Systematic Analysis of Factors Determining Accuracy in Visual Tracking[1]

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A GOOD PART OF EVERYDAY BEHAVIOR of most people depends on the ability to do visual tracking. Moreover, the understanding of this behavior is today a central problem of human engineering, inasmuch as the study of visual-motor tracking typifies the requirements of analysis of the relations between human response and the design of machinery and equipment.

This study is an attempt to develop systematic experimental methods for the comprehensive investigation of the role of different factors in determining accuracy in tracking. Observations are described concerning the effects of the following factors on tracking precision: (*a*) the instrumental relations of the tracking motion, (*b*) the ratios of motion between hand controls and visual cursor, (*c*) learning in relation to different component movements in the tracking response, and (*d*) target characteristics.

Methods

Fig. 1 illustrates diagrammatically the main elements of an apparatus designed to control in a systematic way the factors of significance in determining precision in visual-motor tracking. The operator in this task adjusts a hand wheel or some equivalent device in order to move a cursor with reference to a target. The latter travels radially through a predetermined course approximately in the same plane as the point of the cursor.

The device shown in Fig. 1 consists of (1) a target-cursor display, (2) a hand-control system, (3) a universal tracking control system, (4) a target-course generator system, and (5) an error recording and summating device. The general nature and purposes of these components are described below.

1. *Target-cursor display.* The display is located about 1.3 m from the hand wheel. The target, mounted on a rotating disk, consists of a visual pattern that may be varied in size, color, and form. The outer edge of the disk is hidden by a stationary shield. The cursor is a narrow arm, the center of rotation of which is the same as the target disk. A cursor of a visual angle of 4 minutes in width is typically used. Parallax effects between target and cursor are eliminated, inasmuch as their planes of movement are almost the same. The design of the target-cursor display permits wide variations in the visual characteristics of both these elements of the presentation.

2. *Hand-control system.* The manual control pictured in Fig. 1 is a hand wheel 18.4 cm in diameter. This system permits control of the cursor with either hand or with both hands simultaneously. In addition, the system provides for changing the physical characteristics of the hand control, as well as its inertia and damping. The manual control system is arranged to permit study of all the various bodily components and space dimensions of tracking motions.

3. *The universal tracking control.* The component labeled "Universal Tracking Control" is a device for changing the type of tracking to be performed by the operator. Three types of tracking are possible through the use of this instrument: direct, velocity, and aided tracking. Fig. 2 illustrates the principles underlying these three types. In direct tracking, two component motions are used to position the cursor and change its rate of movement with respect to the target. In velocity tracking, the operator controls the cursor entirely through adjustment of the direction of rotation and the speed of a motor shaft. In aided tracking, direct positioning of the cursor is possible, and in addition the rate of movement of the cursor is controlled through a motor system. There are three basic differences between the different types. Different components of motion are used, and distinct translations and transformations of these motion components occur in each type. Finally, in aided tracking, complex mechanical differentiation and integration of a single basic positioning movement occur.

The universal tracking control picture in Fig. 1 mechanizes all three types of tracking control diagrammed in Fig. 2. Thus, by means of this device, it is possible to study under comparable conditions some of the different types of tracking used in modern machinery.

4. *Target generator system.* The target generator system consists of a ball-and-disk drive actuated by a constant-speed motor and controlled by means of a motor-driven cam that determines the target course. Variable target courses may be obtained by substituting one cam for another. In the studies reported here, a target course involving nine reversals of direction of movement with continuously changing velocity and magnitude of movement in each phase has been used.

5. *The error recording system.* Error recording in

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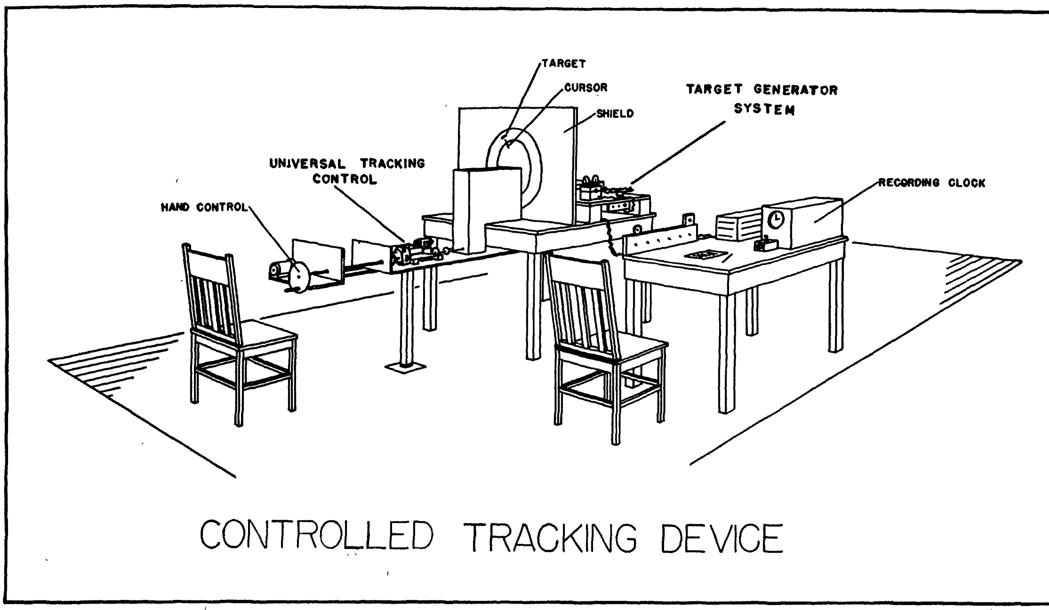

FIG. 1. The components of a preplanned performance situation for analysis of visual motor tracking.

this instrument is accomplished by means of an especially designed differential that continuously compares target and cursor position. The output of the target generator system drives the field of a precision selsyn that is attached to the center of the target disk, and the controlled cursor moves with the shaft of that same selsyn. The generated signal from this selsyn drives a receiver selsyn. The output of the receiver is employed to obtain a graphic error record, as well as an accuracy time score, that represents an integration of both frequency and magnitude of error.

In general, the apparatus described here has been developed to provide quantitative variation and experimental control of all the discrete factors of motor response and visual presentation concerned in tracking motions. In particular, this device makes possible the analytic study of separate body components of motion, of different space patterns of motion as utilized on various types of manual control, of separate component movements in tracking, and of different types of translations, transformations, and physical integrations of human motion used in modern remote-control machinery.

EXPERIMENTS

1. *Precision in different types of tracking.* Fig. 3 illustrates the nature of learning in direct, velocity, and aided tracking. These results show that proficiency in direct tracking is superior at all stages of practice to either velocity or aided tracking. The degree of change that is due to learning is greatest for the velocity tracking. In obtaining the data shown, optimal displacement ratios between the hand wheel and cursor were used for all three types of tracking. These ratios were determined in separate observations. In addition, the aided tracking ratio was set at 0.5

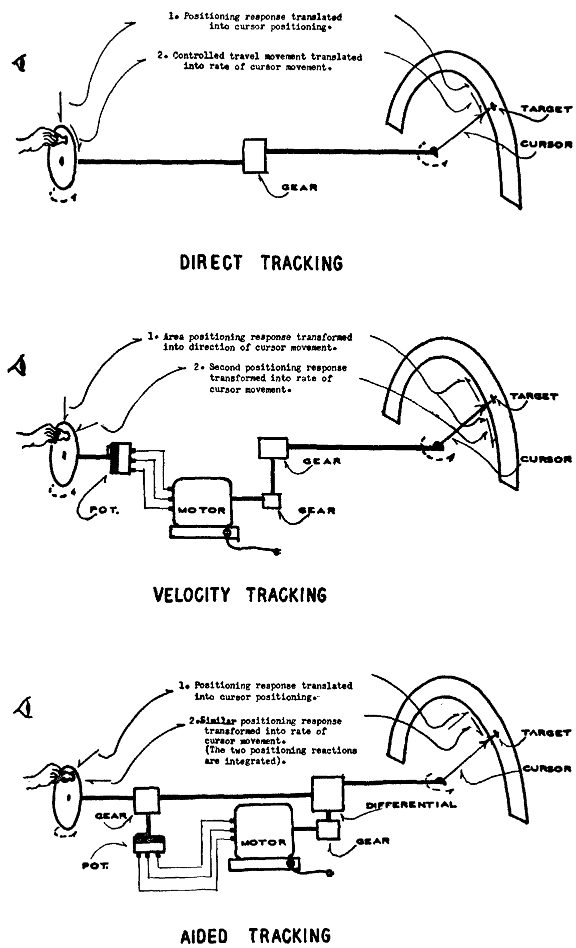

FIG. 2. Types of visual pursuit tracking.

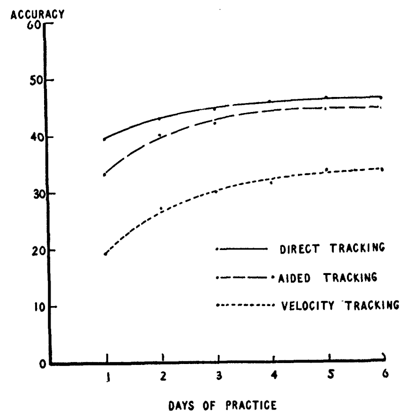

FIG. 3. Accuracy in different types of visual tracking as a function of practice. The accuracy level represents a time score integrating magnitude and frequency of error. These curves are based upon study of three groups of subjects, 18 subjects to the group. Subjects were randomly assigned to the groups.

seconds, a value that has been generally determined to be the optimal ratio for different types of equipment. This value is the one typically built into all modern aided tracking devices. Over all, the results presented here mean that, in the tracking of complex courses, the common types of aiding devices constitute no real general aid to the operator. This statement may not cover special situations in tracking, such as aerial gunnery, etc., in which target course is extremely uniform in direction, and in which rate control, especially that provided by aided tracking, may simplify a component aspect of the tracking problem. But such possibilities require more specific study.

It may be of significance to note that the degree of accuracy is related to the extent to which the manual motion is instrumentally modified in the different types of tracking. In direct tracking manual motion is translated proportionately into cursor motion. This type is most accurate. In aided tracking, one of the translations of direct tracking is retained, but there occurs a transformation of the prime positioning motion with respect to the cursor. Aided tracking is next in accuracy. Finally, velocity tracking involves a complete transformation of all components of the performed motion and is the least accurate of the three types. The effects of practice do not overcome the basic differences in precision occurring in these different types.

2. *Optimal ratios between hand wheel and cursor motion for different types of tracking.* Fig. 4 describes the level of tracking accuracy as a function of the ratios of motion between target and cursor. For direct and aided tracking the ratios indicated represent the unit displacement of hand wheel relative to unit displacement of the cursor. For the velocity tracking, the ratios represent the increment in velocity of cursor movement per degree of hand wheel rotation. The data for aided tracking apply to both component elements of the system, but the figures are given in terms of the ratio for the positioning component.

The results cited are considered preliminary in defining the instrumental relations of the different types of tracking. Data on the velocity tracking are held to be very tentative, mainly because the optimal value changes in relation to training, and the value found is not particularly decisive in its own right. The data show, however, that optimal instrumental relations vary for different types. The experiments also indicate an important psychological aspect of human instrumentation research; namely, the necessity for establishing optimum conditions for different operational

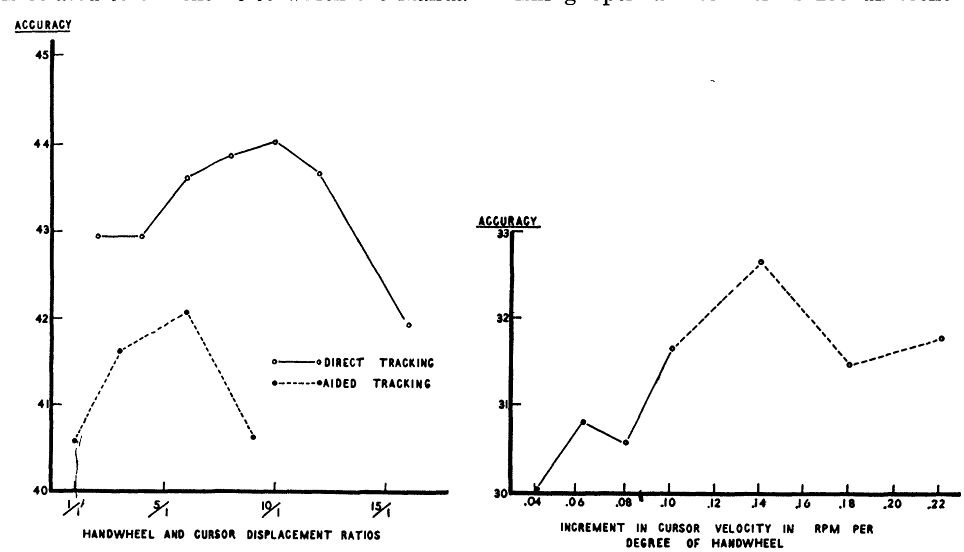

FIG. 4. Optimum ratios of motion between hand wheel and cursor for different types of tracking. The curves for direct and aided tracking are based on two groups of subjects, eight subjects for direct tracking and four for aided tracking. The curve for velocity tracking is based upon two groups of subjects, four to the group. One group tracked the lower ratios, and the other group the higher. The value .10 rpm was common to both groups. The two curves were adjusted in height in order to correct for sampling differences and for differences in practice of the two groups.

functions before these functions can be compared.

3. *Effect of learning on component movements.*[2] The motor pattern in direct tracking is not a uniform single response. In reactive terms, it is made up primarily of two components, a rapidly oscillating positioning motion and a travel motion of longer wavelength that controls rate of cursor movement. Analysis of these components is fundamental to all aspects of understanding the behavior concerned.

In Fig. 5 are shown results bearing upon the effects of learning on different component movements in direct tracking. These curves represent the change in occurrence of response components of different wavelengths as a function of practice. The short wavelengths represent, for the most part, positioning error. The long wavelengths represent mainly rate error. The intermediate curves probably represent a mixture of both components of motion. The curves themselves describe how frequently these different component movements involving error appear with successive days of practice.

Reference to Fig. 5 will show that practice affects mainly the most rapid positioning movements. These error motions are reduced fairly sharply as practice continues. The longer wavelength, rate-control movements of direct tracking seem to display no change in frequency as a function of practice.

Fig. 5 also summarizes the change in occurrence of the different motion components in relation to three different target speeds. The greatest learning change in positioning motions occurs for the fastest and intermediate target speeds.

4. *Effect of target characteristics.* It is generally thought—and this belief is expressed in terms of current designs of cursor and reticle elements in tracking devices—that accuracy in tracking is related closely to the degree of refinement in size and contour cues provided by the target and cursor. We can investigate this problem of perceptual discrimination in tracking in one way by varying target size.

Fig. 6 shows the change in over-all accuracy in direct tracking as a function of target width. There is relatively little change over a width variation of some thirty times. These results were obtained with an overlapping cursor. In some observations made on this problem it has been found that the most accurate tracking is obtained with target sizes exceeding the width of the cursor, although this effect is not clearly seen in the results shown in Fig. 6.

The results just cited are not due to the fact that the error tolerances were changed as a function of target size. In these studies, the accuracy requirements for each target size remained constant. The subject had to center his cursor on the target no matter what its size happened to be. In the investigations on this point, target size was varied by inserting patterns of different radial extent in a special mount on the target disk.

[2] This part of the study was aided by the work of Richard Simon and Thurlow Weed De Crow in the analysis of record data.

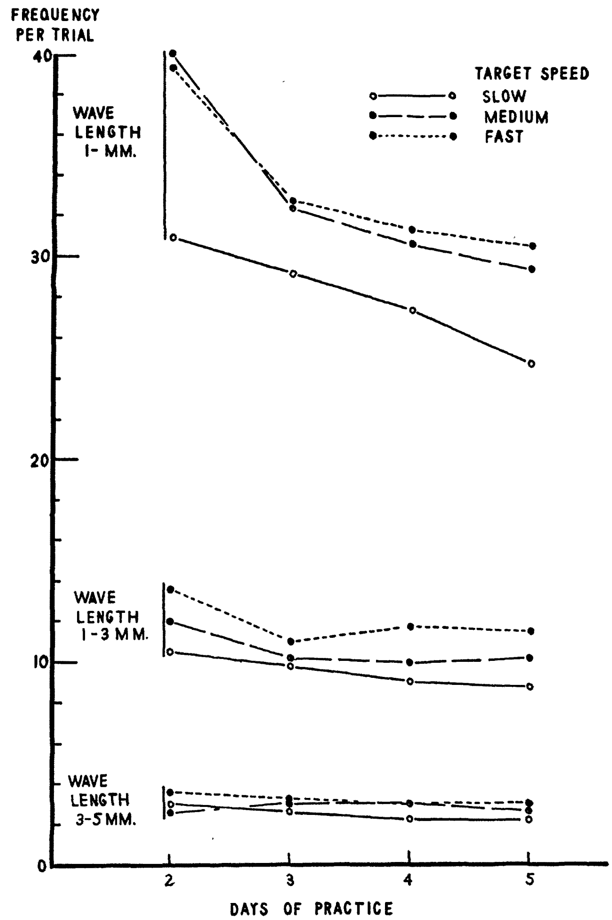

FIG. 5. Frequency of error responses in direct tracking for different target speeds and for wavelength categories as a function of practice. Target speed is designated as slow, medium, and fast. These represent, respectively, motor speeds of the target generator system of 23, 30, and 37 rpm. Because the target course is variable, it is not possible to describe target speed in terms of actual velocity of the target. For obtaining counts of wavelengths of error movements, the recording tape moved at the rate of 5.0 cm/min. Each trial was 1 min in length. Three groups of subjects were used in the experiment, 12 subjects to a group. Separate groups tracked at the different target speeds.

With the use of both overlapping and vernier-type cursors, observations have also been made on effects of changing target width over a range of some ten times the value of the most limited target width. Within these limits, accuracy in tracking does not decline significantly for either type of visual presentation as target width is increased. Such observations suggest that perception in tracking involves discrimination based upon pattern organization of target and cursor. The specific psychophysical function is one of scaling or bisecting of the target rather than one of reaction based on specific alignment of contours.

One of the most decisive perceptual factors determining precision in tracking is the velocity of the target to be tracked. This fact has already been indicated visually in Fig. 5. No other mode of change in the visual presentation, unless it be radical in nature, alters accuracy in tracking as much as target velocity. Furthermore, practice effects do not obliterate the fundamental differences in precision related to the speed of the target. As shown in Fig. 5, the frequency of error movements, especially the positioning movements, is directly related to target velocity. So is the magnitude of these movements.

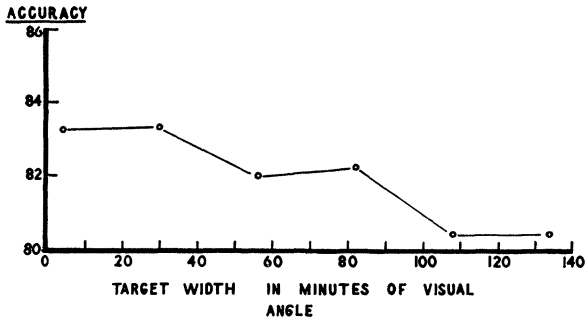

FIG. 6. Accuracy in direct tracking as a function of target width. Seventeen trained subjects were used in the experiment, and all subjects tracked all different target widths.

SUMMARY

The experimental study of visual-motor tracking exemplifies the requirements of systematic analysis that are necessary for understanding many different types of human response and work.

We may systematize the specification of motor behavior for investigation of problems in psychology and human engineering by reference to (1) the reactive components of motion and (2) the different dimensions of motion. Study of the physical and physiological factors determining human motion, as well as measurement of the effects of growth, learning, fatigue, and other dynamic aspects of response on motion, may be carried out in a meaningful way when the basic components and dimensions of a pattern of motion are known and controlled. Dimensional analysis of tracking motions has brought out the following main facts:

1) By the use of appropriate devices it is possible to develop preplanned performance situations in which all the main reactive components and dimensions of human motion in the task may be quantitatively varied and specified for experimental investigation.

2) It has been established that accuracy of performance is greater and the degree of learning is less in direct tracking than in types of tracking in which some aid is provided to the operator. These differences in direct, velocity, and aided tracking may be accounted for in terms of the extent to which the performed tracking motion is modified by the tracking device in producing movements of the observed cursor.

3) The comparison of the different types of tracking devices and of other types of machines in relation to their adequacy for human use involves more than observation of general performance on such equipment. Before comparisons can be made in a meaningful manner, the optimum conditions of translations, transformations, and integrations of performed motion by the different devices must be known. The determination of optimum ratios between manual motion and cursor motion for different types of tracking has been indicated.

4) The positioning and rate control components of tracking motions are affected quite differently by factors determining accuracy in tracking. The learning effects on frequency of error in direct tracking occur almost entirely in the positioning components of the motion. There are no general laws of learning of significance in describing various concrete phenomena of visual-motor tracking.

5) Study of the visual display in direct tracking discloses that the specific psychophysical function of pursuit tracking is one of scaling the target by means of the controlled cursor rather than a function of alignment of target and cursor contours. Target velocity is the prime visual variation of significance in determining error in this behavior.

In general, the present study suggests that a dimensional conception of motion providing for concrete specification and analysis of the components and dimensions of behavior represents a constructive quantitative approach to problems of human engineering and is to be contrasted to efforts to advance this field through generalized theories and analogies supposedly covering all phenomena of human response.