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SPACING OF ON-OFF CONTROLS. I: PUSH BUTTONS

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FOREWORD

This report was prepared by the Psychology Branch of the Aero Medical Laboratory, Directorate of Laboratories under Research and Development Task No. 7182-71514, "Control Design and Arrangement", with James V. Bradley acting as Task Scientist.

Subjects were run and data computations were performed by Ronald A. Wallis at Antioch College under Contract No. AF 33(616)-3404 under the technical supervision of Dr. Jerome Cohen. Contributions of outstanding quality were made by Mrs. Ann Dimmock, to whose artistic talents all figures and illustrations are due, and by Mr. James Campbell whose ingenuity and craftsmanship are responsible for all new elements of apparatus. The authors are also indebted to Dr. W. Dean Chiles for a detailed, critical review of the next to final draft, which improved the final form of the report.

ABSTRACT

Thirty-six right handed male college students performed a standardized control operation in which the center one of three closely spaced push buttons was reached to and operated while avoiding contact with the adjacent controls. Manipulated variables were: diameter of all three controls, orientation of the linear array of controls, and spacing between edges of the controls. Reach-and-operation time, inadvertent touching of adjacent controls, and inadvertent operation of adjacent controls were recorded. It was concluded that efficiency of operation and economy of panel space are best combined when push buttons no larger than 1/2 inch in diameter are arranged in a horizontal (rather than a vertical) array, regardless of the spacing between edges; under these conditions performance efficiency increases rapidly and significantly with increasing spacing up to 1/2 inch between edges, and less rapidly therafter although the trend continues up to the largest interperipheral spacing tested, i.e., 3/4 inch.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

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

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INTRODUCTION

Aircraft instrument miniaturization is desirable for two reasons: (a) the accompanying reduction in weight increases the range of the aircraft, and (b) the reduction in size permits more instruments to be placed within reach and within sight of the operator. There are human factors, however, which limit the degree to which an instrument may profitably be miniaturized. With diminishing size a point is eventually reached at which a display scale is difficult to read or at which a more precise and time-consuming movement is required to grasp and operate a control. Furthermore, when a number of controls are mounted close together, the resultant "crowding" can be expected to increase the time required to operate a given control and, more important, to increase the probability of inadvertent operation of adjacent controls. Such performance decrement has already been investigated as a function of the dimensions of concentrically mounted knobs (9, 6, 5), knob diameter and torque (8) and the spacing between knobs (10, 6, 5). These experiments all involved continuously adjustable controls, investigated under the presumption that they could be inadvertently operated by a light touch. The results obtained, therefore, are inapplicable to detent or on-off controls the operation of which requires the application of considerable force. The present experiment was undertaken to provide this missing information, i.e., performance decrement as a function of the spacing between on-off controls.

APPARATUS AND PROCEDURE

The apparatus is shown schematically in Figure 1. The subject sits facing his panel and depresses the telegraph key with the thumb or index finger of his right hand, whichever digit he intends to use to operate the push button. To signal the start of a trial, the experimenter throws a switch which illuminates the amber light on the subjects' panel. Any time after this signal that he is ready, the subject releases the telegraph key and, under the instruction to give equal weight to speed and avoidance of contact with the adjacent push buttons, operates the center push button, thereby extinguishing the amber light. A time clock on the experimenter's panel measures operation time, i.e., the time elapsed from the release of the telegraph key until proper operation of the center push button.

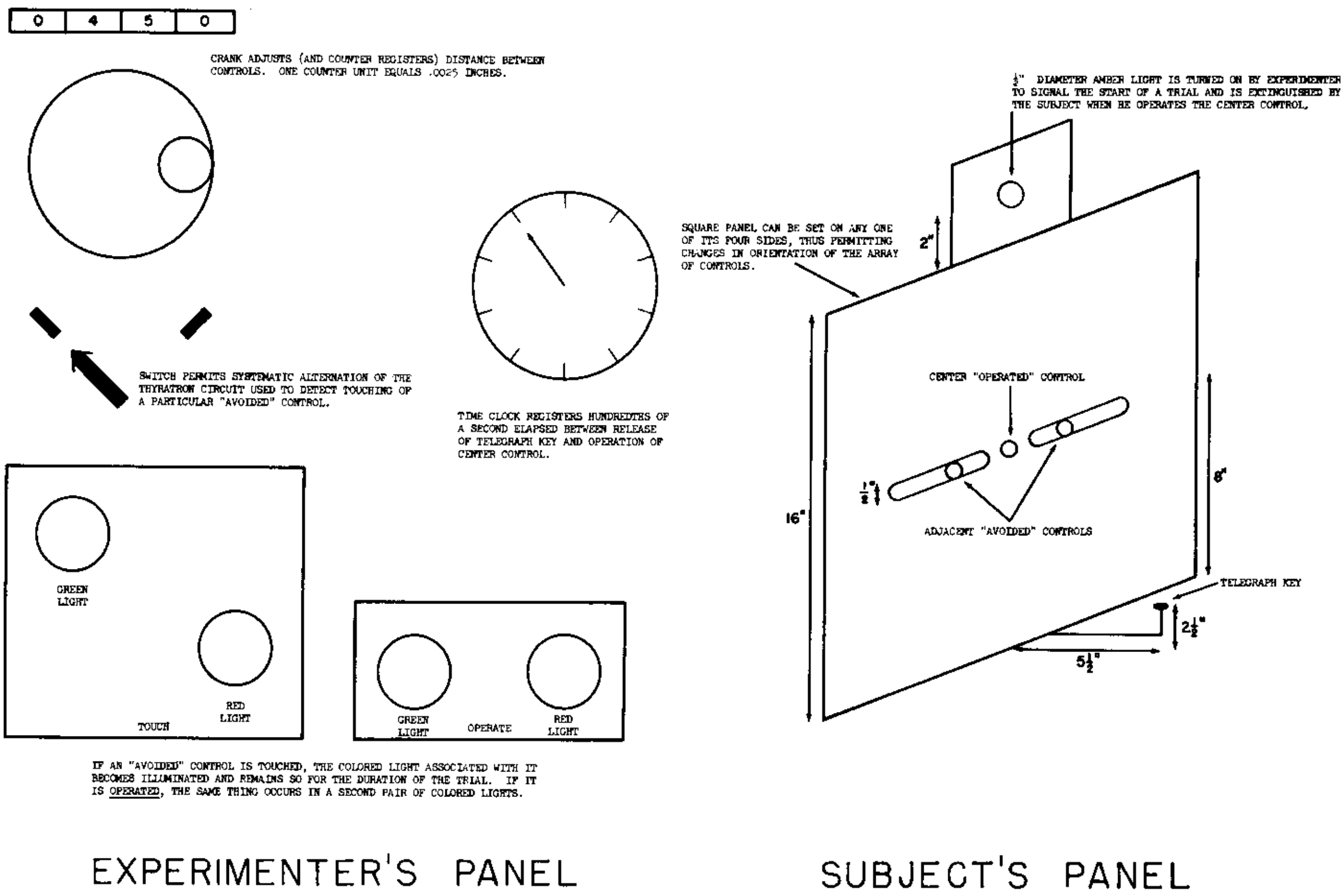


Figure 1. Functional diagram of apparatus components.

The subject is biassed with 45 volts D.C. by means of a battery connected to a bicycle clip worn on the exposed skin of his right arm. Each of the avoided push buttons is the touchplate of a thyratron touchplate circuit. When one of the avoided push buttons is touched by the subject, an identifying light on the experimenter's panel is illuminated and remains so until the experimenter turns it off after recording the "touching error".

If one of the avoided push buttons is contacted with enough force to operate it, an "operation error" light on the experimenter's panel signals that this has occurred and identifies the push button inadvertently operated. The subject was told that he would be timed and that touching errors would be recorded.

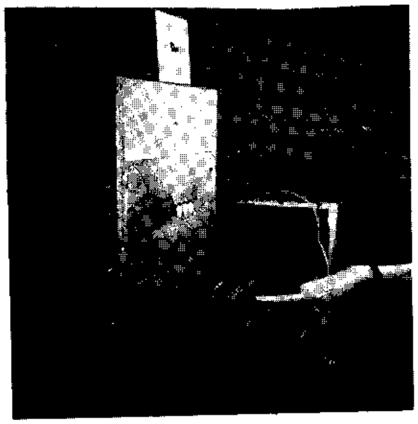


Figure 2. Subject's panel: Horizontal orientation.

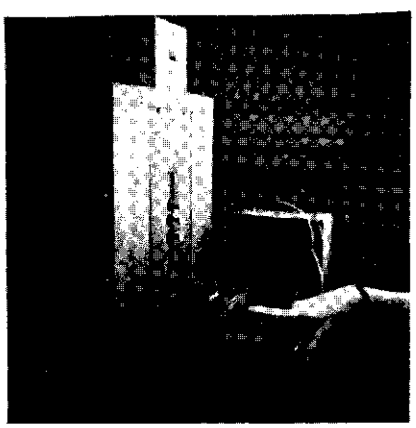


Figure 3. Subject's panel: Vertical orientation.

A switch on the experimenter's panel permitted alternation of the touch-plate circuits serving the two avoided push buttons. Thus any difference in sensitivity between the two circuits could be prevented from introducing a spurious difference in touching-error frequencies recorded for the two avoided controls. For half of the subjects, circuit A was used with control A for odd numbered trials within each condition and with control B for even numbered trials; for the other half of the subjects, circuit A was used with control B for odd numbered trials and with control A for even numbered trials within each condition. This alternation procedure was necessitated by the fact that errors occur more frequently on the initial than on the final trials under each condition.

The mechanism of the operated, center, push button was the same for every experimental condition, differences in diameter being effected by a set of right-cylindrical caps, of different diameters, which could be slipped over and fastened to the shaft of the push button mechanism. Thus the "feel" of the "operated" control was kept constant for all experimental conditions. Caps identical with these were used to change the diameters of the adjacent push buttons; however, since the mechanisms of the avoided push buttons were never alternated, it cannot be stated with certainty that small differences in resistance did not introduce a spurious difference in frequency of inadvertent operation between the two avoided controls. The mechanisms of all three controls were, of course, of the same make. Ten measurements were made of the number of ounces of force required to operate each push button mechanism. Means (and standard deviations) were as follows: center button, 21.55 (.65); left button, 24.00 (1.14); right button, 24.65 (1.42).

Three variables were investigated: diameter, orientation and spacing. Three diameters, 1/2, 3/4 and 1 inch were used in the experiment proper, the avoided push buttons always having the same diameter as the operated button. Two orientations were investigated: three push buttons in a horizontal array and three push buttons in a vertical array, as shown in Figures 2 and 3. The latter orientation was obtained by setting the square panel on its side (i.e., "rotating" the panel by 90°) and replacing the amber light at the "12 o'clock" position. Six spacings were used: 1/8, 2/8, 3/8, 4/8, 5/8 and 6/8 of an inch between edges. The apparatus controlling spacing could set any distances between push button mechanisms (within the range used) to a tolerance considerably better than .0025 inches. This tolerance was considerably finer than that attributable to the lateral play in the push button mechanisms.

Thirty-six right handed male college students were used as subjects and all thirty-six of the possible combinations of experimental conditions were investigated, each subject performing under all conditions. Within each combination of diameter and orientation, all six spacings were run (for a given subject, always in the same sequence) before proceeding to the next combination of diameter and orientation. Each such combination of diameter and orientation was presented the same number of times in each sequential position and was immediately preceded (and immediately followed) the same number of times by each of the other combinations. For each of these six distinguishable permutations of sequential order for diameter-orientation combinations, six subjects were run, one under each of six permutations of spacing order. These permutations were such that each spacing appeared the same number of times in each of the sequential positions and was immediately preceded (and immediately followed) the same number of times by each of the other spacings.

Each subject was given ten practice trials under a condition which attempted to maintain the essential elements of operation common to all experimental conditions without permitting the subject to acquire experience very similar to any of the specific conditions to be investigated. The subject was given no instruction to avoid contact with the adjacent controls. All discussion of "errors" and all instructions concerning the avoidance of contact with adjacent controls were given after the practice session. A diameter of 2 inches was used for the operated push button. Caps were removed from the adjacent push buttons, and the adjacent push buttons were set at the greatest between-center spacing which could be obtained with the apparatus. Because of the large diameter of the operated control, the corresponding distance between push button edges was only 5/8 inch. Removal of the caps from the adjacent buttons caused the front surfaces of these adjacent buttons to be in a different plane from that defined by the front surface of the operated button. These two parallel planes were 1/4 inch apart. The push button orientation used for practice was the same as that to be used for the first experimental conditions; however, because of the large distance between centers and because of the recessing of the front surfaces of the adjacent controls, it seems doubtful that the presence of the adjacent controls had much effect upon the subject's performance. "Orientation", then, was probably an irrelevant variable during practice. The subject was encouraged to use both the thumb and the forefinger as the operating digit during practice in order to decide which digit he preferred.

Each subject performed ten consecutive trials under each condition. "Frequency of inadvertent touching" will refer to a single avoided control and will be understood to refer to the number of trials in which a particular avoided control was touched one or more times. This information will be presented but will not be analyzed statistically. A "touching error" will be understood to mean the inadvertent touching of one or both avoided controls one or more times during a single trial. If the inadvertent contact results in operation of one or both avoided controls an "operation error" will also be said to have been committed. There will thus be, by definition, a maximum of one touching error (or of one operation error) per trial, and no distinction will be made between the avoided controls involved.

STATISTICAL TREATMENT

The data used in the statistical analyses were the sums of time scores or of errors taken over the ten trials per condition. There was thus a single total score per subject under each of the thirty-six experimental conditions. Since there was a constant number of trials per condition, an analysis applied to sums is equivalent to an analysis applied to means. Analyses of variance were performed upon sums of time scores and sums of touching errors, followed by t-tests for matched pairs.

A number of theoretical considerations, which will not be detailed here, point to a violation of assumptions in the data to which statistical tests were applied. (See 7 for empirical evidence of nonnormality and heterogeneity in individual, rather than mean or total, time scores obtained under the conditions of this experiment.) Therefore, as a gross check upon the degree to which the assumptions were violated, distributions of subjects' totals for two widely differing experimental conditions (1/2 inch diameter, 2/8 inch spacing, vertical orientation; and 1 inch diameter, 6/8 inch spacing, horizontal orientation) were examined. Under both conditions, time scores were positively skewed, with standard deviations of 9.39 and 4.43 respectively. Errors were positively skewed under the first named condition, with a standard deviation of 1.95 ; under the second condition, the error distribution was L-shaped with standard deviation of .44. Except for the latter, these distributions appeared to be no more assumption-violating than those investigated by Norton (14) who, in an analogous case, found heterogeneity of both form and variance to distort the probability levels of the F-test in such a way that F's whose tabled probabilities were .05, .01, and .001 had "true" empirical probabilities of approximately .08, .03 and .009 respectively. It is cautioned, therefore, that the statistical tests reported herein should not be considered as exact tests, and the significance levels obtained with them should be treated merely as gross indices identifying the general vicinity in which true cumulative probabilities can be expected to lie.

RESULTS

Results are presented descriptively in Figures 4 and 5 and in the appendix, in Tables I, II and III. When it is desired to make most economical use of panel space, the important consideration is not the distance between edges of controls but rather the distance between their centers. Figure 4 shows that when time scores are plotted against spacing between centers, the curves for the three diameters very nearly overlap. It appears then that when distance between push button centers is held constant, their diameter has negligible effect upon the speed with which they can be operated (within the range of diameters investigated). The pattern of touching errors is not analogous. At a given distance between centers, the general trend is for touching errors to diminish with diminishing diameter. When panel space is at a premium, therefore, Figure 4 suggests that small diameter push buttons should be used since, at constant distance between centers, errors decrease with decreasing diameter. On the other hand Figure 5 suggests that when panel space is abundant large diameter push buttons should be used since, with distance between edges held constant, performance improves with increasing diameter.

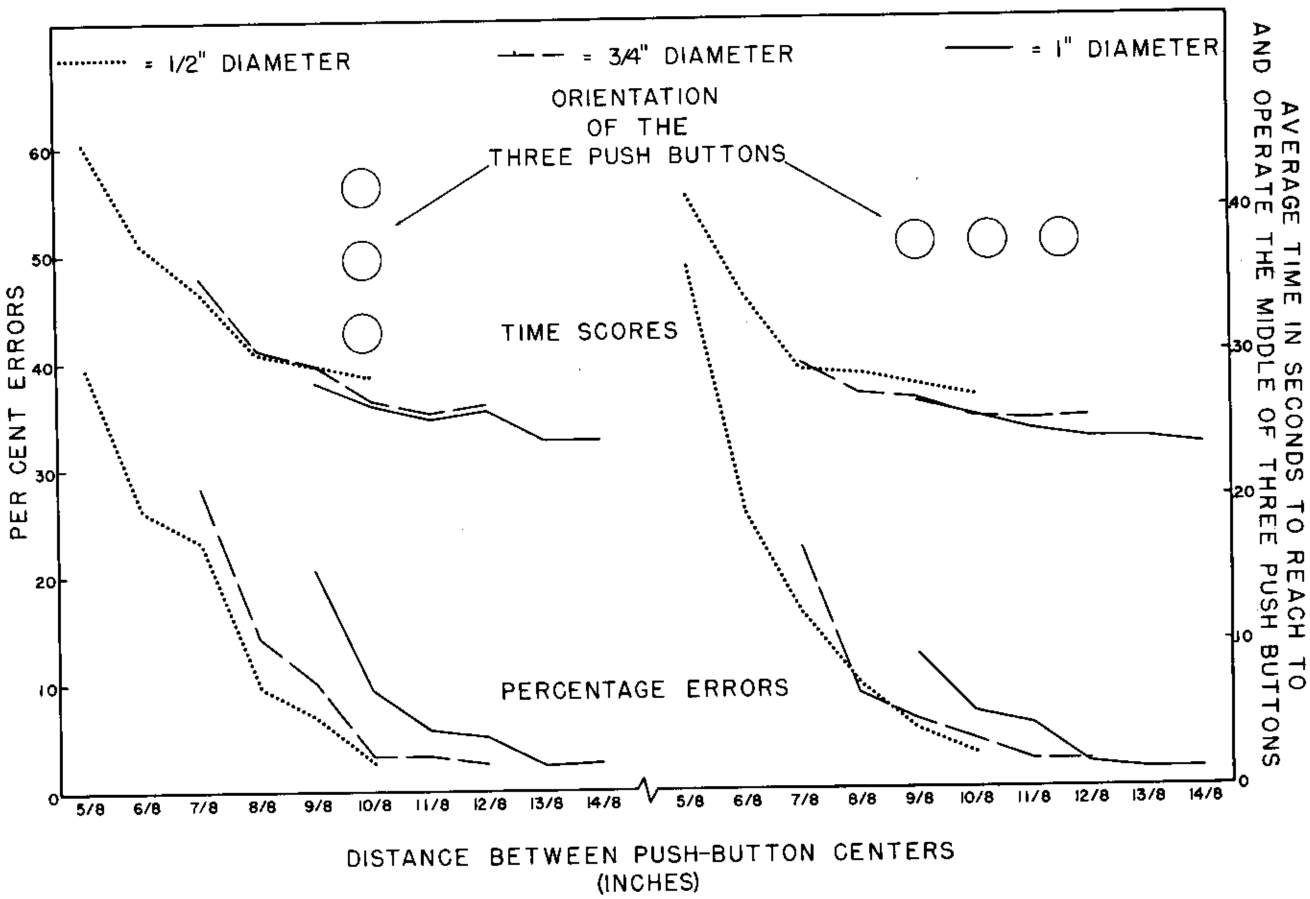
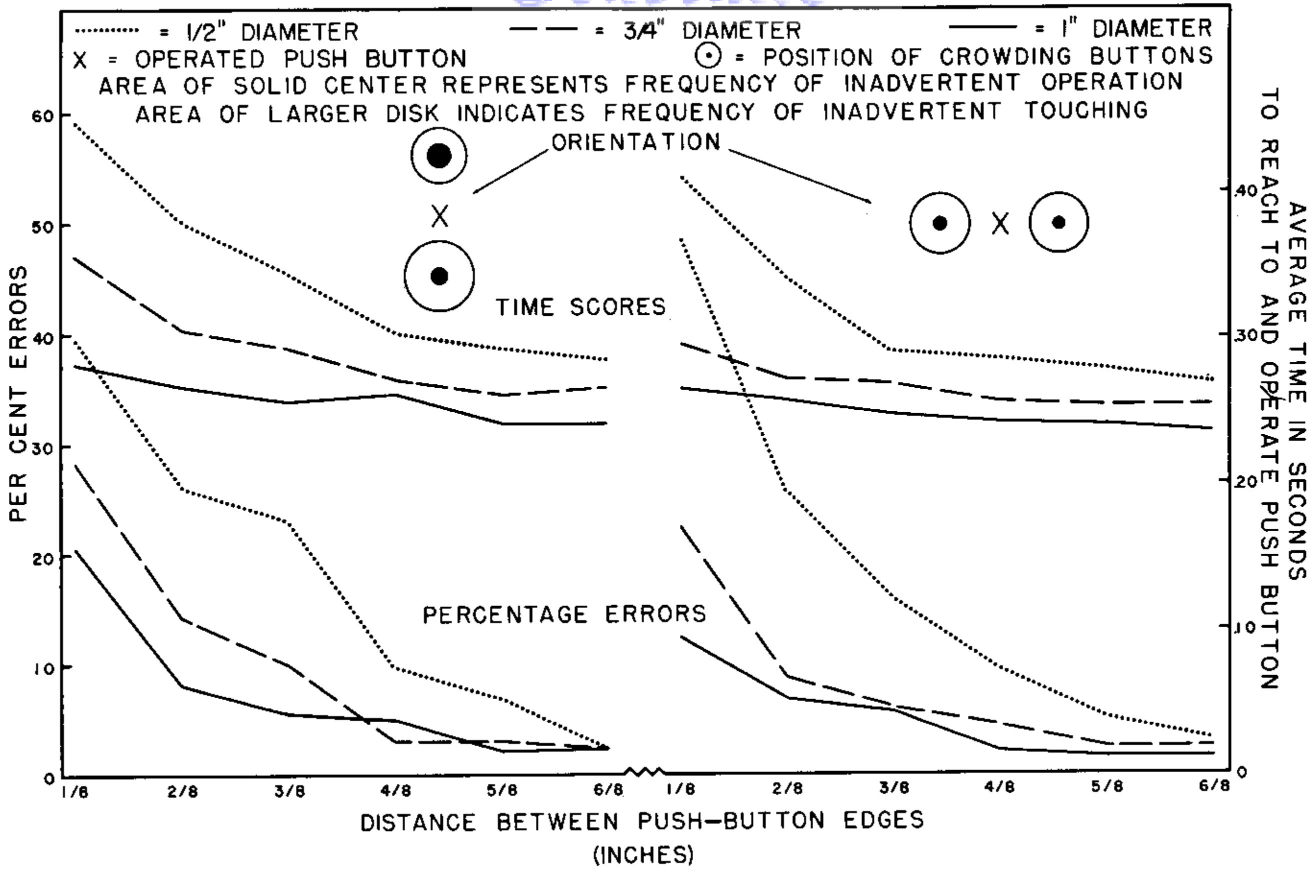


Figure 4. Time scores and touching errors as functions of intercenter spacing.



<u>Figure 5</u>. Time scores and touching errors as functions of interperipheral spacing.

Performance was better when the controls were arranged in a horizontal array than when the line of controls was vertical. This effect was real, but fairly small for time scores and touching errors. Table I suggests that the effect may have been quite considerable for operation errors, although no statistical analysis was performed on these measurements.

When orientation was horizontal, the two adjacent controls were inadvertently touched with about equal frequency and inadvertently operated with about the same frequency. In the vertical orientation, on the other hand, the bottom control was inadvertently touched about twice as often as was the top one, but was inadvertently operated about half as often. It is the opinion of the experimenter that this may be a result of the particular reaching movement required to operate the center control. The hand must sweep forward and upward. If the target is overshot, the result is likely to be a direct blow upon the upper push button; if it is undershot, the result is likely to be a glancing contact with the lower push button.

The statistical analysis is summarized in Tables IV and V of the Appendix. Probably its most useful function is that it indicates that all main effects were real and that the general shapes of the curves shown in Figures 4 and 5 are fairly reliable.

DISCUSSION

A rather remarkable similarity exists between the results of the present experiment and the results of a previous experiment on the degradation of performance with increasing crowding of knobs (10, see Figures 2, 3, and 4). In the latter experiment performance improved with increasing knob diameter (within the range tested), when interperipheral spacing was held constant, but improved with <u>decreasing</u> knob diameter when distance between knob <u>centers</u> was held constant. When plotted against distance between centers, time scores for three knob diameters tended to overlap, although not so closely as in the present experiment.

Touching error data may be considered as operation error data for the extreme case in which the adjacent push buttons offer zero resistance to operation, i.e., can be operated by negligible force. Spacing of controls on the basis of touching error data, therefore, is equivalent to using a force "safety factor" whose magnitude is proportional to the normal force actually required to operate the push buttons. The operation error data obtained in the present experiment are naturally peculiar to the particular resistances to operation of the push button mechanisms used. The touching error data have the greater generality of constituting a conservative upper bound for the spacing required for a specified level of performance excellence.

SUMMARY AND CONCLUSIONS

Push buttons arranged in a horizontal array can be operated more efficiently than those in a vertical array. The effect is moderate but real when measured by operation time; or by touching errors; it is large and convincing (although its reality has not been tested) when measured by operation errors.

The decrease in operation time with increasing distances between push button centers is virtually independent of control diameter (within the range of values used). Operation time improves rapidly with increasing distances between centers up to an intercenter spacing of one inch, after which the trend continues, but less rapidly; the curve becomes nearly asymptotic at the greatest intercenter spacing tested, 1-3/4 inches.

As a corrolary of the first sentence in the above paragraph, operation time improves with increasing push button diameter if, when time is measured, the same distance between edges is used for push buttons of various diameters.

Touching errors decrease with increasing push button diameter when spacing between edges is held constant; they decrease with decreasing diameter when spacing between centers is held constant. The curves for the various diameters appear to converge to a level of about 2.5% touching errors at 3/4 inch spacing between edges. The conclusion may be hazarded that if the controls can be spaced no more than 1-1/2 inches between centers, 1/2 inch diameter push buttons would be superior to larger diameter controls; but that if an intercenter spacing of two or more inches is permissible, push buttons as large as one inch in diameter may be as efficient as smaller diameter controls, or perhaps more so. Touching errors can be expected to increase rapidly when the distance between push button centers is decreased below 1-1/4 inches. It must be assumed that operation errors, though less frequent than touching errors, follow a roughly similar pattern. The above conclusions are therefore extended to operation errors.

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APPENDIX

TABLE I

RESULTS

DISTANCE BETWEEN EDGES

Measurement	Diameter	Horizontal Array 1/8	2/8	3/8	4/8	5/8	6/8	All	Vertical Array 1/8	2/8	3/8	4/8	5/8	6/8	All
Touching Error Frequency	1/2	175	93	58	35	19	12	392	142	94	83	35	25	9	388
	3/4	81	32	22	16	9	9	169	102	51	36	11	11	9	220
	1	45	25	21	8	6	6	111	74	33	20	18	8	9	162
	All	301	150	101	59	34	27	672	318	178	139	64	44	27	770
Percent Touching Errors	1/2	48.6	25.8	16.1	9.7	5.3	3.5	18.1	39.4	26.1	23.1	9.7	6.9	2.5	18.0
	3/4	22.5	8.9	6.1	4.4	2.5	2.5	7.8	28.3	14.2	10.0	3.1	3.1	2.5	10.2
	1	12.5	6.9	5.8	2.2	1.7	1.7	5.1	20.6	9.2	5.6	5.0	2.2	2.5	7.5
	All	27.9	13.9	9.4	5.5	3.1	2.5	10.4	29.4	16.5	12.9	5.9	4.1	2.5	11.9
Operation Error Frequency	1/2	10	10	2	1	1	2	26	16	20	10	0	1	0	47
	3/4	2	2	0	1	0	0	5	11	7	4	2	2	1	29
	1	3	0	1	0	0	0	4	4	1	0	3	0	0	8
	All	15	12	3	2	1	2	35	31	28	14	5	3	1	82
Percent Operation Errors	1/2	2.8	2.8	.6	.3	.3	.5	1.2	4.4	5.6	2.8	0	.3	0	2.2
	3/4	.6	.6	0	.3	0	0	.2	3.1	1.9	1.1	.6	.6	.3	1.3
	1	.8	0	.3	0	0	0	.2	1.1	.3	0	.8	0	0	.4
	All	1.4	1.1	.3	.2	.1	.2	.5	2.9	2.6	1.3	.5	.3	.1	1.3
Mean Operation Time (Secs)	1/2	.409	.341	.288	.286	.278	.269	.312	.449	.379	.344	.302	.293	.285	.342
	3/4	.294	.272	.268	.255	.253	.254	.266	.356	.305	.293	.270	.260	.266	.291
	1	.266	.256	.247	.241	.240	.236	.248	.281	.265	.256	.262	.241	.241	.258
	All	.323	.290	.268	.261	.257	.253	.275	.362	.316	.298	.278	.265	.264	.297

TABLE II

NUMBER OF TRIALS IN WHICH PUSH BUTTON IN A SPECIFIED POSITION WAS INADVERTENTLY TOUCHED

Diameter	Array Orientation	Position of Touched Push Button	Distance Between Push Button Edges 1/8	2/8	3/8	4/8	5/8	6/8	All
1/2"	Horizontal	Left	99	52	25	18	10	2	206
		Right	92	50	35	17	9	10	213
	Vertical	Top	59	37	30	14	8	2	150
		Bottom	100	63	54	22	18	7	264
	All		350	202	144	71	45	21	833
3/4"	Horizontal	Left	39	18	12	11	2	3	85
		Right	45	16	12	6	7	6	92
	Vertical	Top	41	25	14	5	1	1	87
		Bottom	65	29	25	7	10	8	144
	All		190	88	63	29	20	18	408
1"	Horizontal	Left	30	10	12	7	2	4	65
		Right	16	16	10	1	4	3	50
	Vertical	Top	37	13	7	10	5	4	76
		Bottom	37	21	13	8	3	5	87
	All		120	60	42	26	14	16	278
All	Horizontal	Left	168	80	49	36	14	9	356
		Right	153	82	57	24	20	19	355
	Vertical	Top	137	75	51	29	14	7	313
		Bottom	202	113	92	37	31	20	495
	All		660	350	249	126	79	55	1519

TABLE III

NUMBER OF TRIALS IN WHICH PUSH BUTTON IN A SPECIFIED POSITION WAS INADVERTENTLY OPERATED

Diameter	Array Orientation	Position of Operated Push Button	Distance Between Push Button Edges 1/8	2/8	3/8	4/8	5/8	6/8	All
1/2"	Horizontal	Left	5	8	1	0	0	0	14
		Right	5	2	1	1	1	2	12
	Vertical	Top	9	12	7	0	0	0	28
		Bottom	7	8	3	0	1	0	19
	All		26	30	12	1	2	2	73
3/4"	Horizontal	Left	2	0	0	0	0	0	2
		Right	0	2	0	1	0	0	3
	Vertical	Top	11	6	3	1	0	0	21
		Bottom	1	1	2	1	2	1	8
	All		14	9	5	3	2	1	34
1"	Horizontal	Left	3	0	0	0	0	0	3
		Right	0	0	1	0	0	0	1
	Vertical	Top	4	1	0	3	0	0	8
		Bottom	0	0	0	0	0	0	0
	All		7	1	1	3	0	0	12
All	Horizontal	Left	10	8	1	0	0	0	19
		Right	5	4	2	2	1	2	16
	Vertical	Top	24	19	10	4	0	0	57
		Bottom	8	9	5	1	3	1	27
	All		47	40	18	7	4	3	119

TABLE IV

RESULTS OF ANALYSIS OF VARIANCE

Source	Degrees of Freedom	F for .01 Sig. Level	Operation Time F	Operation Time P	Touching Errors F	Touching Errors P
Spacing Between Edges	5/175	3.17	77.41	.01	100.09	.01
Diameter	2/70	4.95	118.92	.01	61.64	.01
Orientation	1/35	7.43	37.75	.01	5.57	.025
Spac. x Diam.	10/350	2.50	17.77	.01	16.63	.01
Spac. x Orient.	5/175	3.17	3.57	.01	0.99	NS
Diam. x Orient.	2/70	4.95	3.47	.05	2.29	NS
S x D x O	10/350	2.50	1.74	NS	3.87	.01

TABLE V

SIGNIFICANCE LEVELS FOR TWO-TAILED t-TESTS FOR MATCHED PAIRS.

Cell Coordinates Define One of the Tested Conditions, X; the Condition with which it is Compared, Y, is the Same Except as Noted in Parentheses.

Diameter:	1/2" Diameter				3/4" Diameter				1" Diameter			
Orientation:	Horizontal		Vertical		Horizontal		Vertical		Horizontal		Vertical	
Measure:	Time	Error	Time	Error	Time	Error	Time	Error	Time	Error	Time	Error
Inter-peripheral Spacing	(Y Spacing = X Spacing + 1/8")											
1/8	.01*	.01*	.01*	.01*	.02*	.01*	.01*	.01*	.40	.05*	.20	.01*
2/8	.01*	.02*	.05*	.40	.50	.20	.30	.10	.30	.70	.30	.05*
3/8	.80	.05*	.01*	.01*	.20	.40	.10	.01*	.50	.02*	.50	.80
4/8	.40	.10	.30	.20	.90	.20	.20	1.00	.90	.70	.01*	.10
5/8	.40	.20	.30	.05*	.90	1.00	.50	.70	.70	1.00	1.00	.90
	(Y Diameter = X Diameter + 1/4")											
1/8	.01*	.01*	.01*	.02*	.01*	.01*	.01*	.10				
2/8	.01*	.01*	.01*	.01*	.10	.50	.01*	.02*				
3/8	.05*	.01*	.01*	.01*	.01*	.90	.01*	.05*				
4/8	.01*	.05*	.01*	.01*	.30	.20	.50	.40				
5/8	.01*	.05*	.01*	.10	.20	.60	.05*	.50				
6/8	.10	.60	.05*	1.00	.02*	.50	.02*	1.00				
	(Y Orientation is Vertical)											
1/8	.10	.05*			.01*	.10			.20	.01*		
2/8	.02*	1.00			.01*	.05*			.40	.30		
3/8	.01*	.02*			.05*	.20			.30	.90		
4/8	.20	1.00			.10	.40			.05*	.10		
5/8	.10	.40			.50	.70			.90	.70		
6/8	.05*	.70			.20	1.00			.60	.60		
	(Y Diameter = X Diameter + 1/4"; Y Spacing = X Spacing - 1/4" so Intercenter Spacings for X and Y are Equal)											
3/8	.60	.05*	.40	.20	.90	.01*	.50	.01*				
4/8	.20	.80	.80	.05*	.10	.30	.70	.01*				
5/8	.30	.70	1.00	.30	.50	.10	.70	.20				
6/8	.05*	.60	.05*	.80	.20	.90	.80	.20				

Probabilities within the .05 level of significance are identified by an asterisk.