a knob with axis pointing toward the operator and in line with his forearm, a diameter of 1 to $3^1/_2$ inches is satisfactory.[84]

One of the primary determinants of the size of a knob is the torque that is to be exerted upon it. This introduces one exception to the superiority of the four-pointed star shape mentioned above: when small torques are desired (65 to 110 pound-inches), a cylindrical knob 2 inches in diameter is preferable. If it is to be placed facing the operator, a circular knob with a heavy rim should be used since this can be easily grasped with the finger tips instead of the entire hand. To develop a torque between 130 and 175 pound-inches, the diameter should be 4 inches.[82]

In continuous-adjustment tasks involving the use of handwheel controls, the results of tests with two wheels were compared, one with a radius of $2^1/_4$ inches and a second with a radius of $4^1/_2$ inches. Relatively better scores were obtained with the wheel of larger radius at slow speeds, whereas the reverse was true at high speeds. Even a handwheel with an 8-inch radius can be used with slight advantage up to 60 r.p.m., although the maximum rate of turning is lower than with the smaller handwheels. This effect of handwheel size is small, but it appears from these studies that an optimum radius would be about 3 to $4^1/_2$ inches provided the friction is small (2 to 3 pound-inches). With handwheels in this size range, accuracy in use tends to increase with increasing handwheel speeds up to near the human limit of turning speed. Maximum accuracy for different handwheels varies from 140 to 200 r.p.m.[85]

e. Gear Ratio. The optimum gear ratio for tasks in which an operator sets a pointer by turning a knob, such as in radio tuning, is approximately $1^1/_2$ inches of pointer movement for every revolution of the knob.[83,86]

When a lever-type, nonlinear control (variable gear ratio) was tried, it was found that subjects responded as though they expected a linear response to their control movements. In a continuous-control task, no consistent differences in accuracy were found between tracking with linear and nonlinear levers.[78] However, when large discontinuous movements were being made, and the nonlinear relationship had not been explained to the operators, there was a marked advantage in favor of the linear lever. When the nature of the nonlinear lever had been explained and large discontinuous responses were made, the errors were reduced. However, there was little improvement with practice and a difference remained in favor of the linear control.

In continuous-control tasks, low handwheel-gear ratios and high handwheel

[84] K. J. W. Craik and M. A. Vince, A note on the design and manipulation of instrument knobs, *Rept. 46/ER2*, Med. Research Council Unit in Applied Psychol., Cambridge University, England, January 14, 1945.

[85] The Foxboro Company, Foxboro, Mass., Inertia, friction and diameter in handwheel tracking, *OSRD Report No. 3464*, 1943.

[86] A. Chapanis, Psychology and the instrument panel, *Scientific American*, **188**, 74–82 (1953).

speeds are advantageous when accuracy is important. This is particularly true for untrained personnel.[65]

f. Friction and Inertia. With continuous-winding tasks, viscous friction and inertia, as from heavy handwheels or flywheels, seem to have a beneficial effect on accuracy of control. In a lever type of control, however, friction has a negative effect.[87] This advantage of inertia tapers off more rapidly for small-radius handwheels than for large ones because of the force necessary to accelerate loads when using the small-radius controls.[85] Viscous friction and inertia are particularly valuable for accurate control under bumpy conditions or where vibration is present. Friction up to 4 pounds at the handle has been found beneficial, but it does not appear likely that the use of higher values would result in any improvement.[87]

In continuous-control tasks using handcranks, coulomb friction, or "stiction" has been found to have a deleterious effect on the smoothness and accuracy of the response. Values up to 7 pounds are increasingly detrimental; higher values are likely to be much more so. This effect is less apparent for high handwheel velocities and heavy handwheels.[86] Although this type of friction is practically always present to some extent in control systems, its reduction is apparently worth while where accurate control is required.

With lever-type controls for continuous-control tasks it is feasible to build into the system a pressure feedback cue that increases with displacement. This cue would supplement the position cue of the control and would probably enable the operator to know the position of his control better and thereby attain more accurate operation. The pressure, however, should not be so great as to interfere with the most rapid movement required in the task. Further, this use of pressure should be limited to situations where the control need not be operated over intervals long enough to result in undue fatigue.[2]

g. A Stable Platform for Operations. The operator of any type of machine or equipment should be able to maintain an upright posture on a stable working platform, whether seated or standing. Deviations from an upright position, such as occur in the bending of the trunk or body or in the extreme movement of an arm or leg, result in the nonproductive use of energy and hence reduce the efficiency of the work. Further, bending or rotating of the head or trunk inevitably alters the visual fields so that the view of the area may be modified or reduced. An operator should be able to move freely, shift his weight, and adjust to a more comfortable position whenever he so desires. He should not be required to carry out repeated major body movements for the performance of his task because of deficiencies in design of the work space.

However, some tasks may require fairly extensive body movements. In such cases the worker can, by movement of his trunk, adjust his center of gravity to the position of his base in many different locations. He can also extend his base in

[87] W. E. Hick, Friction in manual controls with special reference to its effect on accuracy of corrective movements in conditions simulating jolting, *Rept. 47/386*, Med. Research Council Unit in Applied Psychol., Cambridge University, England, June 18, 1945.