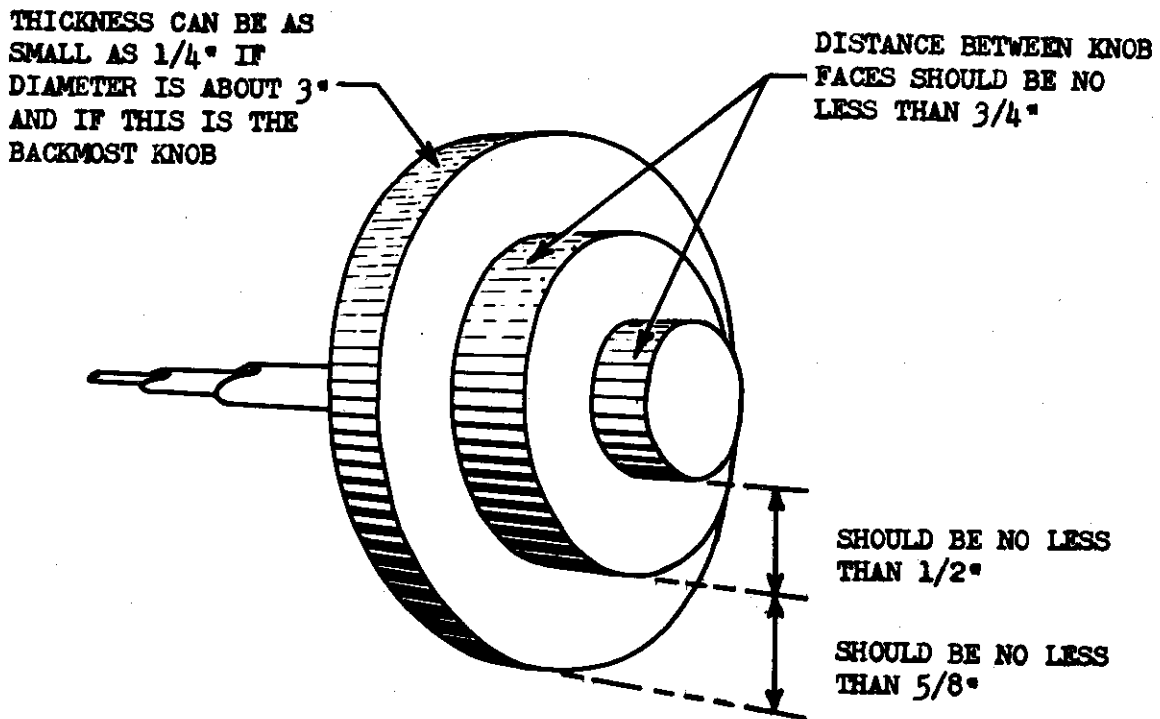
Figure 20: Minimum allowable dimensions for either shielded or unshielded knobs when (a) knobs can be operated by application of moderate torque, (b) frequent inadvertent operation of adjacent controls cannot be tolerated, (c) diameter of the middle knob is between 1 1/2 and 2 1/2 inches.

TABLE XIII

Frequency of Inadvertent Touching of Adjacent Knobs When the Front, Middle or
Back Knob of Three Concentrically Mounted Knobs is Operated

Number of Times in 100 Knob Operations that an Adjacent
Knob Could Have Been Thrown Off Its Proper Setting (i.e.
Sum of Percentages for Back and Front Knob Errors)

Operated Knob	Diameter Difference Between Operated Knob and Knob In Front of It	Unshielded Knobs Operated Knob Thickness				Shielded Knobs Operated Knob Thickness			
		1/4	1/2	3/4	1	1/4	1/2	3/4	1
Front	---	4.1	.9*	(.9)	0	-	(-)*	-	-
Middle	1/2		78.3	40.0	26.7		30.0	31.7	18.3
	3/4		35.8	8.3*	8.3		15.0	11.7*	10.0
	1		17.5	5.8	5.8		3.3	3.3	8.3
	1 1/4		10.8	4.2	(0)		(2.5)	0	1.7
Back	1/2	33.3	20.8	25.0		33.3	20.8	25.0	
	3/4	32.5	20.8	10.0*		32.5	20.8	10.0*	
	1	17.5	15.8	9.2		17.5	15.8	9.2	
	1 1/4	10.8	2.5	5.0		10.8	2.5	5.0	
	1 1/2	3.3	5.8	(.8)		3.3	5.8	(.8)	
	1 3/4	9.2	5.8	2.5		9.2	5.8	2.5	

Criterion for Minimum Allowable Dimension

Minimum Allowable Dimensions Correspond
To Table Entries Which Are:

Statistical	Underlined
An adjacent knob inadvertently touched about once in 100 operations. (Three knobs operated with equal frequencies)	Bracketed
An adjacent knob inadvertently touched less than 10 times in 100 knob operations. (Three knobs operated with equal frequencies)	Starred

The 1/4 in. thickness is not recommended for the front knob since operation time was much longer at 1/4 in. than at the 1/2 in. thickness.

The large diameter differences which are necessary to prevent front knob errors strongly suggest that (when the avoidance of inadvertent operation of adjacent, nondetent, concentrically mounted controls is a critical consideration), panel space will seldom be saved by mounting knobs on concentric shafts. Table XIV permits a comparison of the amount of panel area consumed by concentrically ganged knobs versus that consumed by the same number of nonganged knobs. It will be seen that if a 1 in. diameter difference be used (the smallest diameter difference that would be used if errors were an important consideration) concentrically ganged controls, with one trivial exception, actually require more panel space than the same number of 1/2 in. diameter isolated knobs.

TABLE XIV

Panel Area (Times $64/\pi$) Required for a Given Number of Knobs When They Are Concentrically Ganged Versus That Required When They are Completely Isolated from Each Other (Diameter of Front Ganged Knob: 1/2 Inch)

No. of Knobs	"Clear Space" Margin To Be Left Around Knobs for Finger Clearance	Diameter Difference Between Ganged Knobs				Diameter of Isolated Knobs		
		1/2	3/4	1	1 1/4	1/2	3/4	1
2	None	16	25	36	49	8	18	32
2	1/2"	64	81	100	121	72	98	128
2	3/4"	100	121	144	169	128	162	200
2	1"	144	169	196	225	200	242	288
3	None	36	64	100	144	12	27	48
3	1/2"	100	144	196	256	108	147	192
3	3/4"	144	196	256	324	192	243	300
3	1"	196	256	324	400	300	363	432

The comparison becomes more unfavorable to the concentrically ganged knobs with greater front knob diameter, greater diameter difference, and with larger numbers of knobs to be ganged. Even with large margins for finger clearance (around the backmost ganged knob and around all of the isolated knobs with which
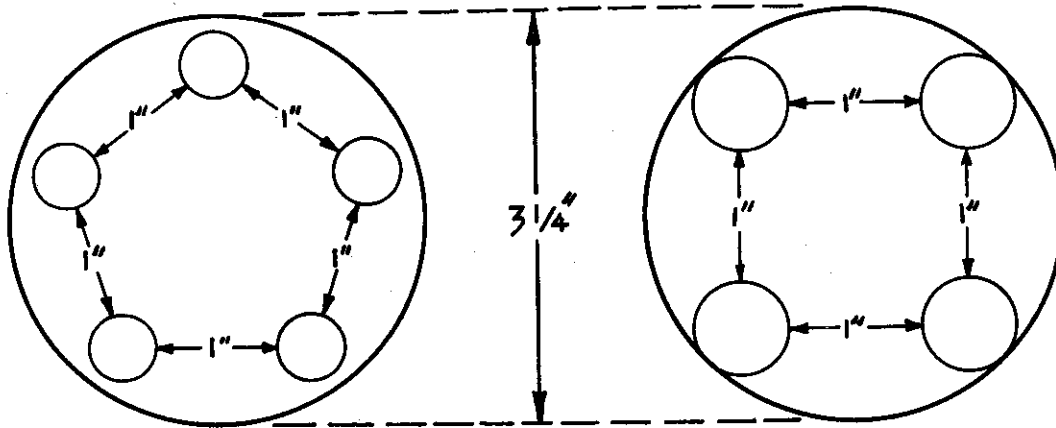
Example 1: Five 1/2 in. diameter
knobs can be placed, 1 in. apart, in
the same panel space as is consumed
by three concentrically ganged knobs
of minimum allowable diameter diff-
erence. (Front ganged knob 1 in. in
diameter)

Example 2: Four 3/4 in. diameter
knobs can be placed in area shown in
Example 1.
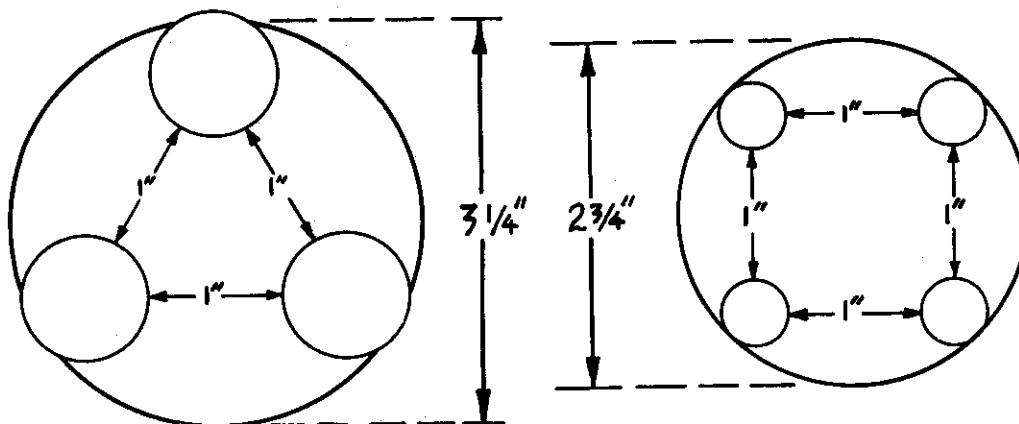
Example 3: Nearly three 1 in. di-
ameter knobs can be placed in area
shown in Example 1.

Example 4: Four 1/2 in. diameter
knobs can be placed, 1 in. apart,
in the same panel space as is con-
sumed by three concentrically gang-
ed knobs of the minimum allowable
diameter difference. (Front ganged
knob 1/2 in. in diameter)

Figure 21: Number of separated knobs of various diameters which can be placed
1 in. apart in the same panel area as is required for three concentrically
ganged knobs. Example 4 is a limiting case. The combination of diameters
shown for the concentrically ganged knobs was not specifically investigated.
It is probably the smallest set of concentrically ganged knobs whose use is
implicitly acceptable on the basis of these experiments.

the comparison is made) no _appreciable_ amount of panel space is saved by concentrically ganging two knobs _unless_ the isolated knobs with which the comparison is made are of large diameter. The table used completely isolated knobs as the comparison. If the nonconcentrically ganged knobs, however, are arranged in a matrix so that the same "margin" can serve for adjacent knobs, the comparison becomes still _more_ unfavorable to the concentrically ganged knobs. (Fig. 21) The allowable spacing of separated knobs arranged in matrices has been investigated under very nearly the same task conditions, measurements, etc., as in the present series of experiments (2). The results of this research indicate that, generally speaking, three small diameter knobs arranged in a matrix result in considerably fewer errors than do three concentrically ganged knobs consuming the same amount of panel space. The data comparisons leading to this conclusion are extensive and complicated and do not lend themselves to concise presentation. The interested reader, therefore, is invited to consult the original data included in both this report and that concerning knob crowding for substantiation of the contention that "crowding" small diameter knobs is a more efficient means of economizing on panel space than is mounting a series of knobs on concentric shafts.

It should be emphasized that the foregoing reasoning is specific to the following conditions: (a) the knobs in question are continuous rotation (i.e. low friction) knobs, (b) frequent inadvertent operation of adjacent coaxial knobs cannot be tolerated, (c) the primary purpose of mounting the knobs on concentric shafts is to save panel space. Where these conditions obtain, it would usually be undesirable concentrically to gang more than two knobs and would frequently be undesirable even for two.

Concentrically ganged controls _may_ still be desirable, however, under the following conditions: (a) when the knob operations involved are sequentially or functionally related, particularly when it is necessary or desirable to proceed from one knob to another without visual reference, (b) when neither inadvertent operation of adjacent knobs nor small delays are critical (e.g. If one knob of a television set controls "focus", the other "volume", the operator will receive immediate visual or auditory feedback of inadvertent operation of an adjacent control which he can then correct with negligible delay.) Here small differences in diameter can be used, and panel space can therefore be saved. (c) when large diameter knobs _must_ be used whether the knobs are ganged or isolated, (d) when it is necessary to save space _behind_ the panel, (e) when detent knobs are to be used, or when certain combinations of detent and continuous rotation knobs are to be used. Detent knobs necessarily consume considerable panel area since a large lever arm is necessary to exert the required torque. A very slightly larger continuous-rotation knob could be placed behind the detent knob at a very small additional cost of panel space. "Front knob errors", when the continuous rotation knob is operated, would be irrelevant since a detent knob cannot be thrown off its setting by a mere touch. Back knob errors, when the detent is operated, could be eliminated by shielding, or could be reduced by increasing the thickness of the detent or by spacing it farther in front of the continuous rotation knob. Panel space would have been saved. Finally, subjects in these experiments were instructed to work for _both_ speed and accuracy. Where speed is not a consideration, accuracy may increase accordingly and smaller diameter differences may be tolerable, at the expense, however, of additional "strain" upon the conscientious operator in making an accurate setting.

BIBLIOGRAPHY

1. Bradley, J. V. *Control-display association preferences for ganged controls*. WADC Technical Report 54-379, August 1954.

2. Bradley, J. V. & Stump, N. E. *Minimum allowable knob crowding*. WADC Technical Report 55-455, December 1955.

3. Lindquist, E. F. *Design and Analysis of Experiments in Psychology and Education*. New York: Houghton Mifflin Co., 1953, 237-238 and 301.

4. Wilcoxon, F. *Some Rapid Approximate Statistical Procedures*. American Cyanamid Co., 1949, 5-6 and 13.

APPENDIX

NUMBER AND PERCENT OF ERRORS AND AVERAGED REACH AND
TURNING TIME SCORES FOR EACH OF THE SEPARATE EXPERIMENTS

TABLE XV

NUMBER AND PERCENT ERRORS AND AVERAGED TIME SCORES FOR PILOT STUDY

Diameter Difference Between Knobs

Measure	Thickness of all 3 Knobs	1/4 Middle Knob Diameter 1	2	3	4	1/2 Middle Knob Diameter 1	2	3	4	3/4 Middle Knob Diameter 1	2	3	4	1 Middle Knob Diameter 1	2	3	4
Back Knob Errors	1/4	23	19	21	27	21	21	21	16	15	11	19	16	3	9	10	19
	1/2	6	18	15	20	13	7	8	10	4	8	9	2	10	0	7	5
	3/4	3	3	0	6	8	0	3	2	3	1	1	4	0	5	3	1
	1	5	4	3	2	4	1	2	4	0	6	0	5	2	0	2	2
Percent Back Knob Errors	1/4	93.3	63.3	70.0	90.0	70.0	70.0	70.0	53.3	50.0	36.7	63.3	53.3	10.0	30.0	33.3	63.3
	1/2	20.0	60.0	50.0	66.7	43.3	23.3	26.7	33.3	13.3	26.7	30.0	6.7	33.3	0	23.3	16.7
	3/4	10.0	10.0	0	20.0	26.7	0	10.0	6.7	10.0	3.3	3.3	13.3	0	16.7	10.0	3.3
	1	16.7	13.3	10.0	6.7	13.3	3.3	6.7	13.3	0	20.0	0	16.7	6.7	0	6.7	6.7
Front Knob Errors	1/4	30	28	30	30	27	24	25	19	4	10	8	17	—	3	7	11
	1/2	25	29	25	21	13	14	16	26	5	8	4	19	—	1	5	7
	3/4	12	19	13	22	10	12	11	20	0	2	8	23	—	1	6	8
	1	17	15	16	20	6	13	11	14	7	4	14	11	—	2	13	15
Percent Front Knob Errors	1/4	100.0	93.3	100.0	100.0	90.0	80.0	83.3	63.3	13.3	33.3	26.7	56.7	—	10.0	23.3	36.7
	1/2	83.3	96.7	83.3	70.0	43.3	46.7	53.3	86.7	16.7	26.7	13.3	63.3	—	3.3	16.7	23.3
	3/4	40.0	63.3	43.3	73.3	33.3	40.0	36.7	66.7	0	6.7	26.7	76.7	—	3.3	20.0	26.7
	1	56.7	50.0	53.3	66.7	20.0	43.3	36.7	46.7	23.3	13.3	46.7	36.7	—	6.7	43.3	50.0
Average Reach Time	1/4	.771	.978	.999	1.179	.823	.600	.964	1.053	1.113	.797	.651	.905	.962	.892	.768	.572
	1/2	.779	.606	.847	.949	.638	.701	.834	.823	.887	.714	.675	.617	.738	.736	.600	.678
	3/4	.832	.941	.712	.639	.869	.711	.564	.712	.567	.521	.733	.891	.622	.552	.772	.741
	1	.780	.712	.578	.758	.769	.715	.758	.592	.671	.489	.736	.643	.505	.673	.688	.769
Average Turning Time	1/4	1.52	2.12	2.21	2.57	2.25	1.36	2.24	1.80	2.51	1.61	1.37	1.42	2.08	1.80	1.60	1.35
	1/2	1.77	1.80	1.57	2.50	1.49	1.69	1.83	1.70	1.85	1.43	1.32	1.58	2.27	1.70	1.36	1.16
	3/4	1.84	1.89	1.46	1.68	1.96	1.71	1.40	1.46	1.32	1.30	1.54	2.31	1.71	1.15	1.74	1.68
	1	1.92	2.05	1.39	1.84	2.07	1.48	1.65	1.42	1.53	1.10	1.58	2.19	1.25	1.40	2.02	1.77

TABLE XVI

NUMBER AND PERCENT ERRORS AND AVERAGED TIME SCORES FOR EXPERIMENTS I-A and I-B

Measure	Front Knob Diameter	EXPERIMENT I-A Front Knob Thickness					EXPERIMENT I-B Front Knob Thickness				
		1/4	1/2	3/4	1	All	1/4	1/2	3/4	1	All
Total Number of Errors	1	3	0	1	0	4					
	2	2	2	0	0	4					
	3	2	1	1	0	4	No Data Taken				
	4	6	0	1	0	7					
	All	13	3	3	0	19					
Percent Errors	1	3.75	0	1.25	0	1.25					
	2	2.50	2.50	0	0	1.25					
	3	2.50	1.25	1.25	0	1.25	No Data Taken				
	4	7.50	0	1.25	0	2.19					
	All	4.06	.94	.94	0	1.49					
Average Reach Time	1	.8531	.6605	.6153	.5459	.6687	.5556	.5470	.4943	.4820	.5197
	2	.8055	.6224	.5426	.5289	.6249	.4888	.5100	.4389	.4564	.4735
	3	.7731	.6170	.5228	.5096	.6056	.4736	.4901	.4670	.4205	.4628
	4	.7608	.6155	.5510	.5276	.6137	.4534	.4989	.4268	.4384	.4544
	All	.7981	.6289	.5579	.5280	.6282	.4929	.5115	.4568	.4493	.4776
Average Turning Time	1	1.845	1.387	1.337	1.366	1.484	1.494	1.460	1.510	1.418	1.470
	2	1.346	1.279	1.212	1.186	1.256	1.291	1.148	1.278	1.208	1.231
	3	1.392	1.191	1.190	1.083	1.214	1.199	1.298	1.156	1.050	1.176
	4	1.433	1.327	1.297	1.179	1.309	1.338	1.363	1.320	1.266	1.322
	All	1.504	1.296	1.259	1.204	1.316	1.330	1.317	1.316	1.236	1.300

TABLE XVII

NUMBER AND PERCENT ERRORS AND AVERAGED TIME SCORES FOR EXPERIMENTS II-A AND II-B

Measure	Diameter Difference Between Front and Middle Knobs	EXPERIMENT II-A Front Knob Thickness 1/2	3/4	1	All	EXPERIMENT II-B Front Knob Thickness 1/2	3/4	1	All
Back Knob Errors	1/4	17	15	27	59				
	1/2	10	5	7	22				
	3/4	3	5	5	13		No Data Taken		
	1	2	2	2	6				
	1 1/4	11	3	3	17				
	1 1/2	4	2	4	10				
	All	47	32	48	127				
Percent Back Knob Errors	1/4	28.33	25.00	45.00	32.78				
	1/2	16.67	8.33	11.67	12.22				
	3/4	5.00	8.33	8.33	7.22		No Data Taken		
	1	3.33	3.33	3.33	3.33				
	1 1/4	18.33	5.00	5.00	9.44				
	1 1/2	6.67	3.33	6.67	5.56				
	All	13.06	8.89	13.33	11.76				
Front Knob Errors	1/4	48	46	43	137	38	38	32	108
	1/2	22	19	21	62	23	29	21	73
	3/4	9	9	2	20	10	16	12	38
	1	3	2	4	9	5	6	9	20
	1 1/4	0	1	2	3	0	2	2	4
	1 1/2	2	0	2	4	0	3	2	5
	All	84	77	74	235	76	94	78	248
Percent Front Knob Errors	1/4	80.00	76.67	71.67	76.11	63.33	63.33	53.33	60.00
	1/2	36.67	31.67	35.00	34.44	38.33	48.33	35.00	40.56
	3/4	15.00	15.00	3.33	11.11	16.67	26.67	20.00	21.11
	1	5.00	3.33	6.67	5.00	8.33	10.00	15.00	11.11
	1 1/4	0	1.67	3.33	1.67	0	3.33	3.33	2.22
	1 1/2	3.33	0	3.33	2.22	0	5.00	3.33	2.78
	All	23.33	21.39	20.56	21.76	21.11	26.11	21.67	22.96
Average Reach Time	1/4	.8933	.9353	.9388	.9225	.9197	.9195	.8018	.8803
	1/2	.7257	.7690	.7538	.7495	.8753	.7630	.7733	.8039
	3/4	.6507	.7363	.7213	.7028	.7277	.7820	.6862	.7320
	1	.6620	.6995	.6965	.6860	.6617	.6193	.6275	.6362
	1 1/4	.6358	.6957	.6897	.6737	.6397	.6178	.6077	.6217
	1 1/2	.6445	.6610	.6892	.6649	.6042	.5995	.6035	.6024
	All	.7020	.7495	.7482	.7332	.7380	.7168	.6833	.7128
Average Turning Time	1/4	1.923	2.025	1.985	1.977	2.275	2.452	2.199	2.309
	1/2	1.750	1.629	1.543	1.641	2.244	2.023	2.196	2.154
	3/4	1.454	1.462	1.384	1.434	1.889	2.061	1.829	1.926
	1	1.381	1.539	1.387	1.435	1.658	1.622	1.803	1.694
	1 1/4	1.471	1.321	1.451	1.414	1.801	1.622	1.637	1.687
	1 1/2	1.344	1.338	1.538	1.407	1.525	1.548	1.751	1.608
	All	1.554	1.552	1.548	1.551	1.899	1.888	1.903	1.896

TABLE XVIII

NUMBER AND PERCENT ERRORS AND AVERAGED TIME SCORES FOR EXPERIMENTS III-A AND III-B

Measure	Diameter Difference Between Front and Middle Knobs	EXPERIMENT III-A Middle Knob Thickness 1/2	3/4	1	1/2 with 1/" gap	All	EXPERIMENT III-B Middle Knob Thickness 1/2	3/4	1	1/2 with 1/2" gap	All
Back Knob Errors	1/2	30	9	6	2	47					
	3/4	15	4	0	3	22					
	1	10	3	2	2	17	No Data Taken				
	1 1/4	13	3	0	0	16					
	All	68	19	8	7	102					
Percent Back Knob Errors	1/2	25.00	7.50	5.00	1.67	9.79					
	3/4	12.50	3.33	0	2.50	4.58					
	1	8.33	2.50	1.67	1.67	3.54	No Data Taken				
	1 1/4	10.83	2.50	0	0	3.33					
	All	14.17	3.96	1.67	1.46	5.31					
Front Knob Errors	1/2	64	39	26	22	151	36	38	22	29	125
	3/4	28	6	10	17	61	18	14	12	8	52
	1	11	4	5	8	28	4	4	10	3	21
	1 1/4	0	2	0	0	2	3	0	2	1	6
	All	103	51	41	47	242	61	56	46	41	204
Percent Front Knob Errors	1/2	53.33	32.50	21.67	18.33	31.46	30.00	31.67	18.33	24.17	26.04
	3/4	23.33	5.00	8.33	14.17	12.71	15.00	11.67	10.00	6.67	10.83
	1	9.17	3.33	4.17	6.67	5.83	3.33	3.33	8.33	2.50	4.37
	1 1/4	0	1.67	0	0	.42	2.50	0	1.67	.83	1.25
	All	21.46	10.62	8.54	9.79	12.60	12.71	11.67	9.58	8.54	10.62
Average Reach Time	1/2	.7342	.6712	.6239	.6388	.6670	.7558	.6706	.6582	.6618	.6866
	3/4	.7039	.6222	.5737	.5800	.6200	.6860	.6243	.6148	.5938	.6297
	1	.6476	.5858	.5501	.5511	.5836	.6632	.6336	.5882	.5980	.6208
	1 1/14	.6398	.5740	.5550	.5504	.5798	.6757	.6140	.5915	.5889	.6175
	All	.6814	.6133	.5757	.5801	.6126	.6952	.6356	.6132	.6106	.6386
Average Turning Time	1/2	1.498	1.445	1.352	1.296	1.398	1.693	1.465	1.472	1.424	1.514
	3/4	1.443	1.206	1.198	1.287	1.283	1.417	1.403	1.388	1.300	1.377
	1	1.363	1.147	1.230	1.258	1.249	1.346	1.372	1.371	1.327	1.354
	1 1/4	1.242	1.221	1.199	1.208	1.218	1.328	1.382	1.398	1.281	1.347
	All	1.387	1.255	1.245	1.262	1.287	1.446	1.405	1.407	1.333	1.398

TABLE XIX

NUMBER AND PERCENT ERRORS AND AVERAGED TIME SCORES FOR EXPERIMENT IV

Measure	Diameter Difference Between Back and Middle Knobs	Back Knob Thickness			
		1/4	1/2	3/4	All
Errors	1/2	40	25	30	95
	3/4	39	25	12	76
	1	21	19	11	51
	1 1/4	13	3	6	22
	1 1/2	4	7	1	12
	1 3/4	11	7	3	21
	All	128	86	63	277
Percent Errors	1/2	33.33	20.83	25.00	26.39
	3/4	32.50	20.83	10.00	21.11
	1	17.50	15.83	9.17	14.17
	1 1/4	10.83	2.50	5.00	6.11
	1 1/2	3.33	5.83	.83	3.33
	1 3/4	9.17	5.83	2.50	5.83
	All	17.78	11.94	8.75	12.82
Average Reach Time	1/2	.7524	.6933	.7230	.7229
	3/4	.6776	.6669	.6581	.6675
	1	.6667	.6494	.6326	.6496
	1 1/4	.6400	.6289	.6108	.6266
	1 1/2	.6339	.6014	.6335	.6229
	1 3/4	.6230	.6442	.5981	.6218
	All	.6656	.6474	.6427	.6519
Average Turning Time	1/2	1.560	1.417	1.575	1.517
	3/4	1.435	1.322	1.355	1.371
	1	1.325	1.378	1.320	1.341
	1 1/4	1.298	1.352	1.272	1.307
	1 1/2	1.326	1.272	1.329	1.309
	1 3/4	1.259	1.349	1.268	1.292
	All	1.367	1.348	1.353	1.356

TABLE XX

NUMBER AND PERCENT ERRORS AND AVERAGED TIME SCORES FOR EXPERIMENT V

Measure	Diameter Difference Between Middle and Front and Back Knobs	Thickness of All Three Knobs		
		1/2	3/4	All
Back Knob Errors	1/2	49	2	51
	1	30	12	42
	1 1/2	19	3	22
	All	98	17	115
Percent Back Knob Errors	1/2	40.83	1.67	21.25
	1	25.00	10.00	17.50
	1 1/2	15.83	2.50	9.17
	All	27.22	4.72	15.97
Front Knob Errors	1/2	68	53	121
	1	30	19	49
	1 1/2	14	10	24
	All	112	82	194
Percent Front Knob Errors	1/2	56.67	44.17	50.42
	1	25.00	15.83	20.42
	1 1/2	11.67	8.33	10.00
	All	31.11	22.78	26.95
Average Reach Time	1/2	1.365	1.165	1.265
	1	1.199	1.045	1.122
	1 1/2	1.160	1.000	1.080
	All	1.241	1.070	1.156
Average Turning Time	1/2	2.601	2.221	2.411
	1	2.196	2.256	2.226
	1 1/2	2.121	2.108	2.114
	All	2.306	2.195	2.251