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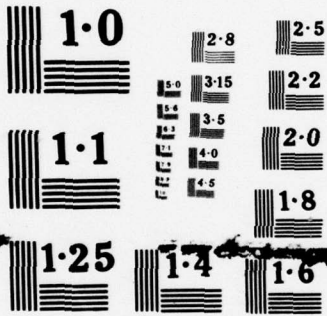
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ABSTRACT

This paper presents a critical review of the ergonomic literature on devices for entry and manipulation of data on a computer graphic display system. A general review is made of the extensive research effort devoted to studies of keyboard design and operation, and to studies of devices for target acquisition and tracking. The main body of the paper reviews the more recent body of published work on devices for man-computer interaction. Conclusions are presented on the nature and limitations of the existing body of human factors data on graphic display interaction devices.

INTRODUCTION

This paper presents a critical review of the ergonomics literature on devices for input and manipulation of data on a graphical display system. The research published on this topic can be divided into three fairly distinct areas: studies relating to the design of keyboards, both alphanumeric and numeric; studies of devices for target acquisition or tracking, which have been developed mainly for use in aircraft or in a related environment such as ground radar stations; and finally, a more recent (post 1965) body of data concerned with new devices used specifically for man-computer interaction. The first two areas will be covered in a general fashion with reference mainly to summary studies. The main body of the paper will deal with the third area in detail, discussing research methods, results and limitations.

KEYBOARDS

The majority of the research effort on data input devices has been devoted to studies of keyboard design and operation. Shackel et al. (Ref. 26) note in the concluding section of their review of computer input devices that 70% of the references are related to keyboard data entry. An excellent summary of the major issues involved in design of keyboards is offered by Alden et al. (Ref. 1). Under the topic of operator characteristics, they review work on physiological characteristics of performance, predicted typing proficiency, and the acquisition of skill. Design standards for individual keys, including key parameters and feedback are discussed, as well as keyboard characteristics such as key grouping, and keyboard slope, tilt and size. The large bibliography included in this report may be supplemented by another extensive one produced by IBM (Ref. 22). Although the authors include a list of general design considerations extracted from their review they conclude that despite a large research effort, "there are few definitive findings on which to base design standards".

Two major aspects of keyboard design, namely operating posture and key layout, are the subject of recent work by Kroemer (Ref. 15) and Ferguson and Duncan (Ref. 6). The main interest of these researchers is the problem of muscular strain and fatigue due to the horizontal position of the standard typewriter keyboard, the non-alignment of key rows to the hands, finger load, and operator seating. Ferguson et al. base their recommendations on keyboard layout for telegraph operators on concepts proposed by Dvorak in 1936. They recommend a key layout which distributes the typing load equally on each hand, and in decreasing keystroke frequency from the index to the little finger. Kroemer proposes that the keys be arranged in a hand-configured group and that the keyboard

sections allocated to each hand be physically separated and declined at an angle of 45 degrees. He demonstrated experimentally that this arrangement halves the number of typing errors compared to a standard keyboard. Both these studies illustrate the sound scientific approach necessary for solving the ergonomics problems associated with keyboard input devices.

In a paper concerned with maximizing the speed of numerical data entry, Hillix and Coburn (Ref. 11) discuss the factors influencing keyset design. The authors stress that the design of such keysets must be based on a thorough analysis of the processes involved in the particular task. This report concentrates on the encoding of input material and on the use of patterned pressing, as the means of increasing speed of transmission.

TRACKING DEVICES

The field of tracking skill and manual control has yielded a huge body of data concerning the influence of various parameters on human performance in target acquisition and tracking. These studies have involved mainly lever or joystick (both isotonic and isometric) controllers and have investigated factors such as the type of control system (i.e., position, rate or acceleration output), the influence of friction, backlash and system lag or lead, the size and type of controller (thumb-, finger-, or hand-operated), proprioceptive feedback, and the type of control output e.g., linear, exponential). A good summary of the major results in these areas is contained in Ref. 16. The following discussion is limited to those studies dealing with target acquisition, and especially to experiments comparing two or more devices.

According to Rowe et al. (Ref. 24), the crucial factor in optimizing the use of any control is the control/display relationship, that is, the ratio between the distance of control movement and the corresponding distance of display cursor movement. The control/display ratio influences both the time required for control slewing to access a distant target and the time for fine adjustment of the cursor for accurate positioning. The authors suggest that the optimum control/display ratio depends on the requirements of the task and should be established empirically for a particular task. Factors affecting the optimum control/display ratio include accuracy requirements, type and extent of display lag, and display size. Unfortunately many of the studies comparing different types of input devices have neglected to control this ratio.

One of the original studies comparing devices for target acquisition was conducted by Thornton (Ref. 28) in 1954. He compared a 5" diameter rollball with a 6" joystick for accessing a

radar pip at various distances along a straight line. Although the joystick was found to be faster for this task than the rollball, there are two factors that compromise this result. The first is the unusual mechanical design of the rollball, which was actually a bowling ball riding on a layer of compressed air. Although no details are given on the starting friction or inertia, these factors were likely much higher than those for present day rollballs which are lightweight and ride on almost friction-free bearings. The second criticism concerns the lack of standardization of the control/display ratio between the two devices tested. A 90 degree rotation of the joystick moved the cursor 10" on the screen, while one revolution of the rollball moved the pointer only 2½". This difference biased the experiment in favour of the joystick for long target distances.

In another study, Fox (Ref. 8) compared the efficiency of target acquisitions using three "hooking" devices: a trackball, a pressure stick (pencil-shaped) and an isometric joystick with a thumb-operated pressure button. Only five subjects were tested, and no differences were found that were statistically significant. Again, no information was given on control/display ratios, although in this study it could be considered that the experimenter was comparing specific hardware device configurations, as opposed to classes of devices.

In addition to producing a fairly comprehensive bibliography on tracking controls, (Ref. 18, 19) Mehr has experimentally compared trackballs and joysticks for a cursor positioning task. In a study in 1972 on manual digital positioning in two axes, Mehr et al. (Ref. 17) tested the performance of 24 subjects with five different devices; four joysticks and one trackball. Three of the joysticks were used as rate controllers, and the remaining joystick and trackball were used for position control. Subjects were required to position a dot (the cursor) inside a target to an accuracy of 0.1%. From an experimental design point of view, the study was not well controlled. The number of subjects on each test varied between 6 and 20 and subjects were not tested on all controls. Also, there is some question whether the experimental instructions were consistent for all subjects; the instructions were not explicitly outlined in the report. Furthermore, the article states that "changes were made in the control configurations... (which) should be considered as matching the characteristics of the control/display system to the operator's characteristic for a particular task". These changes were intended to "optimize" the control/display relationship by changing, for example, friction, control/display ratio, or the physical dimensions of the control. Experimental results are not presented for the various configurations for each control, but only for the "optimized" version. Even in these cases, it is not clear which parameters were changed for each control, and what the

new values were. Finally, the subjects were not allowed any learning time, and although learning curves were presented (based only on the first test), it must be assumed that the final results include the confounding factor of learning.

In the previously referenced study by Rowe et al., the relative merits of joysticks versus trackballs as control devices for moveable reference points and cursors on a CRT display were investigated. The authors' literature review concludes that bad mechanical design and lack of optimization of the control/display ratio have biased previous experiments in this area. They conclude that if the control is "properly adapted" to the particular task, there is no justification, in terms of human performance, in choosing one type of device over the other.

COMPUTER INPUT DEVICES

General Surveys

The majority of studies concerning devices for input and manipulation of data on a computerized display have been done since 1965. Most papers simply review the available devices, usually from a technical viewpoint, and make some general human factors comments about each.

One of the original surveys was done in 1967 by Sperandio and Bisseret (Ref. 27). The report is concerned mainly with the use of keyboards as input devices, although a substantial section considers "marker devices", briefly describing as examples the rolling ball, mouse, joystick, grafacon and light pen. It presents the results of some comparative studies performed elsewhere (Ref. 4, 5, 28). The summary ends with a mention of touch displays and automatic speech recognition, and concludes that all of the studies reviewed are lacking in human factors data. The authors comment that the results of most of the studies were limited by the fact that they involved "trying out" a device in isolation, so producing no basis for generalization from the findings.

A similar, more exhaustive review was done in 1970 by Shackel and Shipley (Ref. 26). Again, the majority of the studies reviewed were devoted to the use of a keyboard as the input device. The authors divide input devices other than keyboards into two categories. The first includes thumbwheels and numerical input devices such as push buttons, and rocker, slide and toggle switches. In this category, an extensive review by Pollock and Gildner (Ref. 21) is cited as the most complete reference manual for the designer. In the second category of "experimental" two dimensional graphical input devices, the authors include the light pen, rho-theta pen,

Rand tablet, and the potentiometer devices such as the joystick and joyball. A short description of each device is given, followed by results from any evaluations of the device. In most cases, the results of the evaluations are often the opinions of the writer, and are not based on rigorous experimentation (e.g., Fletcher (Ref. 7) claims that the rho-theta pen is "easy to use"). Shackel et al. describe the results of the comparative studies which have been conducted to that date. These will be discussed in detail later in this paper. However, their conclusion was that there is little data on the relative merits of the various input devices, and on their suitability for tasks from the user's point of view. More studies should be devoted to optimizing the design of these equipments and such studies should be tackled using a systems approach.

Cropper and Evans (Ref. 3) include a brief discussion on input devices in an article on "Ergonomics and Computer Display Design". Again, their conclusions are limited to the obvious advantages of each device (e.g., the light pen is best for tasks involving pointing at the screen). They remark, for example, that no studies have been conducted on the time and skill required to move a cursor using a device which is not adjacent to the screen. The work by Earl and Goff (Ref. 4) and by English et al. (Ref. 5) are cited as the two major comparisons on the effectiveness of different devices, with the comment that "further work is required to extend the validity of these results to other applications areas".

A more recent survey conducted by Ritchie and Turner (Ref. 23) classifies the common graphical data entry hardware and describes various technical features. This paper contends that graphic input devices perform one of three functions: selection of a displayed item, freehand sketching of pictorial data, and tracing or digitizing of original hard copy. Currently available devices are categorized into four classes: mechanical input devices (roll-ball, joystick and mouse) which rely on feedback from the display to establish position of the cursor; the light pen; electronic data tablets; and the touch entry devices. The paper concentrates heavily on the principles of operation of the various data tablets. According to the author, a critical comparison of the different types of devices is not made since "it is the application which largely determines the suitability of a particular device". No ergonomic data is presented on any device, although the authors conclude that a versatile graphic terminal should include a tracker ball for accurate positioning of a cursor and a transparent tablet for a data selection function and, when detached from the display, for sketching and tracing.

Another report by Hunstad and Brown (Ref. 13) states the advantages and disadvantages of some of the devices used with an air traffic control system, for accessing both randomly positioned PPI information and tabular data. The different types of operator input are classified as: designation of a geographical point, designation of a zone or symbol, functional commands or data input. Rollballs, light pens, touch wire displays and keyboards (both standard and function boxes) are the devices considered for each of the four functions. It is concluded that the rollball is essential for indicating position on the PPI, and that either a touch wire system or a standard alphanumeric keyboard is best for data input, depending on the flexibility required. Again, although the discussion considers the task from the user's point of view, no experimental data is given.

Sawchuck (Ref. 25) also presents a complete review of graphical input devices, with a particularly good summary of the different types of data tablet input techniques, including a chart of the current manufacturers and technical specifications. He states that although any of several devices may be technically capable of performing a given graphical function, the devices may not be "psychologically" equivalent for the function. He calls for more complete evaluations of graphical input devices, particularly from the human factors viewpoint, and stresses the need for comparisons which consider such factors as the learning time of the user, selection times, and fatigue.

Instronics Ltd. recently completed a survey of "pointing" devices for potential use with PPI and tabular displays in an air traffic control environment (Ref. 29). Twelve devices were reviewed from both the functional and ergonomic standpoint, although no actual comparative evaluations were reported.

The devices were divided into two classes: direct devices which have the pointer and the display on the same line of sight (e.g. light pen, graf/pen, touch sensitive digitizer); and indirect, which do not (e.g., function box, rollball, RAND tablet). The report offers the opinion that the direct method of interaction is "natural" and fast, once the pointing device or stylus is in hand. Disadvantages of this method are the time required to actually locate and grasp the stylus, the operating posture, which can be fatiguing, and the fact that there may be some blockage of vision of the screen. Also, parallax caused by the thickness of the display glass or by an overlay may lead to inaccuracies in tasks requiring fine positioning. Indirect methods of interaction are claimed to have the advantage that no screen overlay is required, so the image is not distorted, and the cursor permits relatively accurate positioning. The indirect nature of cursor positioning and the slower speed of target acquisition are cited as disadvantages. Also, data tablets used this way occupy workspace in front of the display.

The report reviews each of the twelve devices individually on the basis of method of interaction, standard applications, type of pointer, configuration, mechanical/electronic considerations, and ergonomical considerations. Few actual experimental studies were used to support conclusions about ergonomic aspects of devices, and the comments tended more to qualitative judgments, such as device being "enjoyable or "natural" to use. The best choice from among the indirect devices was considered to be either the rollball or the joystick. No final choice was made between the two, since although the joystick could be slightly faster, "some controllers seem to prefer the trackball". Of the direct interaction methods, the touch sensitive digitizer was the preferred device, despite acknowledged problems of resolution. The choice was supported by reference to ergonomics experiments on touch wire displays, which are a related type of device. The report claims that from an ergonomics viewpoint, the trackball is more cumbersome and time-consuming to use than the touch sensitive display. However, this claim is not supported by reference to experimental evidence.

Evaluations and Comparisons

This section discusses several experimental evaluations and comparisons of graphic input devices.

One of the earliest studies comparing two input devices was conducted by Hick and Fraser (Ref. 10) in 1953. They compared a joystick-like control with a pencil control for acquiring targets on a simulated radar scope (using 35 mm slides). For subjects trained to a standard accuracy, the pencil control was significantly faster. The experimental apparatus involved mechanical linkages on the control handle which moved on a horizontal plane to the right of the display.

In another experiment, Earl and Goff (Ref. 4) studied two different methods of alphanumeric data entry. They compared the performance of operators typing words (of 3-7 characters in length) with a pointing method of input which simulated light pen selection from a displayed menu. The display was simulated by a large book containing lists of words. Subjects were presented with three source words that had to be searched for and marked on the "display". Any words not found on the display had to be typed on an electric typewriter. (Subjects were cued when all or none of the source words were on the displayed list). Speed and accuracy of performance varied, depending on the number of words the subject had to type. In a comparison between the point-all and the type-all conditions speed was about the same, but accuracy was much higher for the former. For the point-one, type-two words condition, performance was disrupted because subjects found they could not remember which source word had been identified. Since the subjects had to physi-

cally turn away from the source information to use the keyboard, it was difficult for them to compare words typed on the typewriter with the source.

The experimental situation suffered from lack of realism. For example, the stimulus material was typed, making the clarity of presentation better than on most CRT's. Additionally, it is questionable whether marking with a pencil for indication of words is comparable to using a light pen.

One of the few studies to compare several display selection devices, using an actual computer display, was conducted at Stanford Research Institute in 1967. English, Englebart and Berman (Ref. 5) were interested in text manipulation by experienced and naive users in an on-line environment. The task involved choosing the center "X" out of different groups of "X's" on the screen using one of six different selection devices: grafacon, joystick (position or rate control), mouse, light pen or knee control. Eight "experienced" and three naive subjects were used, although the knee control was not studied with experienced subjects.

For inexperienced subjects, the knee control was fastest, followed by the light pen and mouse, but the error rate was smallest for the mouse. Errors rates for the light pen were high. For experienced subjects, the mouse was fastest, followed by the light pen and then the grafacon. Errors were also least for the mouse. The joystick ranked lowest for almost all conditions. No statistical measures are presented, so it is difficult to judge the relative significance of these results. One factor was not controlled was the control-display ratio (ratio of cursor movement to device movement); it was 4:1 for the joystick, and 2:1 for the grafacon and the mouse. A lack of fine control for the joystick may have contributed to its poor showing. As many of the devices had inherent ergonomic faults, (e.g., the mounting on the light pen was "rather clumsy"), the authors caution that the results of their tests should not be applied to the class of device used, but only to the particular examples used.

Morrill et al. (Ref. 20) compared the use of a light pen and typewriter as input devices in computer-aided instruction for a management information system. The instructions concerned basic techniques for entering messages to the management information system and the structure and modification of data files. In an initial learning phase, subjects were scored on the basis of how long it took to complete the instruction sequence and the number of errors made. Subjects were also scored on a test sequence containing the same exercises as the initial learning sequence, but administered three days later.

Statistical tests indicated that during the learning portion of the study, the time taken to enter information with the light pen was significantly longer than with the typewriter, but this finding did not hold in the test sequence. There were important differences in the instructional materials used by the subjects for the two device conditions, despite efforts to make the sequences as similar as possible. For example, use of the light pen involved displacing instructional material from the screen, making it periodically unavailable to the subject. Also, individual differences in subject's performance were sufficiently large for even the experimenters to question the results.

This study illustrates some of the major problems in controlling experiments of this sort. The more complex (and hence realistic) the experimental material, the more confounded are the effects. In many cases there are intrinsic differences between operating devices, especially involving the design of the interface with the computer, that often are not, or cannot be experimentally controlled.

In one of the few experiments to study simple target acquisition times, Goodwin (Ref. 9) looked at the use of three input devices, the light pen, light gun and function box, in a cursor positioning task. She used three standard basic tasks involving tabular data presentations. In the first, subjects were required to find, and replace with an "X", the digits 0 through 9, which were randomly positioned on a display screen otherwise filled with "/". The second task involved sequential replacement of the letter "M" by "X" at ten locations on the screen. The third task was to proof-read a piece of text and "cross out" the mistakes with "X". No difference in speed was found between the light pen and gun, but both were significantly faster than the function box. Unfortunately, the keys for cursor positioning on the function box were not well designed for the task. Instead of the set of four keys - up, down, left, right - usually provided for cursor movement, subjects had to employ the standard space, tab and carriage return. Backspace, and inverse carriage return were coded by shift-space and shift-carriage return respectively. The wide spacing of these keys on the standard keyboard no doubt increased the difficulty of use. The author concludes that the speed of target acquisition in this type of task will be heavily dependent on the actual design features of the device, factors such as the ease of grasping the device, position of the selection button, friction, feedback and the control/display ratio.

Cassell (Ref. 2) reviews the common data input devices, and reiterates the lack of associated data on their operating characteristics, and the requirement for human engineering evaluations. He points out that although systems designers will go to great lengths to validate new software data structures, hardware receives little attention. He describes a seven phase experiment designed to compare the selection of input functions using a function box, a light

pen and menu, or a typed input. Performance, in terms of speed and accuracy, depended on whether the menu or function box displayed all 28 possible choices for each selection, whether a reduced number were shown, or whether the choices were paged in groups of seven. Performance was similar on all devices when all function choices were shown at once, but improved equally for the function box and the light pen when the number of function choices was reduced.

The suitability of the Johnson touch-wire display for application to air traffic control tasks was studied by Hopkin et al. (Ref. 12) in an experiment to compare use of the device with keyboard data entry. The experiment was limited to consideration of this specific application, rather than a general evaluation of the touch-wire display. Even though no attempt was made to optimize the design and implementation of the touch wire display (in terms of number of wires, their spacing, and the layout of the functions), a distinct reduction in the number of operator errors was found with that device. The authors also point out that operation of the touchwire display is less dependent on the order in which aircraft information is received, and that the user can be lead more easily from one step in the operational sequence to the next (and back in the sequence, if desirable).

In a pilot study undertaken to determine the best device for a drawing task which was to be used in subsequent experiments on continuous subjective functions, Irving et al. (Ref. 14) compared the light pen, rollball and joystick. Subjects were required to draw two simple geometric figures, a triangle and a circle. This particular task was chosen because it involved both sketching and pseudo-tracing aspects. Nine variables were defined as performance measures, including the straightness of the sides of the triangle, the constancy of lengths of the sides, the constancy of angles, and the constancy of the radius of the circle. It was found that the trackball was, for most measures, the superior device, particularly for straight line tracing and sketching.

CONCLUSIONS

Very little human factors data exists on devices for graphic display interaction, and particularly for light pens and data tablets. While there have been many reviews describing and comparing the technical aspects of device hardware, very few studies have investigated the ergonomics aspects of device design. There is an especial lack of experimental data on the relative merits of different input devices and on their suitability for the variety of graphics interaction tasks.

The following additional comments can be made concerning the reports reviewed.

1. Many of the early experiments on target acquisition devices and computer input devices have been outdated due to changes or improvements in the design of these devices (e.g., rollball, light pen).
2. Most experimenters compared specific control devices, rather than a representative or even "optimum" sample from a class of controls. This has limited the general applicability of their results.
3. There has often been a lack of detail on, and control of, parameters that could affect performance -- physical design features of a device, feedback, response time, and especially control/display ratio.
4. There is no standard test material encompassing the many types of graphic input tasks (e.g., picking displayed items, entering alphanumeric data, drawing) which can be used for device comparisons.
5. It is difficult to standardize the software interface (i.e., methods and language of interaction) when comparing different devices.

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