NASA CONTRACTOR REPORT

NASA CR-125

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A STUDY OF MANUAL CONTROL METHODOLOGY WITH ANNOTATED BIBLIOGRAPHY

by L. G. Summers and K. Ziedman

Prepared under Contract No. NASw-717 *by*
TRW SPACE TECHNOLOGY LABORATORIES
Redondo Beach, Calif.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1964

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For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $3.50

1. SUMMARY AND CONCLUSIONS

Purpose

The problem of describing human operator behavior in a control system has been an important problem since the early 1940's. Although similar problems of perceptual motor skill have received earlier attention, a number of approaches specifically directed towards describing the human as a controller have been developed in the last twenty years. For the purpose of this review, the approaches have been divided into two general classifications: (1) the study of perceptual-motor-behavior as performed by the general or engineering psychologist and (2) the application of mathematical models based on control theory to the description of the human operator.

The purpose of this study was to determine whether or not these different approaches to tracking research are concerned with the same problems and, if so, to attempt to point out the most useful aspects of each.

Scope and Method

A review of the literature was conducted which covered theoretical and experimental papers illustrative of each approach. Each study was systematically abstracted on the basis of the theoretical model used, conditions of the tracking task, experimental design, performance measures, results and the author's conclusions. These abstracts were used as the basis for the review and discussion in which specific examples of each approach and a general discussion of the engineering and psychological approaches is presented. The range of applicability, differences and similarities, criticism of each approach by the other, methodological problems and areas for future research are discussed.

Conclusions

The following conclusions were drawn from the comparison of these approaches:

- The engineer has been concerned with a limited portion of perceptual motor behavior. The reason for this limitation is that the inputs and outputs of the operator have to be quantified in such a way to provide the proper mathematical description required by the engineer for system design and analysis. The psychologist has investigated a wide range of perceptual-motor behavior utilizing a variety of methods which in many cases have allowed only qualitative description. The conflict in approaches to tracking is not so much between psychology and engineering but between narrowing the field of inquiry to apply quantitative methods versus investigating more complex situations less amenable to mathematical models.

- Control theory models have been criticized in the literature as inappropriate for studying human behavior because many important factors concerning perceptual-motor behavior are ignored in these models, particularly models assuming linearity. However, the limitations in the quasilinear model are understood by most workers and other engineering models are theoretically capable of extension to a broader range of human behavior than simple tracking tasks and linear relations.

- Cross-experimental comparison in the psychological literature and application of the results to system design is difficult if not impossible due to the variety of experimental methods and approaches employed.

- Two major similarities or bridges exist between the two approaches. First, behavioral data have been used to justify and to suggest engineering models. Secondly, both approaches have arrived at a similar conclusion with respect to system design, i. e., system performance is dependent upon the amount of equalization that is required by the human operator.

- In both the psychological and engineering literature, there is generally a lack of definition of the tracking task and inadequate experimental design.

- No one performance measure is generally adequate for the description of both the human operator and system performance. To fully understand both system and operator behavior three general classes of measures should be used. These are:
  - a) A measure of overall system performance,
  - b) A measure of the transfer characteristics of the human operator, and
  - c) A measurement of operator "effort" or "load."
- It is proposed that the following studies should be considered by both the psychologist and the control engineer.
  - a) The importance of visual and proprioceptive inputs and of knowledge of results on learning.
  - b) The effect of proprioceptive or "feel" feedback on operator performance.
  - c) Quantitative specification of display/control relationships
  - d) Measurement techniques to determine instantaneous variations in operator behavior
  - e) Further study of performance measures.

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3. INTRODUCTION

An area of manual control that has assumed a growing importance since the Second World War is the evaluation of human behavior during a tracking task. The operator's task in tracking is to match an actual output with a desired or required output. The desired or required output is presented to the operator by a display to one or more sensory inputs and the operator's output is produced through a manual control operated by a muscular system. In the majority of the tracking literature the displayed information is visually presented and the manual control is either operated by the hand or the arm.

Tracking research was initiated on problems such as tank turret control and anti-aircraft gunnery and soon was applied to aircraft control and more recently to spacecraft control. It is interesting to note that the trajectory type inputs such as following an airplane which stimulated the initial research have been neglected in favor of the random inputs encountered in aircraft control (Garfinkle et al. 21a).[1] The description of human tracking behavior is a small portion of the overall field of perceptual-motor performance which has been investigated by researchers (Adams, 1 , McRuer and Krendel, 113, Ellson, 15a, Taylor, 56a, and Fitts, 16a).

A manual control of aircraft requires the operator to perform many other tasks in addition to maintaining course in the face of random disturbances. As the psychological work on tracking must be run in the context of general psychology, the engineering work must be seen in the context of the general problem of aircraft handling qualities.

Both the psychologists and engineers applied their individual backgrounds and techniques to the study of tracking (McRuer and Krendel, 113). The psychologists used their background from the areas of motor skills, learning and sensory psychology and the experimental techniques of general experimental psychology (Helson, 30a). The engineers saw a possible parallel between human control and servo control and attempted to apply the then fairly new control theory to human tracking. Both

[1] The number following the author's name refers to the number of the abstract in section 8. References not abstracted are given in a separate section starting on page 195, and are indicated by an (a) following the reference number.

groups, of course, used the other's concepts to a certain extent (Craik, 49 , Ellson, 15a, Birmingham and Taylor, 38); however, a difference in approach became obvious as the engineering group continued to concentrate on the control theory description and as some psychologists began to express doubt that this model was appropriate to emphasize their differences and similarities and to try to develop a summary account of what each group has stated is important in examining tracking and manual control. Two things should become obvious in the following discussion.

- The need of the engineer for human operator data in a form suitable for system design is a major factor in distinguishing his approach from the psychologist.
- The engineering-psychology dichotomy is an oversimplification of a wide variety of approaches, and distinctions should be made in terms of specific techniques and methodology.

4. BASIC PROPERTIES OF THE HUMAN CONTROLLER

As a background to both the psychological and engineering approaches to tracking research, a general description of the properties of the human controller is given in this section. Commonly used concepts to interpret tracking data are also included. Topics covered include human response characteristics, intermittency, prediction, perceptual motor integration, proprioceptive feedback, and learning.

4.1 Human Response Characteristics

Analysis of the details of response records has been a major concern of many investigators in tracking. This analysis has examined amplitude and time relations between input and output for both continuous and discrete inputs. This area is related to motion-time techniques used to study human movements in a more general context than tracking. The general study of human motion is, of course, an old problem (Smith and Smith, 52a, Fitts 16a). Typical results for responses to step and continuous inputs and movement analysis as applied to tracking will be presented.

4.1.1 Step Inputs

Although step tracking is of less practical importance to control systems than continuous tracking, it is of theoretical interest as a large amount of step response information has been collected.[2] Furthermore, attitude control of space vehicles in free space is more similar to acquisition of a target than to the random noise tracking predominant in aircraft control. Step tracking provides a simpler situation than continuous tracking for examining models of human information processing, particularly those related to prediction and timing of responses as both responses and stimuli occur at discrete time points. Finally, step tracking behavior should approach continuous tracking in the limit when the interstep interval approaches zero and the number of step amplitudes becomes infinite. This latter possibility has been examined, apparently, in only one report (McConnell and Shelly, 110).

[2] As pointed out by Rogers (137) an important practical step tracking task, the acquisition of a stationary target with a cursor, has not been adequately investigated. His thesis contains a good summary of the work that has been done on this topic.

A single step can be described by its amplitude (including direction) and duration. A series of steps can be described by its amplitude and duration distributions and frequency of occurrence. The operator's output is described by his reaction time (time between step occurrence and response initiation), the durations and rates of component movements of the response, overshoots and undershoots, and final accuracy. The general time course of a step response is an initial movement of nearly constant duration followed by slower and smaller corrective movements (Craik, 49, Searle and Taylor, 138, Vince, 158, Woodworth, 64a). The initial response is generally described as a ballistic movement (Craik, 49) implying that it is preprogrammed and completed without alteration by concurrent events. Searle and Taylor (138) and others have shown that the duration of the initial movement is nearly independent of amplitude so that the rate of movement must be based on step amplitude. In tracking a series of steps, the response amplitude depends on the range of amplitude presented as well as the present step amplitude (Ellson and Hill, 64). McConnell and Shelly (109) found that discrete tracking approached continuous tracking at a step rate between 8 to 12/sec.

4.1.2 Continuous Tracking

The general characteristics of continuous tracking responses have been described by many authors (Fitts, 16a, Ellson and Gray, 61 , Krendel and McRuer, 105, Craik, 49). A major determinant of the response is the predictability of the input signal. If the input can be learned the average lag is low and nearly constant with frequency; if it cannot the lag increases with frequency and amplitude matching is poor (Noble et al., 118). At low frequencies, the response form is smooth and shows small error. At higher frequencies, a discreteness of adjustment can be seen in which the operator apparently corrects in discrete movements about every 0.5 sec (Craik, 49). At still higher frequencies, the operator is unable to follow details of the response and may resort to making aiming movements at the input peaks and for very difficult control tasks he essentially operates in an on-off manner. Humans can track sine inputs up to about 3 cps with a lower limit for random inputs dependent on frequency composition. This overall description is, of course, dependent on many factors such as the controlled element, displays and controls.

4.1.3 Movement Analysis

Manual movements have been described in terms of component movements by several authors. Stetson and McDill (56a) classified motions into tense, motions or positions of a limb in which opposing muscular contractions balance or almost balance each other, and ballistic, in which only one muscle of an opposing pair contracts. Smith and Smith (53a) proposed three movement components, postural, transport and manipulative which they state are integrated at different levels of the nervous system. A distinction between rate and positioning movements is commonly made in the tracking literature (Nobel et al. 118, Craik, 49). Simon and Smith (148) have shown that rate aiding differentially affects different component movements.

Movement analysis has been particularly important in the area of time and motion study. Efforts have been made to establish basic movements and motions which can be used to describe any complex movement (Smith and Smith 53a, Conrad, 10a) and studies on movement accuracy and direction have been reported by a number of workers (e. g., Husikamp, et al., 34a, Briggs and Brogden, 6a).

4.2 Intermittency in Tracking

The concept of intermittency or sampling in tracking has been advanced by a number of authors including Craik (49), Birmingham and Taylor (33), Bekey (22), North (120), Searle (139), Licklider (35a), and Senders (141). A number of theoretical analyses of tracking has been based on the intermittent hypothesis including those of Bekey (22), Searle (139), and North (120). Evidence of intermittent operation is based on observations of discrete corrections in tracking records (Craik, 49 , Vince, 158), from high frequency peaks in the error power spectrum (Bekey, 22) and from other investigations not directly concerned with tracking such as the perception of numerosity White (63a), cycles of cortical excitability, Calloway and Yeager (8a) and reaction times, Augenstine (2a).

In spite of accumulated evidence, intermittency in the human is still a controversial topic, partially because of lack of a consistent definition. In this report, an intermittent process is characterized as one in which information is received, processed, and transmitted at discrete intervals or instants of time. In this definition no requirements are placed on periodicity. Between these intervals information transmission must depend on previous samples, i. e. new information cannot be obtained by the system. The problem of establishing human intermittency is complicated because of the many loci at which such a transformation can occur. Intermittency can occur at the input receptor systems, in central processing, and in the motor output. Shifting of attention, periodic variations in cortical excitability as a function of alpha-rhythm phase and sampling due to eye movements all illustrate the diversity of possible intermittent systems. The frequency of intermittence found has been from about 2/sec for tracking records to 10/sec for alpha waves and other "central" intermittencies. Some of the evidence of intermittency is physiological and concerns specific neural systems, but many studies applied to tracking have only measured the input and output to the operator. There is a need to coordinate the various types, locations, and definitions of intermittency to clarify the use of this term.

4.2.1 Single Channel Model

This model describes the central mechanism as dealing with signals one at a time, so that a second signal which arrives shortly after the first may have to be stored before it can be acted upon (Welford, 161, Broadbent, 7a). The single channel model was based to a large extent on results from experiments requiring the operator to react to a sequence of discrete signals (Broadbent 7a, Vince 158). These studies elaborated the somewhat unfortunate concept of the psychological refractory period originally stated by Telford (59a) in which a refractory mechanism analogous to that of nerve fibers was held to prevent the central mechanism from dealing with a second stimulus until a fixed time after the first.

This concept has been questioned by a number of investigators. Ellson and Hill (64) showed that a model assuming algebraic summation in time could describe step tracking; anticipation or prediction has been found to modify the PRP (Poulton, 128, Adams, 2) and Gottsdanker (83) in testing three models of response to a sequence of steps found his results agreed with Ellson and Hill's model.

Although the PRP by itself cannot support a single channel model, other evidence indicates a one channel model is reasonable in situations in which occurrence of a particular event or its time of occurrence are uncertain (Creamer, 51). Correlation between several events or additional information about the task enable the operator to act as a multi-channel system (Adams and Chambers, 4).

4.2.2 Intermittent Operator Models

These models are discussed in section 6.2 but are mentioned here to relate them to the hypothesis of intermittency. Sampled data models assume the operator samples the input at given times and his output is dependent on the last sample or samples. Various types of input-output transformations have been assumed (Bekey, 22, North, 120, Ward, 160).

4.2.3 Aided Tracking Time Constants

Aided tracking refers to providing the operator with a tracking system in which output, velocity, and acceleration as well as position are proportional to control position. The proper choice of position, velocity, and acceleration components represent a design problem. Theoretical attempts have been made to determine "optimum" aiding constants based on an intermittent hypothesis by Mechler et al., (116) Searle (139) and others and agreement with experimental results has been good in some cases. However, "optimum" aiding constants will often vary with experimental conditions and using intermittency as a basis for such calculations has been criticized (Smith and Smith, 53a).

4.2.4 Time Sharing and Multiple-Dimension Tasks

Another form of operator intermittency is the time sharing necessary when the operator must attend to more than one input source.

Multi-dimensional tracking requires the operator to develop input sampling strategies and output motor coordination. Interaction between inputs and outputs can become severe and is probably the most important problem of multi-dimensional tracking. Sampling behavior has been demonstrated by Adams and Xhignesse (8) and Briggs and Howell (36). Chernikoff, et al., (39) examined the effects of different controlled elements in each axis and Chernikoff and LeMay (40) investigated the relation between display-control configurations and identical and different dynamics in each axis. Adams and Chambers (4) and Adams and Webber (6) have shown that coherency between two inputs can be used by the operator to lower scanning requirements.

The operator apparently needs additional information processing capacity to control sampling between inputs or between different controlled systems (Chernikoff and LeMay, 40) and thus his capacity allotted to control is lowered. This is particularly severe if incompatible display-control relationships are present.

Bilodeau reports several studies (Bilodeau, 25 , 26 , 27 , Bilodeau and Bilodeau, 28) on the relation between component activities in a multi-dimensional task. Whole task performance could be predicted from part task performance based on time-on-target scores for each part. He also found (25) that performance in a given dimension was improved at the cost of degraded performance in another.

In an interesting series of studies, Conrad (43 , 44 , 45 , Conrad and Hille, 46) studied behavior in a multiple input-output task in which the operator was required to scan a number of dials and respond when any dial indication was in a critical region. He distinguished load (number of independent signal sources) from speed (total rate of signal occurrence) as independent variables.

Time sharing between tasks and within tasks is an important problem; although some determinants of this process are known more work is needed, particularly as any operational situation involves time sharing.

4.3 Prediction

The human operator is able to use the past history of the input together with other information to predict or anticipate its future. Predictive ability has been studied by Poulton (128, 129, 130, 131), Sheridan (146), Gottsdanker (25a, 26a, 27a) and others. Prediction has been studied for sequences of step inputs (Gottsdanker, et al., 84, Vince, 157, Adams and Creamer, (3, 5), for continuous pursuit tasks (Poulton, 131), for extrapolation of curvilinear courses (Gottsdanker, 25a, Sheridan, 146) and on compensatory tracking tasks (Poulton, 129).

In a discussion of the general nature of prediction in skilled movements, Poulton (121) distinguishes three types of prediction:

- Effector anticipation - prediction of three types of prediction
- Receptor anticipation - prediction of duration of response movement.
- Perceptual anticipation - prediction of target position at completion of response.

Poulton's analysis indicated the complexity of predictive behavior doubtedly involves several information sources and forms of processing.

Prediction can be based on the immediate history of the input, on the long term history of the input, on instructions, and on deductions or inferences from knowledge concerning the task. Both visual and kinesthetic information are important to prediction (Poulton, 131, Adams and Creamer, 3) and Adams (1) has discussed prediction as both a mediating response and a proprioceptive controlled behavior.

The type of task and input has a strong influence on the predictive behavior shown by an operator including his ability to improve his performance with practice. A coherent input will generally be learned by the operator, the amount of learning depending on the input, the display, the control and other factors (Poulton, 129, Adams and Xhignesse, 8). For example, on a compensatory display, the operator will initially be able to predict target rate on a short-term basis. With continued practice, he may learn the overall course and thus track without the need for a high rate of feedback information. This type of learning sequence has been formalized in a successive organization of perceptual model (SOP) by Krendel and McRuer (105). The

SOP model describes the tracker as progressing from a compensatory (no course knowledge) to a pursuit (some course knowledge) to a precognitive (complete course knowledge, no feedback needed) mode.

Another important example of predictive behavior is the difference between self-paced and forced-paced performance. When the operator can control the rate of stimulus input, he can operate at a higher level than when he has no control over the input (Conrad and Hille, 46). The typical tracking task allows no operator control over rate. However, Sheridan (146) has shown an improved performance in pursuit tracking when the operator can move his pencil freely on an oscillograph trace.

An important process contributing to predictive ability is short-term memory. Short-term memory refers to temporary storage which holds in-coming information until it can be further processed by the central mechanism. Its main characteristic is a rapid decay time, so that not all of the information in short-term storage can be retrieved, forcing the operator to sample the storage. Such a system has been demonstrated for vision (Sperling, 55a, Averback and Coriell, 3a) and Sperling (55a) has proposed a model for short-term memory involving an auditory storage loop which recirculates data. An earlier model was proposed by Broadbent (7a) which was based mainly on auditory and motor skill experiments. A number of other studies on short-term memory have appeared, and it is clear that more than one memory process is being studied as critical storage times from 0.5 to 30 seconds have been defined for different tasks. (For example, an after-image is one short-term storage; repeating a telephone number to yourself is quite another).

Short-term storage is, however, an important limitation on information processing and it warrants further study in the tracking situation with reference to prediction and multiple input tasks. Application to tracking has been shown by Poulton (135) and Sheridan (146).

Related to the problem of prediction is a not-too-well defined behavior, the observing response (Adams, 1 , Holland, 31a). This is an action on the part of the operator which directs attention to a particular part of his environment and is based in part on prior experience with the given situation. It can be a motor act, e. g., eye movements or a hand movement, or only an internal change in attention, e. g., switching attention from visual to auditory inputs. The observing response also seems to be related to the orienting reflex (Sokolov, 54) a complex response of a number of body mechanisms which prepares the organism to receive an input. Although these concepts have not been extensively used in the analysis of tracking behavior, they may be useful in describing sampling and time-varying behavior.

4.4 Perceptual-Motor Integration

This topic refers to the problem of relating the spatial and temporal organization of the operator's input to his output movements. Every area of perceptual-motor skill touches on this problem; it is mentioned separately here to emphasize the perceptual aspects of "motor" behavior which must eventually be included in a theory of tracking behavior. Differences in displays, such as pursuit versus compensatory (Poulton, 129) variations in display control compatibility (Noble et al. 118) spatially and temporally displaced feedback (Smith and Smith, 53a, Held and Freedman, 89) and direction of motion stereotypes (Loveless, 109) are examples of perceptual factors strongly influencing motor responses. The picture emerges of a system which is sensitive to the directionality of the input-output signals as well as to the spatial and temporal displacements of these signals together with the limited ability to modify these sensitivities.

4.5 Proprioceptive Feedback

The proprioceptive senses[3] respond to body or limb position, movement and orientation. They include the vestibular receptors which are concerned with head movements and position and the receptors located in the muscles, tendons and joints concerned with limb position and

[3]The terms proprioceptive and kinesthetic are not often clearly distinguished or are used in a contradictory manner. "Kinesthesis" was originally coined by Bastian in 1880 and was used to mean sensations of movement and position, especially as used by the introspective psychology of the time. "Proprioceptive" was invented by Sherrington in 1906 to describe the sensory systems which underlie the kinesthetic sensations (Boring, 5a). This original psychological-physiological distinction seems to have been lost; current authors generally use one term to refer to all of the deep sensory systems sensitive to movement and position and the other term to refer to a subclass of these systems. However, different writers differ as to which term should refer to the class and which to the subclass. There is a need to clarify the use of these terms on an historical and/or logical basis.

movement.

The importance of this sensory information for vehicle control is generally realized; however, the relations between system parameters and type and amount of feedback, the relative importance of the different types for control and the specific internal loops describing this feedback are not well understood. The discussion will be limited to feedback from limbs, and will ignore whole head position and movement. The importance of motion cues in simulator work has been discussed by Rathert et al., (47a) and others.

A study directly relevant to tracking and proprioception was reported by Notterman and Page (119). The controlled element transfer function in their study was constant, but different portions of the transfer function were assigned to the control stick and to the electronic elements for different conditions. For example, damping could be inserted electronically with a freely moving stick or incorporated into the stick by adding a mechanical damping element. Thus the subject tracked mathematically equivalent systems but with differing proprioceptive feedback. The results indicated the different conditions of feedback had significant effects on performance and they concluded that proprioceptive feedback loops must be included in a model of the human operator.

Proprioceptive feedback has been studied by a number of other workers including Chernikoff and Taylor (42), Bahrick and his co-workers (Bahrick, et al., 16 , Bahrick, et al., 17 , Bahrick, 4a) Gibbs (23a) and Weiss (163 , 62a). The area is a difficult one in which to work because of the difficulty of independently varying the input to the different kinesthetic systems. Although operative techniques can be used on animals and drug studies have been conducted with humans, the usual technique is to vary the control characteristics of spring constant, damping and inertia. By varying these characteristics, one can, for example, determine the relative importance of position versus force information and the relative values of the control constants for optimum performance. General results from this approach have indicated that spring loading is less important in affecting performance than damping and inertia (Bahrick, et al., 16, Notterman and Page, 119). However, the relative importance of displacement and force in affecting accuracy may depend on the controlled element and type of visual feedback (Weiss, 163). Adams and Creamer (3) distinguished between the regulatory role of proprioceptive feedback and its role in aiding anticipation based upon using the proprioceptive stimulus trace as a basis for response timing.

The information concerning kinesthetic information strongly indicates that these systems cannot be ignored in human operator models. At least two major loops must be handled separately, information from receptors in limbs activating controls and information from the vestibular receptors responding to head movement and position. Adequate modeling of these factors would be a major advance in understanding the human operator and in the predictive value of the model.

4.6 Learning

Learning and training in tracking comprise an extensive area and only a few points and studies directly related to this discussion will be covered. These will include prediction of tracking performance, retention of tracking skills, descriptions of the learning process, and research problems posed by operator learning. This area provides examples of many of the factors that psychologists claim are left out of control theory descriptions of tracking and is also a good example of the application of psychological concepts to motor skills. Learning can roughly be considered a change in time of the information transfer process of the human. Either a change in the parameters of a single process can be conceived to occur or the type of process itself may change. The changes can be caused by various aspects of the task, e. g., input or controlled system variations, or by extra task factors, e. g., instructions. It is also possible to distinguish learning of a new input-output relationship from selecting among several already learned relationships.

Prediction of perceptual-motor skill has been studied with the aid of factor analysis in attempts to correlate scores on criterion tests with final performance on the task in question. These studies have shown that performance late in learning cannot be predicted from early performance (Parker and Fleishman, 125) and that external criterion measures are a better predictor of final performance than early performance on the task itself. Based on the criterion measures, tracking performance seems to undergo a progressive simplification in that fewer criterion abilities are used after learning (Bilodeau and Bilodeau, 29). A study by Fleishman and Rich (74) further supports a difference between early and late performance by showing that spatial-visual abilities are more important early in learning whereas kinesthetic cues are more important late in learning. The correlational studies emphasize the difference between an ability, a general, stable trait of the individual, and a skill, performance on a specific task. However, the range of abilities important for a given task cannot always be specified and distinguished from task-specific skills. For example, in the Parker and Fleishman (125) study, an established battery of reference tests of motor-skills abilities were generally unrelated to performance on a complex tracking task involving prediction, sampling and multi-limb coordination. Factor analytic studies generally involve categorizing subjects or groups of subjects according to skill and as pointed out by Bilodeau and Bilodeau (29) skilled performance is a phenomenon exhibited within individual subjects, so that there is a limit to the information on skilled behavior that can be obtained by group comparison.

The essential question is, of course, what does the operator learn? The answer is still somewhat rudimentary although data indicating the nature of the problem is being obtained. The importance of learning to predict the input was emphasized by Poulton (130, 136), Nobel, et al., (118), Krendel and McRuer (105) and many others. The successive organization of perception (SOP) model proposed by Krendel and McRuer (105) is in agreement with general evidence showing a basic change in behavior from early to late in learning.

A related learning model was suggested by Fitts (Fuchs, 75) in which the operator learns to use successively higher derivatives of the input with training, but may regress to lower derivatives when stressed.

The learning and retention of specific movements is also an important part of tracking skill (Battig, et al., 21, Fleishman and Parker, 73).

Equalizing ability as a general tracking ability has been stressed by Birmingham and Chernikoff (30) although this ability must involve elements of both prediction and manipulation. For complex tasks, the operator must learn the task organization and time-sharing procedures as well as the component skills (Briggs and Naylor, 37, Adams, 1). In addition to long-term skill acquisition, the ability of the operator to recognize an abrupt change in the controlled system and adjust to it, presents an important problem.

The research on retention of tracking skill has shown very little decrement of skill after extended periods without practice (Fleishman and Parker, 73, Battig, et al., 21, Bilodeau and Bilodeau, 29). Although losses were reported, skill is rapidly reacquired with a large savings over the original training time (Ammons and Farr, 12).

The effect of knowledge of results and information on learning is complex and it will only be pointed out that a severe problem exists in specifying what effect additional information has on the operator and how he uses it in learning. The consistency of the relation between operator output and feedback information as well as the form of the relation itself is an important limitation on what can be learned (Smith and Smith, 53a, Held and Freedman, 89, Bilodeau, 25). Refer to Bilodeau and Bilodeau (29) for a good summary of this topic.

Learning of many tracking tasks requires an extended period of practice (Battig, et al., 21, Parker and Fleishman, 125). Extended training sessions, on the order of months, have been found necessary to reach a reasonably stable level for a moderately complex task. The majority of tracking studies have trained subjects for only a relatively few trials which gives rise to the interesting speculation that established results might be altered if well-trained subjects had been used. More work is definitely called for on acquisition of tracking skill from both the viewpoint of understanding the learning process and the problem of experimental procedure.

5. PSYCHOLOGICAL APPROACHES

There is no single "psychological approach" to tracking but a variety of approaches ranging from application of traditional methods, ad hoc experimentation with tracking systems, to development of theory embodying a mixture of engineering and psychological models. The language of the control engineer has been adapted by many psychologists (e.g., Birmingham and Taylor, 33). This group of psychologists can be distinguished from those working on tracking and perceptual-motor skills who find the control theory model inadequate for describing details of human information processing (Adams, 1, Poulton, 133, Smith, 149).

Many workers in both of these groups have expressed dissatisfaction with the stimulus-response-reinforcement model of experimental psychology as it has been applied to perceptual-motor skill research and have attempted to reformulate the problems in terms of other models, some based on engineering techniques and some developed from psychological and physiological models.

The emphasis of engineering psychologists on task variables, those describing the machine system, rather than procedural variables, those describing or influencing the state of the operator, has been emphasized by Adams(1). Examples of procedural variables are training, motivation, and stress; examples of task variables are spring loading, display gain and forcing function frequency. Procedural variables are in the realm of general experimental psychology and the alleged failure of the control theory approach to include them has also led to criticism of the latter. A clear separation of these two concepts is often difficult, however, as the particular properties of the operator will depend strongly on task as well as procedural variables.

The following sections present the approaches to tracking followed by several psychologists active in tracking or motor skills research, the use of information theory by psychologists and, finally, a discussion of methodology and performance measures.

5.1 J. A. Adams

Adams (1) presented his general approach to tracking in a review of the psychological literature. He elaborated the distinction between task and procedural variables in terms of the difference in approach between the general psychologist and the engineering psychologist. As the latter has focused his interest on task variables, he has ignored the procedural variables which, Adams states, must be considered for an adequate description of tracking. Adams gave the disenchantment of many engineering psychologists with the traditional measures and theories of experimental psychology as a partial reason for this situation. Because the basic data in tracking are continuous time-varying signals, the breakdown of a sequence of actions into series of stimulus-response sequences has not seemed applicable.[4] Adams objected to control theory as an adequate model of human tracking on two major points. The first objection concerns the assumption of linearity and superposition in linear control theory. The failure of the human to operate linearly[5] in many situations is well known, and in fact, the nonlinearities are "...an inherent, and indeed, the most interesting and challenging, aspect of the human operator" (Adams, 1 , p.59). His second objection concerned the limited number and classes of variables considered in control theory. Furthermore, he states that even if analytical methods become available to handle nonlinearities engineering psychology will not be able to make effective use of them if it continues to exclude procedural variables (Adams, 1 , p.59).

Adams and Webber (7) reported an attempt to examine a Monte Carlo model of tracking which "...represents a step toward the achievement of models that will have eventual use for engineering psychology and perhaps general experimental psychology, too." An earlier report based on a similar analysis was given by Adams and Webber (6). The basis of this model can best be described by paraphrasing the criteria that were used in its development. These were:

- A linear servo approach was avoided for the reasons mentioned above
- In principle, the model was intended to eventually accommodate the general tasks and behavioral complexities found in engineering psychology

[4] The alleged inadequacy of stimulus-response analysis is also elaborated for the case of tracking by Ellson (15a) and by Broadbent (7a) in a more general context of human information processing.

[5] The term linear has been used in different ways in the tracking literature and seems to be partially responsible for a lack of communication between psychologists and engineers.

- A stochastic model was chosen to account for intra-and intersubject variability
- The model should allow any reasonable measure of performance or any transformation of the tracking error function.
- The output data of the model should be such that they can be validated meaningfully against empirical data.

Monte Carlo models were chosen as best meeting these criteria as they impose few restraints on complexity, are inherently probabilistic and are easily simulated with digital techniques.

The model was based on the concept of error peak, an increase in tracking error which is sensed by the operator and nulled. A tracking record was conceived as a sequence of such error peaks (see Figure 1) which were defined on the basis of peak error (E), rise time (t), descent time (T), and in-time (t_i), the time the error is maintained less than a given absolute magnitude. In addition, a learning factor expressed as a function of the number of trials (N) was included.

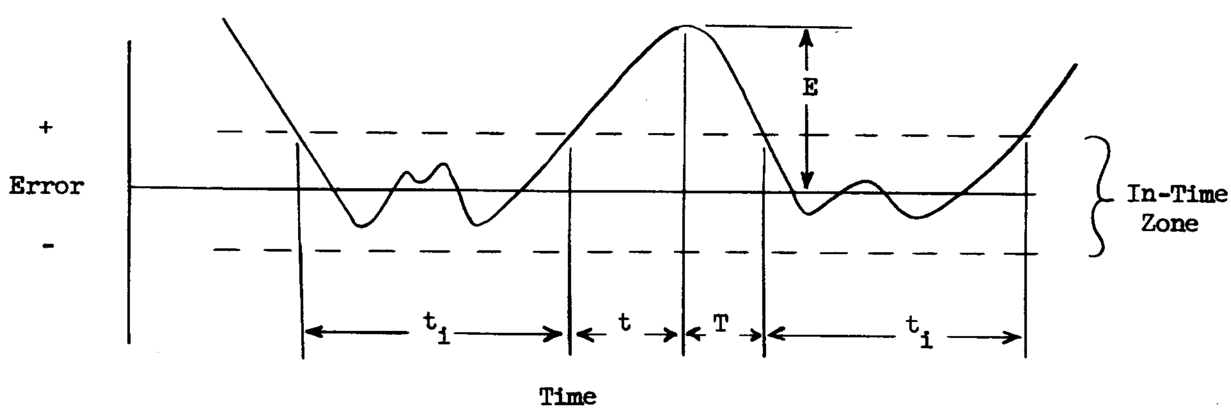


Figure 1. The Error Peak Model (after Adams & Weber, 7)

The essential relations in the theory are as follows:

Variable	Distribution or formula used to obtain variable value
E (error peak amplitude)	E has a Gaussian amplitude distribution, each value of E chosen randomly. $\sigma_E = K_1 N^{-K_2} + K_3$
t (rise time)	$t = \frac{E}{K_4 + K_5 E}$
T (descent time)	$T = \frac{E}{K_6 + K_7 E}$
t_i (in-time)	For $0.1 < t_i \leq L$: $t_i = \frac{\log(-\log p) - \log(-\log K_8)}{\log K_8}$. For $t_i < 0.1$: $t_i = \frac{0.1p}{c}$

where $K_n = c_n N + d_n$, $n = 1,$ N = number of trials

where p = cumulative probability
L = empirical limiting value
c = value of p at $t_i = 0.1$

Curve fitting to obtain the functional forms was done by the method of least squares on data obtained both in Adams' laboratory and from other published data. The specific values of K_n, c_n, and d_n for n = 1 to 8 were apparently computed from the same experimental data used to test the model. To simulate a tracking run, a probability value was randomly chosen and related to the normal curve distribution to choose E which was then used to compute t and T. Another random probability value was chosen to determine t_i. The values of E, t, T and t_i thus calculated were formed into an error peak, and the successive error peaks were combined into a tracking record.

Distribution of error magnitudes and time-on-target scores for six scoring zones were used in examining the model in addition to the following measures for one and two-dimensional tracking.

<u>One-dimensional Tracking Measures</u>

- Frequency distributions of E values on a trial
- Mean number of error peaks on a trial
- Frequency distribution of time intervals between successive peaks

<u>Two-dimensional Tracking Measures</u>

- First and second-order probabilities about where an error peak will occur
- Frequency distribution of time intervals between successive peaks whenever successive peaks are in the same dimension
- Frequency distribution of time intervals between successive peaks whenever successive peaks are in alternate dimensions.

5.2 E. C. Poulton

By taking a response unit (the error peak) as the basic component of a tracking record, Adams and Webber have continued an approach followed by many psychologists. This approach is characterized by an interest in the fine details of the response record of the operator, attempts to characterize individual time segments of the output and a disinclination to accept linear control theory as a ready-made model of human behavior. For example, in an article discussing methods of scoring tracking records, Poulton (133) emphasized simple performance measures which enable the experimenter to be as flexible as possible in testing hypotheses concerning the operator's behavior.

Poulton stated that control theory as used by engineers is limited as a description of human behavior as it does not describe many aspects of human response that are dissimilar to servo system responses (Poulton, 133 , p. 320).

Poulton illustrated the application of his scoring techniques by presenting an analysis of tracking on an oscillograph trace with or without preview. By separating positioning errors from timing errors at points of inflection and reversal of the input, he showed that the operator "...did not simply reproduce the input as accurately as he could with a constant time lag; his timing varied significantly at different points on the input cycle" (Poulton, 133, p. 325). Furthermore, it was possible to distinguish two different response strategies for the two tracking conditions.

This study is a good example of what might be called the "British School." A number of British psychologists interested in perceptual-motor skills have emphasized examination of the time course of the operator's output as opposed to time averaging over significant lengths of the record. These studies have used a variety of tasks such as multiple dial monitoring (Jackson, 99), responding to discrete sequences of stimuli (Vince, 157). continuous tracking (Poulton, 135), and discrimination tasks (Welford, 161). Some topics covered by this approach include studies of response timing by Conrad (45), work on the "psychological refractory period" (Vince, 157), Welford (61a), the study of human predictive ability (Poulton, 131), and the analysis of component movements (Vince, 158 Poulton, 133).

Many insights into skilled performance have been provided by this work. It represents an attempt to discover descriptions of human performance based on working from data to theory; however, because the area covered is fairly broad, the resulting theory has been equivocal to some extent and controversies covering entities such as the "psychological refractory period" have resulted. Work similar to the British studies has not been as systematic in the United States although work by the Naval Research Laboratories, Searle and Taylor (138), Gottsdanker (21a), Simon and Smith (144), Bilodeau (26, 27) and Adams (2) are examples of this approach from this country.

5.3 Birmingham and Taylor

The involvement of engineering psychology with control theory is best illustrated by an important early paper by Birmingham and Taylor (33) in which they discuss a principle of control system design in terms of both control theory and stimulus-response language. Briefly presented, the design principle states that the transfer function required of the man should be as simple as possible and no more complex than a gain, whenever feasible.[6] This concept was based on the assumption that machines can perform integrations and differentiations better than man and that his inclusion in a system should be for other reasons than these two

[6] They also included an input frequency limit of 3 rad/sec

functions, e.g., his perceptual abilities. Based on this principle the necessity arises for augmentation of the machine to relieve the operator of differentiating and integrating, which Birmingham and Taylor discuss under the headings of quickening and unburdening. Various applications of these aiding techniques are discussed, but the important points for our purposes are the implication of this approach for tracking research and the stimulus-response analysis proposed by Birmingham and Taylor.

If the basic human output is taken as force, and if visual error amplitude and direction is taken as the input, they state that a unique relationship between the two exists only when the operator is functioning as a simple amplifier (Birmingham and Taylor, 33, p. 22). If more information than amplitude and direction is needed, a greater amount of data processing must be done by the operator, resulting in the loss of "stimulus-response integrity." Consider the operator tracking a constant velocity input on a compensatory display for the system shown in Figure 2, in which he must correct a constant lag.

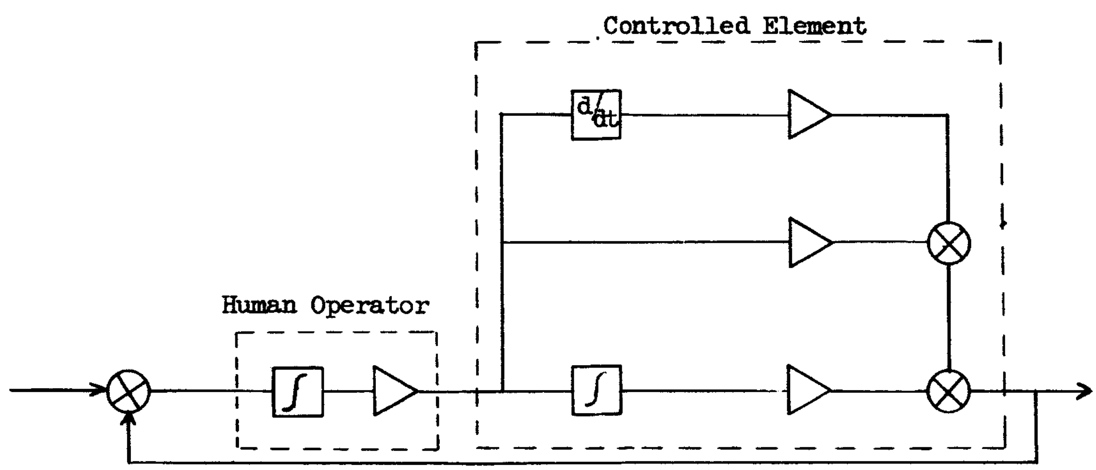


Figure 2

Human Operator Control Loop After Birmingham and Taylor

Without the integration supplied by the human operator, this system will track a constant velocity input with a lag proportional to the velocity.

For zero displayed error, he must deflect the control a constant amount in one direction for a given input direction, in the reverse direction if the input direction is reversed, or hold the stick at zero if the input is zero. Thus, for the same stimulus, zero error, three different responses are called for.[7]

A further result of the Birmingham and Taylor approach is the work it has generated on techniques for unburdening and quickening. For example, Birmingham, et al, (32) have shown that quickening can produce performance improvements that could not be achieved through practice. More recent work from the Naval Research Laboratory has considered the concept of equalization as a specific learned skill and analyzed methods of operator training (Birmingham, et al, 31). This body of work can be seen as lying between the more traditional psychological work and the control theory description as psychological factors are being examined with the aid of the control vocabulary, with minimum formal modeling and analytical work.

5.4 K. U. Smith

Smith has written extensively on his theory of sensory feedback and has applied it to many areas of perceptual-motor performance (Smith, 149, Smith and Smith, 53a). We will only examine his basic ideas and their relevancy to tracking. Smith's essential concept concerns the relationship between neural signals representing the operator's output, say to his muscles, and those representing his input, say from the retina. The nervous systems are such that the spatial organization of the output movements and input signals are represented as neural signals. There are other neural systems which continuously compare neural signals within sensory systems and between sensory and motor systems. It is the output from these comparison systems which is held to be primary in controlling movement. The ability of the operator to perform any task depends upon the compatibility of the spatial and temporal relationship between the

[7]The type of controlled element required to enable the operator to act only as a gain will depend on the input. Furthermore, the generality of force and position as the proper input and output variables can be questioned. For example, for a random input McRuer and Graham (112) describe the operator as acting as an integrator when the controlled element is a gain and as a gain when it is a single integration. This implies the operator is rate matching rather than position matching the input.

signals in the sensory and motor systems. Maximum compatibility occurs when the corresponding spatial elements of the two systems are similarly excited at the same time. Detailed aspects of operator performance, including the learning of specific tasks, depend primarily on these feedback relationships. Although learning, according to the stimulus-response-reinforcement sequence, takes place, it is secondary to the relations imposed by the feedback patterns. Reinforcement feedback, operating to increase the probability of a given response, is distinguished from the effect of sensory feedback which is intrinsic and unlearned.

Smith bases this theory on physiological evidence, studies of temporally and spatially displaced feedback, and other motor-skills studies. Specific quantitative relationships are not given by the theory. Its importance to tracking lies in the emphasis on the spatial and temporal relationships between the input and output and the various feedback systems regulating performance.

5.5 Information Theory

Information theory (Shannon and Weaver, 52a) has been applied to many psychological problems including motor-skills. The theory characterizes the input and output from a system by a set of input signals and a set of output signals together with probability distributions giving the frequencies of occurrence of each signal. If p(i) is the probability that signal i was transmitted, p(o) the probability that signal o was received and p(i,o) the joint probability of signal i transmitted and o received, then

$$p(o/i) = \frac{p(i,o)}{p(i)}$$

is the conditional probability that o was received when i was transmitted. The matrix of conditional probabilities is called the noise matrix; noise is defined as that which makes communication less than perfect. The average information, H(I), contained in the selection of a signal, i, from its set, I, is given by the sum of the amounts of information contributed by each element in the set:

$$H(I) = -\sum_{i \in I} p(i) \log_2 p(i)$$

The amount of information is thus related to the uncertainty of a given signal occurrence, the less likely a signal is to occur the greater the information contained in its occurrence. The information measure, H, summarizes the information carrying characteristics of the set I. Of particular interest to psychology is the measure of information transmitted from the input to the output given by:

$$T = H(o) + H(i) - H(i, o).$$

This measure is zero only if the output is independent of the input; thus T is an inverse measure of the noise contributed by the operator. A given system can also be characterized by its channel capacity, the maximum amount of information per unit that can be transmitted through it.

Much of the work based on information theory has involved discrete tasks including studies of choice reaction time as a function of number of alternatives, the information contained in human judgments, signal discriminability and reaction time, immediate memory span, and motor skills. An excellent review on choice times and discriminability is given by Welford (61a), and other reviews and applications are presented by Broadbent (7a), Miller (43a) and Frick (19a). Examples of the many experimental studies are those of Crossman (52) and Alluisi, et al., (10).

An important aspect of information theory studies is the specification of human channel capacity. A unique measure of channel capacity and information requirements of various tasks would provide a basis for measuring task difficulty and operator loading. Although it has not been possible to assign a single channel capacity for all tasks, work in this area has resulted in better understanding of human information processing and transmission. Fitts and Peterson (18a) and Fitts (70) derived a measure of task difficulty for discrete motor responses based on movement amplitude and required accuracy.

Information transmission in continuous tracking has been studied by Crossman (52) who showed that additional information was transmitted when the operator was allowed to preview the input.

In general, the information processing models of the human consider a perceptual channel, a central or translator channel and a motor channel. The information capacity of each of these systems has been estimated in various ways, summaries of this work are given by Miller (43a) and Welford (61a). Although information theory does provide a useful language for many psychological problems, it does not specify all the important quantities in a given situation. Equivalent information in terms of frequency of occurrence does not always represent equivalent input to the human. A thorough analysis of the basic concepts of information theory, applications to psychology, and extensions of the concept of uncertainty, were presented by Garner (22a).

The concept of human channel capacity warrants further investigation, particularly with respect to the determination of task difficulty. Information measures may provide a common language for continuous and discrete tasks and thus allow a combined description of these two aspects of operator performance.

5.6 Methodology and Performance Measures

To relate tracking behavior to one or more human processes, it is necessary to specify the measures of tracking performance which are suitable for studying the hypothesized processes. This entails stating the process in such a way to enable the deduction of appropriate measures. Tracking research reported in the psychological literature has not proceeded in this fashion. Generally, the most convenient measure of performance has been used, without a careful analysis of the limitations on inferences that can be made from a given measure.

For example, the time-on-target measure was and is used extensively even after difficulties of interpretation were shown. Gray and Ellson (85) showed the correlation between the time-on-target score and mean integrated error depended on the scoring zone. Archer, Wyckoff and Brown (14) concluded that distributions of on-target times provided more information than cumulated time-on-target scores. Bahrick, Fitts, and Briggs (17) showed time-on-target scores could give misleading results on learning performance.

More general methodological studies on tracking were reported by Taylor and Birmingham (155) in which they stressed the dangers of inferring changes in component behavior from system measures; by Gibbs (72) who discussed the terminology and methods of measurement of input-output amplitude relations; by Poulton (133) who illustrated the use of simple scoring techniques; by Gottsdanker (82) who discussed measures of positioning movements; and by Obermayer and Muckler (46a) who discussed performance criteria in simulation studies. Kennedy and Landesman (101) demonstrated a range effect in human engineering studies designed to determine optimum values of task variables.

The diversity of performance measures and the difficulty of cross-experimental comparison is well illustrated by these studies and should be known to every worker in the field. In addition to time average measures, a number of other measures involving details of the response record have been used (Poulton, 135, Adams and Weber, 7, Simon and Smith, 148). In considering other tasks than continuous tracking, the number of measures increases further. Even in the case of continuous tracking, adequate comparisons of all of the common measures have not been made under a wide range of conditions. The usual comparisons made have been for time-on-target scores and average absolute error.

Time average measures, such as time-on-target, mean error and root mean-square error depend on amplitude distributions. Although most reports of error distribution (Adams and Weber, 7, Elkind and Darley, 58, Hall, 86, Bahrick, Fitts, and Briggs, 17) indicate a normal distribution of error, non-normal distributions occur for high frequency inputs and for unstable control systems (Hall, 86) error distributions will change with practice (Bahrick, Fitts and Briggs, 17) and with the type of feedback (Williams and Briggs, 186). Thus, the relationships between different performance measures may change during an experiment and for different conditions. Obermayer, Swartz, and Muckler (44a, 45a) report different interpretations of experimental results using average error, average absolute error, time-on-target and root mean square error and suggest measurement of the amplitude distribution is required in manual control studies.

Terminology used to describe the tracking system is often not clear in the psychological literature and increases the difficulty of cross-experiment comparisons. As examples, the distinctions pointed out by Gibbs (72) and Garvey and Mitnick (76) between control gain, display gain, and system gain have not always been appreciated and the usefulness of describing gains in angular measurement rather than linear (Gibbs, 72 ; Seidenstein, et al, 51a) have been often ignored.

In addition to measures of performance or system characteristics, other descriptions of tracking systems have been used which are on an even more doubtful footing. An example is task difficulty,[8] which, as clearly shown by Taylor (57a) is related in such a complex and sometimes anamolous way to other variables that it indicates little about the specific requirements of a task.

[8] Although specific measures of task difficulty have been developed (see Section 4.2.5) they cannot be universally applied to all tasks.

6. ENGINEERING MODELS OF THE HUMAN OPERATOR

The initial engineering approach in the analysis of manual control systems was to predict system performance from the mathematical expression of input-output characteristics. This approach has led control system engineers to try to construct an adequate model for the human operator from his input-output characteristics.

Servo control theory describes the output of a control system in terms of a time invariant transformation of the input. In this context, the linear transformation is expressed by a linear differential equation, for which the superposition principle applies. The time invariance requires the coefficients of the equation to remain constant. This transformation is shown in the block diagram of Figure 3 where the weighting function $h(\tau)$ is the linear time response of the system when an impulse function is applied at 0 time. The relationship between the response $i(t)$ and any input $i(t)$ can be found from the convolution integral.

$$r(t) = \int_{\infty}^{t} h(\tau)\, i(t - \tau)\, d\tau = \int_{\infty}^{t} i(\tau)\, h(t-\tau)\, d\tau \qquad (1)$$

For working with algebraic equations instead of integrals a Fourier transformation of (1) can be made

$$R(j\omega) = \int_{-\infty}^{\infty} r(t) e^{-j\omega t}\, dt = H(j\omega)\, I(j\omega) \qquad (2)$$

where $R(j\omega)$, $I(j\omega)$ and $H(j\omega)$ are the Fourier transformations of $r(t)$, $i(t)$, $h(\tau)$.

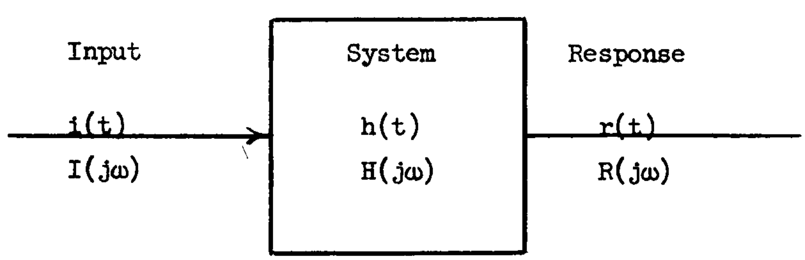


Figure 3

Representation of Linear System

Since World War II, servo control theory has been used extensively to define the handling qualities of manual control systems including aircraft. This factor led to the application of servo control theory to the description of the human operator. However, during the first applications it was realized that basically the human operator was a nonlinear component. This led to the development of the quasilinear model of the human operator where the behavior is described by a linear component plus a remnant term which is not linearly coherent with the input. This approach has been refined to the point of describing a large number of nonlinear control systems by the quasilinear approach with relatively minor deviations in the accuracy of the description (Graham and McRuer, 28a).

Other investigators have used techniques to determine analytical models that would explain time variations or nonlinearities in the human operator. Several recent reviews of the quasilinear model theory and the control theory approach have been presented by Ellson,(15a), Licklider,(38a), and Sheridan,(145).

6.1 Quasilinear Model

In Tustin's study (155) on the application of control theory to the human operator, he defined a linear describing function from harmonic analysis. For an input composed of the sum of 3 sine waves the resulting model was:

$$sG_H(s) = K(1 + Ts)e^{-Ls} \quad (3)$$

where s is the complex frequency variable, L is time delay taken as 0.3 secs by Tustin, and K is the gain and T is the lead time constant.

This model could account for most of the error produced by the human operator. However, there were certain irregularities in the tracking record which the author concluded were random as their harmonics had no direct relationship with the target movement. This unaccounted variation was called a "remnant" term. Tustin defined a quasilinear model of the human operator as a linear describing function plus a remnant. Ragazzini (136) also attempted to describe the human operator by a linear model. His model had the form:

$$G_H(s) = (sa + b + c/s)\, e^{-Ls}$$

Except for an addition of a differentiation term, it is the same as Tustin's description. Raggazini concluded from his experiments that the human response functions are nonlinear and the parameters in the operator's describing function may vary between individuals and between tasks. However, he suggested that harmonic analysis is useful in defining the human's response.

Another early application of control theory was made by two psychologists, Ellson and Gray (61). From their theoretical analysis, they concluded that the human did not have the characteristics of a linear system and they questioned the general usefulness of control theory in analyzing the responses of human operators.

Russell (48a) investigated human tracking using the harmonic analysis technique. He found a transfer characteristic similar to Tustin's (Equation 3) and in experimenting with aided tracking, he found that with the insertion of a simple lag, the operator's performance did not improve. The operator's open loop performance improved at the low frequencies but the amount of error at the higher frequencies increased. Russell postulated that, in this case, a tracker introduced a lead term into his transfer function in order to maintain stability. In experimenting with a second order controlled element with a time constant longer than 2.5 sec, Russell found that the operator did not change his open loop characteristics from that of a position control. Essentially, Russell had extended Tustin's quasilinear model in order to analyze the human operator in various control systems.

Walston and Warren (159) suggested the use of a linear describing function in the analysis of a task where the control gain and display gain were used as variables. They approximated the transfer equation by continuously adjusting the parameters of a model similar to Tustin's (Equation 3) except without the time delay (e^{-Ls}). Because a sum of

3 sine waves was used as an input for the task, the subjects were able to learn the task and therefore compensate for their time delay. They concluded that this describing function could be used to estimate the responses of the human to a particular system.

Krendel (102 , 103) was the first worker to attempt to find the amplitude versus frequency characteristics of the human operator from the measurements of autocorrelation functions of the input and output. He transformed the autocorrelation functions into power spectral densities and was able to determine closed loop amplitude versus frequency characteristics for a time invariant linear system from the following equation.

$$\left|H(j\omega)\right|^2 = \frac{\phi_{ii}(j\omega)}{\phi_{oo}(j\omega)} \tag{5}$$

where ϕ_{ii} is the power density spectrum of the input and ϕ_{oo} is the power density spectrum of the output. However, this did not allow calculation of the phase relationships.

Krendel also stated that this ratio could be obtained for a nonlinear system but it would not have a readily understood meaning. Instead, he proposed that if a system is nonlinear such as the human operator, then it might be more reasonable to plot the power spectral densities separately rather than as a ratio. From the preliminary experiments, he found that this approach could provide useful information about the human response and further concluded that the human's response was nonlinear.

Another study by Benepe et al., (23) using a single sine wave and the sum of two sine waves for input signals, analyzed a pursuit task by computation of the mean square error, power spectrum and autocorrelation functions. After analysis of a large number of runs, the authors concluded that human tracking behavior was not stationary or linear. This led them to the opinion that harmonic analysis of tracking data should be used with caution and to a limited extent.

The quasilinear model theory was developed further by Krendel (35a) and Elkind (57, 60) with the use of cross power spectral analysis which was suggested by Huggins (32a). This theory divides the human's response into two components, that which is linearly correlated with the input and that which is not linearly correlated with the input. The nonlinear portion is treated as random noise and added to the quasilinear transfer function. This is illustrated in the block diagram of Figure 4 where $h(\tau)$ represents the closed loop system.

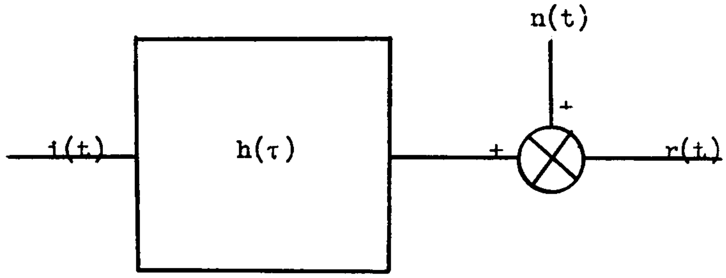


Figure 4

Closed-Loop Block Diagram of Quasilinear Model

This theory is developed on the basis that $i(t)$ or $I(j\omega)$ is a random input signal with a Fourier transform of

$$I(j\omega) = \lim_{T\to\infty} \int_{-T}^{T} i(t)e^{-j\omega t}\, dt \qquad (6)$$

The power density spectrum of the signal expressed in terms of the Fourier transform is

$$\phi_{ii}(j\omega) = \lim_{T\to\infty} \frac{1}{T}\left[I^*(j\omega)\; I(j\omega)\right] \qquad (7)$$

where $I^*(j\omega)$ is the complex conjugate of $I(j\omega)$ and the cross-power density spectrum between the input and output signals is expressed by

$$\phi_{io}(j\omega) = H(j\omega)\,\phi_{ii}(j\omega) \tag{8}$$

where $H(j\omega)$ is the closed loop describing function. The output power spectrum is found from the following relationship

$$\phi_{oo}(j\omega) = \left|H(j\omega)\right|^2 \phi_{ii}(j\omega) + \phi_{nn}(j\omega) \tag{9}$$

From this relationship the linear correlation coefficient ρ or that part of the output that is linearly correlated with the input is

$$\rho = 1 - \frac{\phi_{nn}(j\omega)}{\phi_{oo}(j\omega)} = \frac{\left[\phi_{io}(j\omega)\right]^2}{\phi_{ii}(j\omega)\,\phi_{oo}(j\omega)} \tag{10}$$

The power density spectrum of the tracking error is

$$\phi_{\epsilon\epsilon} = \phi_{ii} + \phi_{oo} - 2\,\mathrm{Re}\,\phi_{io} \tag{11}$$

which can be expressed as the mean square error by

$$\overline{\epsilon(t)^2} = \lim_{T\to\infty} \frac{1}{T} \int_{+T}^{-T} \epsilon^2(t)dt = \frac{1}{2\pi} \int_0^{\infty} \phi_{\epsilon\epsilon}(j\omega)\, d\omega \tag{12}$$

The open loop describing function Y_p which represents the human operator can be found from the closed loop function by the following relationship.

$$H = \frac{Y_p}{1 + Y_p Y_c} \tag{13}$$

where Y_c is the describing function of the controlled element. For a compensatory tracking task with a controlled element of unit gain, Elkind (60) was able to fit a model to the data points of the open loop describing function. He obtained the following model

$$Y_p = \frac{K\,e^{-Ls}}{T_1 s + 1} \tag{14}$$

When the input frequency was low, he found a high linear correlation as this describing function indicates an unstable condition for frequencies beyond the ones measured, and, as there was no evidence of this, it was concluded that the operator attenuates the higher frequencies by the addition of a lag, i. e.

$$Y_p = \frac{Ke^{-Ls}}{(T_1 s + 1)(T_2 s + 1} \tag{15}$$

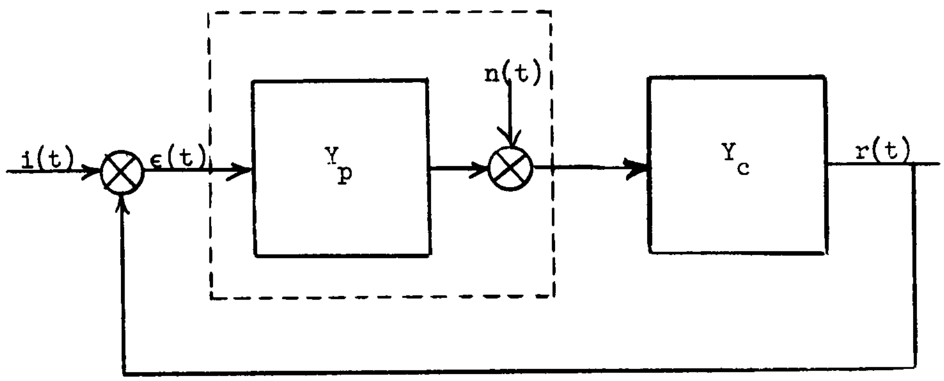


Figure 5

Open Loop Block Diagram

This approach was utilized in determining the human describing function with various controlled element dynamics by using the Franklin Institute F80A simulator (Krendel, 35a, McRuer and Krendel, 113). The open loop describing function was found by computing the cross spectral density functions of the input-output and the input-error where the open loop describing function (refer to Figure 5) was found by

$$Y_p = \frac{\phi_{ic}\ (j\omega)}{\phi_{i\epsilon}\ (j\omega)} \tag{16}$$

It should be noted that the remnant term in Figure 5 is different from the remnant calculated in Equation 10. In using bandwidth limited random noise for the forcing function, the general describing function that could be applied to the data was

$$Y_p = \frac{Ke^{-Ls}(T_2 s + 1)}{T_1 s + 1} \tag{17}$$

It was realized that this transfer function would cause instability at higher frequencies but since no data was taken at the higher frequencies, the additional lag term for stability was not considered. The linear correlation of the tracking runs (ρ) was higher for longitudinal control than for the lateral control where the longitudinal control averaged approximately 0.65 and the lateral control averaged 0.45. From this study and a review of the other studies, McRuer and Krendel (113) formulated a hypothetical describing function of the human operator which was

$$Y_p(s) = \frac{Ke^{-Ls}(T_2 s + 1)}{(T_1 s + 1)(T_3 s + 1)} \tag{18}$$

where L = reaction time, T_3 = neuromuscular lag, $(T_2 s + 1)/(T_1 s + 1)$ = equalization where $T_1 < T_2$ is lead-lag, $T_1 > T_2$ lag-lead, $T_2 = 0$ simple lag, $T_1 = T_2 = 0$ is pure gain, K = gain.

The reaction time delay constant has been found to be relatively constant over the entire range of variables that have been studied. This value has been estimated to be 0.3 to 0.25 sec for step inputs decreasing to about 0.2 secs for random appearing discrete steps and continuous random functions.

The neuromuscular lag time constant T_3 was assumed to exist as higher frequencies would be attenuated in the open loop describing function (Elkind, 60). Because the cutoff frequency of the input was lower than $1/T_3$, the value of $1/T_3$ has been estimated in most studies (McRuer and Krendel, 113). It was felt, however, that this value is a function of the subject's neuromuscular system and will remain relatively constant over a large range of tracking conditions.

The results have shown that $1/T_3$ is approximately on the order of 1 to 10 cps. In recent studies, McRuer (41a) has shown that the neuromuscular lag term will vary with the type of hand controller used in the tracking task. With a pure force controller $1/T_3$ was higher than with a force-displacement controller.

The gain K and the equalization characteristic $(T_3s + 1)/(T_1s + 1)$ have been shown to vary with respect to the forcing function and the controlled element.

In studying tracking performance with a variety of controlled elements, Hall (86) correlated the open loop describing function with pilot opinion and average absolute error. The model that fitted the majority of the situations had the form of Equation 17.

The quasilinear model theory has developed into a useful concept that can be applied to manual control systems analysis (McRuer and Graham, 112). This theory represents the human operator as a generalized quasilinear describing function (Equation 19) for a wide variety of control tasks.
McRuer and Graham (112) summarized the usefulness of this model and stated the conditions that have to be met in order for the model to have validity. These are:

1) The input must appear to be random.
2) The error is presented visually and the input and system output are not known independently of error (i. e. the tracking is compensatory).
3) The system can be stabilized with, at most, a single lead, and
4) The bandwidth of the input (ω_i) is small compared to possible crossover frequencies.

Sheridan (144) developed a method for determining a time varying quasilinear model. This involved presenting the human with the sum of sinusoids.

$$r(t) = \sum_{i=1}^{N} A_i \sin \omega_i t \qquad (19)$$

where the subject's response was formulated by

$$c(t) = \sum_{i=1}^{N} B_i \ (t) \sin \left[\omega_i t + \phi_i \ (t) \right] \qquad (20)$$

The real and imaginary components of the transfer vector can be found by multiplying the subject's response c(t) by $\frac{\sin \omega_i t}{2 A_i}$ and $\frac{\cos \omega_i t}{2 A_i}$ which gives

$$R_i(t) = \frac{B_i(t)}{A_i} \cos \phi_i \ (t) \qquad (21)$$

and

$$I_i(t) = \frac{B_i(t)}{A_i} \sin \phi_i \ (t)$$

For each ω_i the amplitude ratio and the phase angle can be found by

$$\frac{B_i(t)}{A_i} = \left[R_i(t)^2 \ I_i \ (t)^2 \right]^{1/2} \qquad (22)$$

and

$$\phi_i(t) = \tan^{-1} \frac{I_i \ (t)}{R_i \ (t)}$$

This has to be accomplished N times to cover all of the input frequencies. The variance of the measured components due to the finite time interval of sampling and the remnant term is eliminated by filtering the output of the multiplier. It was also indicated that the sample length should be twice the period of the frequency range.

In the application of this technique, Sheridan has shown that the linear characteristics of the human do change rapidly when sudden system changes in the system parameters occur.

6.2 Sampled Data Models

Developing from the "psychological refractory period" (Telford, 59a; Vince, 158) and the "intermittency hypothesis" of human tracking (Craik, 49 ; Hick 92), several investigators have formulated intermittent models to explain this hypothesis (North 120, Ward, 160; Bekey, 82). North (120) described the stochastic portion of the human operator tracking error by a finite difference equation. The equation was used to compute stability boundaries and to deduce values of controller parameters which minimize the error variance.

The approaches by Ward (160) and Bekey (22) utilized a sampled data model with a linear transfer function. The sampled data model that Ward used had a zero order hold circuit and is diagrammed in Figure 6. The function $F_1(s)$ is a lead term developed by Tustin (155) which has the following form:

$$F_1(s) = a + bs + cs^2 \qquad (24)$$

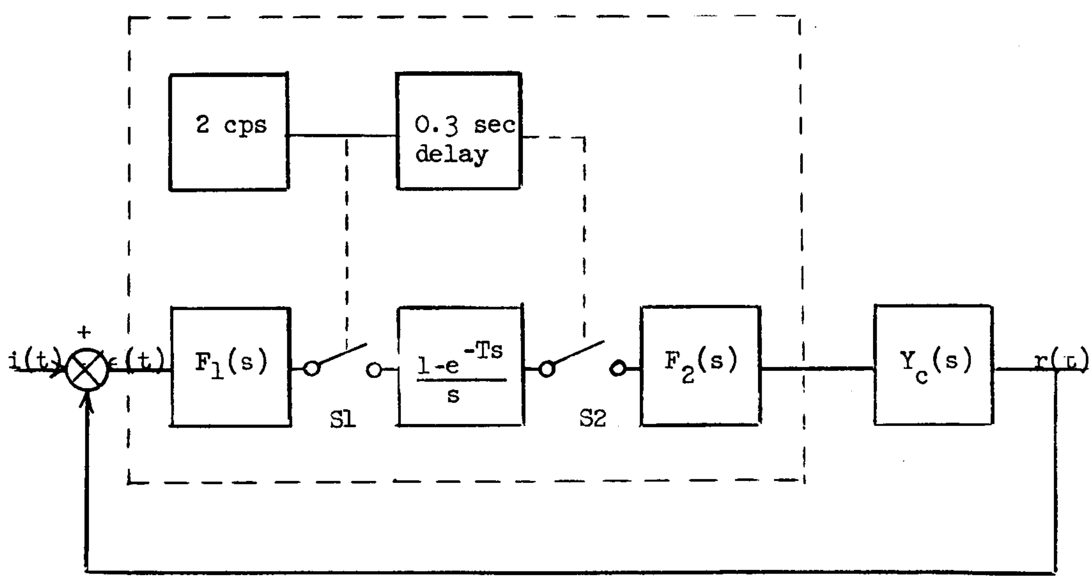


Figure 6

Sampled Data Operator Model after Ward

The term $F_2(s)$ is the delay and neuromuscular lag term also developed by Tustin and has the form:

$$F_2(s) = \frac{e^{-0.3s}}{s(Ts + 1)} \qquad (25)$$

In order to compare the model with the human operator, Ward used visual observation of the model output and human output. The only conclusion derived was that the error term of the model had the same order of magnitude as the error term of the human.

Bekey (22) used a sampled data model with a first order hold and a subsequent linear transfer function as shown in Figure 7. The use of the first order hold comes from the fact that the operator will continue to act on the last sample that he has received. He compared the error and output power density spectra of the model with that of the human operator. The results showed a sharp peak in the spectra of the model in the range of 1 to 1.5 cps when the input bandwidth was high. He found this same characteristic in the human operator's power density spectra. He concluded that a sampling process in the human could produce output frequencies unrelated to the input and thus contribute to the remnant term found necessary in the quasilinear model of the human operator.

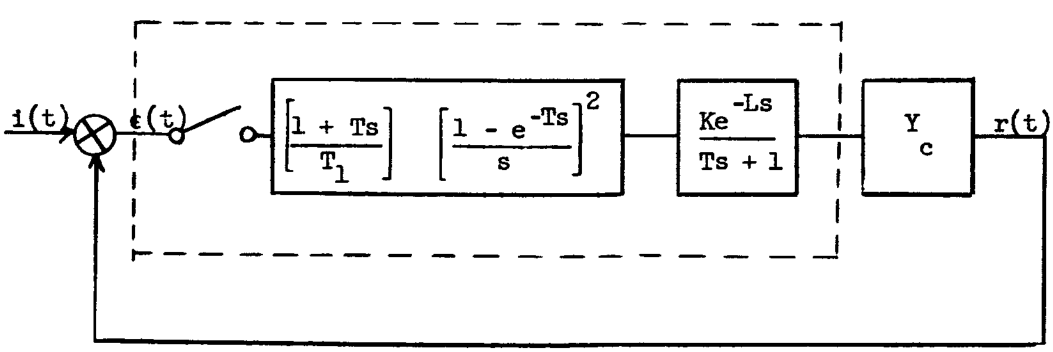


Figure 7

Sampled Data Operator Model Due to Bekey

6.3 Goodyear Study

Along with the development of the quasilinear model, other approaches were developed which considered some of the nonlinear and time variation characteristics of the human operator. Goodyear (Diamantides and Cacioppo, 55) formulated a nonlinear model of the human operator which was primarily based on the known behavior of the human's motor system during manual control. The parameters of the model were adjusted manually by comparing the oscillograph records of the model with the human operator's response. When there was no observable difference between these two records, the parameters in the model were assumed to be the same as those in the human operator. The model that developed was:

$$Y_p(s) = \underbrace{K\left[\frac{K_2}{K_o} s^2 + \frac{K_1}{K_o} s + 1\right]}_{1} \; \underbrace{G}_{2} \; \underbrace{e^{-Ls}}_{3} \; \underbrace{\left[\frac{K_4(K_5 s + 1)}{Ms^3 + Ns^2 + Ls + 1}\right]}_{4} + \underbrace{K_3 G_2}_{5} + \underbrace{\frac{\omega_o + c}{s^2 + \omega_o^2}}_{6} \tag{26}$$

where
1 = Equalization
2 = Threshold
3 = Time Delay
4 = Kinesthesis
5 = Predictor
6 = Dither

It was found that the equalization characteristic and the dither term varied with operator experience and training. The amount of lead varied directly and amount of dither inversely with increase in experience.

6.4 Parameter Adjustment Methods

In recent years, the model matching method such as the one utilized in the Goodyear study has been used in connection with parameter adjustment techniques. These techniques allow computational adjustment of the parameter of the model in order to minimize the difference between the model's output and the operator's response.

One technique is based on the method of steepest descent was utilized by Ornstein (125), Adams (9), Wertz (164) and Humphrey and Bekey (96). Another method based on regression analysis to adjust weighting coefficients of orthonormal filters was used by Elkind et al. (59).

6.4.1 Method of Steepest Descent

The method of steepest descent was developed by Clymer (9a), Margolis and Leondes (40a) and Meissinger (42a). This technique is based on an adjustment strategy where the rate of adjustment of the parameters is proportional to the gradient vector of the error criteria.

Ornstein (123) used the method of steepest descent where the model of the human operator was formulated as a linear differential equation.

$$a_o x + a_1\dot{x} + a_2\ddot{x} \ldots = y + b_1\dot{y} + b_2\ddot{y} + \ldots \tag{27}$$

The computed values of the coefficients a_{ci} and b_{cj} were found from the error function between the input and the output which is defined as

$$E = \sum_{i=0}^{m} a_{ci}\frac{d^i x}{dt^i} - \sum_{j=0}^{n} b_{cj}\frac{d^j y}{dt^j} \tag{28}$$

The gradient vector was found by differentiating E with respect to the parameters a_{ci} and b_{cj}. The rates of correction of the parameters are proportional to the negative of these gradient vectors until the error is minimum and are given by:

$$\begin{aligned} \dot{a}_{ci} &= -G\frac{\partial |E|}{\partial a_{ci}} \\ \dot{b}_{cj} &= -G\frac{\partial |E|}{\partial b_{cj}} \end{aligned} \tag{29}$$

Ornstein applied this technique to determine the parameter values of a human operator model. This model was a quasilinear model developed by McRuer and Krendel in (113) and had the following form:

$$Y_p = \frac{1 + as}{b + cs + ds^2} e^{-0.25s} \qquad (30)$$

In the application of this method to quickened displays and damping the control stick, Ornstein found that differences only occurred in the amount of lead and control gain that the human operator applied

J. J. Adams (9), Humphrey and Bekey (96), Humphrey et al. (97) and Wertz (164) used the same method as Ornstein except the error criteria was the square of the difference between the human output y(t) and the analog model output.

$$E = \frac{1}{2}\left[\left(\sum_{i=0}^{m} a_{ci} \frac{d^i x}{dt^i} - \sum_{j=0}^{n} b_{cj} \frac{d^j y}{dt^j}\right) - y(t)\right]^2 \qquad (31)$$

An alternate computation strategy was developed by Humphrey and Bekey (96) instead of the continuous adjustment, an iterative technique was used in which all of the parameter values except one were held constant and this one parameter was adjusted until another new parameter vector was reached. This process was continued until all the parameters had been adjusted and the cycle was repeated until a minimum mean-squared error value was obtained. This method had an additional stability factor that was missing in the continuous adjustment process.

The describing function that had been used in these techniques was also the quasilinear model (Equation 19) without the reaction time. In these studies not only did K and T_2 vary with different dynamics but T_1 and T_3 also varied, i. e. the subjects increase their lead time constant T_2 and reduced their gain K and lag T_1 and T_3 when a more complex controlled element was used.

As stated by the authors, the advantage of model matching techniques is the ability to utilize nonlinear components in the model. This will allow better approximation to the actual human describing function and if the parameter values are time-variant, this technique will be able to detect this variation.

6.4.2 Regression Analysis with Orthonormal Filters

An approach similar to the method of steepest descent was developed by Elkind et al. (59) based on Levine (31a) and Huggins (33a) work. This method uses an analog model of the operator composed of filters which Elkind termed mimic filters. These filters have weighting coefficients and the summation of these form the analog model. Similar to Humphrey and Bekey's approach, the difference between the human and the model is found and the mean square value is calculated (Figure 8). This can be formulated in the following equation

$$\overline{\epsilon^2(t)} = \frac{1}{T}\int_0^T \epsilon(t)^2 dt = \overline{\left[y(t) - b_j\ z_j(t)\right]}^2 \qquad (32)$$

where $y(t)$ is the human's output, b_j are the weighting coefficients and $z_j(t)$ are the mimic filters.

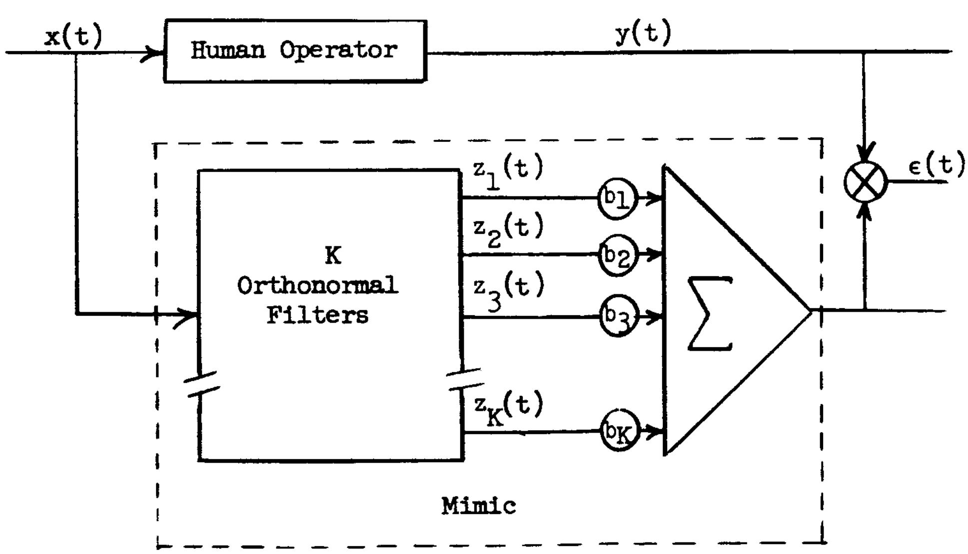


Figure 8

Model-Matching with Orthonormal Filters

The values of the coefficients b_j that minimize the error can be found be differentiating $\epsilon^2(t)$ with respect to each b_j and setting the results equal to zero. This obtains the following covariance matrix.

$$\begin{aligned}
z_1 z_1 b_1 + z_1 z_2 b_2 + \cdots\cdots\cdots + z_1 z_k b_k &= z_1 y \\
z_2 z_1 b_1 + z_2 z_2 b_2 + \cdots\cdots\cdots + z_2 z_k b_k &= z_2 y \\
\vdots \qquad\qquad\qquad\qquad & \vdots \\
z_k z_1 b_1 + z_k z_1 b_2 + \cdots\cdots\cdots + z_k z_k b_k &= z_k y
\end{aligned} \tag{33}$$

where $z_i z_j$ is the sample covariance of z_i and z_j for period T and $z_i y$ is the sample covariance of z_i and y for the same period. Assuming the quasilinear model of the human operator

$$y(t) = \int_{-\infty}^{t} \omega\,(t - \tau)\; x\,(\tau)\; d\tau + n(t) \tag{34}$$

where $x(t)$ is the input, $\omega(t - \tau)$ is the linear weighting function and $n(t)$ is the remnant, proper selection of the mimic filters z_j will yield a set of mimic coefficients b_j so nearly equal to that of the system that the error ϵ will be equivalent to the remnant $n(t)$. This selection requires that the filters be orthogonal to each other and normally distributed.

This choice of orthonormal filters allows the coefficients b_j to be partial regression coefficients that are independent and normally distributed. The sample length T that is required for measurement of the coefficients b_j depends on the variance σ^2_{bj} that is accepted for the coefficients.

According to Elkind, this technique allows the determination of both time invariant and time varying quasilinear models of the operator and it allows shorter sample lengths than spectral analysis.

6.5 Application of Models to Control Synthesis

The analysis of human tracking data with control theory methodology has been used for a limited portion of the entire field of tracking performance. Specifically, control theory has been well defined for compensatory tracking where the forcing function has been unpredictable and only one visual input, i. e., the tracking error, has been presented to the human. The application of control theory to a wider variety of perceptual motor skills results in complex relationships that are difficult to analyze. For example, Elkind (6) tried to determine the transfer characteristics for a pursuit system. His theoretical model had three components: 1) a transfer function for the response to a step input, summated with 2) a predictor, which was 3) then acted upon by a function similar to the transfer function of the compensatory system. He concluded on the basis of this preliminary investigation that he could not accurately describe a pursuit task.

In the system analysis of compensatory tracking, two task variables have been analyzed: the forcing function and the controlled element. The types of forcing function used have been a discrete function, i. e., a step input, and a random noise input in which the bandwidth of the noise was varied. The variables in the controlled element have been gain and the order of the dynamics. The most systematic studies have been with a position controlled element. However, various flight simulators were used in control evaluation which have complex vehicle dynamics.

A systematic analysis on the results of the applications of control theory to human tracking prior to 1957 have been conducted by McRuer and Krendel (113). Since then additional work has been accomplished by Hall (86) and McRuer (41a). A general review of the results of such research and applications to system design is given below.

<u>Gain and Equalization Characteristics of the Human Operator</u>

It has been shown that the human operator adjusts his open loop gain K (Equation 18) to correspond to the gain of the controlled element so that the closed loop gain will be equal to 1 for the frequency range he is tracking. It has also been shown by Elkind (60) that the gain adjustment appears to be a function of individual motivation and training in each particular task. Elkind also found with a position controlled element that the gain (K) was roughly proportional to the time constant of the lag term (T_1) and inversely proportional to the square of the cutoff frequency of the forcing function. Hall (86) showed that the gain is inversely proportional to the average absolute stick force that the pilot applies.

The equalization term (Equation 18) has also been shown to vary with the controlled element which is an example of the adaptive behavior of the human. Elkind (60) showed that the position control could be stabilized by the addition of a lead term to the operator's open loop describing function. In studies with more complex controlled elements (Russell, 48a, Hall, 86, McRuer and Krendel, 53), it has been shown that the equalization characteristic varies with controlled element. McRuer and Graham (112) state that with any particular control system it can be shown that the operator will either adjust to a lag lead $T_1 > T_2$ or to a lead lag $T_1 < T_2$ characteristic in order to produce stability at lower frequencies. As the system becomes less stabilized, the pilot will add more lead time and as the stabilization further decreases, he reaches a point where he operates by discrete pulses and the linear model will no longer hold. In Hall's study (86) and in an analytic evaluation of studies performed by Ashkenas and McRuer, (15) and McRuer and Ashkenas (111), it was shown that the gain and equalization characteristic adopted by the operator can be correlated with pilot opinion ratings. It is found that for "good" ratings, the pilot's equalization characteristic is pure gain where he adds lag there is a slight degradation in his opinion and as lead is introduced and increases, his opinion varies inversely.

From these findings, McRuer and Graham summarized the adjustment rules used by the human operator.

- The human adapts so that the gain and equalization characteristic are appropriate for stable control.
- The human adapts so that the form of his equalizing characteristic is appropriate to good low frequencies closed loop

system responses to the forcing function."

Pilot Analog Studies

With the advent of the quasilinear description of the human operator, the describing function (Equation 18) has been used for the determination of aircraft and spacecraft handling qualities with moderate success. Two methods have been applied. The first method consists of using a fixed parameter model of the human operator to determine the controllability and stability of the pilot-vehicle describing function (Frost, 20a; Taylor and Day, 53a). The other method is to adjust the model's parameters so that the pilot-vehicle model is stable (Ashkenas and McRuer 15, McRuer and Ashkenas, 111, Sadoff, et al., 49, 50). This parameter variation can be done within the limits that are known to exist for the human. Whenever these parameters approach the human's limits, it has been suggested that the human operator's work load is higher (McRuer and Ashkenas, 15, Sadoff, et al., 50).

Learning

Learning has not been a specific topic of study in control theory experiments; however, certain conclusions can be drawn. Elkind (66) and McRuer (41a) have shown that the parameter values of the human transfer function vary with learning and only after a large number of learning trials will they become stabilized. Also, it has been shown by Hall (86) and Diamantides and Cacioppo (55) that the parameter values of different subjects will vary according to the amount of experience the subjects have had in tracking and in aircraft. It has been shown that for highly experienced jet aircraft pilots, the parameter values have less variability and the lead time constant is larger. These relationships can also be reflected in the above section on gain and equalization characteristics in saying that with learning or experience the operator is capable of adjusting his open loop describing function more accurately in order to maintain a "good" control system.

Intermittency

Although the studies by Ward (160) and Bekey (22) have shown that the peak in the error density spectra at high frequencies can be caused by sample data processing, they have not established that sampled data processing does occur in human tracking. However, as the linear model does not predict such peaks, the sampled data model is a more accurate description of this aspect of the operator's output.

7. DISCUSSION

7.1 Differences

Both the psychologist and the engineer have attempted to describe the human operator in a control system in terms of his response to particular inputs. The engineer has simplified his task by describing human behavior in terms of an established model of the form used for describing the other components in the system. The psychologist has not been under the restraint of using a particular language and his descriptions of the human operator have shown a wide range of choice of experimental situations and measures.

The engineer's language has allowed him to quantify certain aspects of the operator's input and output, permitting him to mathematically describe the transfer characteristics of the human operator. The result has been that the engineer focused his attention on both a narrow range of behavior and a limited number of variables affecting behavior. The variables studied by the engineer have been task variables such as the forcing function and the controlled element rather than procedural variables such as learning and motivation.

Another factor is that the engineer idealized the human operator as he does the mechanical portion of the control system. This was accomplished by simplifying the overall models of the human operator and only considering the variables that have primary influence on control system performance. An example of this was in the quasilinear approach where nonlinearities or time varying parameters in either the human operator or the mechanical portion of the control system are evaluated as a time invariant linear system.

For the psychologist, the limited range of tracking behavior is one example of perceptual-motor behavior and, as such, a description of tracking behavior should not be isolated from other perceptual motor phenomena. Because of the complexity and variety of such behavior, this approach has only allowed working with somewhat qualitative descriptions and precludes analytical work.

A useful discussion of this difference in methodology was given by Broadbent (7a). Broadbent contrasted two approaches to the development of theories in psychology. He illustrated the first approach by Hull's concept of learning theory. Hull attempted to make a rigorous statement of postulates and axioms of learning in order to derive laws of learning. The goal of this approach was to obtain a quantitative description of learning. Broadbent states that such an approach is of questionable value for many areas in psychology because the state of knowledge is not sufficient for a theory giving detailed numerical predictions. Broadbent suggested a second approach where choices between classes of theories are made rather than attempt to prove or disprove a given example of a class. Psychological research should initially delineate behavior in a broad manner, developing theories which can be tested qualitatively. These qualitative statements do not have to be vague, e. g., a statement that one condition is superior to another is testable, even though no numerical statements of magnitude are given. If control theory is substituted for learning theory, Broadbent's comments describe the situation to tracking reasonably well and parallel the comments of psychologists such as Adams and Poulton.

Thus, the conflict in approach to tracking is not so much between psychology and engineering but between narrowing the field of inquiry to apply qualitative methods versus investigating more complex situations less amenable to mathematical analysis. The engineer must eventually consider extension of his approach to cover some of the more complex aspects of tracking while the psychologist must consider the engineering models if they provide accurate descriptions of human behavior.

7.2 Similarities

There are similarities or bridges between the psychological and engineering viewpoints. These are in the use of psychological and physiological factors in justifying the analytical models and in certain results on criteria for control system design.

In the analysis of the linear describing function of the human operator certain parts of the function can be justified by psychological and physiological factors. These are the reaction time delay terms which remain relatively constant regardless of the input (McRuer and Krendal, 113), the neuromuscular lag which limits the response at higher frequencies and the "intermittency" hypothesis used in sampled data models

(Ward, 160; Bekey, 22).

Similar results on the evaluation of human performance in control system design can be seen from the discussion on control theory results. In section 5.5 it was indicated the amount of equalization the operator applies in a control situation affects his opinion of the controlled element or handling qualities (Hall, 86; Ashkenas and McRuer, 15). The highest rating ("good") occurred when the operator supplied only gain with no equalization. This agrees with an early statement made by Birmingham and Taylor (33), who stated that man performs best as a single gain in a control system. Therefore, in effect control theory has substantiated an early psychological hypotheses.

7.3 Critiques

The engineering approach has been criticized on two major points by many psychologists: (1) the control theory models are inappropriate for describing human tracking behavior, and (2) many important factors that affect tracking behavior are completely ignored in the control theory models.

The first criticism is made on two counts: (1) the human operator does not satisfy the assumptions of linearity required by control theory, and (2) the type of data analysis used is inappropriate. This criticism has been mostly leveled against the quasilinear approach, because it is futher developed and more familiar than other engineering models.

The criticism of nonlinearity is partly unjustified in that the control engineer recognized that the human operator is nonlinear and only uses the quasilinear model to describe human behavior when the linear coherency is high ($\rho \approx 1$). When linear coherency is low, useful information can still be obtained by examining the sources of the remnant term in addition to the linear terms. It is also true that operator nonlinearities do not show up, to a large extent, in high-gain feedback systems, since the main purpose of a feedback system is to minimize such nonlinearities. Human nonlinearity, therefore, may not be as important in describing the human's response in control as it is in describing the human, per se. In applying his results to manual control systems, the engineer may thus be justified in ignoring certain nonlinearities.

The ability of the quasilinear model to successfully tolerate a certain amount of nonlinearity relates to the second criticism of the engineer. In developing a language for studying perceptual-motor skill, psychologists have developed a number of concepts and tools which have no apparent parallel in control theory. These methods have proven useful for describing much of human behavior and to that extent control theory does not present a strong attraction.

The criticism is to a large extent justified, namely, important factors such as learning, stress, motivation, and some of the information processing models developed by psychologists have not generally been formally considered by those working with control theory. There is little question that it will be necessary to include these factors in human operator models. However, it is also fair to point out that the psychological literature does not contain any clear description of, for example, motor skills learning, that could be used as a quantitative model, although information has been collected which may suggest approaches. Many engineering techniques can include operator nonlinearities and other functions. For example, the Goodyear (55) studies included a threshold, a dither term, and a prediction term. Model-matching techniques, such as the Goodyear Study, can include a variety of functions and provide an instantaneous and average description as well as a model for learning.

The two major criticisms advanced by engineers of the psychological approaches are[9]: (1) that they cannot be used directly in system design, and (2) that psychological experiments tend to be isolated from each other in terms of experimental conditions, conception, and variables making quantitative comparison across experiments nearly impossible.

The types of experiments and data described in the psychological literature have not been suitable for analysis of control system performance except for the studies that have described human behavior in engineering terminology (Birmingham and Taylor, 33). This statement must be qualified to apply only to dynamic characteristics of control systems and not the large body of human engineering data on system design. Dynamic design of control systems requires knowledge of the equalization

[9]Overt criticism of the psychological approach have not generally appeared in print.

characteristics that the human operator uses to minimize the feedback error in the control system. The majority of this work has been performed by flight control engineers (Harper, 29a; Creer, et al, 13a; Sadoff, 49a; McRuer, et al, 111).

The second criticism is not unique to engineers; psychologists themselves recognize the difficulty of the comparison of results between experiments and of obtaining a "crucial test" of a theory. The wide range of conditions that an investigator can and must choose from, the number of factors that can influence the outcome of an experiment, and the general lack of basing experimental work on quantitative models all contribute to this situation.

The consistent use of a particular model enables specific comparisons between experiments; for example, Hall (86) could compare his operator functions to those of Elkind (6) as the system inputs, display/control configurations and analysis of results were similar. An admittedly bad example from the psychological literature is the controversy over the PRP (Welford, 61a; Bekey, 22, Appendix 1; Adams, 2) in which a number of different "models" have been suggested without a careful analysis of the implications of each model. Not all of the psychological literature is this hard to compare and it is also true that only a few extensive studies based on the quasi-linear models have been reported, making the compatibility of results difficult to evaluate.

The frequent lack of adequate description and design of experiments is common to both the psychological and engineering literature. The psychologist is more guilty of the former and the engineer of the latter. This lack has the effect of an uncontrolled variable in comparing the results of different experiments. In most engineering studies, a small number of subjects was used and the design was often confounded such that influences of the important variables could not be assessed independently of each other. On the other hand, there are both psychological engineering studies where these conditions are well defined.

7.4 Task Variables and Performance Measures

In the comparison of the engineering and psychological literature, the experimental conditions were tabulated with respect to input forcing functions, controlled elements and performance measures for the 168 studies reviewed. These results are given in Table I.

Table I

Comparison of Input Forcing Functions, Controlled Element and Performance Measures of the Psychological and Engineering Literature

(Individual numbers refer to the abstract numbers in Section 9)

Forcing Function	Psychological	Engineering
1) Discrete or Linear	2, 4, 5, 8, 14, 20, 21, 24, 25, 26, 28, 48, 51, 54, 63, 65, 66, 67, 77, 83, 85, 87, 94, 138, 152, 153, 157, 163, 167	148, 150
2) Single Sinewave	3, 7, 11, 17, 36, 37, 39, 56, 61, 62, 73, 78, 88, 99, 100, 110, 118, 125, 128, 130, 132, 158	23
3) 2 or 3 Sinewaves	40, 42, 53, 76, 98, 126, 132, 133, 139, 142, 148, 151, 166	23, 28, 121, 122, 153, 156, 159, 160
4) Random Signal or more than 3 sinewaves	32, 75, 78	55, 90, 106, 164
Cutoff Frequency a) <0.2 cps	35, 110, 134, 135	22, 60, 86, 96, 97, 123, 127, 140
b) 0.2-1.0 cps	119, 134, 135	9, 22, 57, 60, 107, 113, 144, 162
c) >1.0 cps	61	57, 60, 102, 103, 104, 113
5) Inadequate Description	6, 7, 23, 30, 72, 95, 147	

Controlled Element	Psychological	Engineering
1) Zero Order or Position (K)	2, 3, 4, 5, 6, 7, 8, 11, 14, 20, 21, 25, 26, 28, 29, 39, 40, 48, 51, 53, 61, 62, 63, 65, 66, 67, 72, 76, 78, 83, 85, 88, 94, 95, 99, 100, 110, 118, 128, 130, 132, 134, 135, 138, 142, 147, 152, 153, 157, 158, 163, 166, 167	9, 22, 23, 57, 60, 86, 102, 103, 104, 106, 107, 113, 136, 144, 150, 159, 160, 162
2) First Order or Rate (K/s)	4, 30, 37, 39, 40, 87, 134	9, 86, 90, 121, 122, 136, 144, 160
3) Second Order or Acceleration (K/s^2)	30, 37, 39, 40, 56, 75, 98	96, 97
4) Third Order (K/s^3)	30, 32	
5) First Order with Lag $\frac{K}{Ts+1}$	17, 37, 88, 126, 148	9, 97, 144, 156, 164
6) Second Order with Lag $\frac{K}{s(Ts+1)}$	35, 36, 37, 42, 73, 77, 125	86, 97, 113, 140, 156, 164
7) Second Order Quadratic $\frac{K}{T_1 s^2 + T_2 s + 1}$	35, 54, 73, 119, 125, 139	9, 86, 113, 123, 127, 140, 164
8) Third Order Quadratic	37	55

Performance Measure	Psychological	Engineering
1) Response Time (T)	2, 4, 5, 11, 24, 51, 65, 67, 77, 83, 128, 130, 138, 157, 158, 167	136
2) Time-on-Target $T\{\lvert e \rvert < L\}$	3, 4, 6, 7, 8, 14, 17, 20, 21, 24, 25, 28, 32, 35, 48, 63, 72, 85, 87, 88, 118, 142, 147, 151, 153, 166	
3) Histograms a) Amplitude	7, 94, 110, 148, 157, 158	86, 150
b) Error Peak	7, 53, 65, 67, 83, 138	
c) Error or Time at Specific Points	7, 53, 66, 94, 99	
4) Average Error $\frac{1}{T}\int_o^t e\,dt$	21, 37, 85, 94, 99, 100, 130, 139, 152, 163, 166	
5) Average Absolute Error $\frac{1}{T}\int_o^t \lvert e \rvert\,dt$	30, 39, 40, 42, 56, 73, 75, 76, 95, 98, 110, 125, 126, 130, 132, 133, 134, 135	86, 107, 127, 160
6) RMS Error $\left[\frac{1}{T}\int_o^t e^2 dt\right]^{\frac{1}{2}}$	17, 36, 54, 118, 119	22, 23, 106, 121, 122, 123, 162
7) Harmonic Analysis	61, 62	23, 107, 136, 144, 156, 160
8) Spectral Analysis		
a) Input Φ_{ii}		22, 57, 60, 86, 90 102, 103, 104, 113 140
b) Output Φ_{oo}		22, 57, 60, 86, 102, 103, 104, 113, 140
c) Error Φ_{ee}	152	22, 60, 102, 103, 104, 162
d) Input-Output Φ_{io}		22, 60, 86, 90, 113, 140
e) Input-Error Φ_{ie}		86, 113, 140
9) Parameter Adjustment	75	9, 55, 96, 97, 106, 121, 122, 123, 159, 164

As previously mentioned, it can be seen that the psychologist has used a wider range of forcing functions while the engineer was mostly concerned with random appearing input functions. The position (K) controlled element was dominant in both approaches and both utilized other controlled elements equally. For performance measures, the psychological literature has utilized time-on-target and average absolute error to a large extent while the engineer has used root mean square error and control theory measures.

Because of the diversity of performance measures, categorization is difficult. One possible basis for categorization is whether or not they account for time variation in the human operator. The average error measures, e.g., time-on-target and spectral density are usually averaged over one tracking period while frequency distributions of the error peaks and parameter tracking allow for variations of the human within a single tracking period. Even this categorization is not clear-cut as the sensitivity of the measures to time variation depends on the period of time that is required to measure them, i.e., average error can be measured for short as well as long periods of time and parameter tracking assumes the human's parameters remain constant over the adjustment period.

Another basis for distinguishing among the measures is in their relation to a particular model. An adequate statement of a model includes the quantities that are to be measured to test the model. In cases for which a formal model is not developed, it is often easy to infer system characteristics not logically derivable from a particular measure. For example, time on target refers to a large class of possible systems which could produce identical time-on-target scores although their outputs may differ in other respects (Bahrick, et al, 17). Power spectral analysis can be used to derive a quasi-linear transfer function that gives a continuous output which describes the operator's average output for the time period analyzed. Recent engineering studies have utilized analytical techniques for describing time-varying quasi-linear models (Sheridan, 144; Elkind, et al, 59) and time-varying nonlinear models (Humphrey and Bekey, 96).

One performance measure, pilot opinion, has generated a sufficient amount of controversy to warrant separate mention. Engineers have been using pilot opinion for years in aircraft design; recently there have been attempts made to systematize the procedure and develop standard techniques for using it (Cooper, 12a). Many psychologists have criticized the approach taken in quantifying pilot opinion. This criticism is based partially on the extensive experience of psychologists with opinion and judgment scaling and their awareness of many factors which can influence these responses other than the objects being rated and partially on the engineer's treatment of opinion data. The usefulness of pilot opinion depends on having a group of subjects with appropriate control experience and who are able to relate this experience to a test situation consistently. A number of problems remain unexamined on this topic including the information contained in the pilot's judgment, the factors influencing his judgments (both system variables and others) and the proper treatment of such data. Pilot opinion is, to a certain extent, a measure of load on the operator. Another technique to measure pilot load is the use of an auxiliary task. The level of performance on the auxiliary task is used as a measure of load required by the main task (Ekstrom, 14a). However, the concepts of operator "loading" and "channel capacity" are still ill-defined although seemingly important.

The proper interpretation of each measure may depend on the characteristics of the system to which it is applied. A given measure may be relatively insensitive to certain system variations or it may be sensitive to the wrong ones. Thus, characteristics of measures should be understood before they are chosen for a particular study. This problem has not been systematically studied with respect to the human operator, although measures of control system performance have been examined by many investigators (e.g., Wolkovitch, et al, 64a; Magdaleno and Wolkovitch, 39a). These investigators have concluded that no single measure is adequate for control system optimization. A similar result for the human operator is implied from the psychological results on various performance measures (see Section 5.6).

It should be clear at this point that a single measure for a complex tracking situation cannot give information concerning both system performance and operator performance. For different tracking systems, the human will change his characteristics so that any overall system measure (root mean square error, average absolute error) cannot be used to infer human characteristics. This, of course, is just the point that Taylor and Birmingham made in 1959 but it bears repeating. The proper method to use in a given situation is more difficult to state and may depend on the purpose of the investigator. For flight control studies, pilot opinion has been held to be more sensitive to system variations than average absolute error. Spectral analysis has been shown to be useful in understanding the operator's characteristics as well as control system design and undoubtedly will be more extensively used in the future as more persons become familiar with the technique and more facilities are available. The development and use of other measures, such as those suggested by Poulton (133) should continue, as they add important information about operator performance and, as Poulton states, they are not incompatible with control theory analysis.

Based on the above discussion it is recommended that at least three types of performance measures be used in any study of tracking:

1) A measure of system performance such as the root mean square error or the absolute integrated error. This measures the operator's capability of handling the task; however, it does not give any information on the amount of "effort" that the operator must maintain in order to handle the task.
2) A measure of the operator's "transfer" characteristics. The quasi-linear model and the parameter adjustment methods make an attempt to measure the human transfer function during a specified tracking task. A thorough understanding of the operator's input-output characteristic would contain a measure of operator loading. Some correlation has been determined between the form of the quasi-linear model and pilot opinion, but separate measurement of these two factors is generally necessary.
3) A measure of operator "effort" or "loading." This measure can be obtained by pilot opinion techniques or by other workload analyses, such as the use of auxiliary tasks.

8. AREAS FOR FUTURE STUDY

As the psychologist becomes more familiar with the quantitative techniques used in control theory he may expand the uses of these techniques to the study of human behavior. By the same token, as the engineer becomes more capable of relating psychological knowledge to the models, he will be able to better approximate human behavior in a control system. It cannot be denied that a large amount of information has been obtained from the quasi-linear model theory on human operator performances in a compensatory tracking situation. The potentials of quasi-linear models have not been fully investigated and further studies along this line are warranted. Display and control characteristics, proprioceptive feedback loops, and learning are factors which should be studied to further test the applicability of this approach. It is also realized that this approach applies to a limited number of perceptual-motor skills and that either control theorists will have to extend their interests to the other situations considered by the psychologists or they will be ignoring an important body of work. Approaches using other engineering and psychological techniques are definitely called for as the field of study is large enough to usefully absorb more than one point of view.

The following areas are considered important for future studies:

Learning

Of the main problems in perceptual-motor learning, the following two seem most directly related to tracking:

- The relative importance of visual and proprioceptive inputs during learning and the relation of proprioceptive feedback to extinction and transfer.
- Systematic work on the various types of "knowledge of results" feedback to discriminate between "reinforcement" feedback and sensory "regulatory" feedback.

Proprioception and "feel" Characteristics

The determination of proprioceptive feedback loops would be an important advance in prediction of operator performance. The line of attack should include both examination of the vestibular and kinesthetic senses with application to description of performance for various vehicle motions and control "feel" characteristics.

Display/Control Relationships

Quantitative specification of information transfer between the operator's input and output as a function of display/control relationships would greatly increase the generality and usefulness of operator models. Techniques are not available for describing the spatial relationships between the operator displays and controls in a manner that is compatible with the time functions now used for the operator's dynamic characteristics. A large amount of work has been done on display/control compatibility (Noble, et al, 118; Smith and Smith, 53a) but a common description of temporal and spatial characteristics is needed. A theoretical study of possible techniques is suggested to determine the feasibility of this concept.

Time-Sensitive Techniques

Measurement techniques of instantaneous time variations in the human operator should be investigated. This would allow the investigation of certain time-varying characteristics that are known to exist in the human operator. Such characteristics include:

- Intermittency due to the operator's sampling behavior as proposed by the sampled data models and the hypothesis of "intermittency"
- Sampling behavior in multi-axis tracking
- Control reversals during tracking
- Short-term attention span.

Extension of Control Theory Models

The control theory approach should be extended to cover behavior characteristics that the psychologist has hypothesized. This would include devising methods from which learning can be predicted in a given control task, investigations of the effects of "feel" characteristics on the human's describing function and the examination of pursuit displays and nonrandom inputs. The study of pursuit displays and nonrandom inputs would provide useful information in order to formulate describing functions of prediction and short term memory by the human operator.

Performance Measures

It is proposed that three general types of measures be studied:
1) A measure of system error, 2) the transfer characteristics of the human operator, and 3) a measure of operator "effort" or "load."

9. ANNOTATED BIBLIOGRAPHY

The following abstracts represent the pertinent psychological and engineering literature on manual control and human tracking performance. An additional list of references referred to in the text but not abstracted are given at the end of this section.

The literature abstract was carefully reviewed and abstracted according to the following classifications so that a comparison could be made.

Purpose of Study

Theoretical Model, if any

Tracking Task

- Type:
- Number of Axes:
- Display:
- Control:
- Forcing Function:
- Controlled Element:
- Subjects:

Experimental Design

Performance Measures

Results

Conclusions

Some of the reviews and theoretical papers were not appropriate for this type of classification in which case a summary paragraph was given. Author's quotations are indicated by quotation marks.

1. Adams, J. A. Human Tracking Behavior. Psychol. Bull., 1961, 58, 55-79.

This article presents a critical review of tracking research and points of view. The relationships between engineering psychology and general psychology and between psychological requirements and control theory are discussed. A number of results from the psychological literature are given.

2. Adams, J. A. Test of the hypothesis of psychological refractory period. J. exp. Psychol., 1962, 64, 280-287.

Purpose To distinguish between the "expectancy" and single channel" explanations of the psychological refractory period.

Theoretical Model "The expectancy hypothesis would predict that refractoriness is a function of the statistical structure of time intervals by making S more expectant for certain classes of intervals, while the one-channel hypothesis would regard refractoriness a function of intervals but not statistical structure.

Tracking Task
- Type: Discrete, pursuit
- Number of Axes: One and two
- Displays: Visual - 3 horizontally arranged lights
  - Auditory - 3 tones, 600, 800, and 1000 cps
  - Visual and auditory feedback
- Controls: Two pencil sticks which moved freely and supplied three electrical positions.
- Forcing Functions: 60 audio-visual stimulus pairs per trial, 20 durations of 1.5, 2.0, 2.5 seconds, each randomized with simultaneous occurrence or with audio delay (see below).
- Controlled Element: Position (K)
- Subjects: 54 male undergraduates, paid.

Experimental Design The subjects were required to track both visual and audio signals using one control for each hand. The audio signal was delayed from 0 to 800 ms after occurrence of the visual signal for two-dimensional tracking. Each subject tracked audio and visual separately. The hypothesis was tested by using three groups, each with a different statistical distribution of audio delay times. Primary variation was in relative frequency of 100 ms delay: Low uncertainty = .80; Medium uncertainty = .60; and High uncertainty = .20.

Performance Measures Average response times between the onset of a stimulus and the occurrence of a response to it. Categorization of response times into Beneficially Anticipatory RT, Non-anticipatory RT, and Detrimentally Anticipatory RT on the basis of the time interval between stimulus and response.

Results "The results are consistent with the expectancy hypothesis. Decrement in response to the second of two closely spaced stimuli was greatest when the stimulus series had high time uncertainty, and was reliably less when time uncertainty was moderate or low."

"Even when the two stimuli were presented simultaneously and Ss had direct and immediate information that a lag was not required, the audio response was still delayed."

Conclusions "Thus, in this study, the decremental effect that has come to exemplify psychological refractory period emerges as a learned tendency to respond with a visual-audio sequence and to lag the audio response when extensive practice has been given under conditions of temporal uncertainty."

3. Adams, J. A., and Creamer, L. R. Anticipatory timing of continuous and discrete responses. J. exp. Psychol., 1962a, 63, 84-90.

Purpose To examine the hypothesis that anticipatory responses are determined by the action of mediating responses and to determine if the locus of the mediating responses are "central-verbal" or "peripheral-motor." The procedure was to provide various types of part-task pretraining to establish mediating responses and then test on the whole task.

Tracking Task
- Type: Exp. I - Continuous pursuit. Exp. II and III - Discrete pursuit, visual and auditory.
- Number of Axes: One for all experiments
- Displays: Exp. I - Trace on paper behind horizontal slit, 7 mm x 30 cm. Exp. II and III - 3 small lights or 3 tones, 600, 800, and 1000 cps.
- Controls: Exp. I - Horizontal handle, radius of 16.6 cm. Exp. II and III - 2 inch stick on arm of chair, continuous movement, 3 electrical positions.
- Forcing Function: Exp. I - Continuous regular input signal which approximated a sine wave. Exp. II and III - Regular sequence of lights back and forth or tones up and down.
- Controlled Element: Position (K)
- Subjects: 47 male paid students, Exp. II, 40 males, Exp. III, 16 male students.

Experimental Design Exp. I (Continuous tracking) - Pretraining groups were: (1) Verbal (V); the S indicated a change whenever the input reversed direction and was instructed to anticipate. (2) Continuous motor (CM) - The S used a small crank to match the speed and direction of the input. (3) Discrete motor (DM) - The S pressed a button at each input reversal. Exp. II (Discrete Tracking) - Pretraining groups were (1) Verbal response to predict visual signal (VV). (2) Verbal response to predict auditory signal (AV). (3) Visual-motor response by pressing button to anticipate visual signal (VM). (4) Same button to auditory signal (AM). Whole task group was used as control (WT). Experiment III - Pretraining groups were (1) Visual tracking with feedback (VF) and (2) Auditory tracking with feedback (AF). Criterion task was whole task (WT) group from Exp. II. All experiments used 60 second runs, 10 trials/subject.

Performance Measures Exp. I - Time between input reversed and S's output reversed, Exp. II, III - Time on Target.

Results Exp. I - Pretraining groups showed lower response time on initial trials than the whole task groups but were not distinguished among themselves in response time. Exp. II - No difference was found between any groups; ascribed to lack of feedback. Exp. III - Groups AF and UF gave greater time-on-target than W but were not significantly different among themselves. No differences were found for the motor vs. nonmotor locus of the mediators.

Conclusions Mediation as a mechanism for anticipation in tracking was found tenable. Time-varying proprioceptive traces and cognitive learning were discussed as explanations.

4. Adams, J. A. and Chambers, R. W. Response to simultaneous stimulation of two sense modalities. J. exp. Psychol., 1963, 63, 198-206.

Purpose To determine if responses to two simultaneous signals are the same as those to signals presented individually.

Theoretical Model The experiment was designed to study sensory interaction as a reason for differences between the responses to simultaneous events compared to responses for single events. "It was hypothesized that the prediction of an event pair, both in type and time, could often free S of directly sensing environmental stimuli before responding and this would minimize sensory interaction as a possible source of impairment.

Tracking Task

Type: Discrete, pursuit
Number of Axes: One and two.
Displays: Visual - 3 horizontally arranged lights.
Auditory - 3 tones, 600, 800, 1000 cps.
Visual and auditory feedback
Controls: Two inch stick, freely moving; 3 electrical positions, one for each hand.
Forcing Function: 50 two second audio or visual events or 50 paired events. Series had redundancy of 68% as a middle light (tone) always followed an end light (tone) whereas a middle light (tone) could be followed by either end light (tone).
Controlled Element: Position (K)
Subjects: 48 Ss (16 per group), male undergraduates, paid.

Experimental Design (1) Mean time on target which was a function of time between stimulus and response onsets, number of errors, and duration of error before corrected. (2) Response times: Correct

TR- time between stimulus and response onsets; Error RT - same but for incorrect responses; Error Correction RT - time between stimulus onset and correction completion. Measured on trials 56 and 57. (3) Simultaneity of responses for paired stimuli (4) Beneficial anticipation (RT of ± 133 ms) and Perfect anticipation (RT of ± 33 ms).

Results For certain events, response to visual stimuli paired with auditory stimuli were faster than to visual stimuli alone. For uncertain events, responses to visual stimuli paired with auditory stimuli were slower than to visual stimuli alone. A longer time to correct errors was found for the audio stimulus when paired with visual stimuli under the uncertain conditions.

Conclusions Learned anticipation for paired events under the certain condition enabled the S to use the auditory signal to trigger the visual response time. It was also suggested that the difficulty level of the task was an important variable in determining anticipation.

5. Adams, J. A. and Creamer, L. R. Proprioceptive variables as determiners of anticipatory timing behavior. Human Factors, 1962b, 4, 217-222.

Purpose To examine the hypothesis that the time varying after-effects of proprioceptive stimulation provide information for controlling the occurrence of a future response.

Tracking Task
- Type: Pursuit, discrete
- Number of Axes: One
- Displays: A horizontal slit, 11 mm x 300 mm, chart paper moved vertically behind the slit. The signal was a pair of red pen lines 16 mm apart.
- Controls: Sliding knob linked to the response pen with and without spring loading.
- Forcing Function: Step change in signal, the pair of red lines disappeared from one side of center and reappeared on the other side.
- Controlled Element: Position (K)
- Subjects: 96 male students, paid.

Experimental Design The variables were spring loading (zero, one pound for wide separation or four pounds for narrow), separation 2.25 inches, 7.75 inches), and intertrial time, (2 sec, 4 secs). A 2 x 2 x 2 randomized factorial design was used. A random series of intertrial times for 300 trials was used for a training series. Eight groups of 12 Ss were used.

Performance Measures Response time was measured from the step input time to the initiation of movement. The criterion for beneficial anticipation was ± 117 msec from the step input time.

Results Spring loading produced more beneficial anticipation than no spring loading. The 2 sec intertrial interval produced more beneficial anticipation than 4 secs. No difference in anticipation was found for movement amplitude. No beneficial anticipation was found for the random group.

Conclusions The results provide evidence for the proprioceptive trace hypothesis. The failure of movement amplitude to influence anticipation suggests a difference between regulatory proprioceptive stimuli and anticipatory proprioceptive feedback, as movement amplitude is known to influence the former.

6. Adams, J. A. and Webber, Carl E. The organization of component response error events in two-dimensional visual tracking. *J. exp. Psychol.* 1961, 61, 200-212.

Purpose to investigate the independence of time-on-target scores (TOT) across the component axes in a multi-dimensional tracking task.

Theoretical Model Random peak model described more fully in reference 7.

Tracking Task

- Type: Pursuit
- Number of Axes: Two
- Displays: Separate stimulus source for each axis, 1 x 7 inch aperture with a red follower and black target source cursor, 0.1 inch wide. Left-hand source mounted vertically, right hand source mounted horizontally. Eye-display distance 28".
- Controls: Two axis joystick, spring-centered, pivoted between legs. Display-control movements compatible.
- Forcing Function: Input was cam controlled, frequency analysis was not given. Two cams: Group I (independence) - "signals that were unsystematic for each component task, as well as unsystematic between tasks." Group NI (non-independence) each cam had a smooth section and an irregular section to force nonindependence of TOT scores.
- Controlled Element: Position (K)
- Subjects: 30 male students

Experimental Design The Ss were divided into two groups, NI and I as given above. Twenty trials a day were given on each of three different days. Data was recorded on trials 1, 4, 8, 12, 16, 20. Tracking runs were 90 seconds long.

Performance Measures 1) Time-on-target scores for 17 zones around zero error 2) Cross correlation between error function for each axis 3) Measure of independence of TOT scores which was

$$P_{xy}(0) - P_{xy}(P) \qquad P_{xy}(0) - P_{xy}(P)$$

where $P_{xy}(P) = P_x(0) \cdot P_y(0) \qquad P_{xy}(P) = P_x(0) \cdot P_y(0)$

$P_{xy}(0)$ = Proportion of time x and y are in a given error zone.
$P_y(0)$ = proportion of time y is in a given error zone
$P_x(0)$ = proportion of time x is in a given error zone
$P_{xy}(P)$ = predicted proportion of $P_{xy}(0)$.

Results Group I showed independence of TOT scores. Group II showed dependence of TOT scores. Cross correlations for individual subjects showed significant correlation, i. e. when an error was reduced in one axis it increased in the other.

Conclusions "Considering all of these findings, we conclude that the independence law has limited generality for understanding the details of responding in complex tracking tasks."

"A more fruitful approach to description of complex tracking behavior would seem to be in terms of error peak models, where an error peak is taken as a distinct response act of visually attending to a stimulus source and executing a motor movement to eliminate the observed error.

7. Adams, J. A. and Webber, C. Monte Carlo model of tracking behavior Human Factors, 1963, 5, 81-102.

Purpose To develop a stochastic model of human tracking behavior that will eventually describe task and behavioral complexities found in engineering psychology.

Theoretical Model A linear servo model is explicitly discarded in favor of a stochastic model. Basic idea is that of the "error peak" defined as an increase in tracking error which is sensed by the operator and nulled. A tracking record is considered to be a sequence of error peaks. The error peak is defined by (1) peak error (E), (2) rise time (t), (3) descent time (T) and (4) In-Time (t_i). Four empirical equations were derived relating these quantities to the number of trials (N) for various input conditions. Equations were obtained by curve-fitting techniques from tracking data. These equations were programmed on a computer and a tracking record generated by use of a random generator to select from the distributions of E and t_i. These records were then compared to actual tracking runs.

Tracking Task

Type: Pursuit
Number of Axes: One and two.
Displays: Rectangular aperture 1 x 7 inches, 0.1 inch wide follower and target cursor, 28 inch display-eye distance.
Controls: Two-axis joystick spring centered, compatible display-control relationship.
Forcing Function: R-Sine 20.8 cpm I - "highly unsystematic"
Controlled Element: Position (K)
Subjects: Four groups of 12 male university students, paid.

Experimental Design Four groups were used: I - Single axis, irregular input, R - Single axis, regular input, II - Two axes, irregular input RR - Two axes, regular input.

Performance Measures (1) TOT for 6 zones around zero, for each axis, (2) Frequency distribution of E values, (3) Mean number of peaks, (4) Frequency distribution of t_i, (5) 1st and 2nd order probabilities governing occurrence of error peaks in both axes, (6) Frequency distribution of time between peaks in the same or different axes and when peaks alternate between axes.

Results The author states that for an overall measure of tracking proficiency like TOT, the model did a creditable job, although there was a slight tendency for the model to under-estimate empirical TOT scores. Moreover, the model was reasonably good in simulating some of the fine grain features of one-and-two dimensional tracking. The probability of error peaks and their timing approximated the empirical data to a moderate degree, but certain of the subtleties, like the probability of three successive error peaks in the same task dimension of two-dimensional tracking were inadequately simulated.

Conclusions "We see our approach as a beginning with many possibilities for refinement of the model. Simple randomness appears a suitable assumption for measures like TOT, but conditional probabilities may have to be introduced for simulating the sequential dependencies among peaks. But rather than change the basic form of the model at this time, it might be a better research strategy to examine the work of our basic model format for tasks with different types of control dynamics, control configurations, number of tasks dimensions, control-display relations, types of inputs, and display modes."

8. Adams, J. A. and Xhignesse, L. V. Some determinants of two-dimensional visual tracking behavior. J. exp. Psychol., 1960, 60, 391-403.

Purpose To study the effects of spatial separation of displays, stimulus correlation, and speed of event change on two-dimensional discrete visual tracking.

Tracking Task

Type: Discrete, pursuit
Number of Axes: Two
Displays: Two sources, each of 3 discrete lamps for stimulus. Feedback lights below source indicated stick position.
Controls: Two 3 position sticks, one for each hand, compatible display-control relationships.
Forcing Function: Inputs defined on basis of probabilities of a given light being illuminated within and between sources. Two inputs used: (1) High-correlation (68% redundancy) (2) Low correlation (37% redundancy).
Controlled Element: Position (K)
Subjects: 96 male undergraduates, paid.

Experimental Design A 2 x 2 x 2 factorial design was used with the following variables: Stimulus correlation, high and low; Spatial separation, displays 5° and 30° apart; and Signal rate, 1/sec and 2/sec.

Performance Measures (1) Time on target (total time stimulus lights and feedback lights simultaneously aligned), (2) All stimulus and response events recorded on selected trials.

Results Performance on high correlation displays was only affected by rate and not by separation. Performance on low correlation displays was affected by both rate and separation. An analysis of response times indicated that the high coherency input allowed response anticipation.

Conclusions "Our findings are a helpful beginning in understanding the role of certain variables in two-dimensional visual tracking, but they also impress upon us our ignorance of prediction mechanisms and the observing response. Our knowledge of prediction is at an early empirical level and is insufficient for clarifying the explanatory processes." The authors stress the importance of the observing response in tasks with separated stimulus sources and suggest eye movement recording as a potentially useful technique in these situations.

9. Adams, J. J. A simplified method for measuring human transfer functions. NASA TN D-1782, 1963.

Purpose Determination of the effectiveness of measuring human transfer functions by the model matching technique.

Theoretical Model A pilot analog model was devised using a lead-lag transfer function of the following form:

$$\frac{K_1 \tau \left[1 + (K_2/\tau)s\right]}{(\tau + s)^2}$$

This model was compared to the operator's output by taking the root mean square difference. This error was acted upon by a set of filters whose products adjusted the parameters K_1, K_2 and τ to minimize the difference between the human and the analog.

Tracking Task
- Type: Continuous, compensatory and some pursuit
- Number of Axes: One
- Displays: Horizontal line on an oscilloscope moving in a vertical direction.
- Controls: Centrally located joystick with $\pm$ 3" movement and 2.5 lbs maximum force.
- Forcing Function: A cam with twelve discrete frequencies; the highest being about 1 cps and nearly all with equal amplitudes.
- Controlled Element: Four sets of dynamics were used; 1, 2/S, 1/S + 1, 2.5/S + 2.5 and $10/S^2 + 3s + 10$.
- Subjects: Four engineering test pilots and one research engineer were used in this study.

Experimental Design Not given

Performance Measures The parameter values K_1, K_2, and τ which were found by the method described above, were used as performance measures. Visual inspection of the tracking records was also used.

Results For the first order lag transform, the term $K_1\tau$ was approximately 1 for three pilots. However, for the second order quadratic transform the $K_1\tau$ term was 0.33 at approximately 0.1 sec while the K_2/τ term varied with the dynamics and each subject. The $1/\tau$ term remained fairly constant over all the runs. In a comparison of compensatory and pursuit tracking with the research engineer, the lead and lag term were larger in the second order quadratic controlled element.

Conclusions These results showed the feasibility of using this method of analysis.

10. Alluisi, E. A., Muller, P. F. Jr., and Fitts, P. M. An information analysis of verbal and motor responses in a forced-pace serial task. J. exp. Psychol., 1957, 53, 153-158.

Purpose To test the hypothesis that the rate of information transmission in the human is proportional to the rate of presentation of information until the maximum amount of information is being transmitted by the human.

Tracking Task The experiment was conducted in two parts. In the first part, the Ss responded by pressing a key (motor) and in the second part, the Ss responded verbally to a forced-paced serial presentation of numbers. Ten Ss were used.

Experimental Design Three levels of stimulus complexity (1, 2, and 3 bits/stimulus) and three levels of stimulus rates (1, 2, and 3 stimuli/sec) were presented in a randomized factorial design.

Performance Measures The number of correct responses in the forced-paced experiment was used to calculate the average amount of information transmission in bits/sec.

Results The maximum amount of information transmission in the verbal response was 7.9 bits/sec while only 2.8 bits/sec were transmitted in the motor response. With increase in rate of presentation there was an increase in information transmission in the verbal responses but a decrease in the motor responses while in both modes there was an increase in information transmission with the amount of information presented per stimulus.

Conclusions The authors concluded that "complex interactions exist in information transmission between amount and rate of information presented and stimulus response measurements."

11. Ammons, R. B. and Ammons, C. H. Movement analysis of the performance of a simple perceptual-motor task under various conditions. WADC Technical Report 54-36, April 1954.

Purpose To develop a reliable method of recording and classifying movements during rotary pursuit, and to use this method to study changes in rotary pursuit performance due to duration of practice, introduction of rest periods, increased accuracy requirements, and increased rate requirements.

Tracking Task
- Type: Rotary pursuit
- Number of Axes: One
- Display: Round disc with a 1/4 or 3/4 inch target on it.
- Control: Stylus that the subject held on target
- Forcing Function: Two speeds of the disc: 40 and 60 rpm
- Controlled Element: Position (K)
- Subjects: 64 male college students assigned in groups of eight.

Experimental Design A 2 x 2 x 2 factorial design was used with each cell using a different group of subjects. The variables were target size; 1/4 and 3/4 inches, frequency, 40 and 60 rpm, and the first and last trial periods.

Performance Measures Motion picture recordings were taken of the stylus and disc. A list of 19 movements were made and each motion picture record was tabulated to determine the total amount of time spent on each of these movements.

Results The results showed that more correct movements were made with practice. The report divided the movements into several groups; maladaptive, semiadaptive, and adaptive which was divided into approximately correct and incorrect movements. With the larget target and lower frequency, the subject's movements were also more adaptive.

Conclusions It was concluded that this method is a feasible technique to show training of simple predictive movements.

12. Ammons, R. E. and Farr, R. G. Long-term retention of perceptual motor skills. J. exp. Psychol., 1958 55, 318-328.

Twenty two groups, ranging in size from 20 to 36 male college students, were trained to either a moderate or a high level of proficiency on a procedural task or on a compensatory pursuit task, then retrained after no-practice intervals up to 2 years in duration. Learning, retention, and relearning were measured. It was found that, on the bases of mean time taken per trial or percentage time on target per trial, absolute loss in level of proficiency was apparently not affected by amount of training and was greater the longer the no-practice intervals. Retraining to the earlier level of proficiency took more trials the longer the no-practice interval and the greater the amount of training.

13. Annett, J., Golby, C. W. and Kay, H. The measurement of elements in an assembly task. - the information output of the human motor system. The Quart. J. of exp. Psychol., 1958, 10, 1-11.

Purpose To compare analysis of skilled movements by the electrical contact technique and high speed film recording.

Tracking Task The task was to move eight pins from holders to corresponding apertures. The same size pins were used throughout the experiments, but four different aperture sizes were used representing four conditions. Three subjects were used who performed 100 trials on each condition.

Performance Measures Contact analysis measured the time of four events: grasping, movement loaded, positioning and movement empty. A film analysis was made in which the same time intervals in the contact analysis were measured.

Results The results showed the total times are almost the same. However, a discrepancy arose in the two methods. In the film analysis, the movement loaded time was the same as the movement empty time and in the positioning, the size of the aperture varied the time significantly.

In the contact analysis, the movement loaded time is twice as large as the movement empty time and varies with the size of the aperture. Fitts formulation for the number of bits of information transmitted was applied to these results. If only the time of movement loaded and positioning was used, an average information transmission rate of 11.6 bit/sec results. Using the total time, as Fitts did, varied the transmission rate from 11.6 to 16 bits/sec.

Conclusion Film analysis is a more precise way of measuring movement than contact analysis. Also, in determining information transmission rate in a task, the tolerance of various elements should be carefully specified and measured.

14. Archer, E. J., Wyckoff, L. D. and Brown, F. G. Tracking performance as measured by time continuously on target. WADC Technical Report 54-210, March 1954.

Purpose To analyze TOT frequency distributions for different amounts of learning and different task difficulties.

Tracking Task
- Type: Continuous, pursuit
- Number of Axes: Azimuth, elevation, and range
- Displays and Controls: The Mast Pedestal Sight Manipulation Test
- Forcing Function: A sequence of eight attacks starting from right or left with two angular velocities, 18.75°/sec and 12.5°/sec.
- Controlled Element: Position (K)
- Subjects: 20 male college students.

Experimental Design The Ss were divided into two groups in which each group received one of two target speeds.

Performance Measures Time on target scores were obtained when the subjects were on the target in azimuth, elevation, range, either singly or in all possible combinations. The margin or error in azimuth and elevation permitted was $\pm$ 10 mils and in range $\pm$ 5 mils.

Results The results were given in the number of hits of a certain duration plotted against the duration time. These plots showed asymptotic-like function where the densities increased with practice and depended on the velocity of the target. It was noticed that the densities of the short durations decreased with practice while the densities of the medium duration were greater. The log of the density and the duration plus density plotted against the duration gave similar results to the other two methods.

Conclusions Scoring in this method revealed certain characteristics of performance which would not be evident in cumulative time-on-target scores.

15. Ashkenas, Irving L. and McRuer, Duane T. The determination of lateral handling quality requirements from airframe-human pilot system studies. WADC Technical Report 59-135, June 1959.

Purpose To apply pilot dynamic response data to servo analysis studies of airframe-human pilot studies and to determine satisfactory handling qualities.

Theoretical Model This study uses the following approximations for the describing function.

$$Y_p = \frac{K_p e^{-\tau s}(T_L s + 1)}{(T_1 s + 1)(T_n s + 1)}$$

where T_n = neuromuscular lag, $(T_L s + 1)/(T_I s + 1)$ = pilot equalization characteristics, K_p = pilot gain, and $e^{-\tau s}$ = reaction time.

This can be simplified to the following equation when no equalization occurs.

$$Y_p = \frac{K_p e^{-\tau s}}{T_n s + 1}$$

Results The closed loop pilot airframe configurations were compared with pilot opinion. When there is a high correlation between the closed loop function and pilot opinion, it is suggested that this technique can be used to determine "good" handling qualities of aircraft. Considering only the situation of closed loop control of bank angle by aileron, these studies revealed a certain combination of parameter system performance degradation which would hypothetically degrade pilot opinion. In this study, limiting values for good airframe dynamics have been evaluated with a roll angle/aileron transfer function given by:

$$\phi_{\delta_a} = \frac{K \delta_a}{(s + \frac{1}{T_s})(s + \frac{1}{T_R})}$$

The limiting values for good dynamics are T_R of less than 1 sec, K between .09 to .45 radians per lb/sec and a T_s/T_R greater than 30 where T_s is greater than 10.

16. Bahrick, H. P., Bennett, W. F., and Fitts, P. M. Accuracy of positioning responses as a function of spring loading in a control. J. exp. Psychol., 1955a, 49, 437-444.

The accuracy of positioning a horizontal arm control as a function of changes in the torque-displacement relation of the control was investigated. It was found that positioning errors were smallest when the ratio of relative torques change to displacement is largest, particularly if the absolute change of torque with displacement is also large.

It is concluded that control forces opposing a movement can provide useful cues in learning to execute different amplitudes of movement, and that their usefulness depends upon the relative and absolute torque change per unit of control motion.

17. Bahrick, H. P., Fitts, P. M., and Briggs, G. E. Learning curves-facts or artifacts. Psych. Bull., 1957, 54, 256-268.

Purpose This report was intended to demonstrate time-on-target scores can lead to erroneous results if learning is involved.

Tracking Task
Type: Compensatory
Number of Axes: One
Displays: CRT with cursor moving horizontally
Controls: Not mentioned in this report
Forcing Function: 0.167 cps sinusoidal function
Controlled Element: Position with .4 second exponential lag and simple position control.
Subjects: 50 male and 50 female

Performance Measures Two types of performance measures were taken on even number 90 second trials: root mean square error scores and time-on-target scores. Three score zones were used for the time-on-target measures, 5%, 15%, and 30% of the maximum error deviation.

Results The learning curves for the time-on-target scores in the tracking task with a .4 second lag suggested that absolute as well as relative improvements were greater for the male Ss than for the female Ss. This effect was particularly true in the 5% target zones. However, the curves indicated a greater improvement for females than for males. The scores also showed that the amount of improvement varies with the target zone where least improvement occurs in the 5% zone and progressively increasing improvements in the larger zone. The simple tracking task with no lag term for which only male Ss were used showed that for the 5% zone the time-on-target scores showed the greatest improvement with learning. The largest or 30% zone showed the least improvement.

18. Bahrick, H. P., Fitts, P. M. and Schneider, R. Reproduction of simple movements as a function influencing proprioceptive feedback. J. exp. Psychol., 1955b, 49, 445-454.

"This study tested the hypothesis that elasticity added to a control should lead to improved spatial accuracy of movements, while damping and mass added to a control should lead to improved temporal accuracy of movements.

To test these hypotheses, Ss performed simple circular and triangular control motions with a joystick when the control was loaded with various degrees of spring stiffness, or damping, or mass.

It was found that an increase of viscous damping or of inertia of the control resulted in greater uniformity of speed in successive reproductions of the same motion. In the case of the triangular motions increased mass and increased damping led to greater uniformity of peak velocity on each side of the triangle on successive trials. These results support the hypothesis regarding the utilization of proprioceptive information.

19. Bates, J. A. V. Some characteristics of a human operator. J. Inst. of Elec. Engr., London, 1947, 94, Part II A, 298-304.

This paper is a review article on characteristics of operator behavior. It gives a brief summary of physiological and psychological laws of visual perception and neuromotor activity. Some elementary response behaviors, such as reaction time in simple responses, transit reception, i. e. responding to the time when two moving signals coincide and operator discontinuity in continuous tracking are discussed. Responses to step functions are categorized into two types: (1) a rapid jerk of the limb which includes the demand to start movement necessarily including the demand to stop, and (2) a corrective movement where the limb rate is sufficiently slow for visual control to be continuously effective. Also discussed are certain aspects of controller design, i. e. control-display gain, friction and inertia, and operator training and learning.

20. Battig, W. F., Gregg, L. W., Nagel, E. H., Small, A. M. and Brogden, W. J. Tracking and frequency of target intermittence. J. exp. Psychol., 1954, 47, 309-314.

Purpose To determine the relationship between proficiency in tracking and frequency of target intermittence.

Tracking Task
- Type: Continuous, Pursuit
- Number of Axes: Azimuth, elevation, and range
- Displays and Controls: Standard Pedestal Sight Manipulation Test
- Forcing Function: Target moving in straight line at constant velocity. Eight conditions of target intermittence were used with the following frequencies: .4, .7, 1.0, 2.1, 4.1, 6.0, 8.2, and 16.1 cps. The light-dark ratio varied for the different frequencies.

Controlled Element: Position (K)
Subjects: 16 male undergraduate students

Experimental Design An 8 x 8 latin square design with three variables; target intermittence, ordinal position, and sequence.

Performance Measures Time-on-target tracking scores were used. One score indicated when the subject was simultaneously on target in azimuth and elevation with a 12 mil band and the other score measured TOT simultaneously in azimuth, elevation, and range with a 6 mil band on range.

Results The results showed an improvement in tracking up to 8.2 cps above which the TOT scored decreased. A significant practice effect was obtained only for the azimuth-elevation score.

Conclusion The authors stated that there was a confounding effect in the stimulus since the light-dark ratio and the target brightness both varied with intermittent rate.

21. Battig, W. F., Nagel, E. H., Voss, J. F., and Brogden, W. J. Transfer and retention of bidimensional compensatory tracking after extended practice. Amer. J. of Psychol., 1956, 69, 75-80.

Purpose To examine tracking performance for long-term periods of practice.

Tracking Task
- Type: Compensatory
- Number of Axes: Two
- Display: CRT
- Control: Joystick
- Forcing Function:
- Controlled Element: For complete description refer to Battig et al., 1955, 68, 585-594.
- Subjects: The four authors

Experimental Design Each S received 10 one minute trials a day for 100 days. Performance feedback was given at least once a week. For sessions 101 and 102, the course-cam was operated in the reverse direction for each trial. For sessions 107 to 110, the control display relationship was reversed. Sessions 103 to 106 and 111 to 114 were standard. Eight months later, four standard sessions were given to three of the Ss.

Performance Measures (1) Time on target. Scoring area on scope was 0.5 in diameter (corresponding to a 0.517° error in stick position). (2) Integrated error for vertical and horizontal axis.

Results Performance improved over the first 80 sessions. Performance with the reversed cam was significantly better than on initial sessions. Severe decrement in performance occurred on the reversed control-display trials. High degree of retention was shown after 223 days.

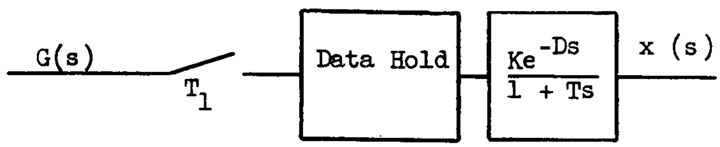
Conclusions The results support the hypothesis that what is learned in the tracking task is precision in making adjustive movements of the control.

22. Bekey, G. A. The human operator as a sampled-data system. IRE Transactions of the Professional Group on Human Factors in Electronics, September 1962, HFE-3.

Bekey, G. A. Sampled data models of the human operator in a control system. Doctoral Dissertation, University of California, Los Angeles, Engineering Department, 1961.

<u>Purpose of Study</u> To compare the response of a sampled data model to the response of the human operator.

<u>Theoretical Model</u> A sampled data model as shown below was proposed for the human operator.



Two data hold models were proposed, a zero order and a first order hold. The transfer function of the first order hold had the following form:

$$G_{s_1}(s) = \left(\frac{1 + T_1 s}{T_1}\right)\left(\frac{1 - e^{-T_1 s}}{s}\right)\left(\frac{Ke^{-Ds}}{1 + sT}\right)$$

Power density spectra of the error and output of the model was compared with those from human tracking data.

<u>Tracking Task</u>

Type: Continuous and intermittent, compensatory
Number of Axes: One
Display: Horizontally moving blip on CRT
Control: Pencil stick type control
Forcing Function: Summation of 10 sine waves with frequencies between 1-12 rad/sec and filtered at .75, 1.5 and 3.0 rad/sec. Also intermittent functions were produced by blanking the display at 2 cps and 3 cps.
Controlled Element: Position (K)
Subjects: A total of 10 subjects were used with varying degrees of experience.

<u>Experimental Design</u> Six levels of forcing function were used as the variables in this experiment.

<u>Performance Measure</u> The RMS error was taken in each run as well as the power spectral density of the error and the output.

Results The results indicated that for inputs of sufficiently high bandwidth, the output and error spectra of human operators are characterized by sharp peaks which occur in the range of 1 - 1.5 cps. These results were consistent with a sampled data model having a first order hold. With the intermittent display there was no significant change in the spectra, however, the sampling peak in the output and error spectra did shift.

23. Benepe, C. J., Narasimban, R., and Ellson, D. G. An experimental evaluation of harmonic analysis to the tracking behavior of the human operator. WADC Technical Report 53-384, May 1954.

Purpose To study error behavior of the human operator during one dimensional tracking using spectral analysis and autocorrelation.

Tracking Task

Type: Pursuit
Number of Axes: One
Displays: The visual display was a 1" by 6" opening in a gray panel with two pointers moving horizontally where the upper pointer was the target and the S operated the lower pointer. An auditory display was provided through a set of earphones where the frequency of a sinusoidal signal could be varied from 900 cps to 1100 cps.
Controls: The control was a steel rod extending 4" out of the panel which could be moved horizontally.
Forcing Function: The forcing function of the first four experiments consisted of a single sine wave at 1/3 cps which had a total excursion of 4". In the fifth experiment, the forcing function was composed of the sum of a 1/3 cps and a 2/3 cps sine wave where the amplitude of the 1/3 cps sine wave was 2-2/3" and the 2/3 component was 1-1/3".
Controlled Element: Position (K)
Subjects: Different sets of twenty two male undergraduate students were used in each experimental group.

Experimental Design Experiments 1 and 3 consisted of ten days of consecutive practice with the 1/3 cps target motion. In Experiment 4 two groups of subjects were run, one subject received the 1/3 cps and a synchronous auditory signal, the second group received the same visual input but the auditory signal consisted of a 1/4 cps variation which is referred to as the nonsynchronous auditory signal. This experiment was conducted for ten consecutive days. In the fifth experiment, the groups of subjects used two sine wave signals consisting of 1/3 cps and 2/3 cps.

Performance Measures The mean square error, power spectrum and autocorrelation analysis were taken for different combinations of records. The records were sampled every 1/2 second for 450 consecutive readings. Sixty autocorrelation and power spectrum points were computed for the 450 readings. In Experiment 3 the error curve was recorded directly as well as through a low frequency band rejection filter set at 1 cps $\pm$ .1 cps.

Results It was found that amplitudes of the components in the spectrum for the tenth day of experimentation were smaller than for the corresponding amplitudes in the first day. The relative components in the spectrum remained constant from the first to the tenth day. In Experiment 3 the filtered data showed a reduction in amplitude at 1 cps which is the region of the filtered operation. Fourier functions were fitted in order to remove the 2/3 cps and the 1 cps components from the autocorrelation curves which would leave a residual autocorrelation curve which will fall to 0 and remain there. The results of the first function

$$\cos \frac{2\pi T}{3} \pm .012 \cos 2\pi T + .132$$

indicated the presence of the third cps component. A 1 cps component and a dc component compared with the second function,

$$.08 \cos \frac{2\pi T}{3} + .18$$

which contained only a 1/3 cps component and a dc component, gave similar results. This indicated that a 1 cps sustained period component was not present in the behavior and a 1 cps transient component is present in the behavior. In Experiment 4 the synchronous group was compared with the nonsynchronous group. The nonsynchronous group showed power spectra that behaved like the previous power spectra. However, the mean spectra obtained for the synchronous group gave data like a spectrum expected of random noise. In Experiment 5 the addition of a 2 cps component increased the 1/3 cps error component above that of the previous results.

Conclusions The authors stated that "in this set of experiments, stationary tracking behavior, i.e. behavior in statistical equilibrium, was found under only one set of conditions, i.e. when an auditory signal mathematically equivalent to the visual signal was presented simultaneously to the auditory input channel. The series of experiments included two independent tests of linearity. In both cases, the behavior was markedly nonlinear. However, it should be pointed out that a test of linearity was not performed under the one condition in which stationary behavior was found."

24. Bennett, Corwin A. Sampled-data tracking: sampling of the operator's output. J. Exp. Psychol., 1956, 51, 429-438.

Purpose To determine the effect of sampling rate with and without transmission time delay and control sensitivity on tracking performances with discrete displaced targets and constantly displaced targets.

Tracking Task

Type: Compensatory
Number of Axes: Single
Displays: A blip signal on a CRT display with crosshairs inside concentric marks with 1/8", 1" and 2" radii.
Controls: A spring-centered joystick with 8" radius and a 2-1/2 lb. maximum force.
Forcing Function: Discrete displacement of the blip on the scope and continuous displacement of the blip on the scope.
Controlled Element: Rate controlled (K/s)
Subjects: Seven subjects were used who were engineers or technicians.

Experimental Design In Experiment 1 five conditions of sampling rate were used: 2, 3, 4, and 6 cycles per second and the continuous cases, and three conditions of hand control sensitivity obtained from previous experimentation and labeled low rate, optimal rate, and high rate. This experiment was performed with discrete displacement of the blip.

In the second experiment, the conditions were with and without transmission time delay, sampling rate and hand control sensitivity. The transmission delay time was .33 seconds and sampling rates were 3, 4, 5, 6, and 8 signals per second. This experiment was performed with discrete displacement of the blip.

The third experiment consisted of the continuous tracking task where five sampling rates, 1,2,3, and 5 cycles per second and the continuous input were given.

Performance Measures For the discrete task the "recovery time" was used, defined as the time from the start of the disturbance until the subject brings the target within the 1/8" circle and maintains it there. For the continuous tracking, the 50% limit was used which was defined as the distance on the display within which the subjects were able to maintain the target 50% of the time.

Results The results from Experiments 1 and 2 showed that the recovery time decreased with an increase in sampling rate except for the sampling rate of nine cycles per second which was the same as the continuous mode. In the second experiment with the transmission delay time, the mean recovery time increased significantly, and the third experiment showed a decrease in the 50% limits with an increase in sampling rate.

25. Bilodeau, E. A. Variations in knowledge of component performance and its effects upon part-part and part-whole relations. J. exp. Psychol., 1955, 50, 215-224.

Purpose To examine techniques for changing whole-task performance by altering performance or component tasks.

Theoretical Model Assuming independence of the distribution of TOT scores on component axes, the joint TOT distribution will by P(xy) = P(x) P(y). P(xy) can then be varied by changing P(x) or P(y) while keeping P(x) + P(y) constant. For example, if P(x) = 0.2 and P(y)= 0.8 then P(xy) = 0.16; however, if P(x) = 0.4 and P(y) = 0.6 then P(xy) = 0.24.

Tracking Task The SAM Multidimensional Pursuit Task was used. Four axes were used, each of which had a separate dial indicator. A right hand control stick was used for two axes, a left hand stick and pedals for one axis each.

Experimental Design Instructions and knowledge of results were varied over a period of 24 days during task practice to alter Ss pattern of attending to the four dimensions of the task.

Performance Measure Time on target.

Results Performance in the component dimension could be altered by both instructions and knowledge of results. Improvement in one component was accompanied by degradation in the others. A small positive correlation between component axes was found; not enough, however, to invalidate the assumption of independence of component dimensions.

26. Bilodeau, E. A. Patterns of internal consistency in multipart skilled performance. Amer. J. of Psychol., 1957a, 70, 550-559.

Purpose To predict whole-task performance from part-task performance on a four axes tracking task.

Tracking Task The SAM Multidimensional Pursuit Task was used. One subject attempted to maintain 4 meter needles on center through the use of a two-axis joystick, one axis "throttle," and rudder pedals. The input was not given.

Experimental Design The subject practices four tasks, each corresponding to a combination of the four dimensions labeled A, B, H, and S. Task 1 was dimension A, Task 2 A and B, Task 3 H, A, and B, and Task 4 S, H, A, B. A standard method of scanning the meters was used. Forty eight 60 sec. trials of each task were administered over a four day period. The order of trials were counterbalanced.

Performance Measure Time on target for individual and joint dimensions.

Results The relative performance on part-tasks varied with total number of parts. Predicted joint scores agreed with obtained joint scores. Predictions were based on $J_n = A \times B \times ...$ where J = joint score, A, B, = individual scores. Part scores tended to correlate weakly with each other but each contributed considerable variance to a whole task score including that part.

27. Bilodeau, E. A. The relationship between a relatively complex motor skill and its components. Amer. J. of Psychol., 1957b, 70, 49-55.

Purpose To predict performance on a whole task from the scores on part-tasks.

Theoretical Model See Results.

Tracking Task A two hand coordination task was used in which the subject moved a pin through a slot by the coordinated turning of two hand cranks. The slot was 6" long and could be rotated about its center.

Experimental Design Twenty-four slot angles were used in multiples of 15^o. Each angle represented a proportion of right hand to left hand turning rate. Twelve groups of 40 Ss each were used, each assigned to an angle and its opposite. They were instructed to move the pin as fast as possible.

Performance Measure Time to complete pin movement.

Results The data from each group having a one hand task (0^o, 90^o, 180^o, 270^o) was used to predict the scores of the two-handed groups by the formula:

$$T_{RL} = A.t_R + (1 - a)t_1$$

where a = proportion of right hand input, t_R = time for right, single axis, t_L = time for left hand, single axis, T_{RL} = time for both hands. The above formula was only partially successful due to a hand by direction of rotation interaction and a hand difference.

Conclusions The author suggests an interaction between learning and time sharing of responses which may require a different analysis of part to whole task relationships for the two groups.

28. Bilodeau, E. A., and Bilodeau, I. The contribution of component activities to the total psychomotor task. J. exp. Psychol., 1954, 47, 37-46.

Purpose To examine the relationship between TOT on an individual axis and the joint TOT for all axes for multi-axis tracking.

Theoretical Model The probability of being on target at any time in a component axis will be related to the probability of being on target for all axes by the following equation if the component probabilities are independently distributed.

$P(x)P(y) = P(xy)$, where $P(x)$ = TOT on x axis, $P(y)$ = TOT on y axis, and $P(xy)$ = joint TOT. $P(xy)$ actual was compared with $P(xy)$ predicted to evaluate independence.

Tracking Task Two tasks were used: (1) The Pedestal Sight Manipulation Task and (2) the Steven's Pursuitmeter. Both tasks involved three dimensions of control. For the PSMT the subject tracked an airplane target on a screen with a gunsight in two axes and simultaneously adjusted a range ring to the size of the target. In the SP, the subject operated a joystick and rudders to center a pip on a scope in two axes and zero meter needle in one axis.

Experimental Design (1) Forty-eight Ss received 12-100 sec trials a day for five days. Scoring areas were 1" in azimuth, 12/16" in elevation, and 5/16" in range. (2) Fifty-three Ss received six training and four test trials of 60 sec duration. Scoring area was 0.5" for each axis.

Performance Measure Time on target.

Results In general, independence of TOT scores was found.

29. Bilodeau, E. A. and Bilodeau, I. Motor skills learning. Ann. Rev. Psychol., 1961, 12, 243-280.

In this review the motor skills learning literature is covered from 1945 to 1959. The major topics covered are apparatus, predictors of skill, feedback, memory, transfer of training, and differential studies. A number of methodological problems are also discussed.

30. Birmingham, H. P. and Chernikoff, R. The concept of equalizing ability in operator selection and training. Wescon, August 22-25, 1961, San Francisco, Paper No. 39/1.

Purpose To study the importance of system equalization as a human ability and its importance in selection and training.

Tracking Task

	Training System A	Training System B	Test System
Type	Compensatory	Compensatory	Compensatory
Number of Axes	One	One	One
Display	Null Meter	Null Meter	CRT
Controls	Knob	Knob	Joystick
Forcing Function	Not Given	Not Given	Not Given
Controlled Element	Zero Order	Third Order	Second Order

Experimental Design Two groups first received 24 practice sessions of 12 trials each on training systems A and B and were then transferred to the test system.

Performance Measure Average absolute error.

Results The group trained on the third order system was superior to the other group on the transfer task until the 27th session.

Conclusions Measurement of equalization ability might be a useful selection technique for predicting pilot performance. Training to equalize high order systems may provide positive transfer to operational tasks. Equalization training might be used to maintain skill.

31. Birmingham, H. P., Chernikoff, R. and Ziegler, P. N. The design and use of "equalization" teaching machines. International Congress on Human Factors in Electronics, The Institute of Radio Engineers, May 1962.

A training device is described for human operated vehicles which can be described by differential equations. Equalizing ability is defined as the ability to compensate for system dynamics. The teaching device presents the operator with a wholly equalized system and gradually removes the amount of equalization as a function of the operator's performance level.

32. Birmingham, H. P., Kahn, A. and Taylor, F. B. A demonstration of the effects of quickening in multiple-coordinate control tasks. Naval Research Laboratory Report 4380, Washington, D.C., June 23, 1954.

Purpose To determine if the addition of quickening in a multiple coordinate control task reduces the load on the operator.

Theoretical Model Based on the Birmingham and Taylor (1954) analysis of the human operator, i.e. optimum performance is obtained when the operator is only required to supply a gain.

Tracking Task

Type: Compensatory
Number of Axes: One through four
Display: CRT, two dots were used, each moving in two axes over one half the CRT face.
Controls: Two spring centered joysticks, one for each hand.
Forcing Function: Low frequency noise.
Controlled Element: Third-order system or third-order system with position and rate quickening.
Subjects: Six naval enlisted men.

Experimental Design Four conditions were used: (1) Left spot moved horizontally, controlled by left-right movements of left stick. (2) Left spot moved in two axes, controlled by left stick. (3) Left spot moved horizontally, right spot vertically. (4) All four axes with quickened display. Four trials of each condition were given each day for ten days. The subject order and conditions were randomized for each day and across days.

Performance Measure Time on target.

Results Condition 4 (four axes with quickening) was significantly better than all other conditions.

Conclusion The results indicate that quickening can produce performance improvement that could not be obtained through selection or training.

33. Birmingham, H. P. and Taylor, F. V. A human engineering approach to the design of man-operated continuous control systems. NRL Report 5333, 7 April 1954. Also published as A design philosophy for man-machine control systems. Proc. IRE, December 1954, 1748-1758.

The authors discuss the viewpoint that optimum manual control can be attained only when the human's task is that of supplying a pure gain. The technique of "unburdening" (relieving the operator of supplying integration) and "quickening" (providing the operator with immediate knowledge of his own responses) are described for a variety of systems.

A stimulus-response analysis was made of these concepts and it was shown that when the operator is required to provide a gain, he can base his response on the instantaneous amplitude and direction of the error. If a more elaborate task is required, the operator must respond to various past aspects of the error, thereby loading himself with additional information processing.

34. Brainard, R. W., Irby, T. S., Fitts, P. N. and Alluisi, E. A. Some variables influencing the rate of gain of information. J. exp. Psychol. 1962, 63, 105-110.

Purpose To determine some of the parameters that influence the linear relationship between information transmitted and reaction time in self-paced and discrete reaction tasks.

Theoretical Model This study was based on the linear relation of reaction time (RT) to the information transmitted (H_t). This can be formulated in the following expression: $RT = a + bH_t$. The numerical values of a and b widely vary from one task to another.

Task and Experimental Design A stimulus response task was given with four stimulus response codes; numerals and light were the stimuli while vocalizations and finger movements were the responses. A self-paced serial reaction task and a forced paced discrete reaction task were used. Three levels of stimulus uncertainty were presented, 1, 2, and 3 bits/stimulus. These were given in a 4 x 2 x 3 design to one S-R code and stimulus group. Each group contained 20 subjects.

Performance Measure Three measures were used:(1) average reaction time, (2) average information transmitted per response and (3) average rate of information transmitted per response.

Results Reaction time was an increasing linear function of information transmitted per event for three of the four S-R pairs. The RTs obtained for numeral-vocal pairs were affected by the number of alternatives in the pair. The self-paced and discrete tasks gave similar results.

Conclusions These findings indicate the importance of overlearning in determining S-R compatibility effects. They also suggest that the S's familiarity in dealing with subsets from familiar alphabets may affect his information handling rate.

35. Briggs, G. E., Fitts, P. M., Bahrick, H. P. Learning and performance in a complex tracking task as a function of visual noise. J. exp. Psychol., 1957, 53, 379-387.

Purpose To determine the effect of decreased knowledge of results in tracking by adding visual noise to a display signal and to study the interaction of knowledge of results with learning.

Tracking Task

Type: A compensatory task in which the subject is required to center a target dot on a CRT by controlling an artificial horizon which simulated an aircraft radar fire control system.
Number of Axes: Two
Display: A CRT with an artificial horizontal line, a circular reticle, a target dot and a time-to-go circle.
Controls: A joystick two axis control was used for this experiment.
Forcing Function: Initial displacement of the target dot from the center of the reticle plus three amplitude levels of Gaussian distributed noise which had a power spectral peak at .167 cps.
Controlled Element: The pitch axis controlled element was a second order quadratic transform times a second order lag whose time constant varied from 1/40 of a second at the start of the run to one second at the end of the run.

$$\left(\frac{K/\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\right) \left(\frac{K}{s\ (t + s)}\right)$$

For the roll dynamics, a third order single lag term was used to move the target dot in yaw where the time constant was again varied from 1/40 of a second at the start of the run to one sec at the end of the run.

$$\frac{K}{s^2 (t + s)}$$

Subjects: 48 college students, divided into four groups.

Experimental Design Each group of subjects received five sessions in which each subject received twenty trials during each session. During the first session all subjects were trained with a noise level of zero. During the next three sessions, group one had a no noise condition, group two had noise level one, group three had noise level two, and group four had a mixed noise condition consisting of blocks of five trials each with four noise levels. For the fifth session, all groups were given the mixed noise condition.

Performance measure Average time on target.

Results During the first three sessions with noise, the performance differences between the groups decreased with an increase in noise. On the fifth session, which was the transferred condition, all groups had the same proficiency as the mixed noise condition group.

Conclusions The conclusions of the report were that learning was not affected by visual noise although noise did affect the performance level.

36. Briggs, G., and Howell, W. C. The relative importance of time sharing at central and peripheral levels. NAVTRADEVCEN 508-2, 1959.

Purpose To investigate time sharing at central and peripheral levels.

Tracking Task

Type: Compensatory
Number of Axes: Two
Display: CRT display with two reticles and two cursors with one cursor moving in the X direction and the other cursor moving in the Y direction.
Controls: Two axis joystick control
Forcing Function: Simple sine waves at .067 cps, .133, and .20 cps.
Controlled Element: Second order single lag term with a time constant of .20 seconds in both dimensions.
Subjects: Six college students served in all combinations of the experimental variables.

Experimental Design A full factorial design was used with two variables. One was three levels of input frequency and the second was separation between the reticles on the display consisting of 0, 6, 12, 18, 24, and 30° of visual angle. For the 0° separation, a single reticle with a single cursor moving in both the X and Y directions was used and a single reticle with two cursors, one moving in the X and one in the Y, was used.

Performance Measure RMS error for a 30 sec trial.

Results Performance deteriorated with both input frequency and separation of the reticle. However, the absolute amount of performance deterioration was greater for the 0.20 cps input than for the other two. There was no interaction between the input frequency and reticle separation.

Conclusions Central time sharing demands a greater amount of exertion than peripheral time sharing for a display separation of less than 30° of visual angle.

37. Briggs, G. E., and Naylor, J. C. The relative efficiency of several training methods as a function of transfer task complexity. J. exp. Psychol., 1962, 64, 505-512.

Purpose To determine different methods of training on tracking performance in a three-dimensional tracking task and to determine the effect of various training methods on transferring from one task complexity to another task complexity.

Tracking Task

Type: Compensatory
Number of Axes: Three
Display: Three center read meters labeled heading, altitude and yaw. In the more complex version, additional meters were given showing altitude rate and/or heading rate.
Control: A three-dimensional joystick was used giving left to right, front to back, and rotational movements which represented changes in heading, altitude and yaw.
Forcing Function: A single sine wave with a frequency of .03 cps was used for all three dimensions.
Controlled Element: Three sets of controlled elements were used which varied in complexity. At the least complex level, the heading control was simple rate K/S, the altitude control was an exponential lag $K/(t + s)$ and the yaw control was positional K. For the intermediate complexity control, the heading was acceleration (K/s^2) with a heading rate meter. The altitude control was a second order lag $K/[s\ (t + s)]$ and the yaw control was an exponential lag $K/(t + s)$. For the most complex level, the heading control was a third order transform with a single lag $K/s^2\ (t + s)$ with a heading rate meter. The altitude control was a second order lag K/s^2 with an altitude rate meter and the yaw control was a second order lag transform $K/[s\ (t + s)]$.

Subjects: A total of 144 college students divided into eight groups were used.

Experimental Design Two independent variables were used, two levels of transferred task complexity, intermediate and complex, and four methods of training. These were:

1) Tracking in all three axes during the training period.
2) Tracking in one axis at a time and then transference to all three axes.
3) Tracking in one and two axes at a time before going to all three axes and
4) A simplified three axes condition in which subjects transferred to the intermediate level of task complexity were trained on the simple level and the subjects transferred to the complex level were trained on the intermediate level.

Different groups of subjects were used for all combinations of these conditions.

Performance Measure Average error.

Results Persons trained on all three axes and those progressively trained on 1, 2, and 3 axes had equivalent performance during transfer for both levels of training complexity and statistically superior in performance to the subjects trained by the other two methods. Also, the three axes and progressive training conditions increased the absolute superiority of transfer performance over the other two methods.

Conclusions Training during one axis at a time did not permit the subject to become efficient in time sharing skills. Subjects trained on a simplified task required a longer time to reach the same level of proficiency as those trained on the complex tasks.

38. Burke, C. J., Narasimban, R., and Benepe, O. J. . Some problems in the spectral analysis of human behavior records. WADC Technical Report, 53-27, July 1953.

This article explains some of the technical aspects in the derivation of the spectral analysis from finite records. It describes mathematically the aspects of finite length of records upon the spectral analysis of a function with and without unsystematic components. It points out the necessity of empirical investigations in the determination of human transfer functions.

39. Chernikoff, R., Duey, J, and Taylor, F. B. Two-dimensional tracking with identical and different control dynamics in each coordinate. J. exp. Psychol., 1960, 60, 318-322.

Purpose To determine the effect of three types of dynamics paired in all combinations of a two-dimensional tracking task.

Tracking Task

Type: Continuous, compensatory
Number of Axes: Two
Displays: A CRT display with a marker dot moving in x and y.
Controls: Spring-restrained joystick
Forcing Function: Forcing function for each coordinate was a single sine wave differing in frequency and amplitude. In the x coordinate the frequency was 1.9 cps while in the y coordinate it was 3.15 cps. The maximum amplitude in x was ± 5" and in y ± 3".
Controlled Element: Three different combinations of controlled elements were used. These were position control (K), rate control (K/s) and an acceleration control (K/s^2).
Subjects: Six naval enlisted men served as subjects.

Experimental Design The first experiment consisted of single axis tracking in both x and y for the three types of dynamics. Following this, the same subjects were given nine combinations of dynamics in two-dimensional tracking. The order in which the experimental conditions were run was randomized for the subjects in each session.

Performance Measure The absolute integral of error over the entire run was used as a performance measure for each trial.

Results In single axis tracking, it was found that the x and y scores were the same. The rate dynamics had the lowest error while the acceleration dynamics had the highest error score. In the two axes case, the results indicated that in all cases minimum error occurred when the dynamics in the two coordinates were the same and error increased as the dissimilarity between the dynamics became greater.

Conclusions These findings are interpreted as suggesting that the human has a limited information handling capacity, that some of this capacity is used to change from one task to the other, and that the greater the differences between controlled tasks, the less the capacity that remains for the performance of either.

40. Chernikoff, R., and Lemay, M. Effect of various display-control configurations on tracking with identical and different coordinate dynamics. J. exp. Psychol., 1963, 66, 95-99.

Purpose This investigation determined the effects on tracking performance of different and identical control dynamics in two coordinates with separate and combined controls and displays for each coordinate.

Tracking Task

Type: Continuous, compensatory
Number of Axes: Two
Display: The display was either one dot or two dots where each dot represented motion in either the x or y axis or both.
Controls: The control was one 2-axis controller for tracking in the x and y axes or two 1-axis controllers, one controller being used for the x axis and the other for the y axis.
Forcing Function: The course consisted of two sine waves with frequencies of 4.7 and 2.9 cpm. A phase difference of 90° was used between coordinates. The amplitude of the sine waves was inversely proportional to the frequency.
Controlled Element: Two types of controlled elements were used, position (K) and acceleration (K/s).
Subjects: Six naval enlisted men.

Experimental Design One and two dot displays were used in combination with three pairings of dynamics, position-position, position-acceleration, and acceleration-acceleration. The total combination of 12 experimental conditions were presented to each subject in a different random order during each experimental session.

Performance Measure Mean absolute error for each axes.

Results The results showed a striking shift in the order of tracking proficiency for the various display-control configurations when there was a change from identical to different coordinate dynamics. When the same dynamics were used, the influence of the display predominates. When different dynamics are used in each coordinate, the controls are the most important determiners of accuracy.

41. Chernikoff, R., and Taylor, F. V. Reaction time to kinesthetic stimulation resulting from sudden arm displacement. J. exp. Psychol., 1952, 43.

To determine how rapidly a human can respond to a kinesthetic stimulus the S's splinted arm was held horizontally by an electromagnet and suddenly dropped. In one situation S responded by releasing a key with his other hand upon awareness of arm fall, and in the second situation he responded by stopping his falling arm as quickly as possible. Auditory and tactual reaction times were obtained, with the key-release as the response.

The kinesthetic reaction time with the arm-stop response differed significantly from the other three conditions; no other differences were significant. The difference in kinesthetic reaction time with the arm-stop response and the key-release response was confirmed by a supplementary study.

The shorter kinesthetic reaction time obtained with the arm-stop response was probably a function of the use of an accelerometer to indicate the onset of the response. However, it was still within the range of reaction times for other modalities.

It was concluded that kinesthetic reaction time is too long to permit continuous voluntary control of short duration hand and arm movements by information furnished through feedback. A dual mechanism of control was suggested, wherein the volitional processes serve the function of intermittently issuing "orders" and the nonvoluntary, lower centers execute these orders without additional voluntary guidance.

42. Chernikoff, R., and Taylor, F. V. Effects of course frequency and aided time constant on pursuit and compensatory tracking. J. exp. Psychol., 1957, 53, 285-292.

Purpose To compare tracking results for both pursuit and compensatory modes with different target frequencies, position and rate controlled elements.

Tracking Task

Type: Continuous, pursuit, and compensatory tracking
Number of Axes: One
Displays: For pursuit tracking, a CRT display with a blip for the target and a vertical line for the follower; for compensatory, a CRT with a vertical line.
Controls: Joystick
Forcing Function: Three different functions were used. The first course was the sum of the sine waves 6-2/3, 4-4/9, and 2-2/3 cps, the second course was 16-2/3, 11-1/9, and 6-2/3 cpm and the third course was 26-2/3, 17-7/9, and 10-2/3 cpm.
Controlled Element: The controlled element was a rate with a lag time constant:

$$\frac{K}{s(\tau s+1)}$$

where τ was ∞ for position tracking, 0.5 sec for rate aided tracking and 0 for pure rate tracking.
Subjects: Eighteen Navy enlisted men, divided into three groups.

Experimental Design Each group of subjects received the six combinations of type of tracking and time constant in a factorial design.

Performance Measure The integral of absolute error of an entire run was used as a performance measure.

Results As the course frequencies increased, there was a rapid rise in tracking error with accompanying shifts in the relative proficiency of the various time constants. With both pursuit and compensatory time constants, the optimum aiding constants shifted upward with increasing course frequencies. For the total range of frequencies covered, the single best time constant was 0.5. Pursuit tracking was superior to compensatory for all time constants for courses of high and medium frequencies. For the low frequency course, compensatory was superior for the 0 and 0.5 time constant dynamics.

43. Conrad, R. Speed and load stress in a sensorimotor skill. Medical Research Council, Applied Psychology Research Unit, APU 134/50, Cambridge, England, 1950.

Purpose To examine performance on tasks presenting parallel channels of information flow to the operator.

Theoretical Model A distinction between speed (the number of events/unit time) and load (the number of separate information channels) was the basis for the analysis.

Tracking Task The S monitored from two to four dials whose pointers revolved at constant, but different speeds. When a pointer and a reference mark coincided, the S was to turn a knob associated with the appropriate dial. The pointer speeds were in the ratios of 0.75:0.90:1.15:1.25. Twenty Naval ratings were used as Ss.

Experimental Design Five speeds (40, 60, 80, 100, 120 signals/min) and three loads were used (2, 3, 4 dials). Each S was tested for 10 minutes under each condition over three days.

Performance Measure (1) Errors of omission, (2) Number of attempts at target, and (3) Errors of timing.

Results Errors of omission increased as both speed and load increased. A significant speed and load interaction was found. The number of attempts increased with speed, but not linearly. Mean time errors did not vary with speed, but did increase with increased load.

Conclusions Speed and load represent different variables, which are, to some extent, independently related to the subject's responses.

44. Conrad, R. Missed signals in a sensorimotor skill. J. exp. Psychol., 1954, 48, 1-9.

Purpose This experiment was one of a series investigating the temporal aspects of skill in a sensorimotor task. The display factors underlying missed signals were studied in this report.

Tracking Task

The S watched a given number of dials, each carried a revolving pointer with marks at the 6 and 12:00 positions. The S has 10 switches on a panel in front of him. Each pointer stopped at a mark if the switch was not held down. The S was instructed to try to keep the pointers from stopping. Performance feedback was given by a large clock pointer which moved backward one step at each pointer stopping, moved forward at each successful response, and moved backward at a rate proportional to the speed of the stopped pointer when a pointer was stopped.

Experimental Design Loads from 4 to 12 pointers were used with a constant signal rate of 25 signals/min. Twelve Naval ratings were given 20 minutes of practice in five consecutive week days on 16 dials at a speed of 15 signals/minute. The test trials were for 5 minutes and were given in a random order over one week.

Performance Measure (1) Omitted responses, (2) Response accuracy, and (3) Time relations between sequences of responses and stimuli.

Results Signals which were not responded to were closer to another response than would be expected by chance. For any given signal response interval, the number of omissions increased with signal rate. However, it was shown that the number of omissions within a speed was not directly related to event density.

Conclusions There was an apparent period of diminished activity immediately before or after a response. This was not a simple refractory period as a delayed response does not occur. The concept of speed stress was introduced to explain the finding that the number of omissions within a speed did not depend on event density around the missed signal but that the total proportion of signals missed did depend on event density across speeds. Speed stress was assumed to be a general stress which is independent of the particular temporal sequence at a given speed.

45. Conrad, R. Some effects on performance of changes in perceptual load. J. exp. Psychol., 1955, 49, 313-321.

Purpose This experiment was one in a series investigating the temporal aspects of sensorimotor skill. The effect of load (number of independent signal sources) was investigated in terms of understanding the temporal conditions affecting performance under different loads.

Tracking Task The S watched a given number of dials, each carried a revolving pointer with marks at the 6 and 12 o'clock positions. The S had 10 switches on a panel in front of him. Each pointer stopped at a mark if the switch was not held down. The S was instructed to try to keep the pointers from stopping. Performance feedback was given by a large clock pointer which moved backward one step at each pointer stopping, moved forward at each successful response, and moved backward at a rate proportional to the speed of the stopped pointer when a pointer was stopped.

Experimental Design Loads from 4 to 12 pointers were used with a constant signal rate of 25 signals/min. Twelve Naval ratings were given 20 minutes of practice in five consecutive week days on 16 dials at a speed of 15 signals/min. The test trials were for 5 minutes and were given in a random order over one week.

Performance Measure (1) Rate of pointer stops and (2) Duration of pointer stops.

Results Significant increases in rate of stops and duration of stops were found with increases in load. The increase in number of "bunches" of signals occurring within 1.0, 1.5, and 2.0 sec intervals from minimum to maximum load was not large enough to account for the above results. A sequence analysis was performed which related correct responses to preceding and following events. It was found that this effect was independent of the temporal distribution of signals but dependent upon load. Recovery from error seemed to be more difficult for the higher loads.

Conclusions In general, the temporal and spatial characteristics of the displayed signals would not explain the effect of load on performance. For example, the assumption that there is increased eye scanning at higher loads is inadequate since signals were responded to at a rate above that allowed by complete scanning. Conrad proposed a load stress factor similar to the speed stress factor he assumed earlier.

46. Conrad, R., and Hille, B. A. Self-pacing performance as a function of perceptual load. J. exp. Psychol., 1957, 53, 52-54.

Purpose To examine performance for a self-paced task under varying amounts of load (number of signal sources). Based on past results, it was supposed that the pace selected would be that which enabled constant performance irrespective of load.

Tracking Task A panel of 16 revolving pointers which were arranged in 4 x 4 manner. Each pointer stopped at the 12 and 6:00 marks, unless the S pressed a corresponding switch. The S was supplied with a control for varying the speed of the pointers. The pointers were linked together and all moved at slightly different speeds.

Experimental Design Eighteen Naval ratings practiced for 30 minutes for eight days on all load conditions. On the ninth day, they worked for 5 minutes each on 8, 10, 12, 14, and 16 pointers in random order. Correct responses and errors were integrated and displayed to the Ss on a single clock.

Performance Measure (1) Signals per minute presented, (2) Correct responses per minute, and (3) Errors per minute.

Results All subjects tended to maintain the same signal rate over all load conditions. Errors increased and correct responses increased with increases in load.

Conclusions The original supposition of constant performance over load was not shown. No further explanation was advanced for the outcome.

47. Craig, D. R. Effect of amplitude range on duration of responses to step function displacements. USAF Tech. Report No. 5913, September, 1949.

Purpose To examine the relationship between response amplitude and response duration for step function tracking.

Theoretical Model The following model was proposed to account for the nonlinearity of responses to step functions. The response to isolated inputs is linearly related to the input. When the input is a series of steps, each step is considered the sum of two components: (1) A step whose amplitude is equal to a function of the preceding steps, $A_{n1} = f(A_{n-1}, A_{n-2}, \ldots)$ and whose mean response duration is constant; (2) a step whose amplitude is equal to the difference between A_{n1} and the presented step $A_{n2} = A_n - A_{n1}$, and whose mean response duration is greater than that for A_{n1}. The total response is then a linear sum in time of the responses to $A_{n1} + A_{n2}$.

Tracking Task and Experimental Design Data used was from Ellson and Wheeler, 1949.

Performance Measure (1) Peak amplitude and (2) Peak time.

Results Peak time was a function of the range of displacements in a series as well as the absolute value of the displacement.

Conclusions The hypothesis describes some but not all of the data.

48. Craig, D. R., and Ellson, D. Comparison of a two-handed and several one-handed control techniques in a tracking task. Memo Report No. MCREXD-694-2L. USAF Air Materiel Command, 1948.

Purpose Comparison of various manipulative techniques in tracking with the Pedestal Sight Manipulation Test.

Tracking Task

Type: Pursuit
Number of Axes: Two
Display: GE Pedestal Sight with a target projected on a screen.
Controls: The Pedestal Sight was fitted with three extended handgrips which permitted tracking with both hands on the offset handgrip, the preferred hand on the corresponding offset handgrip and/or the non-preferred hand on the centered handgrip.
Forcing Function: Linear motion of the target across the screen.
Controlled Element: Position (K).
Subjects: Forty-one male college students.

Experimental Design The five techniques in manipulating the pedestal sight, as given under controls, were studied in a full factorial design.

Performance Measure Tracking performance was recorded by clocks as time on target in azimuth and in elevation, and in azimuth and elevation simultaneously.

Results The use of the preferred hand resulted in significantly superior performance to that of the non-preferred hand for the centered handgrip. The one-handed versus the two-handed performances were equivocal.

49. Craik, K. J. W. Theory of the human operator in control systems. Part I. The operator as an engineering system. Brit. J. Psychol., 1947, 38, 56-61, Part II. Man as an element in a control system. Brit. J. Psychol., 1948, 38, 142-148.

Purpose In these now classic articles, Craik reviews some of the problems in describing the human operator as an element in a control system. Particular attention is given to the intermittent functioning of the operator.

Conclusions (1) The human operator behaves as an intermittent correction servo, the intermittent corrections being ballistic movements. (2) Counteracting processes such as limb inertia and minimum reaction time make the operator's movements seem continuous and (3) electrical models could simulate human tracking behavior.

50. Craik, K. J. W., and Vince, M. Psychological and physiological aspects of control mechanisms with special reference to tank gunnery. Ergonomics, 1963, 6, 1-33.

This article is a posthumous publication of a paper written by Craik in 1943. It describes some of his pioneering work on the accuracy of tracking and the mechanical, physiological and psychological factors affecting operator control ability. Topics covered are control position, movement amplitude, rate of movement, control stiffness, vibration and crank radii. The results are applied to tank gunnery problems.

51. Creamer, L. R. Event uncertainty, psychological refractory period, and human data processing. J. exp. Psychol., 1963, 60, 187-194.

Purpose To test the psychological refractory period (PRP) hypothesis with a sequence of stimuli in which the events occurred at a fixed time but in which the occurrence of a particular event was uncertain and to test the combined effect of time and event uncertainty.

Tracking Task

Type: Discrete, pursuit
Number of Axes: One and two (visual and auditory)
Display: Visual - 3 lights, Auditory - 3 tones. Feedback was supplied by a second set of lights for visual tracking and a complex tone indicating off-target on the auditory task.
Control: Three pushbutton switches for each hand.
Forcing Function: Sequence of paired or single visual-auditory signals.
Controlled Element: Position (K)
Subjects: Seventy-two male students.

Experimental Design The Ss were used in six groups, corresponding to the inter-trial intervals of 0 to 800 msec. Paired presentations were given with the auditory following the visual signal. Unisensory trials were also given for each modality. A second group received a range of inter-trial intervals randomly ordered to evaluate combined time and event uncertainty.

Performance Measure Reaction time.

Results Both groups showed an increased RT to the audio signals for inter-trial intervals less than 200 msec. The time uncertain group had overall longer RT's than the time certain but followed a similar function.

Conclusion The human operator can be considered a one channel system providing event or time uncertainty is present.

52. Crossman, E. R. F. W. The measurement of discriminability. Quart. J. of exp. Psychol., 1955, 7, 176-195.

Purpose To relate the physical characteristics of a system to the time it takes an operator to discriminate between a set of signals.

Theoretical Model If a constant rate of information is being transmitted, then the time to discriminate between two signals will be:

$$t_d = -A \log_2 \frac{x_1 - x_2}{x_1}$$

where x_1 and x_2 are physical values of the stimulus. A is the reciprocal of the information rate. Looking at the ratio x_1/x_2 instead of the difference between x_1,x_2, the ease in discrimination of two points can be determined by the inverse of the log of the ratios. This function can be called the confusion function and defined by:

$$C(1,2) = \frac{K}{\log \frac{x_1}{x_2}} = \frac{K}{\log x_1 - \log x_2}$$

where K is a constant and x_1 and x_2 are the physical sizes of signals 1 and 2.

This theory can be extended to multiple choice tasks where

$$t = \frac{A}{n} = A\ 2/n \text{ (confusion summed over all pairs).}$$

where n is the number of choices and A is the reciprocal of the information rate.

Tracking Task The task was card sorting in which the subject was required to sort into two (or more) piles according to patterns on the face of the cards. The patterns were a random number of spots and circles on the card differing in number by a fixed amount. The subject was required to sort into two classes "more spots" and "more circles."

Experimental Design The subjects were given combinations of cards and required to sort number of spots of 1/10, 5/10, 8/12, 9/12, 8/10, and 10/12.

Performance Measure The amount of time the subject required to complete the task.

Results Completion times did not significantly depart from the theoretical completion times computed from confusion values.

53. Crossman, E. R. F. W. The information capacity of the human motor system in pursuit tracking. Quart. J. of exp. Psychol., 1960, 12, 1-16.

Purpose To analyze continuous pursuit tracking in terms of information theory.

Theoretical Model See Performance Measure.

Tracking Task
- Type: Pursuit
- Number of Axes: One
- Displays: Paper chart, 8.5 cm. wide, moving behind a window adjustable in height.
- Controls: Eighteen inch diameter handwheel, geared to tracking pen, 40° rotation to cover width of paper.
- Forcing Function: $(x) = 1.25 \sin x + 1.0 \sin 8/3x + 1.27 \sin 17/12x$ where x = distance along paper in units of 3.8 cm. Paper speeds of from 1.09 to 8.93 cm/sec were used.
- Controlled Element: Position (K)
- Subjects: Four.

Experimental Design Each subject was run once under each speed with short (1/2 cm) and long preview (8 cm), making 16 runs per subject. Conditions were presented in random order and two practice runs were given each subject.

Performance Measure Sample points chosen were the 94 peaks of the input which occurred every 2.5 to 4 cm apart, slightly less than the theoretical sampling rate of 4.4 cm required by the 8.8 cm smallest wavelength. The subject's track was corrected for time lag and amplitude distortions. Input information was calculated from the amplitude categorization into 16 intervals representing 4 bits. The joint input-output information was calculated from:

$$H(i,o) = f(i,o) \log_2 f(i,o) - \frac{k - 1}{2N}$$

where f(i,o) = frequency of cells in input-output matrix, k = number of cells in occupied regions of matrix, N = number of sample points.

Results There was a clear difference between preview and no preview at all speeds, preview giving a greater information rate. Time lag increased with input frequency for no preview but increased only slightly for the preview case.

Conclusions When tracking with preview, information capacity of the effector system is 2.5 bits/sample with a maximum capacity of 10 bits/sec. Without preview the limit is about 4 bits/sec and is set by the decision mechanism. The information conditions in a tracking task should be specified in addition to the analytic method yielding transfer functions.

54. Crossman, E. R. F. W., and Cooke, J. R. Manual control of slow response systems. International Congress on Human Factors in Electronics. The Institution of Radio Engineers, Long Beach, California, May 3-4, 1962.

Purpose To determine the operator's response in learning to control slow response systems.

Theoretical Model Three theoretical models for this type of control were chosen. For the first model, the output was directly proportional to the error:

$$(V_n - V_{n-1}) = A\ (T_n - T_g)$$

where V_n = voltage setting for the nth cycle, T_n = temperature at beginning of the nth cycle, and T_g = target temperature. The second model included the rate of change of error:

$$(V_n - V_{n-1}) = A'\ (T_n - T_g) + B(T_n - T_{n-1})$$

In the third model the control changes were proportional to error plus the rate of change of error with an exponential decreasing gain:

$$(V_n - V_{n-1}) = \left[A' (T_n - T_g) + B'(T_n - T_{n-1})\right] \exp. (-C_n)$$

Results Through regression analysis, the extent of control alteration was found to be correlated with error and its first derivative. The initial hunting appeared to be caused by the Ss' tendency to make changes rather than absolute settings in response to the error. The transfer function found from this analysis was essentially similar to that found in fast manual tracking except for the absence of fixed delay, but the parameters changed markedly with practice. Subjects, however, frequently behave in an open-loop mode, for instance, correcting small steady errors by large control changes of short duration. They made little use of their physical understanding of the system. The most useful type of prior information concerned the equilibrium temperatures for different control settings, as was shown by comparison of the performance of groups with different instructions.

55. Diamantides, N. D., and Cacioppo, A. J. Human response dynamics; GEDA computer application. Goodyear Aircraft Corporation, GER-8033, 8 January 1957.

Cacioppo, A. J. Pilot information utilization; A study in human response dynamics. Goodyear Aircraft Corporation, GER-7686, 25 July 1963.

Purpose To develop an aircraft-pilot computer system that would simulate some of the communication and control functions of a human pilot.

Theoretical Model The technique used in this experiment was model matching. The analog model of the human pilot was determined from known functions of the human's behavioral motor system during manual control. This model consists of a linear portion, a threshold level, a reaction time, a kinesthetic filter and a one term predictor. The overall describing function of the system can be shown as follows:

$$\underbrace{\frac{k\,(\ell s+1)}{Ms^3+Ns^2+Ls+1}}\left[k\,\underbrace{\frac{k_2}{k_o}\,s^2+\frac{k_1}{k_o}\,s+1}_{2}\right]\underbrace{G_1}_{3}\underbrace{e^{-r_o s}}_{4}+\underbrace{R_3G_2}_{5}+\underbrace{\frac{w_o+c}{s^2+w_o}}_{6}$$

where
1 = the neuromuscular lag and proprioceptive feedback
2 = The linear operation
3 = The threshold level
4 = Reaction time
5 = The biasing effect of the short term predictor
6 = Stick dither.

Parameters of this model were adjusted by visual observation of the oscillograph records and comparing the responses of the analog model with the human operator.

Tracking Task

Type: Continuous compensatory with a moving base simulator.
Number of Axes: One
Display: A 5" CRT with a moving horizon
Control: Joystick
Forcing Function: A random noise to simulate air turbulence.
Controlled Element: Third order longitudinal dynamics where the damping ratio and the short period frequency were varied.
Subjects: Five jet pilots, three light plane pilots, and one subject with no aircraft experience.

Performance Measure The analog of the pilot was adjusted to simulate the pilot's responses so that the model could replace the pilot in the control loop without the pilot's knowledge of the change.

Results The results showed that the degree of gain, dither and anticipation that the pilot carries into the flight situation depends upon the experience of the pilot. Rate is an important source of information for the pilot of limited experience, and acceleration is only of importance for the jet pilot of considerable experience. Results of this study support the hypothesis that derivative control of aircraft dynamics by the pilot is related to his ability to control and length of experience.

56. Duey, J. W. and Chernikoff, R. The use of quickening in one coordinate of a two-dimensional tracking system. IRE Trans. Hum. Factors, March 1960, pp 21-24.

Purpose To determine the effect of quickening in one coordinate of a two-dimensional tracking task on performance in each axis.

Tracking Task

Type: Compensatory
Number of Axes: Two
Display: CRT
Control: Two-axis stick ± 40 degrees movement
Forcing Function: Sinusoid, 1.9 cpm ± 10 inches maximum amplitude. Same input used for each axis with 90 degree phase angle difference.
Controlled Element: Second order system (A) and second order system with rate and position quickening (Q).
Subjects: Eight enlisted men.

Experimental Design Eight conditions were used. Each of the dynamics was tracked separately in each coordinate for single axis conditions (Ax, Ay, Qx, Qy). All combinations of the two dynamics and axes gave four double axes conditions (Ax Ay, Ax Qy, Qx Qy, Qx Ay). Three one-minute trials on each condition were given. Order of presentation was randomized.

Performance Measure Average absolute error.

Results A large increase in error was observed from one to two coordinates for the A dynamics, but not for the Q dynamics. For two coordinate tracking, quickening in one axis reduced error on the Q axis but did not affect the A axis. The errors in the Q axis for the QxAy and QyAx cases were larger than for the QxQy case.

Conclusions The results are attributed to a balance between two factors: (1) Adding a simple task to another simple task should not degrade performance but adding a complex task will degrade performance and (2) adding even a simple task to a complex task will degrade performance.

57. Elkind, J. I. Tracking response characteristics of the human operator. Human Factors Operations Research Laboratories Memorandum No. 40, September 1953.

Purpose To determine system characteristics of the human operator by harmonic analysis when he is tracking a random function.

Theoretical Model The closed loop transfer function can be determined by the power spectral density function of the input and the cross power spectral density function of the input-output

$$\phi_{io}(\omega) = H(\omega)\,\phi_{ii}(\omega)$$

and the output of the human is

$$\phi_{oo}(\omega) = |H(\omega)|^2\,\phi_{ii}(\omega) + \phi_{nn}(\omega)$$

where $\phi_{oo}(\omega)$ and $\phi_{nn}(\omega)$ are the power spectral density of the output and the noise.

The signal to noise ratio is found by

$$S/N(\omega) = \frac{|H(\omega)|^2\,\phi_{ii}(\omega)}{\phi_{oo}(\omega) - |H(\omega)|^2\,\phi_{ii}(\omega)}$$

Tracking Task

Type: Pursuit, continuous
Number of Axes: One
Display: Blip on horizontally placed CRT
Control: Pencil-like stylus "pip trapper" over face of CRT.
Forcing Function: Random noise with bandwidths of 2,4,6 rad/sec
Controlled Element: Position (K)
Subjects: Three subjects

Experimental Design Not given.

Performance Measure The power density spectra

$$\phi_{ii}(\omega),\ \phi_{io}(\omega),\ \phi_{oo}(\omega)$$

were calculated and the Fourier transforms of the correlation functions were computed.

Results The human's response was equivalent to a low pass filter. His transfer function $H(\omega)$ changed with the bandwidth of the stimulus. Both the attenuation and the cutoff frequency of $H(\omega)$ increased with increase in stimulus bandwidth. The signal to noise ratio showed little noise in the low frequency response and an increase in noise at higher frequencies.

58. Elkind, J. I., and Darley, D. L. The statistical properties of signals and measurements of simple manual control systems. ASD-TDR-63-85, July 1963.

Purpose To examine the distributions of signals in a simple compensatory tracking task and the distributions of the power spectra and the open and closed loop describing functions derived from the spectral analysis.

Tracking Task Data used was obtained from Elkind, J. I., and Forgid, C. D., "Characteristics of the Human Operator in Simple Manual Control Systems," IRE Trans. on Auto. Control, Vol. AC-4, pp 44-55, May 1959.

Results Error and remnant signals were found to be normally distributed except for very low and high frequencies. The open loop transfer function, expressed in terms of log magnitude and phase, was found to have approximately a normal distribution. The system closed loop transfer function, however, showed more deviations from normal than the open-loop function. The power density spectra of the error and remnant term were distributed as χ^2. The normalizing transformation, $z = 1/2 \frac{\ln(1+r)}{(1-r)}$, of the input-output correlation did not lead to distributions as normal as would be expected.

Conclusion The signals in the system examined can be considered normal except for very low and high input frequencies.

59. Elkind, J. I., Starr, E. A. Evaluation of a technique for determining time-invariant and time-variant dynamic characteristics of human pilots. NASA TN D-1897, May 1963.

Elkind, J. I., Green, D. M., Starr, E. A. A technique for measurement of time-varying dynamic response characteristics of human operators. International Congress on Human Factors in Electronics, The Institute of Radio Engineers, May 3-4, 1962.

Purpose To determine a time-varying linear describing function of the human operator by the application of multiple regression analysis.

Theoretical Model An analog of the human $y(t)$ composed of a set of orthonormal filters $z_j(t)$ with weighting coefficients b_j. The mean square error between the human and the analog

$$\overline{\epsilon(t)^2} = \overline{\left[y(t) - \sum_{j=1}^{K} b_j z_j(t) \right]^2}$$

is differentiated with respect to each b_j which yields a covariance matrix and each b_j is solved for the minimum $\overline{\epsilon(t)^2}$.

By choosing the appropriate set of orthonormal filters, the coefficients b_j can be approximated to the linear weighting function of the operator and the residual mean square error can be equated to the noise remnant. The coefficients b_j are assumed independent and normally distributed with mean β_j and variance σb^2_j. The sample length T required for analysis is dependent upon the confidence limits that are set on σb^2_j. These values can be calculated for any given set of filters.

The set of filters that was used to approximate the quasilinear model of the human are the following set of orthonormal functions:

$$\phi_i(s) = \frac{\sqrt{2s_i}\,(s-s_1)(s-s_2)\ldots(s-s_{i-1})}{(s+s_1)(s+s_2)\ldots(s+s_i)}$$

where $i = 5$ and s is the complex quantity.

The selection of the values $s_1, s_2 \ldots s_i$ should be real poles logarithmically spaced, and in a region where the residual error variance is at a minimum.

No experimental studies were conducted.

60. Elkind, J. I. Characteristics of simple manual control systems. MIT Technical Report No. III, 6 April 1956.

Purpose To describe the human operator characteristics in a manual control system by quasilinear models.

Theoretical Model This study uses a quasilinear model which consists of a linear describing function plus a remnant term. The values for the closed loop describing function $[H(f)]$ are calculated from the power density spectrum of the input signal $\phi_{ii}(f)$ and the cross power density spectrum of the input-output $\phi_{io}(f)$

$$\phi_{io}(f) = H(f)\ \phi_{ii}(f).$$

The output signal of the model can be divided into two portions, the first part is linearly coherent with the input and the second part is not coherent with the input. This gives the relationship,

$$\phi_{oo}(f) = |H(f)|^2\ \phi_{ii}(f) + \phi_{nn}(f).$$

The fraction of the output which is linearly correlated with the input can be found from the following relation,

$$\rho = 1 - \frac{\phi_{nn}(f)}{\phi_{oo}(f)} .$$

These relationships are valid when the remnant term is Gaussian noise.

Tracking Task

Type: Pursuit and compensatory

Display: Dot and a circle moving in a horizontal direction.

Control: Pencil-like stylus moving on the screen of a horizontal positioned CRT scope.

Forcing Function: A variety of Gaussian noise forcing functions were used in which the amplitude bandwidth and shape of the forcing function were used as variables.

Controlled Element: Position (K)

Subjects: Three subjects were used in all experiments except for the pursuit part of one experiment where another group of three subjects was used. The subjects had a training period of two hours tracking before data was recorded.

Experimental Design Four experiments were conducted. In the first,one group of three subjects was given compensatory tracking in which the chief variable was the interval between runs. The second of the three subjects was given the same conditions except for a pursuit task. The second experiment used a rectangular input power spectrum with a cutoff frequency of 0.74 cps and three levels of rms amplitude. In the third experiment a rectangular power spectrum of constant amplitude was used with 8 levels of maximum frequency, from 0.16 to 4.00 cps. The fourth experiment varied the shape of the input power spectrum. The first part used four levels of filtered spectra. The second part divided the spectra into four bands of which 10 combinations of these 4 bands were given.

Performance Measure Spectral analyses were run on the data from which the following power density spectra were calculated. These are: (1) The magnitude and phase of H(f). (2) The linearly correlated fraction of the output; (3) The normalized value for the power spectra of the remnant; (4) The normalized value for the power spectra of the error; (5) The magnitude and phase of the open loop describing function for the compensatory runs.

Results For compensatory tracking it was found that the linear relationship of the output with the input was greater than 0.97 for input frequencies below 0.64 cps, for higher frequency inputs the value was lower. The author stated there were indications that a large fraction of the noise may result from random variations in characterizations rather than known nonlinearities. The open loop describing functions in compensatory tracking can have the form of:

$$G(s) = \frac{Ke^{-Ls}}{(T_1 s + 1)}$$

or

$$G(s) = \frac{Ke^{-Ls}}{(T_1 s + 1)(T_2 s + 1)}$$

Certain values of the parameters were determined: (1) The transmission time delay (L) was relatively constant with a mean value of 0.12 secs. (2) The gain bandwidth product KT_1 was relatively constant with a value of 1.5. (3) There is a significant relationship between K and the cutoff frequency where $K = \frac{2.2}{f_{co}}$.

For pursuit tracking it was found that the operator had less phase lag since he could see the target and that this resulted in a smaller error spectrum and rms error. The pursuit model was not nearly as well developed and only approximate relations among its parameters and the input parameters were found. The general conclusions from the report were that human operators are nonlinear but quasi-linear transfer functions allow a good description of the human characteristics for simple manual control systems.

61. Ellson, D. G., and Gray, F. E. Frequency response of human operators following a sine wave input. U. S. Air Force Air Materiel Command, MCREXD-694-2N, 22 December 1948.

Purpose Application of servo analysis to test the linearity of the human operator in tracking sine waves.

Tracking Task

Type: Continuous, pursuit
Number of Axes: One
Displays: Two moving pointers
Controls: Double handgrip rotating on vertical axis
Forcing Function: Sine waves with frequency of 1/2, 1,2,3, and 4 cps and a "variable frequency" input with a constant acceleration frequency from 1 to 4 cps at .182 cycles/sec^2.
Controlled Element: Position (K)
Subjects: Four subjects were used.

Experimental Design Three forcing function amplitudes and three control gains in combination were given to each subject.

Performance Measure Amplitude ratio and phase shift of the records were calculated.

Results A phase shift occurred at and above 2 cps. However, this was not regular and varied within a subject at different times. The ratio of amplitudes showed a decrease as the amplitude of the forcing function increased. At higher frequencies, where the phase shift was pronounced, the amplitude ratio was slightly reduced.

Conclusions The human operator does not have the characteristics of a linear system.

62. Ellson, D. G., and Wheeler, L. Resonance in the human operator. Wright Air Development Center, AF Technical Report No. 5834, April 1951.

Purpose To determine whether there is a resonant phenomena in the human operator during sinusoidal tracking. In order to demonstrate the occurrence of a resonant type of phenomena in subjects, the records would have to show a relatively constant amplitude of movements with increasing frequencies of forcing function and a decrease in the amount of energy per movement, or rising amplitudes of movement and a constant amount of energy per movement.

Tracking Task

Type: Continuous, pursuit
Number of Axes: One
Display: Two moving pointers
Controls: A handle which allowed movement of the arm to be parallel to the vertical axis of the body
Forcing Function: The frequency of movement of the input pointer was constant for any given tracking sample but was randomly varied from sample to sample between 0.5 - 25.0 cps in multiples of 0.5 cps.
Controlled Element: Position (K)
Subjects: Twenty-two male university students acted as subjects in this experiment.

Experimental Design Ten input frequencies were presented to each subject. The order of presentation of each frequency was randomly arranged for a given subject. Different randomized frequencies were used for each subject.

Performance Measure Three measures of performance were used. Two measures, taken from the tracking record, were the mean difference between input and output amplitude and the mean phase shift for each frequency. The electromyograph was also taken in order to obtain a measure of the amount of energy used during the tracking task. This figure was given as the mean muscle action potential per cycle.

Results Subjects who tracked with constant rising amplitudes of movements as the frequencies of hand movements increased had a decrease in the mean muscle potential per cycle. It was concluded that there was a phenomena occurring in the human operator that was like resonance.

63. Ellson, D. G. The independence of tracking in two and three dimensions with the G. E. Pedestal Sight. USAF Air Materiel Command Memo Report, 1947.

Purpose To determine whether or not human operators make error corrections simultaneously or independently in two or three tracking dimensions with the G. E. Pedestal Sight Manipulation Test.

Tracking Task

Type: Continuous, pursuit
Number of Axes: Three
Display and Control: G. E. Pedestal Sight
Forcing Function: Target moved across a screen at a constant velocity
Controlled Element: Position (K)
Subjects: Two groups of subjects were used, 12 trained subjects and 48 untrained subjects.

Experimental Design The group of trained subjects operated the sight in azimuth and elevation only. The 48 untrained subjects operated the sight in azimuth, elevation, and range.

Performance Measure Time on target scores were used as a performance measure when the subjects were on target independently in azimuth, elevation, and range, and when they were simultaneously on the target in azimuth and elevation, and in azimuth, elevation, and range. A test of the independence of the tracking scores, the product of tracking of the time on target scores in azimuth and the time on target scores in elevation should equal the simultaneous scores in azimuth and elevation. Any deviation from this score would indicate that tracking is not independent between two axes. The same analysis holds for the three dimensional case.

Results Analysis of the results showed that for both trained and untrained operators, using the G. E. Pedestal Sight tracking errors in azimuth and elevation are independent with respect to the time of occurrence. For untrained operators, tracking errors in azimuth and elevation combined as well as ranging errors were essentially independent.

Conclusions These findings indicate that tracking in azimuth and in elevation may not be integrated by the human operator and that the "tracking problem" might be correctly considered as "the tracking problems."

64. Ellson, D. G., and Hill, H. The Interaction of responses to step function stimuli: I. Opposed steps of constant amplitude. Report No. 13 Aviation Psychology Project, Dept. of Psychology, Indiana University, 19 November 1948.

Purpose To examine the psychological refractory period explanation of tracking behavior to step functions.

Theoretical Model The implications of two models for step function tracking were examined: The psychological refractory period as proposed by Vince (1948) and an algebraic summation of responses proposed by the authors. The essential difference between the two was stated in terms of the reaction times, response amplitudes and movement times to the second of a pair of step functions.

Tracking Task

Type: Pursuit
Number of Axes: One
Display: S viewed stimulus trace on chart paper moving behind a horizontal slot 0.54 x 5 inches.
Control: Low friction stylus grasped with fingers mounted in front of the slot; weight 66.5 grains.
Forcing Functions: Rectangular pulse, 1 inch amplitude, either to right or left of center line, 10 durations from 0.05 sec. to 1.6 sec.
Subjects: Thirty.

Experimental Design Ten responses were obtained for each duration and for each subject in two days. Each duration appeared twice on a test run with 1.6 sec between pulses. No control over order of presentation or practice was provided.

Performance Measure (1) Reaction time; (2) movement time, and (3) amplitude of response.

Results The results supported the algebraic summation in time of normal responses as a more accurate description of step tracking than was the psychological refractory period concept.

Conclusions Within the study limitations, the operator could be represented as a linear system.

65. Ellson, D. G., Hill, H., and Craig, D. R. Interaction of responses to step function stimuli: II. Equal opposed steps. AF Technical Report No. 5911, Wright Patterson Air Force Base, August 1949.

Purpose This study was a continuation of work on tracking responses to step function stimuli. Displacement amplitudes were varied to provide information on (1) the generality of response summation over amplitudes, and (2) the linearity of responses to different amplitude stimuli.

Theoretical Model Responses to closely spaced steps were predicted by a linear addition in time of responses to single steps.

Tracking Task

Type: Pursuit
Number of Axes: One
Display: S viewed stimulus trace on chart paper moving behind a horizontal slot 0.54 x 5 inches.
Control: Low friction stylus grasped with fingers mounted in front of the slot; weight 183 grams.
Forcing Function: Rectangular pulse, 1 inch amplitude, either to right or left of centerline, 10 durations from 0.05 sec. to 1.6 sec.
Subjects: Twenty-one male undergraduates.

Experimental Design Experimental variables were: Displacement amplitude - 1/8, 1/4, 1/2, and 1.0 inches and pulse duration - 0.05 sec. to 1.6 sec. A test roll contained two of each amplitude-duration pairs, one to the left and one to the right in a random order with a total of 64 pulses. Each pulse was presented 10 times to each S over two days.

Performance Measure (1) Peak time, the time from stimulus on-set to initial response peak. (2) Peak amplitude, the distance from zero position to initial response peak.

Results The location of a response peak was successfully predicted based on a linear addition of individual responses for all displacements. The Ss overshot the small amplitudes and undershot the large amplitudes, indicating a nonlinear component in the response.

66. Ellson, D. G., and Wheeler, L. Jr. The range effect USAF Technical Report No. 5813, USAF, Air Materiel Command, May 1949.

Purpose To determine if the tendency of trackers to overshoot large amplitudes and undershoot small amplitudes in step-function tracking is a function of absolute or relative stimuli amplitudes.

Tracking Task

Type: Pursuit
Number of Axes: One
Display: S viewed stimulus trace on chart paper moving behind a horizontal slot 0.54 x 5 inches.
Control: Low friction stylus grasped with fingers mounted in front of the slot; weight 66.5 grains.
Forcing Functions: Rectangular pulse, 1 inch amplitude, either to right or left of center line, 10 durations from 0.05 sec. to 1.6 sec.
Subjects: Fifty subjects divided into two groups.

Experimental Design Two groups were used for (1) Step stimuli of 1.0, 0.5, and 0.25 inches amplitude; and (2) Step stimuli of 1.0, 1.5, 2.0 inches amplitude. Right-left movements were counterbalanced and the order of presentation was randomized.

Performance Measure Amplitude of initial movement.

Results Ss overshot the 1.0 inch input when it was the smallest and undershot it when it was the largest input.

Conclusions The range effect is a function of relative rather than absolute stimulus magnitude.

67. Ellson, D. G., and Coppock, H. Further analysis of the psychological range effect,USAF Tech. Rep. No. 6012, 1951.

Purpose To determine the proportionality of step tracking responses to the input when only one amplitude is given to each subject.

Tracking Task

Type: Pursuit
Number of Axes: One
Display: S viewed stimulus trace on chart paper moving behind a horizontal slot 0.54 x 5 inches.
Control: Low friction stylus grasped with fingers mounted in front of the slot; weight 66.5 grains.
Forcing Functions: Rectangular pulse, 1 inch amplitude, either to right or left of centerline, 10 durations from 0.05 sec. to 1.6 sec.
Subject: Thirty.

Experimental Design Three groups of 20 male undergraduates each were used. Each S tracked 108 displacements of either 0.5, 1.0, or 1.5 inch.

Performance Measure (1) Response time. (2) Response amplitude.

Results The relationship of response amplitude to input amplitude did not vary as a function of input amplitude. A difference was found in response times between early and final trials.

Conclusions The authors favored a linear description of the operator with nonlinearity based on the effect of previous responses. Response time changed with practice. This was attributed to experience with previous experiments.

68. Ellson, D. G., and Gilbarg, D. Application of operational analysis to human motor behavior. USAF Air Material Command, MCREXD-694-2J.

This paper is an early discussion about the feasibility of applying servo control theory to explain certain aspects of human motor behavior. The authors state that servo control theory is similar to experimentally determining motor behavior in that only the stimulus-response characteristics are available, therefore no exact knowledge of the mechanism occurring in the human is required. They agree that such a tool would be useful in prediction of responses in complex inputs. However, they state that this method has limitations and that any such application would have to be experimentally verified.

69. Fitts, P. M., Peterson, J. R., and Wolpe, G. Cognitive aspects of information processing: II. Adjustments to stimulus redundancy. J. exp. Psychol., May 1963, 65, 423-432.

Three experiments are reported in which relative stimulus frequencies were varied in nine choice tasks. The tasks involved naming numbers and pointing to lights. It was found that as redundancy increased, average RT's to the frequent stimulus component decreased, whereas RT's to less frequent components increased, the differences being a linear function of redundancy. These effects were greater for the less compatible (vocal) task. Ss used the frequent response more often and the infrequent response less often than appropriate in responding to redundant sequences. These results are in agreement with predictions from a stimulus sampling and sequential decision model in which it is assumed that RT's and errors are a function of prior probabilities and the payoff matrix for correct and wrong, slow and fast responses, as well as a function of stimulus discriminability.

70. Fitts, P. M. Information capacity of the human motor system in controlling the amplitude of movement, J. exp. Psychol., 1954, 47, 381-391.

Purpose To define motor movements in terms of information theory concepts such as amount of information, noise, channel capacity and rate of information transmission.

Theoretical Model The theoretical concept was that the human motor system has a fixed information capacity. This hypothesis was tested by controlling the amplitude and tolerance limits of a specific task and then instructing the subject to work at his maximum rate. The average time of response then is proportional to the minimum average amount of information per response demanded by the particular conditions.

A binary index of difficulty was used to test the hypothesis. This is defined by the following:

$$I_d = -\log_2 \frac{W_s}{2A} \text{ bits/response,}$$

where W_s is the tolerance range and A is the average amplitude of movement. The index of performance that should remain constant is defined by:

$$I_p = -\frac{1}{t} \log_2 \frac{W_s}{2A} \quad \text{bits/sec}$$

where t is the average time in seconds for movements.

Tracking Task Three skilled movement tasks were used; reciprocal tapping, disc transfer, and pin transfer. In the reciprocal tapping, two plates were alternatively tapped in which the tolerance was changed by varying the width of the plate and the amplitude varied by changing the distance between the plates. In the disc transfer the subject transferred discs from one peg to another. The difference between the diameter of the peg and hole varied the tolerance and the distance between pegs varied the amplitude. In the pin transfer experiment the tolerance was varied by the difference and pin diameters and the amplitude was varied by the distance between the pins. In the reciprocal tapping and disc transfer 16 subjects were used and in the pin transfer 20 subjects were used.

Experimental Design Four levels of each variable were used in a randomized factorial design for all three experiments.

Performance Measure In the reciprocal tapping the number of errors and the average time between taps were recorded and in the two transfer experiments the average time per transfer was recorded.

Results In all three experiments the average transfer time increased with decrease in tolerance and increased in average amplitude. The rate of performance was constant over an optimum range but fell off outside that range. The optimum level was approximately 10 to 12 bits/sec.

Conclusions The author concluded that the fixed information capacity reflects the fixed capacity of central mechanisms for monitoring the results of on-going motor activity while at the same time maintaining the necessary degree of organization with respect to the magnitude and timing of succession movements.

71. Fitts, P. M., Schneider, R. Reproduction of simple movements as a function of factors influencing proprioceptive feedback, J. exp.Psychol., 1955, 49, 445-454.

Purpose To investigate the accuracy of positioning a horizontal arm control as a function of changes in the elasticity, damping, and mass of the control.

Performance Measure The results of this experiment were recorded on film and two measures were taken. One measure determined temporal relations measured by the speed or the time with which the subject moved the control, and the other measure determined the spatial relationship in which the displacement error was measured.

Results Increase in damping and mass resulted in greater uniformity of the temporal relationship. The effect of spring loading on spatial accuracy was significant.

72. Fitts, P. M., Simon, C. W. Some relations between stimulus patterns and performance in a continuous dual-pursuit task, J. exp. Psychol., 1952, 43, 429-436.

Purpose To determine spatial relations of various visual stimulus patterns in relationship to the controls for a continuous tracking task.

Tracking Task

Type: Continuous compensatory
Number of Axes: Two
Displays: Two instrument dials arranged either horizontally or vertically to each other with the pointers of the dials aligned in various positions.
Controls: Two knobs in a vertical position tilted at a 45° angle from one another.
Forcing Function: Not given
Controlled Element: Position (K)
Subjects: Mixed groups of male and female college students were used as subjects.

Experimental Design Three separate experiments were given. The first experiment used two directions of dial separation, vertical and horizontal, and five different positions of the two pointers which were 90°, 180°, 270°, and 360° in a clockwise rotation, and one-position with tips counterpoised. The second experiment used two groups of subjects. One group was trained on the horizontal dials and then transferred to the vertical dials; the other group was trained on the vertical group, and then transferred to the horizontal dials. All subjects practiced alternatively on the 270° and 360° conditions. In the third experiment, the vertical and horizontal dials were used, and the dials were separated by four positions from one another.

Performance Measure The amount of time that the pointers were simultaneously aligned.

Results The results of the three experiments indicated that performance improved when the instruments are close together and aligned horizontally. When instrument alignment factors are eliminated, pointer alignment between the 270° and 90° sector was better than the 90° to 270° sector. However, if instrumentation alignment was permitted to interact with pointer alignment, performance was better when the pointers were aligned at 270° for the horizontally operated instruments and at 360° for the vertically operated instruments.

Conclusions The effects must be attributed to differences in perceptual motor capacities in responding to different kinds of stimulus patterns. One hypothesis was that the simplicity in the total stimulus field accounted for the superiority of pointer alignment over nonalignment, while another hypothesis was that interpretation of movement, in reference to curvilinear or rectilinear display space, accounted for better performance when the pointers are aligned in the left and upper sectors of the rectilinear display.

73. Fleishman, F. A., and Parker, J. F. Jr. Factors in the retention and relearning of perceptual-motor skills. J. exp. Psychol., 1962, 64, 215-226.

Purpose To investigate the retention of a tracking skill as a function of time without practice, level of original learning, type of initial learning, and performance after retraining as a function of retraining schedules.

Tracking Task

Type: Continuous, compensatory
Number of Axes: Three
Displays: (1) CRT as elevation and azimuth indicator. (2) Zero center voltmeter used as slideslip indicator.
Controls: (1) Joystick. (2) Rudder pedals.
Forcing Function: CRT horizontal axis supplied with damped sine wave at 6 cpm with 5% amplitude decay per cycle.
Controlled Element: CRT display and voltmeter coupled as in aircraft: Elevation - 2nd order system. Azimuth - 2nd order system plus lag (τ = 1 sec) from joystick, 1st order system lag from pedals. Sideslip indicator - simple lag from pedals, 1st order plus two exponential lags.
Subjects: Subjects from two earlier experiments were used.

Experimental Design Subjects from two earlier experiments, Group I and Group II, were brought back for retesting after 9, 14, and 24 months (for Group I), and 1, 5, 9, 14 months (for Group II). Group I learned the original task with minimum instructions; Group II had been given detailed instructions and feedback and was superior to Group I. Each retention group was split in two, one half receiving massed retraining trials, the other half distributed trials. One week after retraining all subjects were retested.

Performance Measure Integrated absolute error.

Results Retention was extremely high after 24 months. Up to 14 months retention interval had no effect on retention performance. Most important factor in retention was found to be the initial level of performance during initial learning. Type of initial learning was unrelated to retention when proficiency after initial learning was held constant. Retraining under distributed practice was superior to massed practice; however, at one week no difference was found during retest. Retention was more a function of specific habits acquired during training than ability traits acquired before training.

74. Fleishman, E. A., and Rich, S. Role of kinesthetic and spatial-visual abilities in perceptual-motor learning. J. exp. Psychol., 1963, 66, 6-11.

Purpose To test the hypothesis that sensitivity to spatial-visual cues is more important early in perceptual motor learning while sensitivity to kinesthetic cues is more important late in learning.

Tracking Task The two hand coordinator apparatus (THC) was described in Milton, A. W. (ed) Apparatus Tests, Washington: United States Government Printing Office 1947. The subject attempts to keep a follower on a small target as the target moves irregularly and at various rates around a circular plate. Two crank-type handles are used for controls, one for each axis.

Experimental Design Ability measures for kinesthetic sensitivity (weight lifting) and spatial ability (Aerial Orientation Test) were administered prior to the tracking task. Forty male Ss then received 40 one-minute trials on the THC.

Performance Measure (1) Aerial Orientation Test (AOT) - (number correct), (2) kinesthetic sensitivity - (difference limen) and (3) THC - time on target.

Results Correlation between AOT and Total TOT was 0.49 ($p < .01$). Correlation between kinesthetic sensitivity and Total TOT was 0.58 ($p < .01$). Correlation between AOT and kinesthetic sensitivity was 0.12 (NS). Correlation of AOT and kinesthetic sensitivity with TOT as a function of trial number showed significant correlation of TOT with AOT for early trials but not for late trials, and the reverse for kinesthetic sensitivity.

Conclusions Subjects who can make use of kinesthetic cues can improve their performance late in practice over those who have less ability to use this information. The original hypothesis was thus upheld. External reference tests can be used to describe the components of skill learning.

75. Fuchs, A. H. The progression-regression hypothesis in perceptual-motor skill learning. J. of exp. Psychol., 1962, 177-182. V. 63

Purpose To test an hypothesis of perceptual-motor learning originally stated by Fitts. According to this model the operator learns to respond to the 1st and 2nd derivatives of the error amplitude and weighs these to achieve system stability and minimum error.

Theoretical Model An analog model of the operator was used to examine the above hypothesis. The model was of the form:

$$\theta_c + \dot{\theta}_c + \ddot{\theta}_c = (K_1 \epsilon + K_2 \dot{\epsilon} + K_3 \ddot{\epsilon})\, e^{-0.2\rho}$$

where K = constants
θ = human output
ϵ = error

A technique of on-line fitting of the model parameters to the human was used. Only one parameter was determined per run, the others were set at the average values from previous runs.

Tracking Task

Type: Compensatory
Number of Axes: One
Display: Oscilloscope
Control: Spring-centered stick
Forcing Function: Random signal
Controlled Element: 2nd order
Subjects: Five paid undergraduates

Experimental Design Each subject received nine 120-second trials a day for a 20-day training period. Knowledge of performance was provided. During the final five days, the subjects performed on the primary task and a secondary task consisting of tracking a 0.06 cpm input on a compensatory display. The secondary task was controlled with the left hand and the primary with the right hand.

Performance Measure (1) Error in primary and secondary tasks, and (2) gain settings determined by the computer for K_1, K_2, and K_3.

Results As practice progressed, the velocity and acceleration weightings increased relatively whereas the position weighting decreased relatively. On the transfer condition, the position weighting increased relative to the velocity.

Conclusion The data supports the progression hypothesis that learning a perceptual motor skill involves learning to respond to the error velocity and acceleration and the regression hypothesis that under stress the operator will regress to weighting the error position more heavily than the other two.

76. Garvey, W. D., and Mitnick, I. L. An analysis of tracking behavior in terms of lead-lag errors. J. exp. Psychol., 1957, 53, 371-378.

Purpose To compare the human operator's tracking performance with the performance of simple analogs.

Theoretical Model The performance of the human operator was compared to the performance of a linear model with weighted position, rate and acceleration components.

Tracking Task

Type: Continuous compensatory
Number of Axes: One
Display: A CRT display with a blip
Control: A hand wheel control
Forcing Function: Either the summation of 3 rate inputs or the summation of 3 acceleration inputs
Controlled Element: Position (K)
Subjects: Six Naval enlisted men.

Experimental Design A factorial design with 2 variables: type of course inputs, velocity or acceleration, and the amount of practice.

Performance Measure Average integrated error, considered to be the lag error score.

Results The results of the study indicated that the type of mechanism which may be substituted to provide performance analogous to that of the human operator differed as a function of the amount of practice the operator has had with the system. In general, it was found that at the beginning of practice S performed analogously to a one-integrator system with feed-forward loop; at the end of the amount of practice imposed by the conditions of this study S performed analogously to a two-integrator system.

77. Gibbs, C. B. Controller design: interactions of controlling limbs, time-lags and gains in positional and velocity systems. Ergonomics, 1962, 5, 385-402.

Purpose To investigate optimum gains for controller design as a function of controller limb time lag and controlled element dynamics.

Tracking Task

Type: Acquisition
Number of Axes: One
Displays: CRT, dim light spot
Controls: Joystick, for thumb, hand or arm, supported above anatomical pivot points, $\pm 25^{\circ}$, lightly spring loaded.
Forcing Function: Target spot appeared 22.5 mm from null zone
Controlled Element: Exp. I - Gain plus time lag $(K/[Ts + 1])$
Exp. II - Rate plus time lag $(K/s[(Ts + 1)])$.
Subjects: Sixteen subjects with Naval ratings.

Experimental Design Exp. 1 - Experimental variables were: Limbs - thumb, hand, and forearm and gain - 0.15 to 0.90 expressed in terms of angular movement of spot to angular movement of control. Exponential lag - 0.08 to 2.00 sec and position control. Subjects practiced for 45 min. daily for 10 days for over 1600 runs. The last 5 scores per condition were used for scoring.

Exp. II - same design as above was used except for rate control. Rates were from 0.4 to 4.0 radians/sec for 1 radian stick movement.

Performance Measure Time to position target within ± 1.5 mm from center of scoring zone.

Results Exp. I - The lag, limbs and gains had a significant effect on performance. The thumb was inferior to the hand or forearm and the lags by gains and lags by limbs interactions were significant.

Conclusions An increase of gain or lag alone will degrade performance but an increase in gain can overcome effect of increased lag. The predicted optimum gains agreed with previously published data. Generality of predictions were limited to interpolation and U-shaped performance curves were generally found.

78. Gibbs, C. B. Transfer of training and skill assumptions in tracking tasks. Medical Research Council, Applied Psychology Research Unit, 127/50, Cambridge, England, September 1950.

Purpose To test the learning and transfer effects that follow isolated changes in the display, in motor skills, and in the directional relationship between stimulus and response in a tracking task.

Tracking Task

Type: Continuous compensatory
Number of Axes: One
Display: Rotating pointer which was kept stationary on an index mark
Control: A handwheel of two sizes: 3" diameter and 6" diameter
Forcing Function: The pointer rotated at 18 rpm
Controlled Element: Position with K = 1, 2, and 4
Subjects: Seven matched groups of subjects with 10 men in each group were used. All subjects had Naval ratings.

Experimental Design Five conditions were given: 1) The standard condition had a 1:1 control gain. A clockwise rotation of the handle produced a clockwise rotation of the pointer. 2) A second condition identical to the standard except that a clockwise rotation of the hand gave an anti-clockwise pointer movement. 3) A large pointer arrangement with a 4:1 gain. 4) An arrangement where the subject was required to move in an anti-clockwise direction. 5) A large wheel in which the hand wheel required half as much winding force with a gain of 2:1.

Each group learned the standard arrangement either as an initial or final task. This enabled a common basis for compering all the groups.

Performance Measure Average learning time to reach a given level of proficiency.

Results The results showed that the compatible arrangement was easier to learn than the uncompatible arrangement. However, there was a high positive transfer from the incompatible to the compatible arrangement and little transfer from the compatible to the incompatible arrangement. For the change in display size, the initial learning times were equal for both tasks. Transfer was high and positive between the different display gain conditions and unaffected by the order of presentation.

The task with the small wheel proved more difficult to learn than the large wheel task and there was greater transfer from the difficult to easier task than from the easy to difficult.

Second Experiment

Tracking Task

Type: Pursuit task
Number of Axes: One. The subject was required to track a moving line of electrical contact studs with a pointer.
Controls: A hand wheel
Forcing Function: Two randomly varying tracks; one that was estimated as easy and the other as difficult.
Controlled Element: Position (K)
Subjects: Two groups were used, one group of 10 businesswomen and the other of 10 Naval ratings.

Experimental Design One group of subjects was given the frequencies of difficult to easy and the other group was given easy to difficult frequencies.

Performance Measure The method of scoring was the number of contacts that were made by the pointer on the contact stud. These contacts were summed to give the total number per course.

Results It was found that learning was more rapid when practice was mainly on the difficult courses. The author concluded that a difference in difficulty between two tasks affected the amount of transfer and the rate of learning the task.

79. Gibbs, C. E. Methodology of gain studies in man-machine studies. Psychol Bull., 1963, 60, 147-151.

There are considerable difficulties in communicating data concerning the output-input amplitude relations of man-machine systems. Many such difficulties arise from a lack of agreement on terminology and methods of measurement and this report attempted to examine these differences. The many different terms in use are compared for their clarity and convenience. The uniform use of the term "gain" is recommended; and the terms control gain, display gain, and system gain are defined and distinguished. It is emphasized that linear measures are generally used in studies of gain, but radial measures are superior for describing optimal limb movements for controlling machines.

80. Gibbs, C. B. Servo principles in sensory organization and transfer of skill. Medical Research Council, Applied Psychology Research Unit, 218/54, July 1954.

The paper presents a brief account of biological findings which support the belief that there are essential similarities between the control characteristics of human movement, and those of analogous devices which have been developed, somewhat more recently, by servo engineers.

The bearing of these analogies upon the study of the transfer of skill is briefly discussed, by developing a hypothetical servo model of tracking skill and the placing reaction. It is shown that the invariants of the servo model correspond closely with the varieties of a skilled task between which a trained operator shows high positive transfer. No or negative transfer of skill is found where two tasks differ in such a way that a servo mechanism designed to discharge the first task would need considerable modification to do the second.

The relevance and usefulness of servo models and terminology to the study of the transfer of skill is emphasized, and the practical and theoretical implications are outlined.

81. Gottsdanker, R. M. The accuracy of prediction motion. J. exp. Psychol., 1952a, 43, 26-36.

Purpose To study prediction motion for constant velocity and accelerating target paths.

Tracking Task The apparatus moved a sheet of paper on which the trajectories were drawn behind a narrow slit. The S tracked the trajectory with a pencil. After a given point the trajectory was deleted and the S was instructed to keep tracking in such a manner to continue following the trajectory if it had not disappeared.

Experimental Design Trajectories with negative, positive, and zero acceleration were used. Ten runs on each trajectory were given to each S.

Performance Measure The rate of movement was measured for the entire 6 sec. following termination of the trajectory for the last 8 runs for each subject. An acceleration index was computed for each run by subtracting the rate on the first unguided section from the sixth. A number of other measures were calculated including time-in-run and in-run and between-run consistency.

Results Ss tended to extrapolate at a constant velocity rather than a constant acceleration on the acceleration trajectories.

82. Gottsdanker, R. The intrinsic accuracy afforded by the operator's movements. Minneapolis-Honeywell Aero Document U-ED 6122, May 5, 1959.

This paper reviews experiments on the accuracy of human operator movements without visual feedback. Of particular interest is Gottsdanker's analysis of error measures. He stresses that both a constant error term (the algebraic average of differences between the desired and actual control settings) and a precision term (variability around the operator's mean setting) must be given to evaluate performance. Constant or average error alone or a variability measure around the desired setting alone are equivocal.

83. Gottsdanker, R. The effect of superseding signals. Mimeographed note, November 14, 1962.

Purpose To compare the validity of three hypotheses regarding the response to an initial signal and how it is influenced by a second occurring within the reaction-time period.

Theoretical Model Three hypotheses were examined. (1) Psychological Refractory Period - The initial response should not be affected as the second signal is stored until the first is completed. (2) Commitment time - A period exists after the first signal in which the operator must commit himself to a response. If a second signal occurs in this period it may be responded to and the first ignored. Or if the second occurs just after this period it will be ignored and the first responded to. (3) Linear - The total response is the addition in time of the two simple responses to the individual signals.

Tracking Task

Type: Discrete
Number of Axes: One
Displays: Five lights in a row, center light was "home" base.
Control: Lightweight control pointer slid horizontally in a track beside the lights.
Forcing Function: Uncorrected trial - one of four lamps lighted for about 700 ms. Corrected trial - one of two far lamps was on for a short period, then one of two inner lamps came on.
Controlled Element: Position (K)
Subjects: Eight males, 16 to 44 years of age.

Experimental Design Intervals between signals on corrected trials varied from 50 to 240 ms. Each S received 3200 trials, 2800 uncorrected, over 400 corrected presented in random order. Four one-hour sessions over four days.

Performance Measure (1) Reaction time between 1st signal and response initiation. (2) Amplitude of first maximum point and (3) Duration between initiation and point 1 mm from maximum.

Results Amplitude of response was a function of inter-signal interval. Reduction of amplitude by reversing signal was more pronounced for short than for long inter-signal intervals. The first part of the response seemed to be controlled by the first signal.

Conclusion Linearity hypothesis was generally upheld, although exceptions to linearity occurred frequently enough to demand explanation. Some type of intermittency was suggested but the psychological refractory period theory was held untenable.

84. Gottsdanker, R. M., Broadbent, L., and Van Sant, C. Reaction time to single and to first signals. J. of exp. Psychol., 1963, 66, 163-167.

Choice reaction times were measured for six adult Ss by two procedures. There was a single-choice condition in which, after a fixed warning interval, S was required to move a lever away from himself or toward himself according to which of 2 signal lamps was lighted. In the double-choice condition, there followed 1/2 sec after the 1st signal a 2nd choice involving two other signal lamps and a choice by the other hand. For each S, mean reaction time for the single-choice condition was reliably shorter than that for the 1st choice in the double-choice condition. This was regarded as corroboration of Poulton's thesis that a person's manner of response, including latency, is influenced by his expectations of the requirements of the immediate future.

85. Gray, F. E., and Ellson, D. G. The validity of time-on-target (clock) scores as an estimate of tracking error magnitude. AF Air Materiel Command, TSEAA-694-2F, 23 June 1947.

Purpose To determine the equivalence of time on target scores with integrated error scores.

Tracking Task and Experimental Design Refer to Hill, H., et al, Reference 94.

Performance Measure Both mean error scores and time-on-target scores were measured. The mean error score was found by the absolute integral of error. Six time-on-target scores were obtained, each with different limits.

Results It was found that under certain conditions, the two scoring methods were equivalent but changing the limits of TOT varied this correlation. Optimal size of these limits became progressively greater as the target speed and resulting mean error increased.

Conclusions It was suggested that mean integrated error score should be used when accurate measurement of error magnitude is required. If it is necessary to substitute TOT scoring, the best estimate of error magnitude is found when the TOT limits are set approximately equal to the mean error magnitude and tracking is recorded as on-target, between 50% and 80% of total time.

86. Hall, I.A.M. Effects of Controlled element on the human pilot. WADC Technical Report 57-509, August 1958.

Purpose Application of quasi-linear control theory and pilot opinion to determine the effects of various longitudinal controlled element dynamics on the pilot in a simulation study.

Theoretical Model Cross and power spectral functions were used for obtaining quasi-linear describing functions and the remnant power. For a linear operator, the close loop describing function H can be found from the following expression:

$$\phi_{oo} = \left| \frac{y_p}{1 + y_p y_c} \right|^2 \phi_{ii}$$

where ϕ_{oo} is the spectral density of the pilot output

ϕ_{ii} is the spectral density of the forcing function

y_c is the transfer function of the controlled element.

If the pilot is acting nonlinearly, then the equation can be written as follows:

$$\phi_{oo} = \left| \frac{y_p}{1 + y_p y_c} \right|^2 \phi_{ii} + \phi_{nn}$$

where ϕ_{nn} is the remnant power.

The fraction of the unit output signal contributed by the linear operation on the system excitation is defined as:

$$\rho^2 = \left| \frac{y_p}{1 + y_p y_c} \right|^2 \frac{\phi_{ii}}{\phi_{oo}}$$

where ρ is termed the coefficient of coherency.

Tracking Task

Type: Continuous compensatory
Number of Axes: Two
Display: Oscilloscope with a moving horizon and a target dot
Control: Wheel type aircraft control
Forcing Function: 2 cam wheels for the longitudinal and lateral excitation.

These produced a Gaussian distributed random noise with a cutoff frequency of 0.6 radians per second.

Controlled Element: Three longitudinal controlled elements were analyzed:

1) $$\frac{\theta}{\Delta} = \frac{K(1 + Ts)}{s\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1\right)}$$

2) $$\frac{\theta}{\Delta} = \frac{K(1 + Ts)}{s(\tau s + 1)}$$

3) $$\frac{\theta}{\Delta} = \frac{K}{s}$$

4) $$\frac{\theta}{\Delta} = K$$

The lateral dynamics were equivalent to a Navion aircraft at 5000' and about 120 mph.

Subjects: Two U. S. Navy pilots, one with 1250 hours and the other with 610 hours, were used in this experiment.

Experimental Design Two weeks were devoted to the familiarization of the Ss with the simulator. Six runs were required before the rms error reached a steady value. Each pilot received 3-5 learning runs and 3 data runs for each configuration. Thirty nine configurations were given which were the four transfer functions where the gain, the lag, the damping ratio and the short period frequency were varied.

Performance Measure Spectral and cross power density functions were obtained and linearly describing functions were calculated for each configuration. The linear coherency was also calculated. The pilot opinions were obtained using a 4 point rating scale. Both the average stick force and the average absolute error were taken as performance measures.

Results The following is a summary of the major finding from this investigation: "The pilot describing function forms can be related in a consistent manner to controlled element characteristics, and in particular, for short period approximation dynamics, certain distinct regions can be found in the damping versus period plane, in which these describing function forms remain constant. The forms vary from a double lead to a double lag being developed over part of the frequency range, but for convéntional aircraft dynamics, the pilot adapts a simple lead-lag form.

The measured describing functions may be taken as Gaussian input describing functions.

Two remnant sources are suggested by the data examined. The first, which may well be due mainly to interaction between the two dimensions of the presentation, can be represented by a signal injected at the pilot input. The second, which occurs only with certain extreme configurations, can be represented by a signal injected at the pilot output, and may well derive from the relay-type stick motion adopted when tracking with these configurations.

In combating closed loop instability, the pilot develops phase lead, decreases his gain, and eventually adopts a strongly nonlinear behavior. These are associated with lower opinion and larger tracking error. When tracking with the more sluggish controlled elements, the pilot relaxes to a less energetic technique than is suggested by extrapolation of other data. When tracking with rapid response configurations, the pilot adapts by attenuating the normal output at higher frequencies.

Certain similarities exist between findings in this report and those of others. Except for the higher natural frequencies, the simulator handling quality ratings agree well with those from a previous flight study.

Human operator and other data examined strongly suggested that pilot opinion deteriorates when: (i) the controlled element response is too slow and large average stick forces are required: (ii) the pilot has some difficulty in stabilizing the closed loop and is thus severely restricted in his choice of filtering of the pilot's higher frequency output and again restricts the pilot in his choice of responses. A synthetic opinion may be evolved, based on simple criteria developed from the above dislikes, which will predict the effect of controlled element characteristics on rating."

87. Hammerton, M. An investigation into the optimal gain of a velocity control system. Ergonomics, 1962, 5, 539-543.

Purpose To study the effect of control gain in a velocity control system on human performance by changing the amount of stick deflection.

Tracking Task
- Type: Acquisition, pursuit
- Number of Axes: One
- Display: CRT with a line as a stationary target and a spot as a controlled target.
- Control: Joystick

Forcing Function: Initial displacement of 22.5 mm of the spot from the spot line plus a constant velocity
Controlled Element: Rate control with variable gains as experimental conditions
Subjects: Two groups, each contained five men with Naval ratings.

Experimental Design There were five maximum gain values of 0.121, 0.159, 0.202, 0.236, and 0.271 rad/sec in combination with five values of stick deflection which gave 25 different conditions.

Performance Measure Time to return the spot to the line and hold it within 1.5 mm for 2 sec.

Results and Conclusion The lowest stick deflection values required less time. The highest maximum gain was superior, it was not significant. The author concluded that the typical U-shaped curve of the relation between control sensitivity and time to secure stable acquisition was not found in the circumstances of this experiment.

88. Hartman, B. O. The effect of target frequency on pursuit tracking. U. S. Army Medical Research Laboratory, Fort Knox, Kentucky. 1 August 1956.

Purpose To determine the effect of target frequency on tracking performance.

Tracking Task
Type: Continuous, pursuit
Number of axes: One
Display: CRT with two vertical lines moving horizontally representing target and cursor
Control: Joystick
Forcing Function: Sinusoidal wave at 10, 20, 30, 40, 50, and 60 cpm
Controlled Element: Position with K = 2
Subjects: Eight enlisted men

Experimental Design A sequence of six frequencies was counterbalanced after a training period.

Performance Measure Time-on-target scores with a band of 5% of the maximum error and total number of hits obtained by graphic analysis.

Results The results showed a decrease in mean TOT scores and an increase in mean number of hits with an increase in target frequency. An analysis of variance showed both changes were not significant.

Conclusions Tracking performance decreases as target frequency (number of sweeps per minute) increases. The change in performance is systematic with no marked inflection points. With varying target frequency, hit scores seem to be more sensitive to changes in performance than time-on-target scores.

89. Held, R., and Freedman, S. J. Plasticity in human sensorimotor control. <u>Science</u>, 25 October 1963, 142, 455-461.

This paper discussed the role of sensory feedback in adaptation to sensorimotor tasks. Experimental results on displacement of visual and auditory spatial feedback for motor tasks are presented. The results are interpreted as indicating that successful adaptation to variation in feedback depends upon the regularity of the feedback signal relationship to the motor output. A task which presents a varying sensory feedback-motor output relationship cannot be learned. Furthermore, active movement on the part of the operator is necessary to provide the feedback signals from the motor output to correlate with other sensory inputs such as vision or audition. It is concluded that a freely moving astronaut may be exposed to uncorrelated sensory-feedback motor output relationships and thus lose certain sensorimotor abilities.

90. Henderson, J. G. The estimation of the transfer function of a human operator by a correlation method of analysis. <u>Ergonomics</u>, 1959, 2, 274-286.

<u>Purpose</u> To determine the linear transfer function of the human operator by the best linear approximation.

<u>Theoretical Model</u> The open loop describing function was estimated by dividing the cross correlation of the error-output by the autocorrelation of the error where the fraction due to the remnant was considered negligible.

<u>Tracking Task</u>

Type: Compensatory, continuous
Number of Axes: One
Display: Deflection of a pointer
Control: Stick control
Forcing Function: Random time function
Controlled Element: Rate (K/s)
Subjects: Not given

<u>Experimental Design</u> Not given.

<u>Performance Measure</u> The autocorrelation function of the error and the cross correlation function of the error output were calculated, and the open loop describing function was estimated.

<u>Results</u> The best fit describing function was the following form:

$$G(s) = \frac{K e^{-Ls}(T_1 s + 1)}{s^2 + 2 T_2 s + T_3^2}$$

The value of the time delay is fairly consistent, its average value was 0.16 sec. The reduction in the operator's gain, which occurred after increasing the display gain, resulted in a reduction of the natural frequency of his response and was associated with approximately a two-fold increase in the derivative of error term T_1; i.e., the operator tended to give more weight to the derivative of the error when his gain was reduced. The damping associated with the "motor" system appeared to be such as to give an almost critically damped response.

91. Hick, W. E. Man as an element in a control system. Medical Research Council, Applied Psychology Research Unit, Cambridge, England, 1951.

This paper is a general review of the use of man in control systems. Various types of manual control such as car driving, aircraft flying, and gunnery, and different aspects of manual control systems in terms of the display, the control and the controlled element were discussed. The author also examined attributes of the human operator in terms of information transfer rate, reaction time, and transfer of skills.

92. Hick, W. E. The discontinuous functioning of the human operator in pursuit tasks. Quart. J. of exp. Psychol., 1948, 1, 36-51.

Purpose To examine continuous and discontinuous operator responses. Various aspects of operator responding are discussed including the origin of discontinuities.

Theoretical Approach If discontinuity of operator responses is defined in terms of displacement or rate, it must be continuous for mechanical reasons, but if defined as a force it may be regarded as discontinuous. The author regards the input-output relations of the human in terms of muscular force, i.e., force is proportional to the magnitude of the stimulus. If a constant time lag occurs, the output would be shifted along the time base. In another case, the output might depend upon the time integral of the input. If these two relations are combined in such a way that the integral is not itself the output but merely controls the sensitivity, then a machine would result whose characteristics are constantly changing, i.e., it is capable of learning. This definition would involve, however, a nonlinearity but not essentially a discontinuity. However, in some cases this nonlinearity in performance might be described as a discontinuity. Therefore, the author defines the term "functional discontinuity" where performance may be mathematically discontinuous but may indicate separation points between domains where different continuous functions are reasonably applicable. The author claims that there are two types of discontinuities. One involves threshold frequencies in which the stimulus has to go above certain threshold values before a response is given. The other is the psychological refractory period.

93. Hick, W. E. Why the human operator? Medican Research Council, Applied Psychology Research Unit, APU 181/52, Cambridge, England, 1952, 1-17.

This paper is a discussion of the use of information theory for defining the capacity and amount of information transmitted by the skilled operator. The human operator can be broken into three segments, any of which may act as an information bottleneck. These areas are: (1) The sense organs and the connections to the brain that have an information capacity which were assumed to be greater than can be used. (2) The brain which normally imposes a limit of about 5 bits per second. (3) The output transducers such as the muscular and skeletal systems with associated control circuits which normally have an information transfer rate of 10-15 bits per second.

The author divides tasks into three classifications of information transfer. These are (1) high rate of transfer of 10-15 bits per second, (2) a moderate rate of transfer of 5-6 bits per second and (3) a low rate of transfer of about 3-4 bits per second.

The high rate of transfer is found in tasks with favorable coding. Such tasks would be card sorting and reading lists of words or nonsense syllables in random order. The moderate rate is typical of cases in which the code is arbitrary and therefore has to be learned, such as letter sorting in the post office or ordinary speech. The third rate occurs when an arbitrary code with signals of low information content is given in random succession. The author states a formula taken from Shannon's expression of information which relates reaction time with the amount of information transmitted. This equation is:

$$t = k \log (n_e + 1)$$

where n_e = the number of equi-probable alternatives

k = constant

Regarding the skilled operator as a communication channel, there is some evidence that his normal capacity is about 5 or 6 bits per second, although it may be difficult to transfer 5 or 6 bits per second continuously, due to the use of some channel capacity for feedback.

94. Hill, H., Gray, F., and Ellson, D. G. Wavelength and amplitude characteristics of tracking error curves. AF Air Materiel Command, TSEAA-8, 22 April 1947.

Purpose To determine wavelength and amplitude characteristics of tracking error curves.

Tracking Task

Type: Continuous, pursuit
Number of Axes: One
Displays: Two pointer horizontal display
Controls: Hand grip on a wheel where the subject's elbow coincides with the axis of the wheel. Tracking was done entirely with the forearm (clamps prevented wrist movement).

Forcing Function: Linear motion, 1, 2, 3, 4, and 5 inches/sec
Controlled Element: Position control where 5° of hand wheel movement equaled 1" of display movement.
Subjects: Ten male university students.

Experimental Design Counterbalanced designs of the five speeds in the left or right direction were used.

Performance Measure Error curves were recorded and mean error was found by averaging error magnitude at 1/6 sec intervals. Wavelength analyses were performed in which the following measures were recorded: I, initial error at the beginning of a run, A, amplitude of the error at the peak and W, wavelength of a $\frac{1}{2}$ cycle.

Results Changes in mean tracking error and mean wave amplitude were approximately proportional to target speed. For low amplitude waves, including all examples of rate tracking, wavelength decreased as target speed increased, but for the high amplitude waves produced in position correction tracking, wavelength did not change significantly with target speed. This was considered especially important as it was the high amplitude waves which accounted for a major part of the tracking error and the variability of tracking error curves. Wavelength was also relatively stable at different amplitudes, increasing approximately 50% with a 10 to 1 increase in amplitude.

Conclusions The authors stated there are two types of error waves, one from "rate tracking," which gives small amplitude variation with variation in frequency, and "position tracking," which produces high and variable amplitudes and a small range of wavelengths.

95. Holding, D. H. Guidance in pursuit tracking. J. of exp. Psychol., 1959, 37, 362-365.

Purpose To evaluate mechanical guidance as a training technique in a continuous sensorimotor skill.

Tracking Task
Type: Continuous, pursuit
Number of Axes: One
Displays: Pointers on a vertical scale
Controls: Rotary knob
Forcing Function: Two courses varying in frequency
Controlled Element: Position with unit gain (K)
Subjects: Male students and young university staff members

Experimental Design Two groups of Ss were used. One group received unguided tracking while the other group was allowed to observe the control knob and pointer locked to the target course generator. Kinesthetic and visual cues were separated to determine the effect of each upon guidance. Each group was transferred to the other course.

Performance Measure Integrated error was used as a performance score. The logarithmic value of this score was used in an analysis of variance program.

Results It was found that guidance at an early stage produced the same extent of learning as normal practice. This was the case when a single target course was used and when Ss transferred learning on a first target course to tracking a second. Full guidance was more effective than visual guidance. Visual guidance was superior to kinesthetic guidance, which gave no significant benefit in this instance.

Conclusions These results suggest a reinterpretation on the value of knowledge of results in the theory of motor skill, and a new evaluation of guidance as a training technique.

96. Humphrey, R., and Bekey, G. A. A technique for determining the parameters in a nonlinear model of a human operator. Space Technology Laboratories Report No. 9865-6003-MU000, 1 March 1963.

Purpose To obtain a nonlinear description of the human operator by a model matching method.

Theoretical Model The method of steepest descent was used in this study. An analog model of the human operator was devised that had the form

$$\dot{z} + az = b\dot{x} + cx$$

where

$z(o) = 0$

$a \geq = 0$

x = input (error)

z = operator output

θ = limited or "true" operator output derived from z

$$\theta = \begin{cases} -1, & z \leq -1 \\ z, & -1 < z < 1 \\ 1, & z \geq 1 \end{cases}$$

The difference between the operator and the model was squared and multiplied by 1/2. This error term was partially differentiated with respect to the parameters (gradient vector) and the rate of adjustment of the parameters was set proportional to the negative of the gradient vector until the error was minimized. At this point, the parameter values were said to be proportional to those of the human.

Tracking Task

Type: Compensatory

Number of Axes: One

Display: Vertically moving blip on a CRT

Control: Pencil stick on-off controller

Forcing Function: Sum of sine waves with 2 bandwidths

1) .112 - .825 rad/sec and

2) .491 - .825 rad/sec

Controlled Element: Acceleration with on-off control where the output was given by:

$$\frac{-K}{s^2}, \ \theta \leq -1$$

$$0, \ -1 < \theta < 1$$

$$\frac{K}{s^2} \quad \theta \geq 1$$

Subjects: 8

Experimental Design Each Ss' runs were counterbalanced where four conditions (2 bandwidth x 2 gains) with one replication were given.

Performance Measure The parameter values were used as performance measures as found by the parameter tracking method.

Results Mean value were calculated for the parameter values. These were:

$a = 7.5 - 13\ (\text{sec})^{-1}$	N. S.
$b = 3 - 15$	Significant difference for K
$c = 7 - 14$	N. S.

Conclusions This was a useful method of determining the parameter values of an assumed nonlinear model of the human operator.

97. Humphrey, R. E., Bekey, G. A., Rose, R. E. and Meissinger, H. F. Study of model matching techniques for the determination of parameters in human pilot models. STL Report No. 8426-6002-RU-000, 1963.

Purpose Utilization of a model matching technique to determine model the parameters in a time invariant linear model of the human operator.

Theoretical Model The following model of the human operator was used.

$$\ddot{z} + \alpha_1\dot{z} + \alpha_2 z = \alpha_3\dot{x} + \alpha_4 x$$

The method of steepest descent as explained in Humphrey and Bekey (1962) was used with three adjustment strategies: a) continuous on all 4 parameters simultaneously, b) iterative adjustment of one parameter at at time for a short period and repeating successively until the minimum error has been reached and c) a relaxation process which adjusts one parameter until a minimum has been reached and doing this successively for each parameter.

Tracking Task

Type: Continuous

Number of Axes: Single

Display: Vertically moving blip on CRT

Control: Pencil stick controller

Forcing Function: Random noise with cutoff frequency of 1 rad/sec

Controlled Element: Three controlled elements were used:

1) 1st order lag $\frac{K}{s + 1}$

2) 2nd order lag $\frac{K}{s(s + 1)}$

3) 2nd order $\frac{K}{s^2}$

Number of subjects: Two

Experimental Design Not given.

Performance Measure The average parameter values found by the adjustment techniques.

Results The parameter values were found to differ for the various adjustment techniques; however, since no statistical tests were performed it was not known if these were significant differences. These results were in the same range as found by J. A. Adams (1963).

98. Hunt, D. P. Tracking performance as a function of feedback specificity. WADC Technical Report 58-584, Wright Patterson AFB, March 1959.

Purpose To relate the number of displayed error categories, task difficulty and practice, to performance on compensatory tracking.

Tracking Task

Type: Compensatory

Number of Axes: One

Displays: CRT either continuous or discrete error display

Control: Spring loaded joystick

Forcing Function: Easy course: 2/3 + 1 1/3 + 3 1/3 cpm sinusoids with 90 sec period.

Controlled Element: Second order (K/s^2)

Experimental Design Four degrees of feedback (3, 7, and 13 discrete categories, continuous) were combined with the hard and easy courses. Eight Ss were used in each group. Fifteen 90 second trials were given.

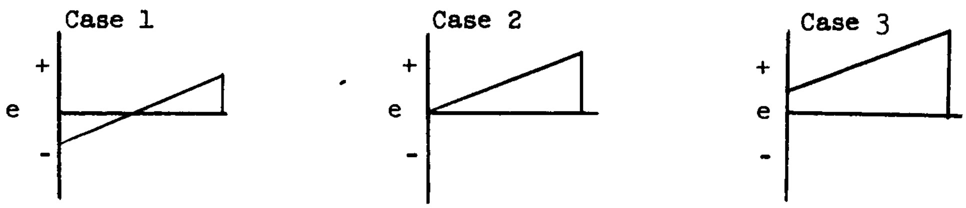
Performance Measure Average tracking error and average control motion were used.

Results The mean error decreased in proportion to the number of error categories for both courses. Relative improvement depended upon stage of practice and control motion did not vary with error categories but decreased with practice.

99. Jackson, K. F. Behavior in controlling a combination of systems. Ergonomics, 1958, 2, 52-62.

Purpose To determine how variation in the number of controlled systems affects operator behavior.

Theoretical Model A model was presented for deriving $\bar{t}_i$, the average duration of interruptions when controlling a number of systems. Three cases were outlined for determining the error increase during an interruption, given a residual error, .



$$E = \int_0^{t_i} e_1 dt = \frac{vt_i^2}{2} + \frac{e_r^2}{v} - e_r t \qquad E = \int_0^{t_i} e_2 dt = \frac{vt_i^2}{2} \qquad E = \int_0^{t_i} e_3 dt = \frac{vt_i^2}{2} + e_r t_i$$

The average duration of interruption will be: $\bar{t}_i = nt_m + (n-1)\ t_c$ where n = number of systems, t_m = average time for changeover, and t_c = average duration of control movement. No analysis was presented for the sinusoid signal actually used in the experiment.

Tracking Task
- Type: Compensatory
- Number of Axes: One to five
- Display: Dial and pointer
- Control: Knob
- Forcing Function: Sinusoidal, 1 cpm with maximum amplitude of $\pm 4.5^\circ$. ($\pm$ two scale division).
- Controlled Element: Position (K)

Experimental Design Twenty Ss were given five minute trials on each number of dials (one to five). The number order was counterbalanced and initial practice trials were given. The Ss were instructed to work systematically around the dials.

Performance Measures 1) Integrated average error for interruption phases, 2) Integrated average error for control phases, 3) Average duration of interruptions, 4) Average duration of movements and 5) Number of movements per trial.

Results Amplitude of control movements, speed of control movements, and rate of working increased with number of dials. Duration of control movements decreased with increase in number of dials. Average error increased for both interruption and control phases. Number of anticipations decreased as number of dials increased but was constant for 2 and 3 dials.

Conclusions "It has been shown that in terms of the overall measure of performance, namely the modulus mean error, the situation deteriorated considerably as the number of dials increased, but we know from the results of the more elementary measures that the operator did much to prevent the deterioration. He made quicker change-over movements from one control to the next, he made quicker control movements and he anticipated coming events. Overall measures of performance conceal the details of behavior, both those that are adaptive and those that are not."

100. Katz, S. and Spragg, S. D. S. Tracking performance as a function of frequency of course illumination. J. of Psychol., 1955, 40, 181-191.

Purpose To examine an hypothesis of receptor intermittency as an explanation of periodicity in tracking performance.

Tracking Task
- Type: Pursuit
- Number of Axes: One
- Display: Chart paper moving behind 2" x 3" window illuminated by neon lamps with 0.05 sec flashes
- Controls: Handheld pencil
- Forcing Function: 1/4 cps sinusoid with a 1" amplitude and an irregular course with amplitudes from 0.25 to 1 inch.
- Controlled Element: Position (K).

Experimental Design Eighteen male Ss each performed under six flash rates for both courses. Flash rates were from 0.5/sec to 4/sec. A second experiment compared rates of 4/sec and continuous.

Performance Measure Mean error from chart paper

Results Mean error decreased as flash rate increased. The change in error from 4 sec to continuous was statistically significant. No difference was found between courses.

Conclusions The results favored the continuous response interpretation of tracking as compared to the intermittent or refractory period interpretation because inputs occurring at a rate greater than 2/sec were used by the operator.

101. Kennedy, J. E. and Landesman, J. Series effects in motor performance studies. J. of appl. Psychol., 1963, 47, 202-205.

This experiment was a methodological study concerned with the determination of optimum values of stimulus variables for task performance. The authors hypothesized that a series effect, i. e. dependence of performance on the range of the stimulus variable as well as on a particular value, might be a contaminating factor in human engineering studies. In particular, this effect might partially account for the typical U-shaped performance curve, in which an optimum value is generally found between extreme values of the range. The hypothesis was tested by studying the effect of work table height on performance of a manipulative task. Two groups were used, each group was given a different but overlapping range of heights. A different optimum was found for each group, thus substantiating the hypothesis for a particular situation.

102. Krendel, E. S. A preliminary study of the power-spectrum approach to the analysis of perceptual-motor performance. AF Technical Report 6723, Wright Air Development Center, October 1951.

Purpose To examine a theoretical background for obtaining information about human frequency response in the control of a piloted aircraft.

Theoretical Model This was Krendel's first approach in applying servo analysis theory to determine and describe the responses of a human operator. The basic quantities he discussed were the power spectral density of the output and the power spectral density of the input. The ratio of these two quantities is the amplitude part of the frequency response function for a linear time invariant system whose input is a random function. Krendel stated that this ratio can be obtained for a nonlinear system but that the ratio does not have a readily understood meaning. If a system such as the human operator is not linear, it may be more reasonable to plot both power spectral densities individually rather than combine them into a ratio.

In determining the linear portion of the human operator, it should follow that amplitude frequency responses should not change as a function of input amplitude. Another question of interest would be to determine if the coefficients of the amplitude function are invariant.

Tracking Task
- Type: Continuous Compensatory
- Number of Axes: One
- Display: Blip moving horizontally on CRT
- Control: Joystick
- Forcing Function: Random step functions with a maximum frequency of 2 cps. Two courses were used with mean amplitudes 1 cm and 2 cm.
- Controlled Element: Position (K)
- Subjects: One S

The subject was given considerable practice with the apparatus. The only variable was the average amplitude of the two courses.

Performance Measure Autocorrelations were made of the stick motion, the forcing function, and the error signal. Power spectra of the error, stick and forcing function were calculated from the autocorrelations. From these power spectra, the amplitude ratios of each combination of the power spectra were calculated.

The amplitude ratio ϕ_o/ϕ_1 is the amplitude ratio across the open tracking loop, ϕ_o/e is the amplitude ratio across the human operator's section of the loop, ϕ/ϕ_1 is the amplitude ratio for the closed loop.

Results Although the procedures used to determine the power spectra were of low accuracy, the results indicated that the power spectrum approach showed promise of yielding useful information about human responses in a tracking problem. Several amplitude ratios were determined but these curves could not be considered definitive.

103. Krendel, E. S. The spectral density study of tracking performance. WADC Technical Report 52-11, Part I, January, 1952.

Purpose Application of spectral density analysis to the study of human responses in perceptual-motor tasks.

Theoretical Model (Refer to Krendel, E. S., 1951.)

Tracking Task (Refer to Krendel, E. S., 1951).

Experimental Design Both Ss were given intensive training in the tracking problem. The experimental variable was the instructions to the Ss. The instructions differed in the S_1 was told to return the blip to the vertical line as accurately as possible and S_2 was told to return it as rapidly as possible. In the second part of the experiment the instructions to the two subjects were reversed.

Performance Measure Refer to Krendel, E. S. (1951)

Results From the RMS scores, it was shown that S_1's error was the same with both instructions while S_2's error decreased with the instruction to track rapidly. The open loop responses showed a deviation from unity at low frequencies which was explained by computational errors or error in the experimental apparatus. Because of this error, it was stated that the various amplitude ratios would not discriminate between subjects and instructions.

104. Krendel, E. S. The spectral density study of tracking performance. WADC Technical Report 52-11, Part II, January 1952.

Purpose Application of spectral density approach to the study of human responses in perceptual motor problems.

Theoretical Model Refer to Krendel, E. S., 1951.

Tracking Task Refer to Krendel, E. S., 1951.
Subjects: Two males with no previous experience in tracking were used as subjects for this experiment.

Experimental Design The variables in this experiment were the amount of practice given to each subject and the mean amplitudes of the forcing function.

Performance Measure Refer to Krendel, E. S., 1951.

Results It was found the the open loop frequency ratio was not unity at low frequencies as one would expect. The same reasons were given as in Krendel, E. S., 1952.

105. Krendel, E. S. and McRuer, D. T. A servomechanisms approach to skill development. J. of Franklin Inst., 1960, 268, 24-42.

The authors described a model consisting of three stages for the learning of tracking skill. The model assumed that the subject is able to improve his performance by learning predictable aspects of the input signal and using this information in addition to the immediate input to control his movements. The process of learning goes through (1) the compensatory stage in which the operator's responses are not distinguishable from the system's response, (2) the pursuit stage in which the operator learns to predict the future input but must still depend on feedback and (3) the precognitive stage in which the response sequence occurs in a preprogrammed fashion, with no feedback control.

106. Lackey, R. B. and Roeca, Jr., W. B. An adaptive control system with application to the measurement of human operator parameters. International Congress on Human Factors in Electronics, May 3-4, 1962.

Purpose To apply an adaptive control principle to obtain a measurement of human operator parameters.

Theoretical Model A model matching technique was used to obtain the describing function. The squared error difference served as the adjustment criterion. The parameters were perturbed by a sinusoidal signal. A detector sensed when the e^2 was at a minimum and adjusted the parameter to the value giving the minimum. The following model was used:

$$G(s) = \frac{K\left[a_1 s^2 + a_2 s + a_3\right]}{(K_1 s+1)(K_2 s+1)(K_3 s+1)}$$

Tracking Task
- Type: Compensatory, continuous
- Number of Axes: One
- Display: Cursor in center of CRT
- Control: Spring centered control stick
- Forcing Function: Random signal
- Controlled Element: Position (K)
- Subjects: 6

Performance Measure RMS error scores and the parameter ratios of a_3/a_2 and a_3/a_1 were determined as a function of training.

Results The above ratios decreased with learning indicating increased leads. The authors concluded that the results supported the hypothesis that a higher level of control is attained with learning.

107. Lemay, L. G. The simulation of human operator tracking using an intermittent model. International Congress on Human Factors in Electronics, IRE, May 3-4, 1962.

Purpose To test a sampled data model of the human operator to explain the intermittency hypothesis.

Theoretical Model A sampled data model with a zero order hold and a simple delay was used for the human operator. The absolute difference of the human output to the model output was used as a criteria for adjustment of the model's sampling and delay times. A linear model was used for comparison which had the form of:

$$G(s) = \frac{Ks^{-Ls}(1 + sT_2)}{(1 + sT_1)s}$$

Tracking Task
Type: Compensatory, continuous
Number of Axes: One
Forcing Function: Random with cutoff at 0.63 cps
Controlled Element: Position (K)
Subjects: 3

Performance Measures The integral of absolute error and cross correlation analysis between the operator and the model were used.

Results The author concluded that there was a better fit with the sampled data model to the human operator than with the continuous model.

108. Lincoln, R. S. and Smith, K. U. Systematic analysis of factors determining accuracy in visual tracking. Science, 1952, 116, 183-187.

Purpose To study tracking performance as a function of type of tracking, control-follower ratios, learning, target characteristics, and target velocity.

Tracking Task
Refer to Simon and Smith, 1956.

Experimental Design Five experiments were conducted: (1) a comparison between direct, velocity, and velocity aided tracking, (2) variation in control/follower motion ratios (3) effect of learning on component movements (4) variation in target size and (5) variation in target velocity.

Performance Measure A function of integrated error was used.

Results Direct tracking was superior to velocity and aided tracking. Different optimum control/follower motion ratios were found for the different types of tracking. Rapid positioning movements decreased with practice, but slow frequency rate movements did not. Cursor size had only a small effect on accuracy.

Conclusion The authors suggested that a detailed analysis of response components represents a constructive approach to human engineering problems as contrasted to generalized theories and analogies.

109. Loveless, N. E. Direction of motion stereotypes: A review. Ergonomics, 1962, 5, 357-383.

"The effects of directional relationships between controls and displays are examined, with special reference to the influence of experience and of conditions of stress. Methods of investigations are discussed. The literature is reviewed to determine what stereotypes appear to be reasonably well established, and attention is drawn to a number of deficiencies in current knowledge. Consideration is given to the effects of the operator's orientation, the hand he employs for response, the initial position of the display, and the direction of scale numbering."

110. McConnell, D. and Shelly, N. W. Tracking performance on a sequence of step functions which approaches a continuous function as a limit. J. exp. Psychol., 1960, 59, 312-320.

Purpose To investigate pursuit tracking performance for a discrete input as the input approaches a limiting continuous function.

Tracking Task

Type: Discrete and continuous, pursuit

Number of Axes: One

Displays: 5" CRT, target and follower were horizontally moving vertical lines.

Controls: Lever, pivoted at subjects' elbows, fingers grasped knob at end of the lever, no spring centering.

Forcing Function: Triangular function of 10, 20, and 30 cpm. Random functions with normal distribution of amplitudes peaked at 10 cpm. Each input was either continuous or discrete, with the number of discrete steps equal to 2, 4, 8, or 12. For the 4 and 8 step inputs, three distributions of increment sizes were used; for the 2 and 12 step inputs all increments were equal.

Controlled Element: Position (K)

Subjects: Five males, paid.

Experimental Design All 36 conditions were presented 6 times in a random order over 8 days. Sixty-five second trials were used.

Performance Measures (1) Theoretical error between the step function and continuous function was given as:

$$E = \frac{\int_0^t \left[x_s(t) - x_c(t)\right]^2 dt}{\int_0^t dt}$$

where x_s = step function position and x_c = continuous function position.

(2) Two measures were taken in each run, one gave the integrated difference between the target and cursor (E_t) and the others the difference between the target and underlying continuous function (E_t):

$$E_t = \frac{\int_0^t e^2_T(t)\, dt}{\int_0^t t\, dt}$$

where e_T = Difference between follower and target.

$$E_c = \frac{\int_0^t e^2_c(t)\, dt}{\int_0^t t\, dt}$$

e_c = difference between follower and continuous signal from which discrete signal was derived.

3) Amplitude distributions were collected for the random input on even trials, on odd trials lead-lag error distributions were recorded.

Results A linear relationship was found between average error (E_T) and average size of step input for both random and triangular inputs but error was not related to distribution of step amplitudes. For all triangular conditions, the subjects lead the target; the amount of lead increased with increasing number of steps.

Conclusions The subjects minimized error by increasing lead as target frequency increased (for triangular only, lead-lag not recorded for the random input. The form of performance approached the performance of a continuous function independently of the form of the input. The transition from discrete to continuous response was between 8 and 12 steps/sec.

111. McRuer, D. T., Ashkenas, I. L., and Guerre, C. L. A systems analysis view of longitudinal flying qualities. WADD Technical Report 60-43, January 1960.

Purpose To derive a systems oriented theory which will allow the prediction of vehicle handling qualities from a knowledge of pilot performances in the control movement.

Theoretical Model From a review of pilot dynamic capabilities in closed loop simulation studies and given a set of controlled element dynamics, an estimate was made of adopted pilot describing functions. From the adopted describing function, an estimate was made of the pilot opinion relative to a particularly good control situation.

Results Following this approach, estimations were made about both the closed loop dynamics effect on pilot opinion and the pilots open loop form. If a first or second order model is adequate for closed loop description, the system gain cross over frequency should be greater than cut-off frequencies for good opinion. For systems where first and second order modes are required to approximate the closed loop dynamics, then good opinion is found when the closed loop damping ratio is greater than .35. The best opinion for an open loop gain occurs when no pilot equalizing is required. A well-defined open region exists for these non-equalized cases. In configurations where pilot lead is required, a differential opinion occurs proportional to the amount of lead required by the pilot. Also, configurations where pilot lag is required result in an opinion degradation from the nonequalized pilot case.

112. McRuer, D. T. and Graham, D. Pilot vehicle control system analysis. AIAA Guidance and Control Conference, Paper No. 63-310, August 12-14, 1963.

This paper reviewed the human operator's function in a manual control system. The authors expressed the opinion that the operator is adaptive and adjusts his behavior in order to stabilize the control system. The first step in this analysis was to state than an ideal transfer function would conform to the requirements of a "good" control system. The next analysis was to determine how parameters in the quasilinear model (refer to McRuer and Krendel, 1957) vary when the human adapts to the controlled element stability. The authors summarize the adjustment rules by the following: 1) "The human adapts so that his gain and equalizing characteristics are appropriate for stable control. 2) The human adapts so that the form of his equalizing characteristic is appropriate to good low-frequency closed loop system response to the forcing function."

113. McRuer, D. T. and Krendel, E. S. Dynamic response of human operators. WADD Technical Report 56-524, October 1957.

Purpose To develop a systematic methodology for the evaluation of control systems by compilation, correlation and codification of human response data and experimentation in order to arrive at a mathematical or analog description of the human operator.

Theoretical Model From a systematic analysis of the literature and experimental results from simulation studies, the human operator was formulated as a quasi-linear model (linear component plus a remnant) where the linear component had the following characteristic:

$$Y_p(s) = \frac{K_p e^{-\tau s}(T_1 s + 1)}{(T_1 s+1)(T_n s + 1)} K_T \frac{\alpha_T}{\sigma_T}$$

where τ = reaction time delay, T_n = neuromuscular lag, $(T_L s + 1)$ $(T_I s + 1)$ = equalization characteristics, K_p = gain, and $K_T(\alpha_T/\sigma_T)$ = "indifference threshold".

The characteristic of this model can be found from cross spectral analysis: $Y_p = \phi_{ic}/\phi_{ie}$ where ϕ_{ic} is the cross spectral density of the input and the output and ϕ_{ie} is the cross spectral density of the input and error.

The following experimental work was performed on the F80 simulator at the Franklin Institute.

Tracking Task
- Type: Compensatory
- Number of Axes: (1) One and (2) azimuth and elevation
- Display: A dot and a moving horizon
- Control: Aircraft joystick control
- Forcing Function: Random noise with cutoff frequencies at 1, 2, and 4 rad/sec.
- Controlled Element: (1) Position, (2) Simplified F 89 longitudinal and lateral dynamics.
- Subjects: (1) 2 Ss and (2) 6 Ss

Experimental Design The variables were three forcing functions

Performance Measures Both the open loop and closed loop describing functions (Y_p) and (H_p) and the linear correlation ρ were found from the cross power spectral and power spectral density functions, i. e.

$$Y_p = \frac{\phi_{ic}}{\phi_{ie}}, \quad H_p = \frac{\phi_{ic}}{\phi_{ic}} \quad \rho = 1 - \frac{\phi_{rn}}{\phi_{cc}}$$

Results The data could best be fit by the following linear describing function.

$$Y_p = \frac{K_p e^{-\tau s} (\alpha T s + 1)}{(T s + 1)}$$

where τ is between 0.20 - 0.30 sec, the dc gain K_p was the same for all bandwidths, and the values of α depended on the bandwidth where α_1 α_2 α_4 where subscript denotes rad/sec of bandwidth.

114. McRuer, D. T. and Krendel, E. S. A review and summary of tracking research applied to the description of human dynamic response. 1958 Wescon Convention Record, Part 4.

"The development of control system analytical techniques over the past two decades has been paralleled by their application, as a unifying doctrine, to many interdisciplinary fields. An outstanding example is provided by the problem of describing human dynamic behavior of man/machine systems. Here the joint efforts of engineers and psychologists have resulted in a series of quasi-linear mathematical descriptions of the human being which define the human's status as a system element in continuous control closed loop tasks. This paper reviews the major findings of some of these studies in their historical perspective, and attempts to delineate the present state of operator description as quasi-linear mathematical models."

115. McRuer, D. T. and Krendel, E. S. The human operator as a servo system element. J. Franklin Inst., 1959, 267, 381-401, and 1959, 267, 511-536, Parts I and II.

These papers consider the role of human elements in certain closed loop control systems. It gives a brief description of human dynamics in terms of quasi-linear mathematical models. This model is composed of two components, a describing function and a remnant. The describing function, which for linear systems is identical with the conventional transfer function, characterizes that portion of the operator output which is linearly correlated with his input, i. e. describing functions are determined from power spectral analyses of the human operator in a controlled system where a random forcing function is used. These describing functions formulate the human operator as a time invariant linear system.

After presenting the analytical basis for measurement of human dynamic systems, statistical describing functions measured by various experiments are discussed and the behavior of the human operator is demonstrated. Also, a possible source for the origin of the remnant is discussed on the basis that the principle mode of operation of the human is linear.

The authors concluded that knowledge of the range of parameter adjustment of which the human operator is capable in his adaptation, as well as knowledge of his criteria for adjusting these parameters, enables the designer to specify input functions and operator controlled dynamics compatible with both human operator behavior and good system performance.

116. Mechler, E. A., Russell, J. B., and Preston, M. G. The basis for the optimum aided-tracking time constant. J. Franklin Inst., 1948, 248, 327-334.

The authors provided a mathematical analysis of the optimum aiding time constant for aided tracking systems. The description of aided tracking used was

$$\dot{y} = A(\dot{x} + ax)$$

where y = output, x = input, and 1/a = aiding time constant.

The authors derived a difference equation relating tracking error to time for a system operating on intermittent signals. The solution to the equation was:

$$y_{(n\tau)} = K\,(n\tau) + Y_o\,(1 - r\tau)^n$$

where Y_o = initial error, $Y_{(n\tau)}$ = error at nth time interval, and K = target rate.

For a constant K, the optimum value of (a) will be $1/\tau$ for zero error. If the human is assumed to be intermittent with a 2/sec frequency, the optimum aiding constant will be 0.5 sec.

117. Narasimban, R. and Benepe, J. The use of autocorrelation functions in the harmonic analysis of human behavior. AF Technical Report No. 6529, October 1951.

The tenability and possibilities of harmonic analysis of continuous human behavior are discussed. The Wiener method of analysis is presented. The autocorrelation and spectral density functions are analytically defined. Approximations necessary for their practical applications are presented. The limitations and assumptions of the method as applied to practical problems are discussed and research problems concerned with these limitations and assumptions are pointed out.

118. Noble, M., Fitts, P. M., and Warren, C. E. The frequency response of skilled subjects in a pursuit tracking task. J. exp. Psychol., 1955, 49, 249-256.

Purpose: To examine input-output relations for a pursuit tracking task with different sine wave inputs.

Tracking Task

- Type: Continuous, pursuit
- Number of Axes: One
- Display: CRT, target and cursor were vertical lines 0.5 x 18 mm long moving horizontally. Cursor was displaced 10 mm below target.
- Control: Lever, pivoted at elbow
- Forcing Function: Sine wave, p-p amplitude was 1.0" (2.04° visual angle).
- Controlled Element: Position (K)
- Subjects: 3 highly skilled males, paid.

Experimental Design Seven 1 hour practice sessions in which 2 successive trials of a given frequency were run; otherwise conditions were randomized for a total of 140 practice sessions. Test trials were given during 12 one hour sessions, 20 trials per hour and 60 sec per trial. The same procedure as above was followed for sequence of presentation. The first 6 sec of each run were not scored.

Performance Measures. RMS error and TOT (+ 5% or ± .025" on-scope).

Results No marked discontinuity in response was observed up to 240 cpm. A monotonic increase in error with frequency and a significant improvement with practice was found. Increase in error amplitude at high frequencies was primarily due to lack of time synchronization between input and output. At lower frequencies, the subject tended to lose synchronization for 1/2 to 3 cycles of the input apparently requiring a constant time for correction. Variability in output amplitude and a constant error in output amplitude were other sources of error.

Conclusions The model that fitted the results included a basic intermittency of information processing and a predictive capacity used to adjust output to match input.

119. Notterman, J. M. and Page, D. E. Evaluation of mathematically equivalent tracking systems. Columbia University, Electronics Research Laboratories, CU-5-60-NOM-266(42) - ELR, 31 July 1960.

Purpose To study tracking performance for systems which have identical overall transfer functions but which differentially locate the systems dynamics between the hand controller and electronic components.

Theoretical Model The study was based on statement by Birmingham and Taylor (1954) to the effect that human tracking performance will remain unchanged if the overall transfer function of the control system remains constant.

Tracking Task

Type: Compensatory

Number of Axes: One

Displays: (1) Variable dynamic stick (2) Pressure Stick and (3) Displacement stick with low inertia, damping, and spring force.

Forcing Function: Random Gaussian noise with corner at 1/3 cps with two stages of RC filtering.

Controlled Element: A 2nd order quadratic

$$\frac{K/\omega_n}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Subjects: 3 males, paid.

Experimental Design Three basic experiments were performed, one with each controller. In each experiment, the same range of values of spring constant, damping ratio, inertia and natural frequency were used. For experiment I, the variable dynamic stick was changed to vary the dynamics, for experiments II and III, an analog computer was used. Fourteen combinations of spring constant and inertia were combined with four values of damping ratio in such a way as to result in four values of natural frequency. A number of sub-experiments were performed concerned with learning, interactions of input frequency, tracking task and displays, cross-correlational analysis between input and output, and psychological scaling of control forces.

Performance Measures Integrated squared error

Results (1) Performance varied as a function of the location of system dynamics. The order of performance for the three controllers, from best to worse, was: variable dynamic stick, pressure stick, and displacement stick. (2) Gain variations affected performance least while inertia and damping ratio variations had a significant effect on performance. An interaction was observed between the effect of the damping ratio and control type.

Conclusions The authors interpreted the results as due to differences in kinesthetic and proprioceptive feedback with the different control systems. They concluded that an adequate description of the human tracker must, therefore, include these feedback terms as part of the signal flow as the human will not operate the same when these terms are present as when they are absent.

120. North, J. D. The human transfer in servo systems. Automatic and Manual Control, Academic Press, N. Y., 1952, 473-501.

Purpose of Study Primarily a mathematical analysis, based on compensatory one-axis tracking with a rate aided controller.

Theoretical Model The tracking error x_o was assumed to consist of two parts

$$c_o = x + \bar{x}_o$$

where $\bar{x}_o$ is the deterministic or mean value of the error, while x represents the stochastic error. The stochastic error x(t) arises from a disturbance which the operator adds to the output of a linear model, characterized by:

$$\frac{Y(s)}{x_o(s)} = \left(\frac{A}{B} + B\right) e^{-Ts}$$

where $x_o(t)$ is the input signal and y(t) is the human operator's output. The controller and controlled element were assumed to be related by the expression:

$$\frac{C(s)}{Y(s)} = \frac{D}{s} + E$$

where C(s) = controller transfer function and Y(s) = controlled element, which corresponds to a combination of position and rate control ("aided-lay control"). "Discontinuous Model" substitution of the controller characteristics into the assumed human operator equation leads to a difference-equation for the stochastic error x(t). This equation is transformed into a linear difference equation by:

(a) $$\frac{dx}{dt} = \frac{x(t_n) - x(t_{n-1})}{T}$$

where $x(t_n)$ represents the value of x at the nth sampling constant and T is the sampling interval; and (b) letting $k\tau = T$ where K is an integer (i. e. the sampling interval is taken as an integral number of reaction times).

Results North then proceeds to compute stability boundaries for the solution of the third order difference equation for x in terms of the parameters of the model (A, B, and C) and of the controller (D and E). The stability boundaries converge to that for the continuous system as T is reduced. Optimum controller parameters can be selected (theoretically) by examining curves in the paper which relate the variance ratio σ_x^2/σ_n^2 to various parameters, where σ_x^2 is the variance of the stochastic error and σ_n^2 is the variance of the additive void at the operator's output.

Hypothetical sources for the noise (such as variation of reaction time, errors in judging stimuli, etc.) are discussed.

121. North, J. D., Lomnick, E. A., and Zaremba, S. K. The design and interpretation of human control experiments. Ergonomics, 1958, 1, 314-327.

Purpose To determine the characteristic of the asymptotic learning curves of the human operator and to predict the effect of sensitivity on error by regression analysis.

Theoretical Model The difference between the expected tracking error and the actual tracking error is caled "noise." The subject in learning a task will reduce this "noise" so that his error term will approach the expected value. The expected value of the mean square error is a function of sensitivity by the following expression:

$$E(1/n\sum e_i) = A\mu + B\mu + C$$

Regression analysis is used to fit this curve to the data.

Tracking Task
- Type: Continuous, compensatory
- Number of Axes: One
- Display: Blip on CRT
- Forcing Function: Sum of 3 sine waves with 0.20 cps on the highest frequency.
- Controlled Element: Rate (K/s)
- Subjects: 6 Ss

Experimental Design Ten values of control gain with 20 replications were given in a randomized design to the six subjects.

Performance Measure Mean square error and regression analysis

Results Typical learning curves were obtained. Regression curves using the above model were fitted to the results and the authors concluded it was a good fit.

122. North, J. D. and Lomnicki, Z. A. Further experiments on human operators in compensatory tracking tasks. Ergonomics, 1961, 4, 339-353.

Purpose Continuation of studies in North, et al., 1958.

Theoretical Model Refer to North, et al., 1958.

Tracking Task
- Type: Continuous, compensatory
- Number of Axes: One
- Displays: Blip on CRT
- Control: Isotonic and Isometric hand controller
- Forcing Function: Sum of 3 sine waves with highest frequency of 0.20 cps. Two targets with a 90° phase difference.
- Controlled Element: Rate (K/s)
- Subjects: 6 Ss

Experimental Design Three experiments were conducted: (1) Each S tracked one of the two forcing functions with 10 values of control gain and 26 replications. (2) Each S received 5 sensitivities x 2 display magnifications with 37 replications. (3) Ss used an isometric control at 10 levels of sensitivity with varying numbers of replications.

Results The results of the first experiment confirmed the findings of those previously described by North, et al., on the influence of changing control sensitivities on the accuracy of performance; this experiment differed from that previously reported in the application of two different targets composed of the same harmonics with changed phases instead of one. In the second experiment, the manner in which magnification of the display were varied jointly influenced accuracy. In the third experiment, tracking and isometric controls were investigated; in this type of control the error is compensated not by the free movements of the handle, but by the operator exerting varying forces on the control with very small handle movements. Performance with this type of control under these particular experimental conditions was found to be superior to that with isotonic controls.

123. Ornstein, G. N. The automatic analog determination of human transfer function coefficients. Med. Electron. Biol. Engrg., 1963, 377-387.

Ornstein, G. N. Applications of a technique for the automatic analog determination of human response equation parameters. NA 61H-1, 2 January 1961.

Purpose To study a model matching technique to determine the describing function of the human operator.

Theoretical Model This paper used a model matching technique using method of steepest descent for adjustment. The partial derivatives of the parameter coefficients with respect to the error measures are used to adjust the model so that the error is minimized. The error measurement that the author used was the difference between the input and the output of the human operator. A model for the human was stated by the following differential equation.

$$a_1 x + a_2 \dot{x} \ldots = y + b_1 \dot{y} \quad \ldots$$

and the error criteria used for a parametric adjustment was the following:

$$E = a_1 x + a_2 \dot{x} \ldots -y -b_1 \dot{y} \ldots$$

and the parametric coefficients were adjusted by the following equation:

$$\dot{a}_1 = -K \frac{E}{a_1}$$

Tracking Task

Type: Continuous, compensatory

Number of Axes: One

Display: Moving horizontal bar on a CRT display

Control: Aircraft joystick where centering and damping could be varied.

Forcing Function: Random signal with a spectrum flat to 1 radian per second with 24 db/octave drop off.

Controlled Element: 2nd order quadratic $\frac{K/\omega_n}{s^2 + 2 \omega_n s + \omega_n^2}$

Subjects: 4 were used, three of whom were jet pilots.

Experimental Design Two experiments were conducted. In one experiment, 3 levels of quickening were added to the display. In the second experiment, 3 values of damping were added to the control stick.

Performance Measure The mean square error and the parameter coefficients were used as performance measures.

Results The general form of the transfer function of the human operator was given by:

$$G(s) = \frac{(1 + T_1 s) e^{-Ls}}{(T_2/K)s \quad (T_3/K)s^2}$$

It was found that when quickening was added to the display the lead time constant T_1 was reduced significantly while on the other hand when damping was added to the control stick, the lead time constant T_1 increased.

124. Obermayer, R. W. and Muckler, F. A. Performance measurement in flight simulation studies. AIAA Simulation for Aerospace Flight Conference. August 26-28, 1963.

This paper presents a review of performance measurements applied to simulation studies and discusses criteria for their evaluation. Six simulation studies are compared. It was concluded that basic problems concerning the meaning and relationships of the commonly used performance measures are unsolved.

125. Parker, Jr., J. F., and Fleishman, E. A. Ability factors and component performance measures as predictors of complex tracking behavior. Psychol. Monogr., 1960, 74, Whole No. 503.

Purpose To investigate the relationships between ability variables and the learning of a complex perceptual motor task.

Theoretical Model It is assumed that a number of abilities exist within the subject population which are used in performing a tracking task. An ability is defined as a general, stable trait used for performing a number of tasks. Skill is defined as a task-specific behavior. Factor analysis was used to relate scores on 50 ability tests to scores on a tracking task.

Tracking Task
Type: Compensatory
Number of Axes: Three
Displays:
Controls: Refer to Fleishman and Parker, 1962.
Controlled Element:
Subjects: 203 freshmen and sophomore AFROTC students, paid, no pilot training.

Experimental Design A reference battery of 21 printed and 23 apparatus tests of coordination, visualization, etc. were given to the subjects before the training began. These tests resulted in 50 reference scores. They were selected primarily on the basis of their factor loadings in previous studies.

Following this, 357 one minute trials of the tracking task divided into 17 sessions of 21 trials were administered over a period of 1 to 1 1/2 months.

Performance Measure The first 3 trials of each session were ignored, the following 18 were divided into 3 groups of 6 trials each. Each group of 6 trials was called a time segment. The error measures were: Absolute sideslip error = z and weighted absolute error = t = $1/2\ x + 1/2y + z$ (as subjects tended to neglect rudder pedals, z was weighted heavier than x and y). Ten stages of practice were selected for factor analysis. The loading of each factor was examined as a function of practice stage.

Results (1) Correlational Analysis - Fifteen factors were extracted and were interpreted in terms of various abilities. The amount of error variance accounted for by all factors was 25%. Only two factors, spatial orientation and multi-limb coordination showed a change with practice stage, the former having greatest importance in the middle stages and the latter gradually increasing in importance over stages. (2) Learning - the learning curves were just reaching an apparent asymptote at the final practice stages. TOT was held to be a poor performance measure at the extremes when the S is continuously out or in tolerance.

(3) Correlations among Measures - Reliability of the measures were computed by correlating values on successive runs. Reliability of the component measures including TOT were around 0.6 at the early stages as compared to 0.83 for the t score. Reliabilities generally increased for the final stages. Intercorrelations were computed for all performance measures and final absolute error for time segments 1 and 25. All measures from time segment 1 were uncorrelated with final weighted absolute error. For segment 25, a higher correlation (on the order of .4) was shown with final weighted absolute error.

Conclusions (1) "The kinds of perceptual-motor abilities which previously have been found to be related to performance on laboratory criterion tasks do not account for any substantial amount of the variance in performance with the present task. It is hypothesized that the complexity and particular dynamics of the tracking task used in this study require different kinds of abilities. Such abilities as Rate of Arm Movement apparently are not as important to the mastery of complex tracking activities as with laboratory psychomotor tasks. In tracking the important determiners of proficiency may be found in those abilities found used in the prediction of appropriate response movements, rather than in abilities related directly to control manipulation. (2) Initial component and total scores taken from the tracking task itself do not predict advanced proficiency levels. If one must choose between intratask and independent measures, the independent test measures give a better prediction of advanced tracking proficiency."

126. Pearl, B. E., Simon, J. and Smith, K. U. Visual Tracking: IV interrelations of target speed and aided-tracking ratio in defining tracking accuracy. J. of Appl. Psychol., 1955, 39, 209-214.

Purpose To examine the effect of velocity on the aided tracking time constant and target velocity on tracking performance.

Tracking Task and Experimental Procedure
Refer to Simon and Smith, 1956.

Performance Measure
Some function of integrated error

Results
A significant interaction was found between aided time constant and target velocity.

Conclusion Rate aiding is optimum when it provides the least interference with rate control and when rapid positioning movements comprise the major tracking error. Rate aiding may degrade performance when accurate positioning movements are necessary and rate following is less important.

127. Platzer, R. L. A nonlinear approach to human tracking. Office of Naval Research, Technical Report No. I-2490-1, 1955.

Purpose To use the phase-plane as a method for analyzing tracking behavior and as a basis for the design of a tracking display.

Theoretical Model A formal model of the operator was not used, but the phase plane was used as a tool to provide data on operator nonlinearities. The response characteristics were obtained by observing phase-plane trajectories. The slope of the phase plane trajectory was:

$$\frac{dy}{dx} = \frac{p - x - 2y}{y}$$

where x = error and y = error rate. An optimum tracking strategy based on the phase plane was derived. This required the operator to act as an on-off control, the direction of control being given by optimum switching lines in the phase plane. A display called the ∅ display was derived which gave a one dimensional indication of the error on the phase plane.

Tracking Task
Type: Continuous, compensatory
Number of Axes: One
Display: Blip moving vertically on CRT and on the phase-plane
Forcing Function: Random noise with 1 rad/sec cutoff frequency
Controlled Element:

$$\frac{1}{s^2 + 2\zeta s + 1}$$

Subjects: Not given

Experimental Design Tracking was performed on a standard display, phase-plane display, and ∅ display. Continuous and sampled presentations were also examined.

Results The ∅ display was initially superior to the standard display, but the difference was minimized with practice. On the sampled input, the ∅ display maintained superiority.

Conclusions Tracking was nonlinear on the standard compensatory display as indicated by piece-wise constant movements. Error rate information was shown important for good tracking.

128. Poulton, E. C. Perceptual anticipation and reaction time, Quart. J. exp. Psychol., 1950, 2, 99-112.

Purpose To demonstrate that the increase in response time in tracking is due to the anticipation of the next response instead of the "psychological refractory period."

Tracking Task
Type: Continuous pursuit, and discrete movement of key to left or right.
Number of Axes: One
Displays: A plastic board with 3V shaped patterns and two audio signals.
Controls: Stylus and key
Forcing Function: 3V patterns, one above the other and a binary signal.
Controlled Element: Position (K)
Subjects: Exp. I, 24 Ss with Naval Ratings, Exp. II, 8 Ss with Naval Ratings.

Experimental Design - Experiment I Three procedures were used on different days. In the normal tracing path, each traced all three v's in the shortest time possible and was given knowledge of the results. On one of the days, the Ss were given an audio signal indicating to the S to stop tracing after the first 2 v's. On the second day, the S was instructed to trace only two v's and if the audio signal was given, he was to trace out the third v as well. On the third day, the S was told to disregard the audio signal, and half of the Ss traced out the first two v's and the second half traced out all three v's. These three procedures were arranged in a Latin Square design with varying lengths of time between the audio signal and the time the S reached the end of the second.

Experiment II - Ss were given two auditory signals, the second signal following the first after a short interval of time. In one part, he was instructed to pay attention to the second signal and in the other part, where the second signal occurred twice in a period of 12 signals, the S was instructed to pay attention to his reaction to the first signal. The two parts, two signals and two responses were arranged in a Latin Square design. The Ss were given knowledge of results.

Performance Measures Response times and over-shoot errors in both experiments.

Results Experiment I - It was found that the Ss'mean reaction time at the start of the tracing was 0.25 seconds longer than the Ss' simple reaction time, i. e., when he was instructed to break the first contact with the stylus. When the S was forced to change his performance unexpectedly, he required 0.25 seconds longer than the mean reaction time to stop his movement and a medium time of 0.35 seconds longer before he could start to extend his movement. Also, an unexpected extension of S's response showed additional errors in over and undershooting the path. It was also shown that when the audio signal was given 0.6 seconds before the point at which the S altered his performance, the reaction time for the response was eliminated.

Experiment II - The mean reaction time to the second signal was longer than .08 seconds than the reaction time to the first signal. If the second signal was unexpected, the response time was longer by .3 sec.

Conclusions The so-called psychological refractory period appears to be due to the S's response to the next signal, i. e., if he is not expecting the signal he must prepare himself for it; if he is expecting it he may not have had sufficient time to prepare himself for the signal. The conclusion appears to be that the refractory period is not due to recovery from the previous response but to the amount of preparedness for the following response.

129. Poulton, E. C. The basis of perceptual anticipation in tracking. The Brit. J. of Psychol., 1952, 43, 295-302.

A number of experiments dealing with anticipation on pursuit and compensatory displays are described. The author's summary follows:
1) "In anticipating with a two-pointer display, speed cues can be used (speed anticipation). In the early stages of practice, before the characteristics of the course are known, they are the only available source of information upon which anticipation can be based.

2) Once the characteristics of the course are known, they can be used in anticipation with both two-pointer and one pointer displays (course anticipation). Certain course characteristics are in fact assumed in speed anticipation. Course anticipation is particularly important in one-pointer balancing in which 'stimulus' speed cues are not normally available; and in two-pointer matching with fast 'stimulus' cam speeds, when the 'stimulus' speed changes so rapidly that it is of little predictive value by itself. 3) The accuracy of perceptual anticipation depends principally upon the number of the events at the end of which prediction has to be made. The time over which the events are spread is of only secondary importance. 4) The principal deficiency of a one-pointer display, as compared with two pointers, is that control movements cannot be apprehended directly in relation to the 'stimulus movements'. For the greatest accuracy in tracking, control and 'stimulus' movements must be presented for direct comparison in the same sense modality, and in such a way that an immediate comparison is possible. 5) The simple absence of 'stimulus' speed cues in one-pointer balancing was found to be a significant but less serious handicap. 6) The simple absence of a visual representation of the control movements in one pointer balancing was not found to be a significant handicap."

130. Poulton, E. C. Learning the statistical properties of the input in pursuit tracking. J. exp. Psychol., 1957, 54, 28-32.

Purpose To study the relation between various sources of visual information and tracking performance.

Tracking Task

Type: Continuous, pursuit
Number of Axes: One
Displays: Drawn course on cardboard
Controls: Pencil
Forcing Function: The course consisted of 3 W's or M's side by side with no gap between them. Half of the courses were patterned with respect to variation in the W's or M's. The other half of the courses were random with respect to the length of the lines of the W's or M's.
Controlled Element: Position (K)
Subjects: 16

Experimental Design A 2 by 4 design was used in which the pattern and length of course was one variable and four levels of information presentation was the other variable. The first level allowed the S to look at the course before starting and without a mask over the course while tracking. In the second level the S looked at the course before starting and a half mask was used so that he could only look back. In the third level, the S looked at the course before starting and a full mask was used so that he could not see ahead or look back. In the fourth level, the S did not look at the course before starting and a full mask was used.

Performance Measures Three scores were used. The total time to cover the course, mean constant error of the course calculated by subtracting overshoots from undershoots, and mean error derived by summed distance travelled regardless of the sign.

Results For both the mean constant error and the mean error measures, knowledge without a mask differed significantly from the three other conditions. The mean constant error for the condition of knowledge with the half mask and random course was significantly different from the no knowledge and full mask. The random course did not differ significantly from the pattern course.

Conclusions Overshoot at a corner was found to be less when the position of the corner could be predicted either from the sequential structure of the pattern course or from knowledge of the common statistical properties of the course. Visual information acquired before tracking was found to be less effective than visual-kinesthetic information acquired while tracking.

131. Poulton, E. C. On prediction in skilled movement. Psychol. Bull., 1957b, 54, 467-478.

Purpose A review article on prediction and skilled movements in pursuit tracking.

Theoretical Analysis Rapid Acquisition of a Stationary Target - The response time for rapid aiming is about .5 seconds. Therefore, predictions of the nature and size of the muscular contraction required are considered an elementary form of prediction termed effector anticipation.

Rapid Acquisition of Moving Target - In a moving target, the subject has knowledge of the advanced position that the target will occupy when his response movement finishes. Therefore, in addition to his effector anticipation, he must predict the duration of the movement; termed receptor anticipation. Furthermore, in a target containing certain statistical properties known by the subject from past experience, the subject will be capable of predicting the direction and rate of movement. This was termed perceptual anticipation.

Matching the Movement of a Target - The acquisition task can be extended to matching the movement of a target by a series of rapid acquisition movements where the S is aligned every 0.5 seconds but in the interval between he would be either ahead or behind the target. In practice, when receptor and perceptual anticipation is possible, the S tends to match the rate or acceleration movements of the target. If the target is displayed ahead or predictable, the subject's response has no lag. However, if it is unpredictable, the subject's response will tend to have a lag equal to his mean reaction time.

Skilled Movements - In this section, the author described smooth complex movements, serial aiming movements, and mixed movements in terms of the prediction categories that have been stated above. He defined a closed skill movement as a movement that can be carried out without reference to the environment. This type of movement requires both effector prediction and receptor anticipation. However, closed skill movements can be made to fit the environment as perceptual anticipation is added. On the other hand, an open skill movement is one that has to fit either an unpredictable series of environmental requirements or a very exacting series whether they are predictable or unpredictable.

132 Poulton, E. C. On the stimulus and response in pursuit tracking. J. exp. Psychol., 1957c, 53, 189-194.

Purpose To determine the information sampling performance of the human operator by the use of intermittent displays.

Tracking Task
- Type: Continuous, pursuit
- Number of Axes: One
- Displays: Input pointer and a response pointer moving in the vertical direction.
- Controls: Exp. I - a wheel control with a 6 inch diameter and Exp. II - a horizontal handle on a wheel.
- Forcing Function: Exp. I - Single sinewave .167 cps and a sum of three sine waves. Exp. II - 1 cps sine wave.
- Controlled Element: Position (K)
- Subjects: 30 subjects with Naval Ratings.

Experimental Design This study was divided into two experiments. The first experiment was a Latin Square Design with 2 forcing functions and .2, .4, .3, 3.0 and 4.7/sec intermittent displays. Either the stimulus, response or both the stimulus and response needles were intermittent. The subjects were divided into two groups; group practiced with brief intervals (.05 - .95) between glimpses and group L practiced with longer intervals (.5 to 4.5 sec). In the second experiment, the subjects tracked continuously with their eyes open and shut for alternate five second periods.

Results Performance deterioration was greater when the stimulus needle was intermittent than when the response needle was intermittent. When both the stimulus and response needles were intermittent, the only appreciable deterioration occurred with the complex signal. For the intermittent response signal, the simple signal deteriorated at .2 sec and the complex at 1.3 sec. For the intermittent stimulus signal, the simple signal deteriorated at 4.7 sec and the complex at 0.4 sec. In In comparing both intermittent stimuli and the intermittent response, the simple deteriorated at 0.4 sec and the complex at 30 sec. Group L had less error than Group B with longer intervals between glimpses with the complex input. In the second experiment, the mean error was better by a factor of 1/2 with practice when the eyes were closed. However, with the eyes open the error decreased by 1/2. It was also found that sudden discrete corrections of misalignment followed only a minority of the glimpses of the invisible pointers.

133. Poulton, E. C. On simple methods of scoring tracking errors. Psychol. Bull., 1962a, 59, 320-328.
__________, A source of nonlinearity in pursuit tracking, Symposium on Complex Vehicular Control, Farnborough, England (1962), U. S. Office of Naval Research.

Purpose To show that relatively simple measures can reveal the response strategy which the subject adopts.

Theoretical Model The scoring strategy used in this report requires measuring the mean constant error and the standard deviation of the error in position and in time. Specified points on the tracking record were utilized in measuring these errors. For position error, the point at which the stimulus signal reversed was used, and for time errors, the point of reversal, the inflection of the stimulus signal and the midpoint between the point of inflection and the reversal were used.

Tracking Task
Type: Continuous, pursuit
Number of Axes: One
Display: Irregular curve drawn on a paper tape which moved towards the subject at a rate of 1 inch per second.
Controls: Ball-point pen was used as a stylus.
Forcing Function: The forcing function consisted of 26 cpm, a 21 cpm and a component of 10.5 cpm which had twice the amplitude of the other two frequencies.
Controlled Element: Position (K)
Subjects: 12 naval men without tracking experience.

Experimental Design Two conditions were used, one with preview in which the input could be seen 2 1/2 seconds ahead of the stylus and a slit version in which the subject could only see the input at the point the stylus moved. Half of the subjects started on the preview version first, and the other half started on the slit version first.

Performance Measures Errors in position and time were measured for the overall sample and the reversal points. Errors in time were measured at the point of inflection and at one-eighth cycle before and after the reversal point. Average scores across subjects and the standard deviation across subjects were used for the mean constant error and the standard deviation of the mean constant error respectively.

Results The position errors showed a significant difference between the preview and slit versions in both the overall sample and at the point of reversals. Also, at the point of reversals, the mean constant error showed a significant difference between the preview and slit version. For the error and time scores, both the mean constant error and standard deviation showed a significant difference between the preview version and slit version based on comparison between the overall sample, the reversal points, the inflection points, and midpoints.

Conclusions The author concluded that this method yielded insight into tracking behavior that cannot be obtained with other methods. He points out that the average time lag of the intermediate points in the preview version vary significantly and that this could not be easily determined by servo analysis. The author states that most other measures confound errors of positioning with errors of time.

134. Poulton, E. C. The human operator as an integrator. Symposium on Complex Vehicular Controls, Farnborough, England, 1962b, U. S. Office of Naval Research.

Purpose To determine how the human operator responds when the controlled element is a differentiator.

Tracking Task
Type: Pursuit
Number of Axes: One
Displays: Blip on CRT
Controls: 4" fingertip control
Forcing Function: Two forcing functions: low frequency white noise between 0.020 - 0.167 cps and high frequency white noise between 0.093 and 0.750 cps.
Controlled Element: Integrator (Ks), position (K) and rate (K/s).

Experimental Design Two forcing functions with cutoff frequencies at .167 cps and .75 cps against three controlled elements; integrator, position and rate.

Performance Measures Integrated mean error

Results For the low frequency input, the integrator controlled element gave a performance four times worse than the position or rate controller. For the high frequency input, the integrator and position controller gave the same performance while the rate controller was poorer by a factor of 1.33.

Conclusions The records suggest that in the low frequency task, the S's instability increases the error while in the high frequency task, the high frequency task, the S was unable to reduce his error.

135. Poulton, E. C. Sequential short-term memory: some tracking requirements. Ergonomics, 1963, 6, 117-132.

Purpose To study the effect of delay between the stimulus and required response in a tracking task.

Theoretical Model
Type: Pursuit with a variable preview period of input before the required response.
Number of Axes: One
Displays: Signal generated on oscillograph, masks were used to expose desired portion of record.
Controls: A ball-point pen was used as a stylus
Forcing Function: Cam generated, maximum amplitude was 1.75" Three inputs: Fast-equal displacements of 52 and 42 cpm and a displacement of twice this size of 21 cpm. Medium-1/2 frequency of Fast. Slow - 1/4 frequency of Fast.

Experimental Design - Exp. I The required delays between the input disappearance and the time at which the subject had to track were 0, 0.5, 1.0 and 2.0 sec for the fast input, 0, 1.0, 2.0, and 4.0 sec for the medium input and 0, 2.0, 4.0, and 8.0 sec for the slow input. Because paper speed was constant (1.0 inch/sec), the required memory tasks were the same for each input. These were measured in terms of the average number of reversals with an amplitude of 5 mm or greater and were 0, 0.6, 1.2, and 2.4 sec respectively. In the preview version, the input could be seen for 2.5 sec before disappearance; in the slit version it could be seen for only 0.1 sec. Practice trials were performed before the experiment and before each new condition was given. Latin square designs were used with speeds and versions counterbalanced.

Exp. II - This was a control experiment to examine the effect of separation between the input pointer and response pointer. Medium speed input was used with separation of 0 to 8 in. for both the preview (2.5 in. slit width) and the slit (0.1 slit width) versions. S only tried to copy input as it disappeared from view.

Performance Measure Exp. I - II. Scoring was restricted to the last 10 reversals in which it was clear that the subject responses. The position and time at which the input reversed direction were compared to those corresponding to the subject's output. The constant errors and standard deviation were computed.

Results Exp. I - The subject responded early for both preview and slit versions, the effect being greater for the latter. The slit version resulted in more response omissions and greater positioning variability. For both versions performance was primarily related to the required delay, not the amount of information.

Exp. II - Separation and version were significant and there was a separation preview interaction. Separation could account for some, but not all of the effects of delay in Exp. I.

Conclusions In summary, effects of time and events upon the accuracy of the receptor-effector span are: without rehearsal, delay is highly detrimental; if order of information is not important, the number of events in the span is irrelevant, but if it has to be recalled, the number of events should be as small as possible. In contrast, with rehearsal, delay is highly desirable; and the fewer the events in the span the better, whether or not order of information is important.

136. Ragazzini, J. R. Engineering aspects of the human being as a servomechanism. (1948).

Purpose To determine the describing function of a human operator which was estimated by harmonic analysis by the following equation:

$$Y_p(s) = K(K_1 s \quad K_2 + \frac{K_3}{s}) e^{-Ls}$$

where L represents the time delay of the human operator.

K_1, K_2, and K_3 are the differential operators.

Tracking Task
- Type: Continuous, compensatory
- Number of Axes: One
- Display: Blip on CRT
- Forcing Function: Not given
- Controlled Element: Position and Rate (K/s)
- Subjects: Not given

Experimental Design A set of 3 experiments were conducted. In the first set of runs, the subject's task was open loop tracking. In the second set a discrete input was superimposed upon the continuous forcing function. The third set of tasks was the same as the second except the subject was controlling the rate.

Performance Measure Harmonic analysis

Results Although the human response is nonlinear, a linear approximation can be made to it. The coefficients in the operator's describing function vary from individual to individual and from test to test. The other factor that causes variability in the subject is the amount of learning and ability to learn. It was also found that there was a minimum transmission delay from the stimulus to the response in the limb. From knowledge of these factors, the author formulated the describing function of the human.

137. Rogers, J. C. Adaptive aiding: a new method of aiding for discrete manual tracking. Master's Thesis, Engineering Department, University of California, Los Angeles, 1963.

Purpose To examine an aiding technique in which system gain is a function of the rate of control movement for discrete positioning movements using a track ball control.

Theoretical Model For acquiring fixed targets with a cursor, a high control gain reduces slewing time but makes fine positioning movements less accurate; a low gain results in accurate positioning but longer slewing time. The proposed system makes system gain a function of control rate, taking advantage of the fact that rate of movement produced by the operator is proportional to target distance.

The equation describing this system is

$$\frac{dy\ (x)}{d(x)} = A_1 + A_2 \frac{dx}{dt}$$

where y (x) = cursor input, x = control output, A_1, A_2 = constants, A_2/A_1 = aiding ratio.

Tracking Task The task was acquisition of a fixed target with a cursor using a 1" track ball control. A ten inch CRT display was used.

Experimental Design Experiment 1 - Mean acquisition time without aiding was studied as a function of target distance and display/control ratio. Experiment 2 - Mean acquisition time with aiding was studied as a function of target distance and display/control ratio.

Results Experiment 1 - Distance, display/control ratio and Ss were significant. Overall mean time was 3.1 sec, for the best condition it was 2.7 secs. A single optimum aiding ratio was found for all conditions, between 1.1 and 2.0. Experiment 2 - Trials, subjects, and aiding constant were significant but distance was not. Optimum display/control ratio was 0.1 for an aiding ratio of 1.0. Overall mean time was 3.0 sec while for the best condition it was 2.7 sec.

Conclusions Significant reduction in distance variance for the aided conditions indicated that distant targets are more easily tracked with aiding than without. The small difference in overall means was attributed to the fact that the Ss were still learning. Further study should include the learning problem and the nature of the system optima.

138. Searle, L. V. Studies of tracking behavior. I. Rate of time characteristics of simple corrective movements. NRL Report No. R-3248, 3 March 1948. Also published under same title by Searle, L. V. and Taylor, F. V. in the J. exp. Psychol., 1948, 38, 615-631.

Purpose To investigate the rate and time characteristics of hand movements during step function tracking.

Tracking Task
Type: Discrete, pursuit
Number of Axes: One
Displays: Target line moved behind narrow horizontal slit
Controls: The subjects either tracked directly with a pencil or controlled the pencil mounted on a slide by moving a pulley coupled knob.
Forcing Function: Step displacements 5 to 80 mm amplitude
Controlled Element: Position (K)

Experimental Design Four experiments were conducted. (1) Display slit oriented left-right, S held pencil, 5 Ss. (2) Display slit oriented forward-backward, S held pencil, Ss. (3) Right steps only, pulley control used with (a) minimum friction and inertial, (b) 19 ounces of running friction, or (c) 112 ounces of inertia, 6 Ss.

Performance Measures (1) Reaction time from step onset to beginning of response. (2) Duration of response from response initiation to completion. (3) Maximum rate of response. (4) Average rate of response. (5) Variability of 1st response amplitude peak.

Results (1) The maximum rate increased with increases in step magnitude. (2) The reaction time was relatively constant over step magnitudes, although the RP of the 20 and 30 mm steps were lower than the others. (3) The response duration increased only slightly as step magnitude increased. (4) The increased control-display ratio increased hand movement rate. (5) Friction increased rate and decreased duration, whereas inertia has an opposite effect.

Conclusions Ss tended to maintain a constant response time regardless of step magnitude. Same type of intermittency must exist in the stimulus-response loop as movement times are shorter than reaction times.

139. Searle, L. V. Psychological studies of tracking behavior, Part IV. The intermittency hypothesis as a basis for predicting optimum aiding time constant. NRL Report 3872, October 1951.

Purpose To use the hypothesis of intermittent error correction in human tracking to predict optimum aiding time constants.

Theoretical Model The assumptions in the model were: 1) The operator makes a corrective movement every 0.5 seconds, 2) The control is not moved during the 0.5 second interval and 3) The movement is a step function. The aiding constants are derived as follows: Assume at some time the position error is zero and that on the average the rate is zero, however, the acceleration output from the control stick fails to match the target's acceleration (assuming a system in which a given position of the control stick generates a position, velocity and acceleration signal). One sample period later (0.5 sec), the position error will be $P = A/2\ (0.5)^2$ and the velocity error will be $V = A(0.5)$. Thus, the ratio ov P;V;A is 1:4:8. For a single movement to simultaneously correct all three errors, the ratio of position: velocity: acceleration in the controller output must also be 1:4:8.

Tracking Task
- Type: Compensatory
- Number of Axes: One
- Displays: CRT
- Control: Joystick
- Forcing Function: Sum of 1/6, 1/9, and 1/15 cps sine waves. Three inputs were used.
- Controlled Element: 2nd order quadratic $K/(s^2 + T_1 s + T_2)$ where K, T_1 and T_2 were presented as ratios.

Experimental Design Three experiments were performed consisting of 5 groups of aiding ratios. Within each group, 2 ratios were held constant and the third varied. The range of ratios for each group was (1), (2), (3) 1:4:0 to 1:4:16, (4) 5:4:8 to 1:4:8, and (5) 1:1:8 to 1:6:8.

Performance Measures Average error in mils

Results The aiding ratio of 1:4:8 resulted in lower error, except for group 5 in which the 1:2:8 error was found to be best.

Conclusions The assumptions in the model are discussed and further analysis of their importance is considered necessary to refine the model.

140. Seckel, E., Hall, I. R., McRuer, D. T. and Weir, D. R. Human pilot dynamic response in flight and simulator. WADC Technical Report 57-520, Wright Patterson AFB, Dayton, Ohio.

Purpose The purpose of this study is to determine the difference in pilot tracking behavior between flight and ground simulation.

Theoretical Model Quasi-linear describing functions were determined from spectral and cross spectral analyses. The formula used for the describing function was:

$$Y_P = \frac{K_p e^{-Ls}(T_2 s + 1)}{(T_1 s + 1)}$$

Tracking Task
- Type: Continuous, compensatory
- Number of Axes: Three
- Display: A 5" CRT display with a target spot and a moving horizon. In the flight experiment, the subjects had the normal aircraft flight instruments including attitude gyro, directional gyro, air speed indicator, altimeter, bank and turn, angle rate of climb, tachometer, manifold pressure, etc. They did not have an external view.

Controls: Controls were the conventional pedal and wheel control of the Navion aircraft.

Forcing Function: Gaussian distributed random noises were used in both the vertical and horizontal forcing function signals with a cutoff frequency of 1 rad/sec and a dropoff of 18 db per octave.

Controlled Element: In the flight experiment the controlled element was the aircraft responses and in the simulation approximations of the aircraft responses were used.

Subjects: Eight subjects were used of which six were Naval aviators with similar background and training.

Experimental Design Each S was given two data flights and the equivalent simulator runs. One half of the Ss were first tested in the simulator and the other half were first tested in flight to determine if the order of experience had any effect.

Performance Measure A spectral and cross spectral density function was calculated from the tracking results. From these functions, the amplitude ratio, the phase shift, and the linear correlation were calculated of the pilot's quasi-linear function for both the lateral and longitudinal controls. From these, comparisons were made between the flight and simulator data.

Results Statistical analyses of describing function and linear correlation data revealed that (1) individual run phase angle (in degrees), amplitude ratio (in db), and linear correlation data are approximately normally distributed about their mean values for all runs. (2) The mean values of pilots' describing functions in longitudinal flight and simulator control exhibit significant differences in both amplitude ratio and phase angle. (3) The mean values of pilots' describing functions in lateral flight and simulator control exhibit significant differences in phase angle and no significant differences in amplitude ratio. (4) Significant differences between flight and simulator linear correlations were present for both lateral and longitudinal control. (5) The flight and simulator variances for lateral amplitude ratio and lateral and longitudinal phases were significantly different. No significant differences appeared between flight and simulator variances for longitudinal amplitude ratio and lateral and longitudinal linear correlation.

The differences between flight and simulator results then implied that: (1) The pilots' effective reaction time delay, L, for both the lateral and longitudinal control mode was longer in flight than in the ground simulator by approximately .12 seconds for longitudinal control and .20 seconds for lateral control. (2) The pilots' gain K_p for longitudinal control in flight was approximately one half that in the ground simulator.

141. Senders, J. W. Human tracking behavior. Minneapolis-Honeywell Aero Document U-ED-6141. 27 November 1959. Documentation index and bibliography for study on human engineering of control systems. Minneapolis-Honeywell Aero Report 1508-TRI, 17 November 1959.

This extensive review was conducted as part of the ANIP program to examine the status of tracking knowledge, especially with respect to its application for system design. Three hundred and fifty six studies were included.

142. Senders, J. W., and Cruzen, M. Tracking performance on combined compensatory and pursuit tasks. WADC Technical Report 52-39, February 1952.

Purpose To examine tracking performance for displays exhibiting varying amounts of compensatory and pursuit components.

Tracking Task

Type: The display was varied between 100% pursuit and 100% compensatory by assigning various ratios of the course voltage to the target and to the follower.
Number of Axes: One
Display: CRT
Control: 3-1/4" knob, .07 degrees visual angle/1.0 degree control movement
Forcing Function: Cam, sum of 2 sinusoids
Controlled Element: Position (K)

Experimental Design Five subjects were given five conditions of compensatory and pursuit: 100%P, 0%C, 75%P, 25%C, 50%P, 50%C, 25%P, 75%C, 0%P, 100%C. Each subject performed five runs under each condition.

Performance Measure TOT

Results TOT scores increased as greater amounts of the pursuit component were added to the display. After 50% pursuit component was added, little improvement was found.

Conclusions Superior tracking under pursuit condition was attributed to the prediction of target motion.

143. Shackel, B. The human limbs in control. Optimum control-display ratios at different display distances. Medical Research Council, APU 215/54, Cambridge, England, April 1954.

Purpose To test the hypothesis that optimum control gain expressed as the ratio of (optimum angular control movement)/ (angular target movement) is a constant.

Tracking Task A simple positional tracking task was used with a CRT compensatory display. A stick controller was provided with the S's pivot point at his forearm.

Experiment Design The Ss tracked at three distances (12, 20 and 60 inches) and at three display-control relationships including the optimum value (assumed) of 1:3.

Results The results support the hypothesis.

Conclusions If fully valid, the results suggest angular ratios of input/output might be a useful measure; further comparisons between systems may be misleading unless optimum D/C ratios were used.

144. Sheridan, T. B. Time variable dynamics of human operator systems. Dynamic Analysis and Control Laboratory, Massachusetts Institute of Technology, March 1960.

Experimental analysis of time-variation of the human operator's transfer function. Automatic and Remote Control, Proceedings of the First International Congress of the International Federation of Automatic Control, Moscow, 1960.

Human operator's time-varying transfer characteristics in the study of perception and fatigue. British Institution for Mechanical Engineers Symposium on Automatic Control.

Purpose To devise a technique for studying the time varying characteristics of the human operator by a time varying quasilinear model.

Theoretical Model The input to a human can be formulated by a random appearing sum of sinusoids.

$$r(t) = \sum_{i=1}^{n} A_1 \sin \omega_i t$$

where ω_i are not harmonically related. The response of the human operator can be formulated by

$$c(t) = B_i(t) \sin \left[\omega_i t + \phi(t)\right]$$

The amplitude ratio $B_i(t)/A_1$ and the phase angle $\phi(t)$ are found at frequency ω_i by multiplying the system response c(t) separately by $\sin \omega_i t/2A_i$ and $\cos \omega_i t/2A_i$ which will give the real and imaginary components of the transfer locus at ω_i.

$$\frac{B_i(t) \cos (t)}{A_i} \quad \text{and} \quad \frac{B_i(t) \sin (t)}{A_i}$$

Since these components are only average over a finite time interval these values will have certain responses not coherent with the input which are filtered. The minimum sample length is twice the bandwidth frequency.

Tracking Task

Type: Continuous pursuit or compensatory
Number of Axes: One
Display: CRT with horizontally moving blip and vertical bar
Control: Joystick
Forcing Function: Summation of five sinewaves of varying amplitude in order to give 20 db/slope. Frequencies were 0.1, 0.23, 0.44, 0.68, and 0.92 cps.
Controlled Element: Position (K), Rate (K/s) and 1st order with lag (K/ts + 1).
Subjects: Number of Ss in the experiment were 1, 2, and 8.

Experimental Design The first experiment had four variables where types of display, controlled element and forcing function were varied during the runs. In the second experiment, 1st order lag dynamics were varied during the run and in the third experiment the length of experiment was varied to induce fatigue. All experiments lacked complete design.

Performance Measure The real and imaginary components of the transfer vector were plotted for each frequency.

Results It was found that when the characteristics of the control system changed, the average transfer loci of the S changed rapidly. It was also found that experienced Ss changed their loci consistently within 30 seconds while naive Ss showed more variability. Two Ss varied their transfer loci due to drowsiness in the fatigue experiment but return back to their original values when awakened.

145 Sheridan, T. B. The human operator in control instrumentation. Progress in Control Engineering, 1962, 1, 143-187, Heywood and Co., (London).

The author both reviews a number of engineering descriptions of the human operator and attempts to interpret some of the pertinent physiological and psychological literature in engineering language. Some general problems in studying the human operator are covered. The topics included are (1) Introduction and point of view, (2) Historical development, (3) Quasi-linear models of the human operator, (4) Nonlinear models, (5) Engineering use of the human operator in stationary tasks, (6) Displays, (7) Hand controls, (8) Time varying models and learning, (9) Information transmission models, and (10) Prospects for the future.

146. Sheridan, T. B. On precognition and planning ahead in manual control. 4th National Symposium on Human Factors in Electronics, IEEE, May 2-3, 1963, Washington, D.C.

"Conclusions. Several experiments have been described concerning tracking inputs which may be predicted or actually previewed. It is concluded that future efforts to model the human operator of a control system should seek to take account of several significant characteristics relevant to predicting or previewing input information.

"(1) When the input may be previewed it is likely that the operator's attention to and weighting of values of the previewed input diminishes quickly as a function of previewed distance (time). For the random appearing input experiments cited herein the preview had little effect farther ahead than 1/2 wavelength of the lowest input component, even though the controlled process had much longer time constants. The short preview appears to aid more in tracking high frequencies than lows. The preview weighting function would appear to be a compromise between anticipation and cancellation of motor delays and impulse response on the one hand and the time-decrement in precision of remembered information on the other. (2) The human predictive mechanism is relatively insensitive to accelerations and higher time derivatives, but makes an extrapolation on velocity with a correction factor based upon average past experience in predicting trajectories of different accelerations. When initial velocity is zero and acceleration is more apparent, the velocity is not extrapolated. (3) When the operator's attention turns away from the feedback or output of the controlled process for periods of time in excess of several periods of an input component, the gain diminishes to about 1/2 its original value and settles there, while noise and/or variation in transfer coefficients increases markedly. In time the new open-loop gain-phase relationship tends to settle to a "comfortable state" independent of any lead or lag compensation originally assumed by the operator."

147. Simon, C. W. The presence of a dual perceptual set for certain perceptual motor tasks. WADC Technical Report 54-286, June 1954.

<u>Purpose</u> To examine tracking performance under different motion relationships between the display pointer and control.

<u>Theoretical Model</u> An attempt was made to distinguish between different percepts of the same display/control arrangements which were varied so that either a curvilinear of linear motion relationship could be perceived, with one or the other dominant.

<u>Tracking Task</u>

Type: Compensatory
Number of Axes: One
Displays: Meter with pointer
Controls: Knob and stick
Controlled Element: Position (K)
Subjects: Twenty-four female students.

Experimental Design Two experiments, one with the knob and one with the lever control were conducted. Two null pointer positions (12 and 6 o'clock) were combined with two motion relationships (clockwise and counterclockwise). This gave four combinations of linear and curvilinear motion relationships with three combinations of compatibility.

Performance Measure TOT

Results (1) An interaction was found between the pointer position and display/control motion relation. (2) Performance was a sum of the effects of the linear and curvilinear relationships. (3) Ss tended to respond more to the compatible curvilinear relationship with the knob and to the compatible linear with the stick.

Conclusions The subject sees the motion with two perceptual sets, curvilinear and linear. Performance is a result of both sets combined with the particular display/control relationship.

148. Simon, J., and Smith, K. U. Theory and analysis of component errors in aided pursuit tracking in relation to target speed and aided-tracking time constant. J. of Appl. Psychol., 1956, 40, 367-370.

Purpose To examine the types of errors found in aided pursuit tracking.

Tracking Task

Type: Pursuit
Number of Axes: One
Display: The target was mounted on a rotating disc
Control: Handwheel, 18.4 cm. in diameter
Forcing Function: Target course involved nine reversals of direction with constantly changing velocity
Controlled Element: Position plus velocity aiding (K/Ts + 1)

Experimental Design Twenty-seven Ss tracked three target speeds and three aiding time constants (0.25, 0.5, 1.0 sec). Each S tracked each condition in an order determined by one of nine sequences occurring in a 9 x 9 Latin Square.

Performance Measure Error category, Short E; 1.0 sec, Medium E; 3.5 sec and Long E; 3.5 sec.

Results Increased aiding decreases frequency of short and long wavelength errors but increases medium wavelength errors. The medium errors comprise the largest group of errors.

Conclusions The effects of aiding on component movements is complex, as different types of movements are affected differently. An "optimum" aided tracking constant cannot be regarded as related only to a specific reaction time or intermittent process.

149. Smith, K. U. Environmental research and sensory feedback analysis of behavior. Proc. Inst. Environmental Sciences, 1962, 353-368.

In this paper, Smith discusses his concept of the role of sensory feedback in regulating behavior, particularly motor-skills activity. His concept of sensory feedback is based mainly on experimental work with time displaced and space displaced visual feedback using a closed circuit TV system. He also discusses the neurological basis of feedback control where he attempts to show that the spatial and temporal relationships between movements and their feedback signals are primary in establishing the limits of perceptual-motor performance. Learning in the response-reinforcement sense is secondary and dependent upon the primary sensory feedback relationships. A number of experimental results and the usefulness of the displaced feedback experiment are included.

150. Smith, O. J. M. Nonlinear computations in the human controller. IRE Trans. Bio-Med. Elect., 1962, BME-9, 125-128.

Purpose To determine the response of the human forearm when maximum muscle effort is required for a step input.

Tracking Task

Type: Discrete, pursuit
Number of Axes: One
Display: Vertically placed lights in a 10" window
Control: Vertical handle with moving pointer in window, various weights, dash pot and zero centering springs could be added to the handle
Forcing Function: Discrete functions
Controlled Element: Position (K)
Subjects: Not given

Experimental Design Not complete but the mass, viscous "friction" and inertia were the variables.

Performance Measure Position and velocity of the movements were recorded.

Results The muscle force was calculated and the author stated that at best performance approached the same kind of response as that of a maximum effect, minimum time, optimum bang-bang servo in which the magnitude of the error is compared with a nonlinear function of the stored energy in the load. The muscle forces were relatively constant for each individual regardless of the dynamics of the load or the magnitude of the command.

151. Smode, A. F. Learning and performance in a tracking task under two levels of achievement information feedback. J. exp. Psychol., 1958, 56, 297-304.

Purpose To assess performance and learning effects independently as a function of performance information supplied during training. The general question asked was whether performance improvement due to information feedback can be attributed to increased learning or to a greater effort due to increased motivation.

Tracking Task

Type: Compensatory
Number of Axes: One
Display: Zero center meter 3-1/4" diameter
Control: Knob, 3-1/2" diameter
Forcing Function: $\theta_1 = (12 \sin \omega t + 7.5 \cos 2 wt) A$

$\theta_2 = (12 \sin \omega t + 7.5 \sin 2 wt) A$

Controlled Element: Needle movement slightly underdamped otherwise position (K)
Subjects: One Hundred Sixty male volunteer undergraduates

Experimental Design A transfer of training design was made. Two initial groups were both given θ_1 and divided according to feedback information. High (H) feedback received clicks representing on target and an accumulated visual TOT display. Low (L) feedback received their TOT score verbally at the end of the run. Both groups were transferred to all four combinations of θ_1, θ_2, H and L resulting in eight final groups.

Performance Measure TOT ($\pm 5^o$) and absolute integrated error were used. Protocols were obtained from the subjects of their responses to this task.

Results The H group was superior to the L group during early trials. The H to ($H_1\theta_1$) group was significantly superior to the others. Comparisons between groups trained under different but tested under similar feedback conditions showed H-trained groups were superior. TOT and absolute integrated error showed generally similar results.

Conclusions Increased performance was due to increased motivation but the basis for the motivation increases was not clear. The specific factors enabling the H group to do better on the transfer tasks could not be specified. Analysis of the protocols suggests that feelings of tension, self-competition, and a game playing attitude may be bases for the motivation increase.

152. Sutton, G. G. The error power spectrum as a technique for assessing the performance of the human operator in a simple task. Quart. J. of exp. Psychol., 1957, 9, 42-51.

Purpose The use of the error spectral density curve as a measure of human performance.

Theoretical Model The power spectral density with respect to error may give more information than RMS error. However, it is acknowledged that the operator is nonlinear and the describing function does not give an accurate description.

Tracking Task

Type: Discrete, compensatory
Number of Axes: One
Display: Horizontal moving blip on CRT
Control: Joystick
Forcing Function: Blip moved to predetermined mark, S asked to hold it for 30 secs
Controlled Element: Position (K)
Subjects: Four male subjects with tracking experience

Experimental Design Each subject repeated the test 16 times over a 2 day period.

Performance Measure The total squared error and the power density spectra of the error were used as measures.

Results Most of the error was below 3 cps and there was a peak at 7 to 9 cps.

153. Taylor, F. V. and Birmingham, H. P., Psychological studies of tracking behavior. II. A Study of the acceleration pattern of quick manual corrective responses. NRL Report No. R-3249, 3 March 1948.

Purpose To examine the time patterns of control forces produced during tracking of step function inputs.

Tracking Task
Type: Discrete, compensatory
Number of Axes: One
Display: Blip on CRT viewed through collimating lens.
Control: Horizontal joystick 67 inches long, 6 grams of sliding friction.
Forcing Function: Step displacements of 1.5°, 3°, or 6° of visual angle requiring a joystick movement of 2.25 in., 4.5 in., and 9 in. respectively.
Subjects: 10

Experimental Design: Each subject was presented with 60 steps, 30 left and 30 right, 10 steps of each magnitude. Twelve practice trials were given. Instructions stressed speed rather than accuracy.

Performance Measures Maximum rate, maximum acceleration, maximum deceleration, maximum acceleration for three periods, time to maximum rate, time to complete response and under or overshoot were recorded from continuous records.

Results The magnitudes of all measures increased with increased step magnitude but the range of response magnitudes was less than input range. Ss decelerated more slowly than they accelerated and no periods of constant velocity or acceleration were found.

Conclusions Movements were interpreted as being continuously controlled rather than ballistic, as a continuously changing force pattern was found. Some type of pre-programmed cam-like mechanism was postulated to explain the results.

154. Taylor, F. V. Nonlinearity in human response. Naval Research Laboratory Report No. 8-14, November 1949.

This article is a review of experiments on the human tracker conducted at the Naval Research Laboratories. Particular attention is paid to nonlinear responses to step function, intermittency in tracking, and response patterns as functions of time.

155. Taylor, F. V. and Birmingham, H. P., That confounded system performance measure - a demonstration. Psychological Review, 1959, 66, 178-182.

An analogue computer demonstration was given in which the performance of three different "man" - machine systems are compared, using an amplifier in place of the human subject. Although the "behavior" of the robot man was held constant in all three system configurations, the system performance curves were all very different. This clearly showed that the behavior of a system element cannot always be directly inferred from the performance of a system of which the element is a part. The reasons for this fact are analyzed. Implications of the demonstration for the study of human motor skills are presented.

156. Tustin, A. The nature of the operator's response in manual control, and its implications for controller design. Inst. of Elec. Eng., (London), 1947, 94, Part II A, 190-202.

Purpose To study the feasibility of describing the human operator in terms of a "linear error-actuated automatic servo."

Theoretical Model A continuous linear model based on harmonic analysis with the addition of a term of unknown origin to account for nonlinear effects in the output. This term was called the "remnant". The model was of the form:

$$G_H(s) = K \frac{K_1}{s} + K_2 e^{-Ls}$$

where s is the complex frequency variable, L is the time delay (0.3 second), and the K's are parameters which depend on the controlled element dynamics. A theoretical analysis of tracking accuracy and controller design is given.

Tracking Task

Type: Pursuit
Number of Axes: One
Display: A target moving back and forth on a horizontal line
Controls: Hand spade-grip controller, spring centered. Operator and sight mounted on motor driven turn-table.
Forcing Function: Sum of 3 sine waves
Controlled Element: (a) Position-rate up to 3/sec, lag occurred above 3/sec. (b) Turn-table rate proportional to displacement and rate of controller with three time constants, (c) Turn-table rate proportional to controller displacement, rate, and acceleration.

Experimental Design No specific design. Tracking performed under various frequencies and controlled elements.

Performance Measures (1) Examination of oscillograph records (2) Harmonic analysis (phase and amplitude of output frequencies corresponding to the input frequencies) of the error and controller signals.

Results "The present series of tests and the analysis given in the paper go a considerable way towards establishing the nature of the dependence of the movements given to a controller on the variation of the error, which is the task to correct. In the particular case of laying a sight on a moving target, it appears that the speed of control-handle movement is mainly linearly related to the error and the rate of change of error with a time-delay, but that subsidiary effects such as superimposed jerkiness, haphazard variability and other factors, act like an additional disturbance, superimposed on the controller movement, which may for some purposes be considered quite arbitrary."

"The behaviour of the complete system is such as would necessarily result from an operator response of this nature, the error being partly and predominantly that would occur with a linear error-actuated automatic servo, but including also a considerable additional irregular variation, which is partly random and the harmonics of which are in no direct relationship to those of the target movement."

157. Vince, M. A., Some exceptions to the psychological refractory period in unskilled manual responses. Medical Research Council, APU 124/50, February, 1950, 24 pp.

Purpose: Three experiments were performed based on previous "psychological refractory period" evidence. Three questions were asked:

1) "Is there any evidence that stimuli are grouped and responded to as a unit when the inter-stimulus interval is very short?'

2) "Can a second stimulus or response which is not grouped with the first prevent, or modify, the first response?"

3) "Is there any evidence of sensory overlap, i.e. are there any paired responses where the execution of the first and the organization of the second movements take place at the same time?"

Tracking Task All three experiments used a step tracking task. For the first, Ss tracked steps on a rotating drum with a pencil, for the second and third, the Ss tracked on a moving oscillograph record with a knob control.

Performance Measure Reaction time and error amplitude.

Experiment 1

Ss tracked pairs of opposed steps of three amplitudes (1.5, 2.5, 3.5 cm) and with inter-step intervals from 0.05 to 1.6 sec. Results showed a lengthening of RT to the second stimulus for intervals less than 0.5 sec. Second responses with normal RT's did occur for intervals less than 0.5 sec and in some cases at intervals of 0.2 and 0.3 sec normal RT's to first and second stimuli were found. A few cases were found in which the movement amplitude of the first response was shortened by the occurrence of the second stimulus.

Experiment 2

Step stimuli were presented singly or in pairs at intervals from 0.05 to 1.6 sec. Ss were told that they were to respond only to the second stimuli if they had not yet responded to the first. The task was found to be very difficult. On successful trials the RT of the single response to both stimuli occurred earlier than a second response RT when each was responded to separately.

Experiment 3

Reaction times to single or double responses were measured. The double responses were two steps superimposed on one or the other side of center or on opposite sides of center. Order of response for the latter was optional. Results showed the RT's to a double response only slightly larger than to a single response.

Conclusions: "The conclusion to be drawn from these experiments is that the psychological refractory phase is not absolute; in fact, when a stimulus is followed rapidly by a second stimulus, the first response may be suppressed, or modified by the second response in a minority of cases. Also, in some cases there may be overlap between the execution of one and the organization of the second response."

158. Vince, M. A., Corrective movements in a pursuit task. Quart. J. of Exp. Psychol., 1948, 1, 85-103.

Purpose Five experiments were conducted to investigate the following questions:

1) What is the hand reaction time to a kinesthetic stimulus?

2) What is the relationships between response duration and accuracy?

3) What is the least duration of a response which can be guided by visual cues and does the kinesthetic sense supply feedback for control?

4) Does removal of the visual input after movement initiation effect accuracy and how brief can the exposure be without impairing response accuracy?

Theoretical Model The motivation for this research was from Craik's (1948, 1949) hypothesis of the human operator as an intermittent correction device.

Tracking Task Several different tasks were used based on a rotating drum for stimulus presentation, lines drawn on the drum for inputs and mechanically coupled levers for controls.

Performance Measures (1) Reaction Time and (2) Error Amplitude

Results (1) Kinesthetic reaction time was 0.16 seconds

(2) Accuracy of movements were a function of movement time, however, for times greater than 0.6 seconds there was little change in accuracy.

(3) For movement times less than 0.4 seconds, visual cues could not be used to guide the movement and kinesthetic information was probably not used also.

(4) For "ballistic" movements (less than 0.4 sec) removal of the visual stimulus at the onset of movement did not affect accuracy.

Conclusions Tracking is considered a series of ballistic movements, dependent for accuracy on the initial impulse. This process is a compromise between speed and accuracy.

159. Walston, C. E. and Warren, C. E. Analysis of the human operator in a closed-loop system. Research Bulletin, 1953 AFP TRC-TR-53-32, Air Force Personnel and Training Research Center, Lackland Air Force Base, San Antonio, Texas.

Purpose To describe the behavior of the human operator by the use of a mathematically equivalent system.

Theoretical Model A describing function of the human operator was estimated by the following equation:

$$G_H(s) = K_1 + \frac{K_2}{s}$$

Parameters of this model were continuously adjusted so that they approximated the responses of the human operator.

Tracking Task
- Type: Continuous pursuit and compensatory
- Number of Axes: One
- Display: CRT display with two vertical bars
- Control: Manual arm control
- Forcing Function: The sum of 3 sine waves. A single sine wave motion was used with frequency of 30 cpm.
- Controlled Element: Position (K)
- Subjects: 6

Experimental Design Pursuit or compensatory, control gain and display gain were used as variables. There was no evidence of any factorial design.

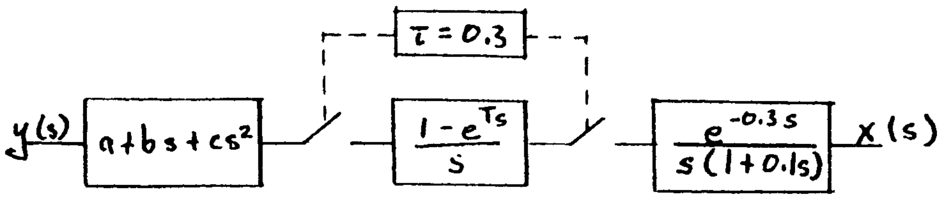
Performance Measure Mean square error was used as a performance measure.

Results From this preliminary study, it was concluded that certain assumptions could be made about the human describing function and the use of the describing function to estimate response of the human to a particular control system was practical.

160. Ward, John R. The dynamics of a human operator in a control system. Ph. D. Thesis, Department of Aeronautics, University of Sidney, May 1958.

Purpose Formulation of a sampled data model for the human operator based on "intermittency" hypothesis in human tracking.

Theoretical Model Author describes a sampled data model where one sample precedes a zero order hold and is followed by another sample that is delayed 0.3 sec after the first. This model also includes a lead term before the first sampler and a time delay plus lag after the second sampler. The model has the following form:



Adjustment of the model was by visual observation of the output.

Tracking Task

Type: Compensatory, continuous
Number of Axes: One
Display: Horizontally moving blip on CRT
Control: Joystick type of control
Forcing Function: Sum of 3 sine waves where the amplitude and frequency were varied between runs where highest frequency was 0.2 cps.
Controlled Element: Position (K) and velocity (K/s)
Subjects: 3 subjects with little tracking experience.

Experimental Design

The variables were frequency of forcing function at three levels and type of control (position or velocity.) Subjects practiced until their average absolute error scores became level.

Performance Measure

Average absolute error scores of the human and model were taken, and the traces and autocorrelation function of the human and model were compared.

Results The results showed that the error magnitude of the model was the same as that of the human, which might account for some of the remnant noise at the higher harmonics.

161. Welford, A. T. The measurement of sensory-motor performance: survey and reappraisal of twelve years' progress. Ergonomics 1960, 3, 189-229.

In recent years the importance of perceptual and central organizing activities in sensory-motor performance has been increasingly recognized and progress has been made towards a genuinely quantitative treatment. This article sketches the historical development of the work in this area and attempts a reappraisal under five main headings:

(a) There appears to be in the central mechanisms a "single channel" which processes signals or groups of signals one at a time so that signals coming in rapid succession may have to "queue" before they are dealt with.

(b) Choice reaction times are discussed in relation to the theory that the subject gains information, at a constant rate. Conceptual models of the subject's detailed behavior when making choices are also considered.

(c) Information theory models relating to the speed and accuracy of movement are outlined and discussed.

(d) Several formulae attempting to relate time taken to discriminate quantities of different magnitudes and the fineness of the difference between them are examined.

(e) A number of wider implications of the work surveyed are outlined. Perhaps the most important of these are new approaches to "mental" and monitoring tasks which have so far not been amenable to the normal methods of work study.

It is concluded that there is a need for joint psychological and physiological research which would be able to go beyond descriptive mathematical formulae to the study of detailed micro-behavior and neuro-muscular mechanisms.

162. Weltman, G. System variables affecting team performance in a visual tracking task, Report No. 62-59, Dept. of Engineering, University of California, Los Angeles, November 1962, Ph. D. Thesis.

Purpose To examine the relation of tracking system parameters, training, team-makeup, and team operating modes to team performance.

Tracking Task

- Type: Compensatory
- Number of Axes: Exp. I, 1 axis, Exp. II, 2 axis, and 1 axis.
- Displays: Oscilloscope, 5 inch. Target was bright dot, normal sitting posture.
- Controls: Vertical stick, spring loaded cam follower
- Forcing Function: Sum of ten sine waves 0.094 to 0.940 cps.
- Controlled Element: Position (K)
- Subjects: Exp. I - 36 male engineering undergraduates; Exp. 2-4 male engineering undergraduates.

Experimental Design (Experiment 1) - The independent variables were: team configurations, knowledge of configurations, forcing function and controller gain.

The experimental design was based on an elaborate analysis of variance utilizing complete, confounding of the third order interactions. 150 second tracking runs with last 120 seconds were recorded. Each subject was given 10 two-minute practice runs.

Performance Measures (Experiment 1)

1)

$$S = K_1 \int_o^{120} (e_s)^2 \, dt$$

e_s is individual or system error

K_1 is constant

Log transformation of S scores used to obtain normality

2) Cross-correlation on selected data
3) Spectral analysis on selected data
4) Multiple regression analysis

Results (Experiment 1)

1) Knowledge of team configuration improves system error
2) Serial and parallel teams were found to be better than the average and better team member, but only at low controller gains.
3) System error in serial configuration most highly correlated with lead tracker's error.
4) Under the parallel configuration, an effect called "response dominance" occurred in which one tracker reduced or greatly decreased his output, letting the other tracker take over.
5) Cross-correlation analysis showed the in-loop reaction time of the dominant tracker was invariably the lower of the pair.
6) Increase of high frequency power accompanied high controller gains and the parallel configuration. Data showed secondary peaks at high frequencies providing evidence for a sampled-data model of tracking behavior.

Experimental Design (Experiment 2)

This experiment analyzed the relations of team makeup to team performance, the effect of team interaction on the individual tracker, and the effect of practice.

Performance Measure (Experiment 2)

1)
$$S_R = K\int_0^{120} (e_R)^2 \, dt$$

e_R is instantaneous radial error

2) S_x, S_y as in Experiment 1.

Results (Experiment 2)

1) Configuration (1), parallel, produced lowest error scores
2) Learning occurred over ten trials, stabilized before termination of the experiment
3) Team response differed between the bi-dimensional configurations only when the comparison was based on the better tracker
4) During training, the trend was from response dominance to response sharing.

Conclusions "The results of this study have demonstrated that if system parameters are well chosen, it appears possible for the two-man tracking team to perform consistently better than the individual tracker. Statistically significant reduction of a log mean squared error criteria was seen for both serial and parallel teams in uni-dimensional tracking, and for parallel teams in the bi-dimensional case. Moreover, it was shown that the tracking team was superior not only to the mean team member, but also to the better team member.

163. Weiss, B. The role of proprioceptive feedback in positioning responses. J. exp. Psychol., 1954, 47, 215-224.

Purpose To examine the relationship of control force and distance to the accuracy of control positioning.

Tracking Task
Type: Acquisition
Number of Axes: One
Display: Spot of light on CRT
Control: 20" joystick
Forcing Function: Step displacement
Controlled Element: Position (K)
Subjects: 11 males, ages from 24 to 31 years.

Experimental Design Two sets of force displacement conditions were used. In one the maximum force required on the stick was 30 lbs and the displacement varied from 3° to 30°. In the other, the displacement was held constant at 30° and the maximum force varied from 3 to 30 lbs. The S viewed the CRT and was instructed to return the offset target spot to a baseline. During his control action, the spot disappeared and reappeared after its completion. For each force-displacement condition, four levels of displacement were used corresponding to 25%, 50%, 75%, and 100% of maximum in the fore and aft directions. A latin-square design was used to control sequence effects. Each S made a total of 128 settings, 16 for each displacement.

Performance Measure Mean constant error expressed as a percentage of the total range and the standard deviations of the relative errors.

Results For a constant force range, mean percentage constant error and relative SD decreased as range increased. For a constant displacement range, no change occurred in mean percentage constant error and relative SD as a function of force range.

Conclusion In this situation, distance was a more informative cue than force. The discrepency between the experiment and others showing superiority of force over displacement controllers was explained by differences in controlled elements and feedback.

164. Wertz, H. J. Adaptive control of systems containing the human operator. Ph. D. Dissertation, Electrical Engineering, University of Wisconsin.

Purpose Determination of human parameters by the model matching technique.

Theoretical Model The author uses the quasilinear model as described by McRuer and Krendel (1957) which has the following form:

$$G(s) = \frac{K(T_2 s + 1)\, e^{-Ls}}{(T_1 s + 1)(T_3 s + 1)}$$

He concludes from Ornstein's work that only K and T_2 vary between control systems. He applied a parameter adjustment scheme using the method of steepest descent where the error term was the difference between the human operator and an equivalent mathematical model for finding the parameters K and T_2.

Tracking Task
- Type: Pursuit
- Number of Axes: One
- Display: Two horizontal bars with target and pursuer on a CRT
- Control: Stick type
- Forcing Function: Random noise
- Controlled Element:
  - (1) Position with lag $\frac{K}{\tau s + 1}$
  - (2) Rate with lag $\frac{K}{s(\tau s + 1)}$
  - (3) Second Order Quadratic $\frac{K/\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$

Subjects: 5 subjects were used, four of which had jet aircraft experience and one with light plane experience.

Experimental Design Not given

Performance Measure The parametric coefficients of K and T_2 were used.

Results It was found that lead time constant T_2 varied with the controlled element dynamics. However, the system gain K was constant over the range of values investigated.

165. Wertz, H. J. A learning model to evaluate and aid human operator adaptation. International Congress on Human Factors in Electronics, May 3-4, 1963.

Theoretical paper on the use of the method of steepest descent for parameter adjustment of a describing function model in order to obtain close approximation to the human operator.

166. Williams, A. C. and Briggs, G. E. On target versus off-target information and the acquisition of tracking skill. J. of exp. Psychol., 1962, 64, 519-525.

Purpose To determine the effects of off-target feedback and on-target feedback on tracking performance.

Tracking Task
- Type: Compensatory
- Number of Axes: One
- Display: CRT 5"
- Control: Not described
- Forcing Function: 6 cpm + 12 cpm sine functions
- Controlled Element: Position (K)

Experimental Design Twenty-two Ss assigned to each of four groups. Group C received no additional feedback, group I received feedback when tracking was on-target, group O received feedback and direction formation when off-target. Feedback was provided by auditory clicks at a rate of 2/sec, direction formation was provided by using left or right earphones. Scoring band was ± 0.08 inches. Eighteen 30 sec trials were administered, the first 13 were the training trials under the experimental conditions, the last five were transfers to the no additional feedback condition.

Performance Measure

1) Average Error
2) TOT

Results

1) Groups 1, O, and O-D were superior to Group C during training and transfer on average error.
2) Groups O superior to I and O-D on average error
3) Groups I, O, and O-D were less variable than Group C.
4) Group 1 ranked differently with respect to O, and O-D with TOT scores although all three were still superior to Group C.

Conclusion It follows that augmented feedback based on a simple off-target criterion was the most effective training condition. An analysis of the data suggested that this superiority was a result of the emphasis on off-target criterion places on occasional large tracking errors. The group trained on this condition apparently learned to reduce such errors more quickly and efficiently than did the on-target criterion group.

167. Young, M. L. Psychological studies of tracking behavior. Part III. The characteristics of quick manual corrective movements made in response to step-function velocity inputs. NRL Report 3850, August 20, 1951.

Purpose To determine if responses to step function velocity inputs are similar to those to step function position inputs.

Tracking Task
Type: Discrete, compensatory
Number of Axes: One
Display: Blip on CRT viewed through collimating lens.
Control: Horizontal joystick 67" long
Forcing Function: Step increases of target velocity of 2, 4, 8 or 16 degrees per second measured at the eye point.
Controlled Element: Position (K)
Subjects: 10 adults

Experimental Design Each subject received 64 trials a day for 3 days. A total of 160 experimental trials of each of the four velocities to the right and left were presented. Order was counterbalanced. The first 64 trials were considered practice and 16 practice trials were given on days 2 and 3.

Performance Measures 1) Amplitude, velocity, acceleration and acceleration of each response as a function of time. Probable maximum values of above quantities used, although not stated by author. 2) Response time, 3) Reaction time.

Results Amplitude, velocity, and acceleration increased with increased input velocity. Response time was nearly constant and reaction time decreased with increasing input velocity.

Conclusions Response to a velocity step is similar to the response to an amplitude step, the subject perceives the target motion and velocity and executes a preprogrammed response to reduce the error to zero. No correction is applied during the time of the response.

168. Ziegler, P. N., Birmingham, H. P., and Chernikoff, R. An equalization teaching machine. NRL Report 5855, U. S. Naval Research Laboratory, Washington, D. C., November 20, 1962.

"The design and operation of a teaching machine is described for use in the selection and training of operators of higher order vehicle systems. In order to control such vehicles, the operator must compensate for the time lags that are characteristics of higher order systems. This compensation process has been termed "equalization".

The device consists of a third-order, two coordinate tracking system with a servo mechanism for adjusting the values of the quickening gains. Varying the amount of quickening in the system changes the equalization requirements of the tracking task. A naive operator is initially presented with a quickened task needing little equalization. As long as he maintains a small error, quickening continues to be removed. If, however, the operator begins to make errors greater than a predetermined level, more quickening is added until he can again maintain a small error level. This technique of continuous variation of the amount of quickening as a function of error provides at all times an equalization task which is appropriate for the operator's level of proficiency."

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