HUMAN FACTORS, 1969, 11(4), 353–360

Optimum Knob Diameter

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When frictional resistance is heavy, the optimum knob diameter is about 2 in. The curve relating turning time to knob diameter is roughly U-shaped, and diameters outside the range of 1¾ to 2½ in. are significantly inferior to the 2-in.-diameter knob. When frictional resistance is reduced to a moderate level, the curve becomes essentially flat in the region from 3¼ in. (the largest diameter tested) to 1 in., but rises steeply and significantly with decreasing diameter at diameters smaller than 1 in. (i.e., ¾ in. and ½ in). There is an indication that if friction were reduced to a very low level, the curve would flatten out still further to include in its flat region all practical diameters smaller than 1 in. Evidence is cited in support of this indication. Evidence is also presented to the effect that the above findings are valid over a wide range of rotary inertias. Reach time was independent of frictional resistance, but increased with decreasing diameter at diameters smaller than 1½ in.

INTRODUCTION

It is important that controls should not be too small to be handled easily. On the other hand, panel space should not be wasted by using larger controls than those required for efficient operation. By using knobs of the smallest diameter for which operation time is minimal, both considerations will be served. The present experiment was designed, therefore, to determine the relationship between knob diameter and operation time, particular interest being centered upon that diameter, or range of diameters, at which operation time is a minimum.

APPARATUS AND PROCEDURE

Forty-eight right-handed, male college students served as subjects. Each subject made six clockwise and six counterclockwise "standard" knob operations, with each of twelve ½-in.-thick, knurled, aluminum-alloy knobs ranging in diameter (in ¼-in. increments) from ½ in. to 3¼ in. Knob thickness was not varied, since Bradley and Stump (1955) had indicated that, over a wide range of values of both variables, thickness does not interact with diameter.

A standard knob operation (see Figure 1) was followed. The subject, seated before the knob panel, depressed a telegraph key with his right hand. The experimenter threw a switch illuminating the amber light in front of the subject. This signalled the subject that, whenever he was ready, he could release the telegraph key, grasp the knob and rotate it (from its extreme position at the start of the trial) until the amber light was extinguished and remained extinguished (the light was extinguished when the black radial line on the face of the knob was in a narrow adjustment zone 2° wide located at about the 12 o'clock position). The subject then released the knob and returned his hand to the telegraph key. After the experimenter disconnected his time-clocks from the circuit, the subject reset the knob so that the indicator line was at the opposite extreme from its starting position at the beginning of the trial just completed. The starting position of the indicator line was thus alternated between the mechanical stops at the 8 o'clock position (calling for a clockwise setting) and the 4 o'clock position (calling for a counterclockwise setting).

The experimenter's apparatus recorded reach time (the time elapsed from the release of the telegraph key until the knob just starts to turn) and turning time (the time, after the knob starts to turn, during which the knob is outside the narrow adjustment zone in which

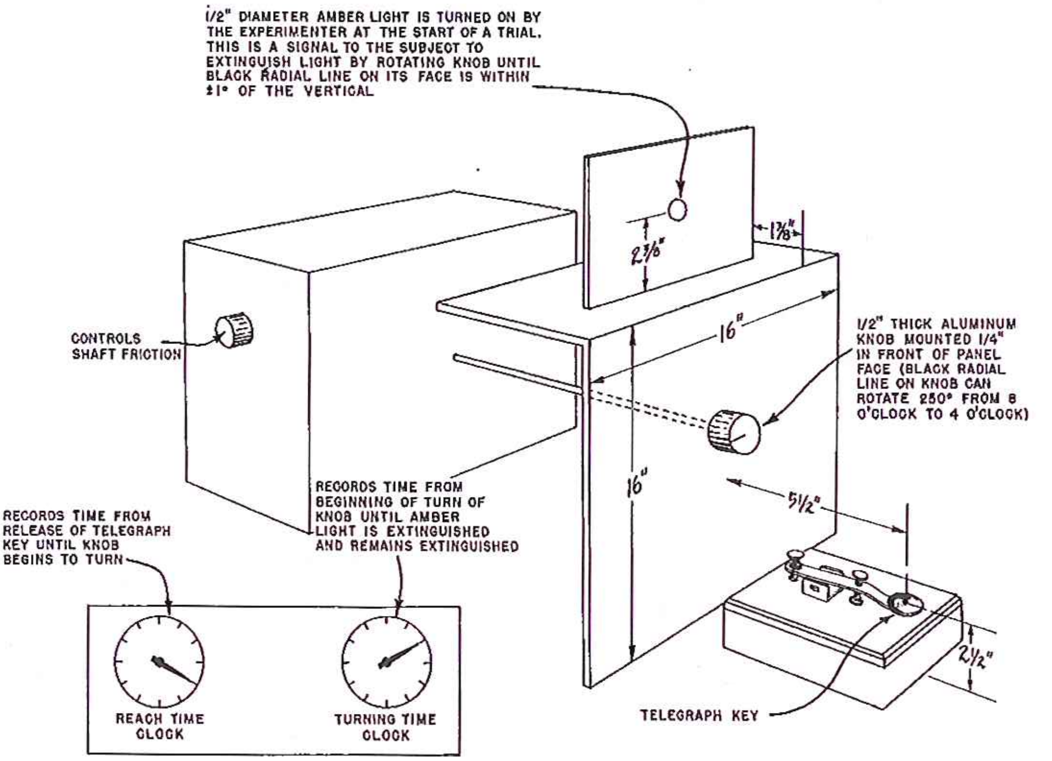

Figure 1. Apparatus

the black radial line is vertical and the amber light is extinguished).

Two conditions of shaft friction were investigated. For the first 24 subjects the "natural" shaft friction of the apparatus was used. Thus the amount of torque required to turn a knob was determined by the "real" shaft friction of the apparatus and the frictional resistance of the wiper arm on the potentiometer controlled by the knob. Eight pairs of measurements were taken of the torque required to turn the shaft during this part of the experiment. Clockwise torque ranged from 60 to 90 inch-grams (in.-g.) averaging 77; counterclockwise torque, from 78 to 90, averaging 85. The second group of 24 subjects operated under "heavy" shaft friction, which was obtained by coupling the end of the knob-and-potentiometer shaft with the shaft of a device whose friction could be varied. Torque measurements were taken following the runs of each 12 subjects. Clockwise torque ranged from 150 to 190 in.-g., averaging 171; counterclockwise torque, from 150 to 200, averaging 181. Moment of inertia for nonknob apparatus components which rotated with the knob was .2 g.-in.^{2} for the moderate friction condition and 1.76 g.-in.^{2} under the heavy friction condition.

For each subject, the 12 settings made with each knob were done successively, so that 12 settings with a knob of one diameter were followed by 12 settings with a knob of another diameter, etc. A table of random numbers was used to establish a single random order for the 12 knob diameters. The sequences of presentation of diameters to the first 12 subjects differed only as to the starting point within this order. Each knob diameter was presented once first, once second, once third, etc., and the diameter of the knob immediately preceding it was always the same, as was that of the knob immediately following it (except for the cases where the knob was presented first or last, respectively). The order was reversed for the second 12 subjects and the same procedure was used for establishing sequences of presentation. For each of the second 24 subjects, the sequence in which diameters were presented was identical to that used for his counterpart in the first 24 subjects. In order to obtain scores of greater reliability, the first two operations with each knob were considered practice and were not included in the data which will be presented as results. Subjects were not informed, however, that any of their trials were for practice.

RESULTS

Both parametric and distribution-free statistics (the analysis of variance and the Friedman test with Wilcoxon's [1949] modification for testing interaction) were used to test main effects and interactions. The results obtained by these two types of test, i.e., the standard significance levels reached, were identical. Diameter, friction, and the diameter × friction interaction all had a significant effect upon turning time ($p < .01$). Reach time, however, was significantly influenced only by diameter ($p < .001$).

Individual comparisons between time scores at adjacent diameters were made both with the t-test and the distribution-free Wilcoxon test. Results were highly similar, so further individual comparisons were made with the Wilcoxon test alone. The results of these individual comparisons are shown graphically in Figures 3 and 4.

Reach time was significantly affected by diameter but not by shaft friction. Reach time was smallest for the 2½-in.-diameter knob. However, the reach time curve is essentially flat between the 1½-in. and 3¼-in. diameters and shows a significant and convincing upturn only when diameter is decreased to 1¼ in. or less. The statistically significant difference between the 2½- and 2¾-in. diameters loses much of its force when it is remembered that seven such comparisons must be made in the flat section of the curve. Nor is the significant difference supported by the general trend of the curve. It must therefore be considered a largely chance effect.

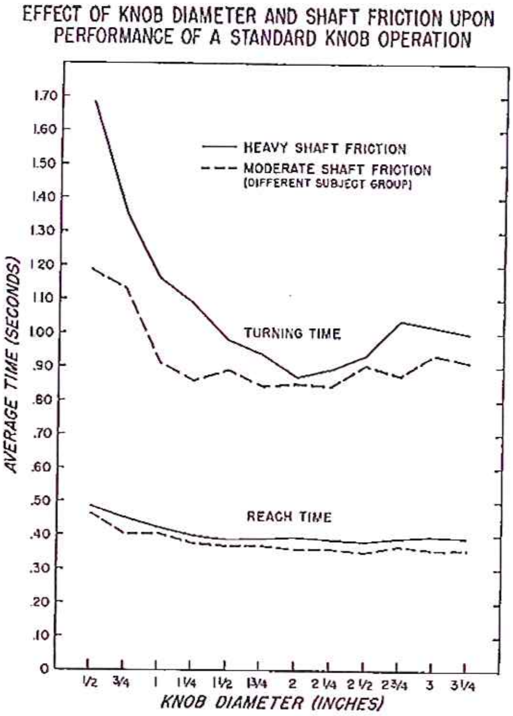

Figure 2. Performance of a knob operation as a function of knob diameter and shaft friction. A 2-in.-diameter knob optimizes performance for the greatest variety of conditions.

Turning time was affected by diameter, friction, and the diameter × friction interaction. With moderate shaft friction, the smallest turning time was for the 1¾-in.-diameter knob. However, the turning time curve is essentially flat between 3¼ in. and 1 in. and shows a significant upturn only when diameter is decreased to ¾ in. For heavy shaft friction, the smallest turning time was at a diameter of 2 in. The flat section of the curve extends only from 1¾ in. to 2½ in., with scores for diameters outside of this region differing significantly from those for the 2-in.-diameter knob.

Figure 4 shows turning time differences between the two friction conditions at each knob diameter. The general shape of the curve is such as to suggest that the deterimental effect of heavy friction is negligible at the

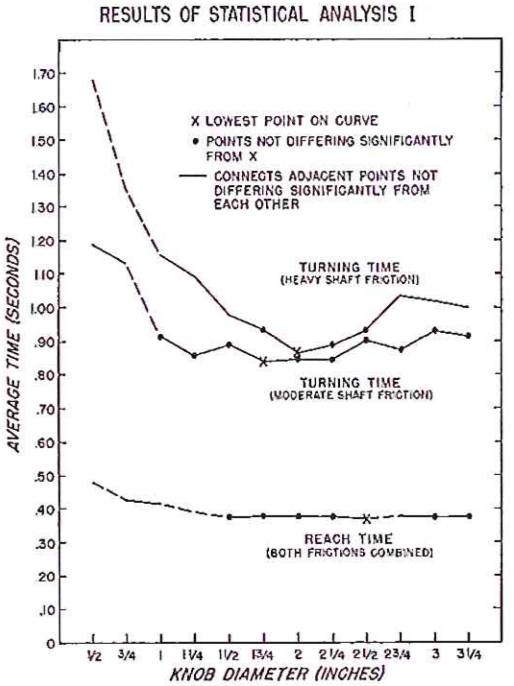

Figure 3. Statistical significance, based on two-tailed test at $\alpha = .05$, *of performance decrement at nonoptimal diameters. Heavy shaft friction narrows the range of statistically indiscriminable diameters, when turning time is the performance measure.*

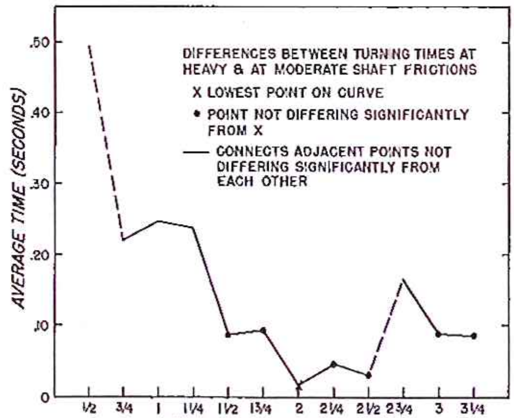

Figure 4. Effect of increasing shaft friction from moderate to heavy, as a function of knob diameter. The resulting performance decrement is smallest for a 2-in.-diameter knob, and increases with increasing departures from this optimum diameter, especially when the departure is a reduction. Criterion of statistical significance is $p \leq .05$ *for a two-tailed test.*

optimum diameter but that it becomes increasingly serious with increasingly large departures from the optimum, particularly as diameter is decreased. This indication is only partially supported by statistical tests, however.

Both the data and the results of statistical analyses are given in somewhat greater detail by Bradley and Arginteanu (1956).

DISCUSSION

It seems likely that the slight but real increase in reach time with decreasing diameter at diameters smaller than 1½ in. simply means that reach time is a function of the size of the target which must be reached to and grasped. Furthermore, it suggests that when knobs must be turned through angles so large that the knob must be released and regrasped one or more times while making a single setting, knobs between 1½ and ½ in. in diameter may be considerably more inferior to the larger knobs than the present experiment would imply.

The results indicate that as shaft friction is decreased from a high to a moderate level, the range of statistically indiscriminable diameters (as measured by turning time) expands from a narrow region centered at about 2 in. to a wide, essentially flat zone extending from about 1 in. to at least 3¼ in. and probably beyond. This strongly suggests that if shaft friction were decreased to a low level, the turning time curve would flatten out even more, so that knobs considerably smaller than 1 in. in diameter might be as easily turned (but not reached to and grasped) as the 2-in. knob.

An experiment by Stump (1953) supports this conclusion. Stump's experimental conditions and time measurements have been "collapsed" to form a single curve, indicating the relation between knob diameter and turning time (see Figure 5). A ½-in.-thick knob on a low-torque, low-inertia shaft had to be turned through approximately two-and-one-quarter rotations and set in a zone 4½° wide (as contrasted with approximately one-third of a rotation and a zone 2° wide in the present

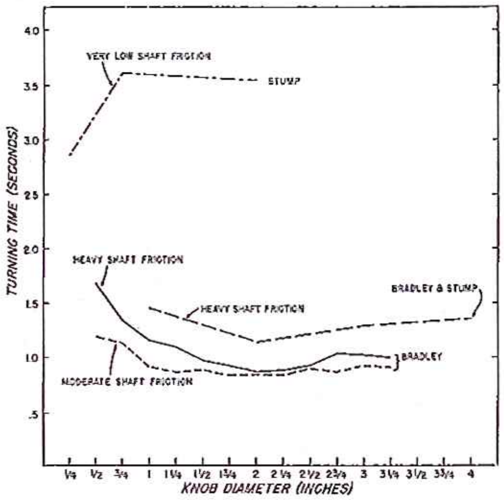

Figure 5. Effect of shaft friction upon the variation of turning time with knob diameter. As shaft friction is reduced, smaller and smaller diameters can be used without appreciably increasing turning time. (All knobs were ½ in. thick, but the distance turned was much greater for Stump's experiment than for the other two experiments.)

experiment). Knob diameters of 2 in., ¾ in., and ¼ in. were tested. In the four analyses of variance performed, diameter effect either fell short of significance or was significant at the .05 level. In the data for which the diameter effect was significant, the shortest time scores were for the ¼-in.-diameter knob.

Stump's subjects turned the ¾-in. and 2-in. knobs using the conventional wrist movement but were observed to turn the ¼-in. knob by rolling it between thumb and index finger. The two-and-one-quarter rotations required by the task could therefore be accomplished with much less releasing and regrasping of the knob when the ¼-in.-diameter knob was used than when the larger knobs were presented. The apparent superiority of the ¼-in. knob therefore probably depends upon multirotation (or large-angle-of-turn) setting requirements as well as upon low shaft friction. It is doubtful that the ¼-in. knob would have been superior if only one-third of a rotation had been required, as in the present experiment. Nevertheless, the fact that Stump's experiment shows no appreciable increase in turning time going from the 2-in. to the ¾-in. diameter (where the same wrist motion is used), or from the ¾-in. to the ¼-in. diameter, tends to confirm the indication of the present experiment that if friction is sufficiently decreased, all diameters within a large practical range can be turned through one-third of a rotation with nearly equal speed.

Unless unusual measures are taken, the rotary moment of inertia of commercially available knobs of a given material may be expected to vary as the square of their radii. If such knobs are solid cylinders of equal thickness, this variation is inevitable. This was the case in the present experiment and, therefore, moment of inertia is confounded with knob diameter, but confounded in an entirely realistic manner.

There is good reason to believe, however, that the same results would have been obtained had moment of inertia been held constant at any value realistic to the practical situation. That is to say, inertia does not appear to be an important variable either by itself or in interaction with diameter. An experiment by Bradley and Stump (1955) supports this conclusion. See Figure 6.

For the 1-in.-diameter plastic knob, most of the total moment of inertia is due to apparatus components other than the knob itself (i.e., shaft, gears, collars, wiper arms). So little is due to the knob itself that the inertia curve shows practically no rise with increasing knob thickness. On the other hand, for the 4-in.-diameter plastic knob, most of the total moment of inertia is due to the knob and the inertia curve rises steeply with increasing knob thickness. Despite the fact that total inertia varies negligibly with thickness at one diameter and varies tremendously with thickness at another diameter, turning time does not vary significantly with thickness at either diameter, the curves being essentially parallel. This strongly suggests that, within the ranges of values involved, turning time is independent of moment of inertia. It is possible, of course, but not probable, that with increasing knob thickness, a beneficial effect due to greater grasping surface is cancelled by a detrimental effect due to greater knob inertia, and that both of these effects are negligible in small diameter knobs but increase rapidly with increasing knob diameter.

This possibility is explored by plotting comparable data from Bradley and Stump (1955) and from the present experiment on the same graph (see Figure 7). Knobs are of equal thickness and have equal shaft friction. Essentially parallel curves are obtained, relating turning time to knob diameter, despite great differences in the variation of total moment of inertia with knob diameter. For the three diameters common to the two studies, turning times differ by +.30, +.28, and +.28 sec., while the corresponding inertia differences are +48, +28, and −54 g.-in.^{2} The generally longer time scores for the Bradley and Stump experiment are probably due to differences in group ability or to slight differences in apparatus and procedure such as distance between knob and panel, spatial position of knob, type of surface on knob edge (i.e., milled or knurled), etc.

Although not rigidly demonstrated, the evidence very definitely favors the conclusion that, over the range of diameter and inertia values likely to be encountered in practice, moment of inertia has little or no effect upon either turning time or upon the effect of diameter on turning time.

SUMMARY

The knobs used in this experiment varied in diameter from ½ in. to 3¼ in., in ¼-in. increments. They were ½ in. thick, separated by a ¼-in. gap from the panel, had knurled edges and were made of aluminum alloy. The knob had to be reached to, grasped, and rotated 125° so that the radial line on its face pointed to the 12 o'clock position within a tolerance of ±1°. Two shaft frictions, corresponding to

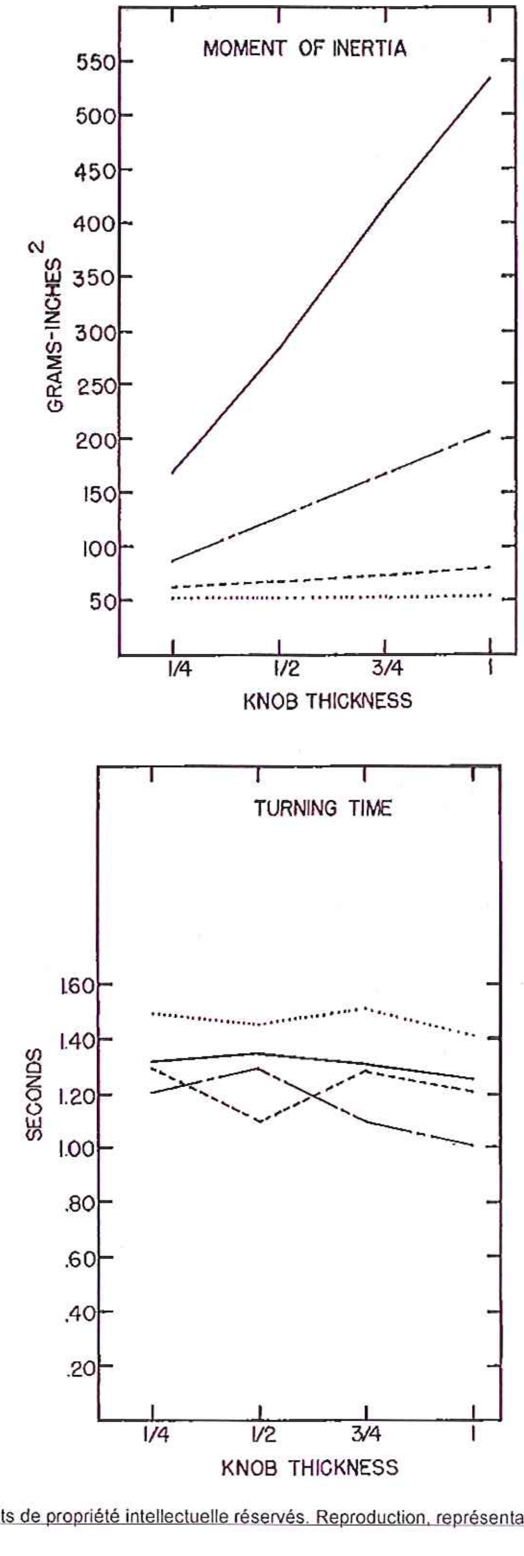

Figure 6. Parallel curves relating turning time to knob thickness are obtained for knobs of different diameters despite the fact that total moment of inertia varies greatly with thickness at some diameters but negligibly at others. (After Bradley and Stump; . . . . . 1-in. diameter; — — — — 2-in. diameter; — - — 3-in. diameter; ———— 4-in. diameter.)

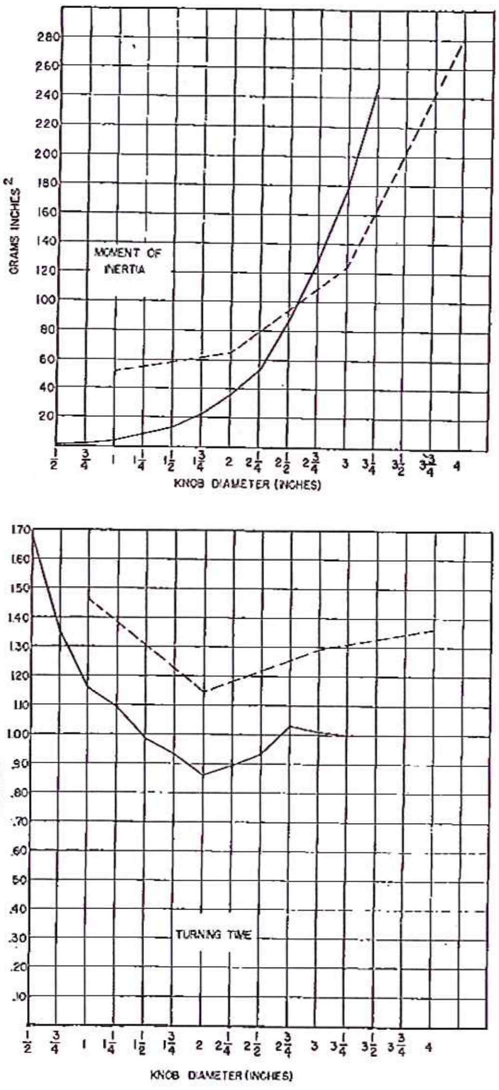

Figure 7. Parallel curves relating turning time to knob diameter are obtained for knobs equal in thickness and shaft friction but differing in inertia characteristics. (— — — — Bradley and Stump, 1955; ———— present experiment.)

average torques of 81 and 176 in.-g. for moderate and heavy shaft frictions, respectively, were tested with a different subject group operating under each friction condition. Previous experiments indicate that the results of the present experiment will be valid over a wide range of knob thicknesses and rotary moments of inertia. While it is felt that the following results can justifiably be generalized to still further departures from the experimental task, great caution should be exercised in applying them to multirotation knobs; they should probably not be applied to detent knobs under any circumstances.

1. Reach time is not significantly affected by shaft friction.

2. Reach time is not appreciably affected by knob diameter in the range from 3¼ to 1½ in. Between 1½ and ½ in., reach time increases with decreasing diameter.

3. When shaft friction is very low, Stump's (1953) experiment suggests that, if inertia is not large, diameter may be reduced to ¼ in. without increasing turning time.

4. When shaft friction is moderate, turning time is essentially independent of diameter in the range from 3¼ in. to 1 in. Between 1 in. and ½ in., turning time increases with decreasing knob diameter.

5. When shaft friction is heavy, turning time is least for a 2-in.-diameter knob. Turning time becomes significantly longer than this minimum when diameter is increased beyond 2½ in. (up to at least 3¼ in.). Turning time increases rapidly with decreasing diameter at diameters smaller than 2 in. and becomes significantly longer at diameters smaller than 1¾ in.

6. The data very strongly suggest that operation time will be minimal over a variety of shaft frictions for a 2-in.-diameter knob only (±¼ in.). The data further suggest that operation time is only very slightly (if at all) increased by considerably increasing shaft friction when a 2-in.-diameter knob is used, but that increasing shaft friction has a more and more drastic effect upon operation time the farther knob diameter departs from 2 in., especially when the departure is a reduction.

CONCLUSIONS

For smooth operating (i.e., nondetented), single-rotation, cylindrical knobs, operation time will be minimized, regardless of frictional resistance, by using a knob diameter of 2 in.

A diameter as small as 1 in. can be used without greatly increasing operation time when frictional resistance is moderate (i.e., when 50 to 100 in.-g. of torque are required to turn the knob). When frictional resistance is heavy (so that 150-200 in.-g. of torque are required to turn the knob), diameter cannot be reduced below 1½ in. without considerable increase in operation time.

ACKNOWLEDGMENTS

The friction device used in this experiment was designed by Norman E. Stump. Jules Arginteanu ran the subjects and performed the statistical analyses.

The reported research was conducted by personnel of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Further reproduction is authorized to satisfy needs of the U.S. government.

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