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THE DESIGN OF OPERATOR CONTROLS: A SELECTED BIBLIOGRAPHY

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FOREWORD

The work described in this report was initiated under contract by the Aerospace Medical Laboratory and the Flight Control Laboratory, Directorate of Advanced Systems Technology, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio. Research was conducted under Air Force Contracts No. AF 33(616)-5472 and No. AF 33(616)-7752 entitled, "Human Engineering Support to the Air Force Flight Control and Flight Display Integration Program." These contracts support Task 71573, "Human Engineering Support of the Instrument Evaluation Facility," of Project 6190, "Flight Display and Flight Control Integration Program." Mr. J. H. Kearns, Flight Control Laboratory, is the Air Force Project Engineer. R. H. DiVall, Captain, USAF, Engineering Psychology Branch, was the Task Scientist and Contract Monitor until 15 August 1960. At that time, Captain DiVall was succeeded by 1/Lt. J. P. Loftus, Jr. Dr. F. A. Muckler and Mr. M. R. Green served as Principal Investigators for The Martin Company.

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ABSTRACT

The purpose of this report is to present a bibliographic survey of research on critical variables in the design of operator controls. Major emphasis in selecting articles was placed on the problems of (a) types of manual operator controls, (b) selecting operator controls, (c) physical dimensions of operator controls, (d) inadvertent control operation and control coding, (e) environmental factors and personal equipment, and (f) layout of controls. Where pertinent, material has been added in the areas of (a) skilled operator movement characteristics and (b) display-control relationships. Of prime interest was the physical characteristics of operator controls.

PUBLICATION REVIEW

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TABLE OF CONTENTS

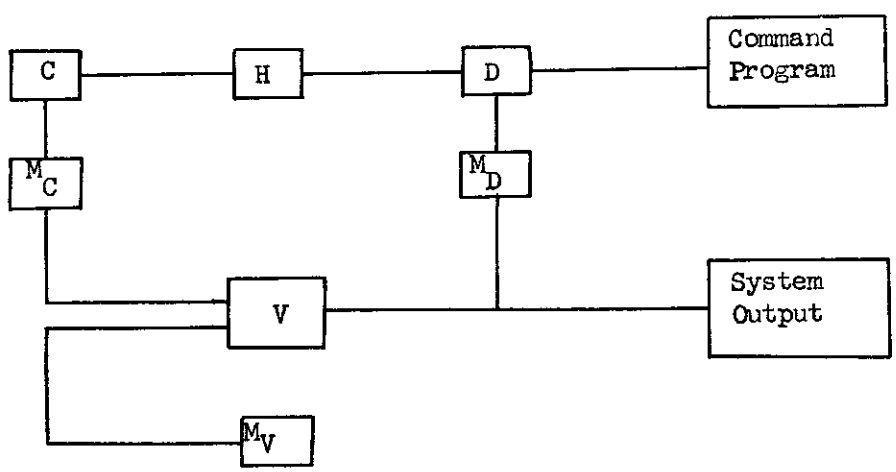
INTRODUCTION

Objectives of the Present Report

Design Elements of a Man-Machine System

The ultimate objective of any man-machine system is to achieve some desired system output. The effectiveness of any element of the system, whether machine or man, must finally be judged in terms of the contribution of that element to the total system output. An obvious design objective, therefore, is that the elements of the system be designed to make the maximum positive contribution without compromising the other elements. However, moving from these platitudes to actual system design is by no means a simple transition. The major problem encountered is the immense complexity of most man-machine systems, and the problem is most evident in the detailed design of the system elements directly connected with the human operator.

Even in simple diagrammatic form, the smallest number of pertinent system elements related to performance appears to be eight-fold. Taking for example, the closed-loop manual tracking situation, the following major elements may be distinguished:



These elements are labelled as follows:

- D = Display Information
- H = Human Operator
- C = Operator Controls
- V = Vehicle (Machine) Elements
- M_V = Modification of Vehicle (Machine) Dynamics
- M_C = Modification Performed on Operator Control Output
- M_D = Modification Performed on Feedback before Display

For most man-machine systems, each of these elements represents a major technical area. Literally hundreds of research publications are available, for example, on the display of information to the operator (D). And, if the system under design is as complex as manned aircraft, this element (D) may represent dozens of instruments all of which supply some item of information to the pilot or crew member. Further, in the case of manned aircraft, the unit (V) representing vehicle (or machine) elements consists of hundreds of separate items.

The Design of Operator Controls

The present report is concerned primarily with one of the units in the preceding figure, namely, the unit labelled "C" or operator controls. There is a growing literature pertaining to this subject, and the present report attempts to collect as much of that literature as possible in bibliographic form. The final section of the report, therefore, lists some 372 references that pertain to the design of operator controls. The major purpose of this bibliographic survey is to gather in one place sources of information that may be usable by design specialists in solving particular problems in operator control design.

However, no attempt has been made at this time to describe or evaluate the data contained in these references. The original reports obviously should be consulted for detailed information. For discussions of the general problem area and various aspects of the technical issues involved, the reader is referred to the list of General Sources presented in Section II.

Major Topic Areas

Selection Criteria

In the majority of investigations of man-machine systems, some form of operator control is used. Thus, a survey of the literature on operator controls could include all such studies where some form of control was involved, and it would probably become a survey of the entire field of man-machine systems. However, extensive bibliographic surveys of the field are already available (cf., e.g., 276*). Rather, an attempt was made to restrict the survey to the characteristics of manual operator controls alone. In so doing, a number of major topic areas were selected :

1. types of manual operator controls
2. selecting operator controls
3. physical dimensions of operator controls
4. control forces
5. skilled operator movement characteristics

*Throughout the various sections of this report, underlined numbers refer to the reference citation in the BIBLIOGRAPHY.

6. inadvertent control operation
7. control coding
8. environmental factors and control operation
9. layout of controls
10. personal equipment and control operation
11. control-display relationships

In some cases, an attempt was made to cover the particular area thoroughly. In others, pertinent literature only was cited since the topic went beyond the objective of this survey yet was a part of the overall problem of the design of operator controls.

A basic dichotomy may arbitrarily be established between (a) the physical characteristics of the operator's control and (b) the behavioral characteristics (e.g., speed, force, accuracy, etc.,) of the operator's response in using the physical control. In actual practice, of course, these variables are inextricably bound, but in evaluating the research literature it is sometimes useful in maintaining a distinction between them. With reference to the diagram on page 1, the physical characteristics of the control are represented by the box labelled "C". The operator's behavioral characteristics belong in the box labelled "H". The major interest in this report concerns "C", but it is impossible to exclude some of the related data on behavioral phenomena.

Types of Manual Operator Controls

Ely, Thomson, and Orlansky (114) list nine major control types:

1. hand pushbutton
2. foot pushbutton
3. toggle switches
4. rotary selector switches
5. knobs
6. cranks
7. handwheels
8. levers, and
9. pedals

The literature cited here is in large part concentrated on these particular controls. The selection criteria for citation were either studies which systematically investigated parameters of the control, studies involving a unique application of the control, or studies where a new control type was used.

Quantitatively, the literature appears to center predominantly on knobs, cranks, and levers. Investigation of crank parameters is among the earliest in the available literature, particularly with respect to the extensive studies reported from the Foxboro Company during World War II (132-136; 187). While many kinds of levers and sticks have been studied, much of the literature is devoted to the aircraft joystick. The recent widespread use of pushbuttons incites considerable interest in this control type, but the number of published studies is not large. The Bell Telephone Laboratories are understood to have conducted a very extensive program in the study of pushbutton parameters (e.g., 104).

There are a number of examples of complex control systems involving either combinations of the basic types or unique applications. Varieties of keyboards or keysets have been subjected to study (e.g., 6; 116) involving combinations of either pushbuttons or switches. There are many combined controls; for example, some operational aircraft joysticks may have as many as five knobs and switches mounted on the primary control. One type of combined control which has wide application is the ganged or concentric control (33; 43). Particularly of interest are two- and three-dimensional controls, of which the aircraft stick or wheel is the most common example. One of the earliest references to human engineering improvement of a complex control system is the attempts to improve the typewriter keyboards during the 1930's (e.g., 26). Despite very vigorous efforts in this area, little was accomplished presumably in large part because of the immense re-training problem involved. Two applications of complex control problems of great interest are investigations of remote control (91) and the design of prosthetic devices (177). The latter is, of course, a specialty area in itself.

Some controls have recently found application outside conventional lines. One pertinent example is the use of the small-sized "bowling ball" control for two-dimensional control tasks in replacement of other control types (e.g., 351). Even the simple stylus, so well known to psychologists through decades of research with rotary pursuit apparati (e.g., 3, 4, 5), has found other uses (e.g., 32). Perhaps the most disturbing lack in this literature, however, has been the apparent avoidance of the most common operator controls of all, namely, the design of hand tools. Only one reference could be found in this area- on hammer size (49). This would appear to be an area of great promise for control design.

Finally, there have been occasional passing attempts to classify control types particularly from the behavioral point of view (e.g., 86). Obviously, the classification of control types at present is simple enumeration based on common names, cranks, sticks, levers, knobs, etc. However, some of these types have very similar properties; for example, the rotary selector switch is very close to the knob except that the former is for discrete positioning rather than continuous positioning. Whether or not it would be useful to expend some effort on the problem of control type classification is a matter for debate.

Selecting Control Types

There are a number of excellent general discussions of this problem and the material will not be repeated here (cf., e.g., 114; 293). In general, the main criterion for the selection of the appropriate control type appears to be the overall task requirements; in short, what is the operator expected to do? Once the task and control requirements are stated, the control type or types are fairly clear and the rest is a matter of detailed design (cf., e.g., 114, pp. 2-7).

Experimentally, the major issue is the comparison of various control types for given operator tasks. A surprising number of studies were found in this area. Over 50 studies would appear to be applicable. However, with the exception of the studies of force-displacement gradients (e.g., 12; 155; 358) which have a remote application to begin with, there is no systematic series of studies on this problem. A wide range of experiments is possible, and it is believed that the results of these investigations would have very wide applicability. The need, however, is for systematic studies using a variety of controls and operator tasks rather than for additional isolated investigations.

Physical Dimensions

One of the most basic and most important aspects of control design is the physical dimensions of the control device. Most of the experimental literature on this problem appears to be concentrated on knobs and cranks. For example, some seven studies on the problem of crank radius alone are listed. A number of sources provide recommended physical dimensions for control devices (e.g., 114) based on a number of criteria.

The criteria for selecting optimum physical dimensions appears to differ according to the control involved. Cranks and levers are more closely bound to task requirements than other controls. The lever, for example, frequently must be designed to provide some mechanical advantage, and thus considerations of the operator may be secondary. This was certainly the case with the early aircraft joystick prior to the introduction of boosted controls. On the other hand, push-button sizes are often determined primarily by finger dimensions and spacing requirements. This might lead to the possible generalization that the physical dimensions of at least some if not many control devices are irrelevant to task requirements, provided minimum anthropometric and layout standards are met. Experimentally, studies of the interaction of control types, operator tasks, and control physical dimensions are implied.

Control Forces

In discussing the problem of control forces, the writer has found it useful to distinguish between the physical forces inherently a part of the control device* and the muscular forces exerted by the operator. The literature is very extensive in this area, and some attempt has been made to collect most of the directly pertinent studies. General discussions of the literature are not easy to find. Fitts (121, pp. 1316-1331) and Hick and Bates (199) are the best sources for basic experimentation since they discuss research results in the framework of general system theory. Chapanis, Garner, and Morgan (72, pp. 315-323) provide a very clear elementary report. Design recommendations for control forces may be found in Ely, Thompson, and Orlansky (114) and Woodson (371). For general treatments of control force problems in aircraft and flight simulator design, McFarland (280), Orlansky (287) and Muckler, et. al. (268) may be consulted. The question of human muscular force is properly that of the area of biomechanics and an annotated

*Ely, Thomson, and Orlansky (114) use the general phrase control "resistance" to refer to physical control forces. This distinction, although useful in distinguishing between physical control forces and operator muscular forces, will not be used here.

bibliography of pertinent studies is available (181). The extensive work of Dempster (105) provides significant data while at the same time superbly illustrates the immense complexity of the technical problems.

Physical Control Forces. Any operator control will include inherently many of the various parameters subsumed under the rubric of physical control forces. Control friction, inertia, damping, elasticity, loading, stiffness, centering- all these names represent forces against which the operator must work when he uses the control. Among these forces, effects of variations in control friction has been most widely investigated. Unfortunately, no clear pattern of results has emerged. Much the same can be said for the entire literature.

In most cases, the design engineer attempts to minimize force effects (e.g., friction and inertia). In other cases, however, the force feedback on the control provides information about the status of the system, and in aircraft control, force feedback may be systematically and deliberately introduced (e.g., 102) as part of the total pilot-aircraft guidance and control system. This technique implicitly assumes that the operator is able to discriminate and use changes in physical control forces. Thus, it may be seen that physical control forces may range in importance from undesirable residual effects to fundamental parameters in control system design. This fact is sometimes ignored when recommendations for physical control forces are made.

Operator Control Forces. Chapanis, Garner, and Morgan (72, p. 316) have succinctly summarized the significant problems in this area:

"In dealing with the question of control forces, there are usually three different values we would like to know for a particular control. One is the maximum control force, the greatest force that an operator can exert under any and all conditions of using the control. On the other end of the scale, we are interested in minimum control force. This is not a matter of physical exertion but rather of psychophysical discrimination.... Then, thirdly, there usually is an optimum control force, some value in between the minimum and maximum forces, which gives the best performance."

Each of these topics can be examined separately.

The study of maximum muscular exertion is predominantly a problem of biomechanics, and a number of studies has been published defining limit values (e.g., 64, 94, 160, 192, etc.). Much of this literature was motivated by aircraft design problems. Maximum pilot forces have been a major practical problem for some time, and, as aerodynamic loads have increased with aircraft performance, it has been necessary to add supplemental forces for the pilot (cf., e.g., 310). A major deficiency in this literature is the fact that, for the most part, too few subjects were used.

As Chapanis, Garner, and Morgan noted, the question of minimal control forces involves discrimination rather than strength. If physical control forces are introduced to provide information to the operator, it is reasonable to ask if the operator can indeed discriminate force changes. Definitive and classic data on this problem have been provided by the studies of Jenkins (226; 227; 228) for joystick controls.* Briefly, to indicate the type of findings, Jenkins' data and Hick's data (196) indicate high and positive constant errors with small forces, and a trend toward less error around 10 lbs.

The series of studies investigating the effect of varying force and displacement cues on performance is more sophisticated. The studies of Bahrick (12; 13; 14; 48), Gibbs (154; 155), and Weiss (358; 359; 360) represent superb examples of experimental rigor. Of particular interest are the studies of Gibbs where displacement cues are minimized and the so-called isometric or pressure control is used. Gibbs presents evidence that the pressure control is superior to the free-moving type control. The literature is not, however, consistent on this point, and a great deal more work is indicated.

The fundamental problem is that of the effect of feedback on skilled performance. Force and displacement cues provide proprioceptive feedback to the operator, and the question is, do these cues aid in skilled performance. This is hardly an academic question when control systems are being designed to deliberately provide these cues to the operator.

Optimum Control Forces. Despite the extensive literature in this entire area, the current state of knowledge can be summarized by a quotation from Ely, Thomson, and Orlansky (114, p. 25):

"An optimum amount of resistance cannot be specified as yet, and should be determined empirically for each specific task."

This is certainly not very helpful to the designer of operator control mechanisms.

Skilled Operator Movement Characteristics

In addition to the problem of operator force exertion and discrimination, effective control operation will be determined by the basic speed and accuracy abilities of the operator. That is, the characteristics of skilled movement must be known in order to predict control performance. The study of skilled movement has had a long theoretical and experimental history. There are a number of thorough reviews (e.g., 56; 185; 278, pp. 277-319; 323), so no attempt was made to collect this very extensive literature. One of the major activities of time and motion study has been the determination of the molar and molecular characteristics of skilled behavior (cf., e.g., 22).

The majority of this literature, however, have been concerned with the behavioral elements of skilled movement. There have been a number of investigations examining skill and accuracy of linear arm movements (e.g., 57; 191) and rotary hand movements (e.g., 70; 165). In fact, a rather large amount of literature has collected solely on precision settings with control knobs. Anaylsis of this type can be on the very molecular level (e.g., 182; 321). On the other hand, there appears

* The studies of force discrimination date back, however, at least to the beginning of this century (cf., e.g., 137, 372).

to be no systematic attempt to examine skill characteristics with various types of controls. For example, many of the variables studied with control knobs could also be studied with other types of controls.

On a somewhat more molar level, some studies have been concerned with simple speed and accuracy of reaching movements to various control areas. The classic study concerned the accuracy of blind positioning movements (122). Speed and accuracy of reaching for visual positioning movements have been investigated for the prone (50) and seated (163) positions. The findings of these studies have rather strong implications for the placement of controls spatially with respect to the operator.

A very old problem in skilled movements is handedness. This literature is immense, and no attempt was made to exhaust it bibliographically. Illustrative examples, however, include handedness and crank operation (303), handgrip controls (84) and knob operation (38).

As noted, the analysis of skilled movement is an old and complex area. No attempt is made to cover this literature which, in fact, would be an undertaking of great magnitude. Reference was made to literature and theoretical reviews, and they should be consulted for any operator control design.

Inadvertent Control Operation and Control Coding

Regardless of precautions, inadvertent and accidental control activation is probably a certainty for most control panels. The design objective is frequently said to be to make the control "idiot proof", but this is always difficult so long as the unconscious ingenuity of the operator exceeds that of the designer. The classic study of accidental control operation errors is Fitts and Jones (124) in their analysis of "pilot errors" in the use of aircraft controls. This study has apparently served as the impetus for a substantial amount of literature in the prevention of control operation errors.

As Ely, Thomson, and Orlansky (114, pp. 40-44) point out, there are a number of ways of preventing (or at least reducing) accidental control errors. They list such methods as: (a) recessing, (b) isolation, (c) orientation, (d) covering, (e) locking, (f) operation sequencing, and (g) control resistance. The most effective technique will probably be a function of the particular control situation.

By far, the most widely studied technique, however, is control coding. Control coding should achieve two objectives, first, reduction of accidental errors, and, second, improvement of operator performance. Many coding techniques have been studied including color (68), forms (10), letters (10), numerals (10), shape (47), size (27), and spatial reference (142). Quantitatively, the majority of the studies have investigated shape coding, and a great deal is known about this particular problem area. The definitive monograph by Hunt (215) on aircraft control coding is strongly recommended. The effectiveness of many of the coding techniques rests on the fundamental ability of tactual discrimination; illustrative examples of which have been included in the bibliography.

Many control operation errors are caused simply by inadequate layout and spacing of controls. The work of Bradley in this area for such controls as knobs (44), pushbuttons (45), and toggle switches (46) is definitive not only for the specific data provided but also for methodological elegance. Practical examples of crowded control panels are extremely common, and they may become even more so with control miniaturization. Reducing control sizes may solve some problems, but the overall gain may be negligible if it means increased operator error in the use of the controls.

Environmental Factors and Personal Equipment

For many man-machine systems, the environment in which the operator must work is hostile. This is particularly true of high performance manned aircraft, but it is also true of many terrestial occupations such as with arctic conditions. Operator control performance may be strongly affected by environmental factors, and accordingly, these problems must be considered in control design. Perhaps the most widely studied area in this context is the effect of acceleration on performance; several surveys of the literature are available (55; 157), and no attempt has been made to cover this field. Reflecting the advent of space flight, studies are beginning to appear on the effects of weightlessness and performance (e.g., 109; 332). In one area, environmental variables have been rather closely correlated with control performance. This is the study of the effects upon performance of either hot (66) or cold (250; 283) temperatures.

One direct way that environmental factors affect performance is through the use of personal equipment which provides protection against adverse environmental factors. Thus, the effect of clothing on dexterity (273), performance decrement (319), and muscular exertion (131) are examples of the kinds of studies of importance to control design. The effect of gloves on performance has been widely investigated particularly by Bradley (36; 39) and Grothe and Lyman (178; 179; 256; 257). With small control knobs, Jenkins (220) has reported the surprising result that gloved operation was superior to bare-hand operation.

The most extensive examples of the effect of personal equipment on performance come from investigations of flight pressure suits. Games, Lutz, and Vail (138), for example, were able to show in detail limitations in control accessibility and operator mobility due to wearing a pressure garment. Fine hand control under pressurization has been studied (e.g., 288) as well as gross mobility restrictions for various control areas (164). These kinds of data are particularly useful for control design and layout where pressure suits must be worn by the operators. It would appear, however, that each particular design problem will have to be examined specifically since the effects of suit pressurization appear to be based on rather complex interactions between the control and the individual subjects (e.g., 164).

Protection from adverse environments is essential for many man-machine systems, and this protection will be supplied predominantly by various forms of personal equipment. It is evident that personal equipment variables directly affect control design. Unfortunately, many current control panels do not take this factor into account, even where the application is clearly in less than optimum environments.

Layout of Controls

In the preceding discussion, several references have been made to the arrangement and layout of controls. The practical applications of this area are obvious, and extensive literature is available. An attempt was made to collect as much of this literature as was directly pertinent. However, the sample is selective, and more thorough bibliographies and surveys should be consulted (e.g., 7; 8; 113; 114). The handbook entitled "Layout of Workplaces" written by Ely, Thomson, and Orlansky (113) is specifically recommended.

Each of the major control types has received experimental study with results appropriate, in part at least, to the control layout problem. Thus, empirical data is available, for example, on (a) general panel layout (326), (b) cranks (150; 151), (c) ganged controls (43), (d) joysticks (333), (e) keyboards (6), (f) knobs (35), (g) levers (19), (h) pedals (209), (i) push-buttons (45), (j) toggle switches (46), etc. Many of these studies, in addition, have investigated interaction effects of great interest as, for example, the studies of Gerall, Sampson, and Spragg (149; 150; 151) on crank performance as a function of crank position, radius, and loading.

Previous mention has been made of physical dimensions of controls; these data also have obvious implications for layout. A central issue for control layout is minimum allowable control dimensions without performance decrement. Many complex control consoles require careful space saving. The extensive work by Bradley on a number of different controls is well worth careful study.

Somewhat more complex is the problem of spatial orientation of controls. The relative spatial position of the operator and the controls will distinctly affect operator force exertion (e.g., 209) particularly with respect to the prone (e.g., 51) and seated operator positions (e.g., 105). From the standpoint of performance *per se*, the plane of rotation of cranks has been studied extensively (e.g., 170) as well as the planes of movements of linear (lever) movement controls (e.g., 249). In these cases, however, performance levels appear to be determined not simply by control orientation, but rather by the relationships between control and display elements. This topic will be examined in the following section.

A final word on control layout concerns anthropometric data. The physical dimensions of the human operator must necessarily be considered in control layout. A great deal of anthropometric data is available (e.g., 76; 181; 193), but unfortunately these data are often ignored in practical applications of control layout. They are difficult to interpret and the interrelated phenomena are complex (cf., e.g., 105), yet effective layout is not possible without anthropometric evaluation.

Control-Display Relationships

As noted, many of the most important behavioral consequences of control variables are due not to control phenomena alone, but rather to the interactions between control and display characteristics. The study of control-display relationships is perhaps the most vigorously pursued research field in human engineering and dozens of publications are available. Since the area has received thorough bibliographic attention elsewhere (7; 8; 330), there was no reason to duplicate those effects here. Only that literature which seemed directly applicable to the previously discussed topic areas has been included.

An elegant study by Narva (282) illustrates the kinds of complex effects that may be involved in control-display relationships. Subjects positioned a spot of light on a scope face by using a small stick control. This control was used in three spatial planes: vertical, oblique, and horizontal. In each of the three spatial planes, two display-control sensings were studied. One sensing ("natural") was based on congruency between control and display movement (up-for-up in the vertical plane, for example), and the other sensing ("acquired") was based on a specific control-display movement relationship similar to aircraft control, (for example, backwards-for-up in the horizontal plane). Superior performance was obtained when the control moved in the same plane and in the same direction as the display element. Performance with natural sensing and vertical plane movement was consistently superior to other plane-sensing combinations. The data clearly indicate that performance levels were determined not solely by the control plane variable, but also by the interaction of control and display characteristics.

The results of this study are similar to others in this general area, and a major implication for control design may be stated. Changes in the level of operator performance (e.g., speed, accuracy, and force) may occur with variations of control parameters. In addition, however, changes in control parameters may result in complex interactions with display elements. The designer should be aware of this possibility when designing operator control mechanisms and systems. A simple change in the control may well introduce undesirable control-display relationships.

Summary and Conclusions

The purpose of this report is to present a bibliographic survey of research on some of the critical variables in the design of operator controls. Major emphasis was placed on the problems of (a) types of manual operator controls, (b) selecting operator controls, (c) physical dimensions of operator controls, (d) inadvertent control operation and control coding, (e) environmental factors and personal equipment, and (f) layout of controls. Where pertinent, additional material was used in the areas of (a) skilled operator movement characteristics and (b) control-display relationships. Of prime interest were the physical characteristics of operator controls, and the survey was designed to serve as a bibliographic source of research in this area.

In an overview, research in this context is often characterized by thorough, systematic, and methodologically elegant programs. The studies relating to control coding, force and displacement cues, and the effects of gloves on control performance are examples. For the most part, however, the majority of the studies are isolated empirical demonstrations of particular phenomena which point to a possibly critical area, yet fail to provide the kind of detailed research data that is necessary for control system design. It is to be hoped that future research programs in this area will not suffer from this deficiency.

The literature in this area comes from a vast variety of sources, many of which are not generally available. It is very probable, therefore, that published studies have been missed which clearly belong within the general context. Omissions of this sort are probably inevitable, and it can only be hoped that the number is small. Access to the actual reports is another major problem; in some cases it may be surmised that the reports are simply not widely available and that obtaining them is a matter of great difficulty. Citations were not eliminated on this basis.

GENERAL SOURCES

It is difficult to find any thorough discussions of problems and facts connected with the design of operator controls. There are, however, a number of useful sources which examine certain aspects of the many variables involved in control design. Some of these general sources are listed below; for the most part their titles will be self-explanatory.

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SUBJECT INDEX

A

B

*Numbers following subject item refer to the citation number referenced in the BIBLIOGRAPHY.

C

D

E

F

G

H

P

R

S

T

V

W

AUTHOR INDEX

*Numerals following the author's name refer to the numbered citation in the BIBLIOGRAPHY

D

E

F

G

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