WADC TECHNICAL REPORT 57-582
AD DOCUMENT No. AD 131082
Cleared: August 28th, 1979
Clearing Authority: Aeronautical Systems Division

MAN-MACHINE DYNAMICS

CHAPTER VII
of the
JOINT SERVICES
HUMAN ENGINEERING GUIDE TO EQUIPMENT DESIGN

JEROME H. ELY
HUGH M. BOWEN
JESSE ORLANSKY

DUNLAP AND ASSOCIATES, INC.

NOVEMBER, 1957

SPONSORED BY THE
JOINT ARMY — NAVY — AIR FORCE STEERING COMMITTEE
OF THE
U. S. DEPARTMENT OF DEFENSE

WRIGHT AIR DEVELOPMENT CENTER

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified requesters may obtain copies of this report from the ASTIA Document Service Center, Knott Building, Dayton 2, Ohio.

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C., for sale to the general public.

Copies of WADC Technical Reports and Technical Notes should not be returned to the Wright Air Development Center unless return is required by security considerations, contractual obligations, or notice on a specific document.

WADC TECHNICAL REPORT 57-582
AD DOCUMENT No. AD 131082

MAN-MACHINE DYNAMICS

JEROME H. ELY
HUGH M. BOWEN
JESSE ORLANSKY

DUNLAP AND ASSOCIATES, INC.

NOVEMBER 1957

Aero Medical Laboratory
Contract No. AF 33(616)-419
Project No. 7180
Task No. 71501

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

300 – October 1959 – 7-217

FOREWORD

This report was prepared for the Psychology Branch, Aero Medical Laboratory, Directorate of Laboratories, Wright Air Development Center, under Research and Development Task Number 71501, Human Engineering Guide, with Mr. Charles A. Baker as Task Scientist. This work supports Project 7180, Human Engineering Applications to Equipment Design, with Mr. Julien M. Christensen as Project Scientist. Dr. Walter F. Grether was Project Scientist of Project 7180 when this work was initiated.

This report is being issued as a preliminary draft of a part of the Human Engineering Guide to Equipment Design being prepared under the direction of the Joint Services Steering Committee for this guide. After further review and revision it is planned that this material will become a part of that guide. The purpose of the Human Engineering Guide to Equipment Design is to provide designers of military equipment with human engineering data and general design recommendations for maximizing efficiency of human operation and use.

Users of this report are invited to submit comments which would be useful in revising or adding to this material prior to its publication in the Joint Services Human Engineering Guide to Equipment Design. Comments should be sent to: Chief, Psychology Branch, Aero Medical Laboratory, Directorate of Laboratories, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

This report has been released to the Armed Services Technical Information Agency, Knott Building, Dayton 2, Ohio. This report has further been released to the Office of Technical Services, Department of Commerce, Washington 25, D. C. for sale to the general public.

During the preparation of this report, the authors received assistance and guidance from Dr. Walter F. Grether, Mr. C. A. Baker, Mr. M. J. Warrick, Lt. Richard Pew, and Mr. John Senders of the Psychology Branch, Aero Medical Laboratory, and Dr. Franklin V. Taylor and Mr. Henry Birmingham of the Engineering Psychology Branch, Naval Research Laboratory. In addition to the aforementioned, the report was reviewed by Dr. J. C. R. Licklider, Massachusetts Institute of Technology, and Dr. A. Chapanis, The Johns Hopkins University.

The preparation of the report was also aided by the following representatives of Dunlap and Associates, Inc.: technical advice on servomechanism theory by Mr. I. Rosner and Dr. E. Mishkin, art work by Mr. H. Montaine, editorial assistance by Miss A. Cleven, and typing by Mrs. M. Callahan and Mrs. J. Montgomery.

ABSTRACT

This report identifies and discusses factors affecting human performance in tracking and in watchkeeping (vigilance) tasks, and makes recommendations toward improving the performance of such systems. Whenever these recommendations are the direct outgrowth of published research, the appropriate studies are cited. Other recommendations have been developed by the authors from their own experiences.

The report is divided into three main parts: General Information, Important Design Factors in Closed-Loop Systems, Human Time Lags. A table of contents and a subject index are provided as aids to the user.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

TABLE OF CONTENTS

PART 1

GENERAL INFORMATION

This part presents general introductory and background information. There are two main sections:

1.1 Description of closed-loop systems.

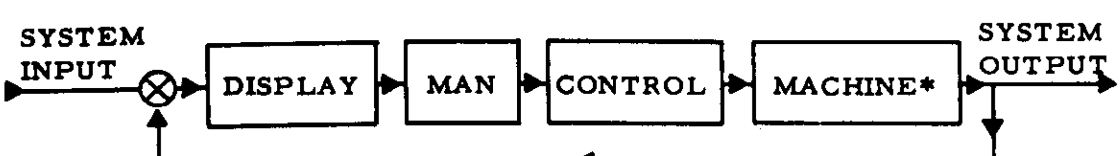
1.2 Human responses to various inputs.

1.1 DESCRIPTION OF CLOSED-LOOP SYSTEMS

1.1.1 General Reference Terms

a. closed-loop system

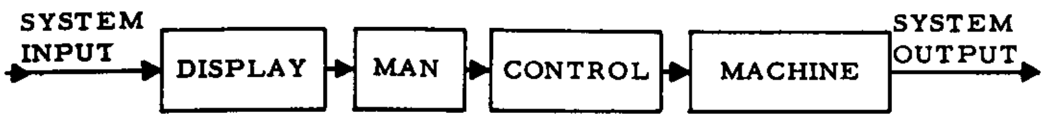
A system in which information about an output is fed back to an earlier stage in the system.



*Machine is defined in this report as comprising all components within the system other than the display, man and control.

b. open-loop system

A system in which no information is fed back. With a human operator present, there can be no pure open-loop system because there are "internal" feed-back loops within his body. However, as long as there are no "external" feed-back loops, the system is considered open-loop.



c. manual tracking

The process by which an operator continually attempts to minimize some measure of the difference between a desired and an actual output.*

d. operator inputs

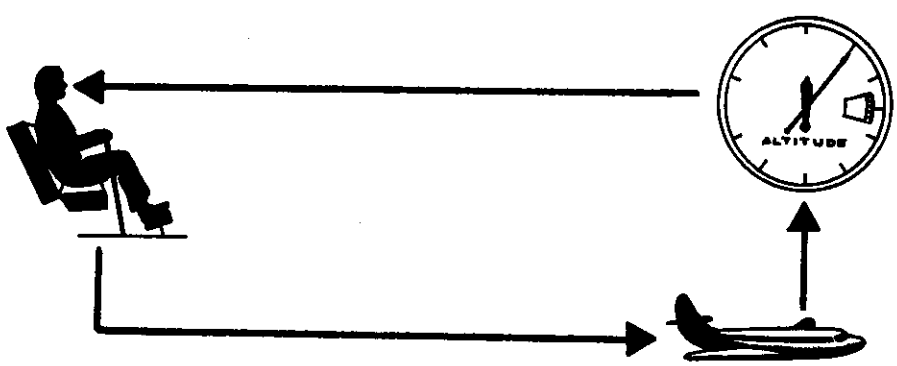
The information which is received (sensed) by the operator. The most common types of inputs are: 1) direct sensing, 2) verbal or visual commands, and 3) visual displays.

*In such systems the operator acts primarily as an "error corrector" and, as such, his task is comparable to that of a servomechanism. This similarity has led to numerous attempts to describe operator performance in manual tracking systems by using servo terminology.

e. operator outputs

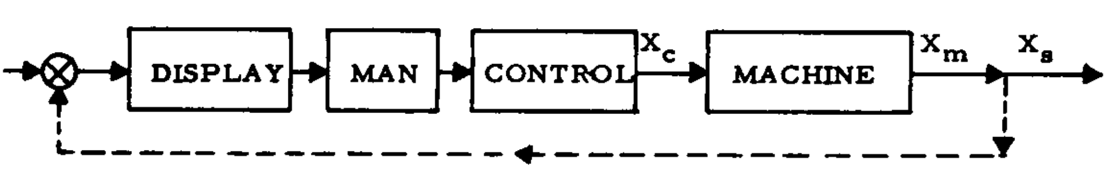
The action taken by the operator. The most common types of operator outputs are: 1) manipulation of controls and 2) verbal commands.

Example: A pilot is instructed to change his altitude from 20,000 feet (actual machine output) to 15,000 feet (desired machine output). His task (manual tracking) consists of manipulating his controls (operator output) so that the altimeter needle (operator input) will move to and remain at the desired altitude indication.

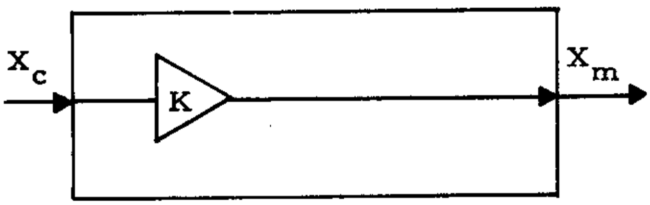


f. control order

The order of the differential equation describing the transmission properties of the machine.



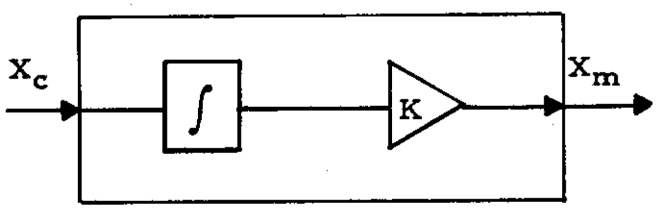
In zero-order control, the operator's control output (X_c) directly determines the machine output (X_m). This is commonly called position control.



$$X_m = KX_c$$

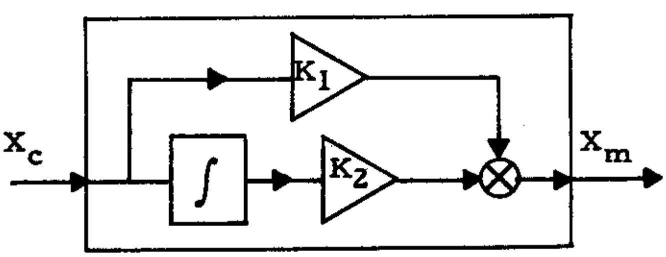
K is a constant representing the "gain" or "amplification" factor.

In first-order control, the operator's control output directly determines the rate of change of the machine output. This is commonly called rate control or velocity control.



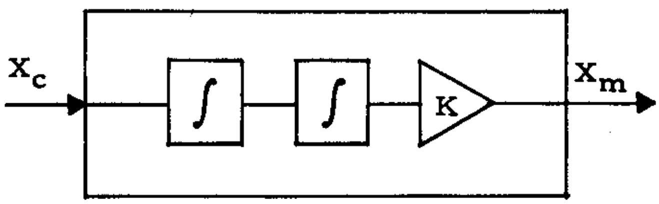
$$X_m = K\int X_c dt$$

First-order control can also include the position term. This is commonly called rate-aided or velocity-aided control.



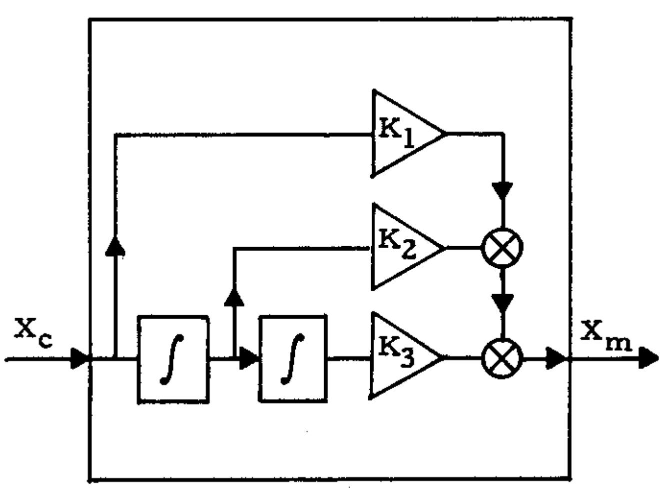
$$X_m = K_1X_c + K_2\int X_c dt$$

In second-order control, the operator's control output directly determines the acceleration of the machine output. This is commonly called acceleration control.



$$X_m = K \iint X_c dt$$

Second-order control can also include all lower-order terms. This is commonly called acceleration-aided control.



$$X_m = K_1 X_c + K_2 \int X_c dt + K_3 \iint X_c dt$$

In general, for n'th-order control, the operator's control output directly affects the n'th derivative of the machine output and can also affect any or all lower-order terms.

1.1.2 Human Transfer Functions*

a. need for descriptions of tracking systems

For automatic closed-loop control systems, considerable work has been done in developing mathematical descriptions of the behavior of the system and of its various components. Such descriptions permit the designer to manipulate the system conceptually rather than physically. In like manner, the value of a description of human performance in a tracking system is to save the designer the requirement of measuring such performance for the design of each new contemplated system.

Transfer functions describe input-output relationships. Hence, a "human transfer function" would describe the operator's outputs (e.g., control movements) in a tracking task, as a function of his inputs. If his behavior were "linear," it would be describable by a linear differential equation, and, most important, his response to complex inputs would be easily predictable.

> "Linearity" implies that the operator's output to a complex input, which is the sum of a series of simple inputs, is the sum of his responses to each of the simple inputs. This superposition of solutions is useful in that the operator's inputs can, by a Fourier analysis, be separated into a series of sine waves. Thus, if it were known how an operator tracks sine waves of all frequencies and amplitudes, his tracking performance for any complex input could be predicted.[40]

*A comprehensive coverage of this topic is presented elsewhere.[83]

b. linear models*

Linear models show that the human operator performs best when his task is no more complex than that of a low-pass filter with a time lag, i.e., within a limited bandwidth of input frequencies his output is proportional to his input but with some lag in between.

Although generally useful as approximations of human tracking behavior, linear models* are somewhat incomplete in that they fail to account for the following characteristics of operator performance:

1) It varies from individual to individual.

2) It varies from time to time for any one individual. This is due in part to learning and in part to subtle factors such as motivation, fatigue, operating instructions, etc.

3) It is affected by the total context of the situation rather than by any single input-output relationship.[44] Thus, in correcting an error, the operator's response is affected by his previous experiences in tracking as well as by the immediate error.

4) It is often uneven ("jerky") in nature, the unevenness possibly being one way in which the operator receives feedback information which helps in his learning the nature of the system.

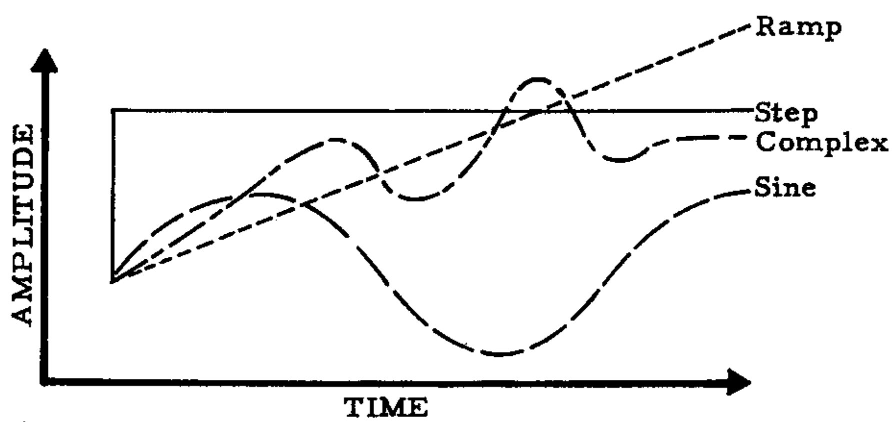
*Research is progressing in the field of non-linear models but has not gone sufficiently far to result in general findings as yet.

5) In tasks such as controlling aircraft pitch, trained pilots tend to initiate corrective actions for pitch rate errors only after these errors have reached a degree far greater than threshold (i.e., far greater than the point at which the pilot is first able to detect the error), and tend to hold their joysticks at some fixed position, after having made a correction, until the pitch error approaches zero.[56]

1.2 HUMAN RESPONSES TO VARIOUS INPUTS

1.2.1 Typical Types of Inputs

There are many different types of inputs. Typical ones include steps, ramps, sine waves and complex inputs which are combinations of these.



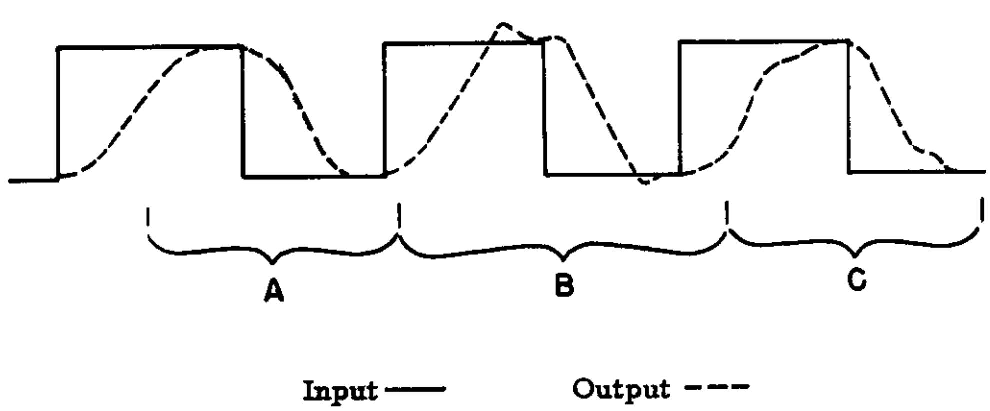
Human responses to each type of input are described below.

1.2.2 Step Inputs

a. typical responses

Three typical responses to step inputs with position control are shown below. In all three, there is first a lag before the operator starts to move his control. Such lags are generally between 0.25 and 0.40 second;[31, 42, 109] however, they are affected by many factors and may vary considerably from these figures. (See Section 3.2 for detailed coverage.)

Following this initial lag, the operator takes an additional period of time to move his control to its desired position. His first movement (called "primary movement," "gross adjustment" or "slewing") may bring him exactly to his desired position, as illustrated in A below. However, unless highly practiced, he usually either overshoots, as shown in B, or undershoots, as shown in C; and must, therefore, make a second movement (called "fine adjustment" or "secondary movement") in order to reach his desired position.[30]



b. effects of control design

Performance in correcting a step input, like all control movements, is affected by control design. Among the important factors in design are type and amount of resistance, and amount and direction of control and display movement. (These factors are covered in detail elsewhere.[46])

c. effects of amplitude

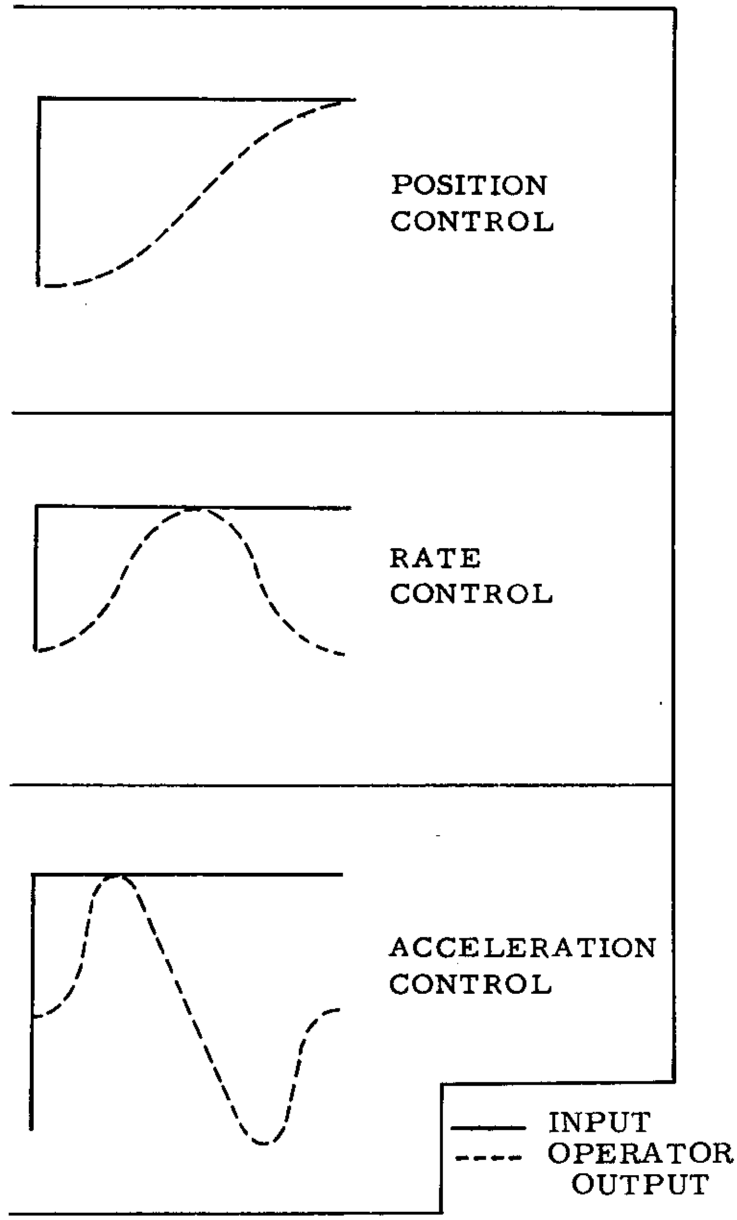
Although the correction of large step inputs takes longer than that of small inputs because the control must be displaced a greater amount, the velocity of control movement tends to increase as the amplitude of the input increases. As the magnitude of the required corrective movement increases, the operator tends to apply more force to the control in both starting and stopping, to apply force faster, and to maintain its application over a longer period of time.[96, 104, 107]

d. "range effect"

In correcting a series of step functions of varying amplitude, operators tend to undershoot the larger errors and to overshoot the smaller ones. This "range effect" is a function of the relative amplitudes of errors and is independent of the absolute magnitudes.[44, 96] Thus the operator is responding to a total situation, and any mathematical description of his input-output relationships must take into account the entire situation rather than a single input.

e. control order

The adjacent illustration shows an "ideal" operator response to a step input with position control, rate control, and acceleration control. The minimum number of control movements increases by one with each succeeding control order.



When the amplitude of the step input is sufficiently small that it can be corrected by a single limb movement with the control, position control is better than rate control, which is better than acceleration control, etc.[62] (For a detailed coverage of control order, see Section 2.3.)

f. presentation rate

In correcting a rapid series of step inputs, the operator's performance is affected by the rate of presentation of the inputs. Depending upon the time interval between adjacent inputs, the operator may do any one of the following:

1) Respond to each input individually and at the proper time.

2) Respond to several inputs as if they comprised a single input.

3) Respond to each input individually but spread out in time.

4) Fail to respond to some inputs.

(For detailed coverage, see Section 3.2.)

1.2.3 Ramp Inputs

a. target velocity

With position control, the greater the target velocity, the greater will be the force applied by the operator to correct the resulting error. Response time tends to be relatively independent of the slope (velocity) of the ramp.[115]

b. "range effect"

The "range effect," present for step inputs, is also present for ramp inputs. For steeper ramps (higher rates), the operator tends to undershoot or to lag behind, while for ramps which are less steep (slower rates), he tends to overshoot or to "lead."[115]

c. position control vs. rate control

Theoretically, in using rate control for tracking a ramp input, the operator would make one control movement which imparted the proper rate, and then the machine would continue automatically to match input with output. In practice, however, the operator has some finite reaction time which results in an initial lag. Therefore, with rate control he must impart a rate greater than that of the input in order to catch up, then gradually slow down until the two rates match. With position control he must continue to move his control at some constant rate. Although better than position control, rate control still requires frequent control adjustments.[53]

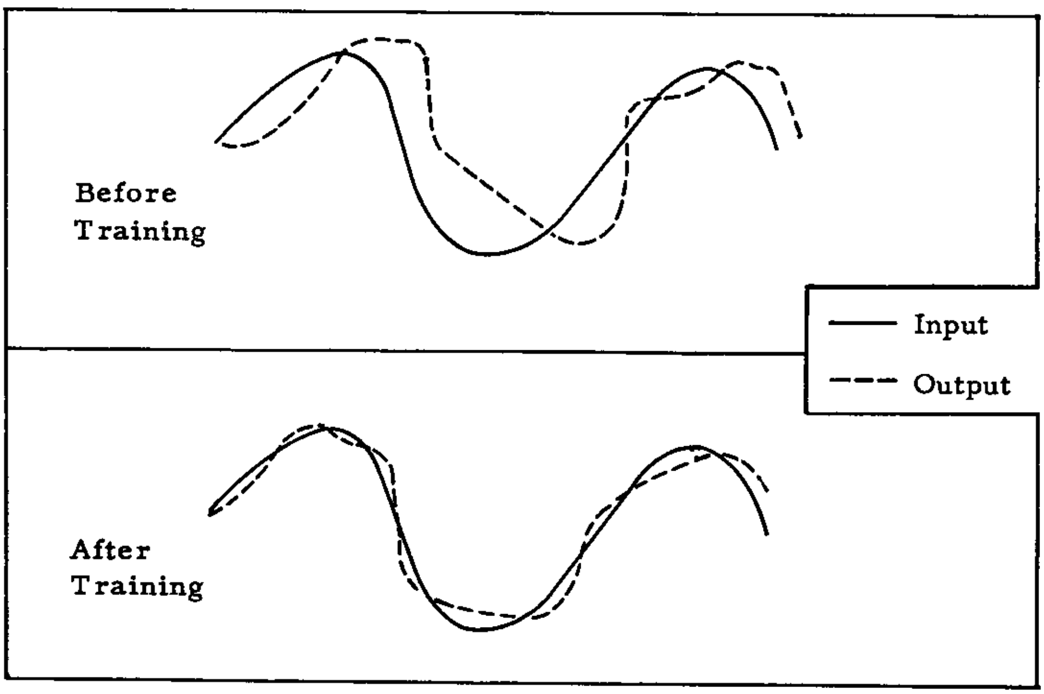
d. anticipation

In tracking a ramp input, once the operator recognizes the nature of his input (i.e., realizes that it will continue to change at a constant rate), his performance can improve to a point where he tracks continuously with little error. Essentially, he learns to anticipate the future movement of the target and to respond in such a manner that both present and future errors will be minimized.

1.2.4 Sine Wave Inputs

a. general

In tracking sine waves (or any other repetitive input) with frequencies in the region of 1/4 to 1/2 cycle per second (cps), an operator can learn to do an excellent job.[41, 43, 48, 87] Although there are individual differences, movements become smoother and more continuous with training, and time lags due to reaction time and movement time tend to disappear because the operator learns to anticipate his future desired positions. Shown below is a typical example of an operator's response to a sine wave input with position control before and after training.

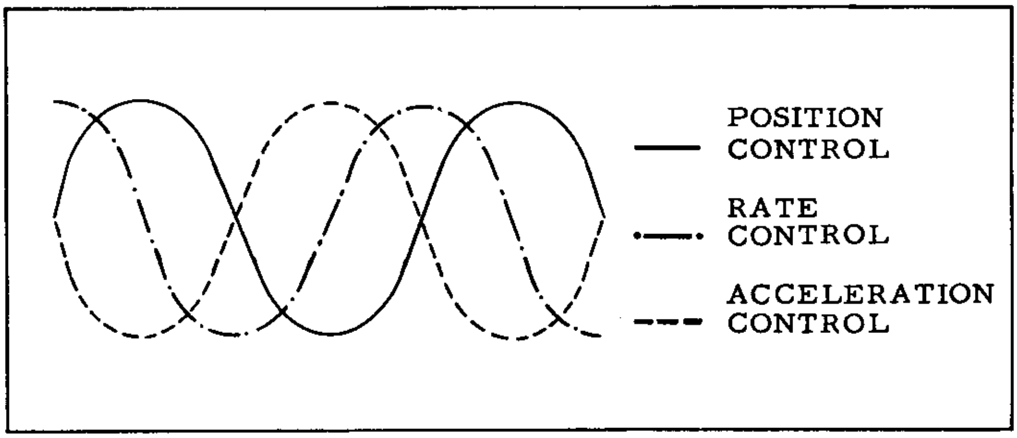


b. input frequency

For frequencies between 1/6 cps and 4 cps with position control, time-on-target falls off as frequency increases.[88]

c. control order

Theoretically, the operator's output in a perfect tracking performance would be the same whether he had position control or some higher-order control, with only a phase shift required for a change in control order. The curves below indicate a perfect response to a sine input for various control orders.



In practice, however, tracking a relatively high frequency sine input is considerably better with position control, while higher-order control becomes increasingly superior as frequency decreases.

1.2.5 Complex Inputs

a. general

Responses to complex inputs are similar to those for simpler inputs.[38] Characteristically, there is a time (phase) lag, which is reduced when the operator has information which permits him to anticipate the future behavior of the input. (For a discussion of ways to present anticipatory information, see Section 3.2.)

b. input frequency

As cutoff frequency increases, performance becomes poorer.[39]

c. control order

The effects of control order upon tracking performance depend upon the input frequencies. For very low frequencies, rate control enables an operator to track better than does position control. However, as input frequency increases, there is a shift so that position control becomes better.[24]

PART 2

IMPORTANT DESIGN FACTORS IN CLOSED-LOOP SYSTEMS

This part covers five important design factors present in closed-loop systems. Each is covered in one of the main sections:

2.1 Pursuit and compensatory displays.

2.2 Intermittency.

2.3 Machine dynamics.

2.4 Aided tracking.

2.5 Quickening.

2.1 PURSUIT AND COMPENSATORY DISPLAYS

2.1.1 Definitions

a. pursuit and compensatory tracking

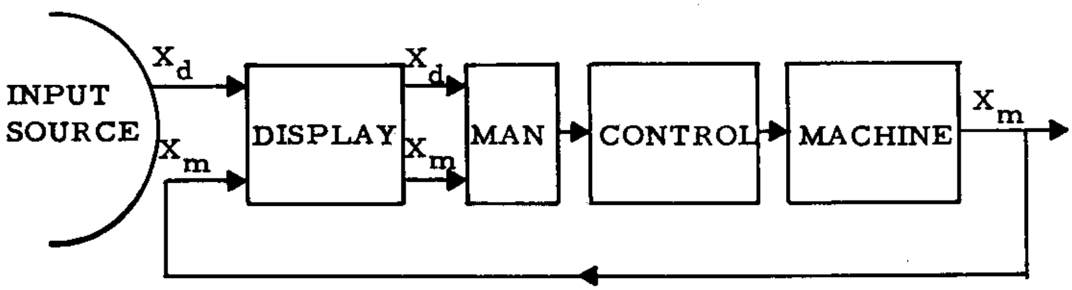
In both pursuit and compensatory tracking, the operator's task is to match an actual output with a desired (or ordered) output.

(See also Section 1.1.1.) The two types of tracking differ only in the type of display used with each (viz., pursuit display and compensatory display, as defined below).

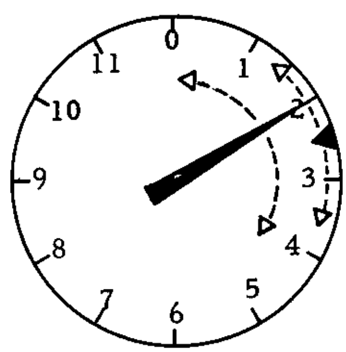
> Note: Although not covered as a separate topic in this section, a single display can be a combination of both pursuit and compensatory displays.[101]

b. pursuit display

A pursuit display contains two moving elements, one representing an actual output (X_m) and the other the desired output (X_d). There is no separate indicator representing error (ϵ); error is estimated from the difference between elements representing actual and desired output ($\epsilon = X_m - X_d$).



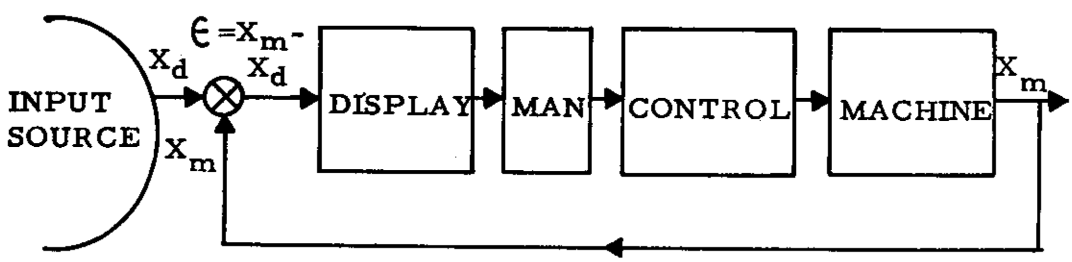
Example: The circular dial has a moving pointer which indicates the actual output and a moving "bug" on the periphery which indicates the desired output. The operator's task is to keep the pointer on the "bug."



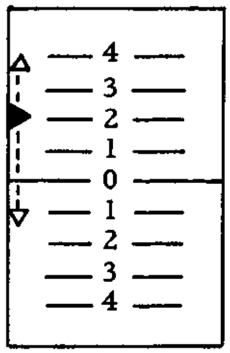
Because many pursuit displays have pointers as their moving elements, pursuit tracking is sometimes called "pointer matching."

c. **compensatory display**

A compensatory display contains one moving element, representing error (ϵ). Error is the difference between an actual output (X_m) and the desired output (X_d); however, there are no separate indications of the latter twc terms.



Example: The vertical dial has one moving pointer which indicates error on a fixed scale. The operator's task is to keep the pointer centered on the display at a zero mark (the point at which error is zero, i.e., where the actual output is the desired output).



Because many compensatory displays have a single pointer and a zero mark, a compensatory display is sometimes called a null indicator.

2.1.2 Anticipation in Tracking

a. pursuit display

A pursuit display permits the operator to see a time-varying desired output (e.g., target course) and an actual output, and to estimate the rate and acceleration of each. From such information, he can: 1) estimate where his desired output will be in the future, i.e., anticipate future conditions, and 2) initiate corrective actions slightly before they are required. Hence, his responses are no longer limited by his own reaction time. In general, his actions are determined not merely by the immediate momentary state of the display but also by the continuing information which is available.

b. compensatory display

A compensatory display provides information about error only. Perfect tracking with such a display would result in no movement of the moving element.[101] When the moving element does depart from the zero-error position, the operator cannot tell whether the error is caused by: 1) a change in the desired output, or 2) a change in the actual output, brought about by his control movement, or 3) a change in both. Hence, he cannot anticipate the future state of the desired output.

With training he may learn the relation between his control movement and the moving display element and, by mentally subtracting actual output from the error appearing on the display, estimate the change in desired output. However, this is a difficult task, especially for higher-order systems.

c. comparison between pursuit and compensatory displays

Insofar as anticipation is concerned, a pursuit display is superior in helping the operator to learn the nature of the desired output and to anticipate future conditions.[25] For higher-order control systems, the pursuit display is better at helping the operator learn the dynamics of the machine, for with a pursuit display he can always observe the relation between his control motion and the machine output.

Note: A naive operator may be unaware of the lags present in the tracking system. In correcting a very simple input (e.g., step) on a compensatory display, he might generate his own errors without realizing it and "track himself" for some time. Such a condition cannot arise when he has a pursuit display.

2.1.3 Factors Affecting Display Selection

a. desired output

When there is only one desired output (e.g., a step-input in order to maintain a given heading), both types of display are equally good. The superiority of the pursuit display in helping the operator anticipate future conditions is not needed because the desired output is not time-varying. As the desired output increases in complexity, pursuit displays become increasingly better than compensatory ones.[23, 24, 92, 98, 101] (The output interacts with machine dynamics, as discussed below.)

b. machine dynamics

With position control, pursuit displays are superior as long as the desired output (or input) is time-varying.[22, 24, 98, 101] With rate control, pursuit displays are superior except when the cut-off frequency is about 0.1 cycle per second or less.[24] With higher-order control systems, pursuit displays remain superior; and their superiority is directly related to the frequency of the desired output (i.e., the higher the frequency, the more superior the pursuit display).[23]

c. movement rate

When the moving elements of the display (e.g., pointers) move very slightly or slowly, the operator's ability to estimate rate of movement is poor. Under such conditions, he cannot accurately predict future positions; therefore, the superiority of a pursuit display is nullified.[98] Slow or slight rates of movement may result from two conditions: 1) a desired output which changes very slowly (as covered in the preceding paragraph), or 2) a display which is so small that even large output changes are represented by small pointer movements. Hence, when the display must be very small and the frequency of the desired output is low, pursuit displays tend to lose their superiority.

d. clarity of background

The prime advantage of a pursuit display results from the operator's seeing two moving indicators. If the display background were completely unstructured (e.g., two pointers being the only visible objects in a darkened room), the operator could easily observe relative movement but would have difficulty in discerning whether the first, second, or both indicators were moving. This difficulty would disappear if he could also see a stationary structured background behind the indicators. Therefore, for a pursuit display to be effective the background should be sufficiently well defined that the operator can easily observe the movement of each indicator relative to the background.[98]

e. aided tracking

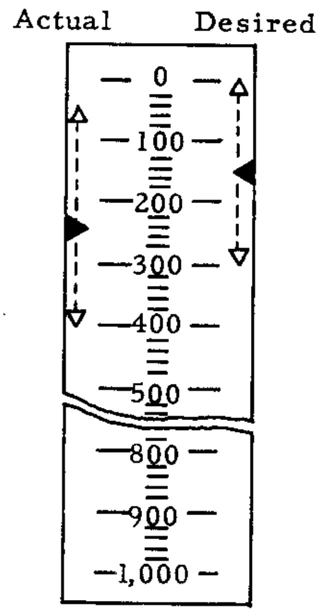
The value of an aided tracking system (see Section 2.4) is that the machine automatically supplies the proper derivative terms when the operator corrects positional errors. Thus, with aided tracking, the operator performs best by making his corrective response proportional to error only. This is his normal mode of response with compensatory displays. However, with pursuit displays, he usually "anticipates" and responds to both error and error rate. The latter type of response is undesirable in an aided system; in this case, a compensatory display is superior.[22, 24]

Note: The superiority of compensatory displays with aided systems also applies with "quickened" systems (as described in Section 2.5) for the same reason.

f. display size

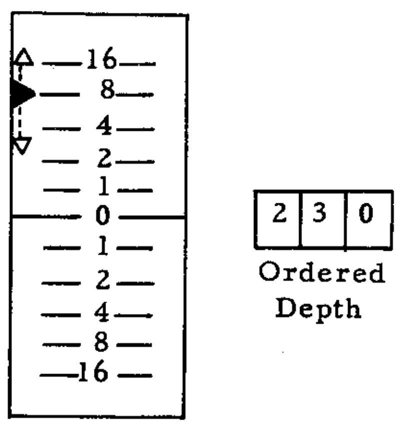
A pursuit display must normally show the entire range of desired and actual outputs. When the range is limited or when high precision is not required, the size of the display is not seriously affected. However, when the range is great or when precision requirements are high, then either: 1) the display must be enlarged considerably, or 2) both actual and desired output must have more than one moving element each (e.g., a counter-pointer combination), or 3) each output step must be represented by a very small distance on the display.

Example: If submarine depth varies from 0 to 1,000 feet and must be maintained within 6 inches, a pursuit display with only one depth marker is prohibitively large. A 20-inch vertical dial still results in a 6-inch change of depth being represented by 0.01 inch of marker movement.



A compensatory display normally does not have to show the entire range of outputs, but only those of immediate concern to the operator. Therefore, it can display output steps in an enlarged form without increasing the total size of the display. Also, if there is a non-linear relationship between control and display, a non-linear scale is better suited to compensatory displays than to pursuit displays.

Example: For submarine depth, the display need only show the depth range within which the submarine is operating. For depth keeping, a non-linear scale is an effective display to aid the operator maintain depth within the required accuracy. However, some means must be provided for setting the desired depth into the display system.



g. training

Under those conditions where pursuit tracking is superior for untrained operators, it tends to remain superior for trained operators but to a lesser degree.[23]

2.1.4 Recommendations

a. general

Neither a pursuit nor a compensatory display is always superior to the other. The one to use depends upon the requirements of the specific task at hand. Enumerated below are the general conditions under which each should be used.

b. use of pursuit display

To be effective, a pursuit display should be sufficiently large and the background sufficiently structured that the movement of both indicators can be easily seen. If this requirement is satisfied, pursuit displays should be used when any of the following conditions is present:

1) The course contains high frequencies.

2) The system is of zero-order control.

3) The operator must know the actual output and not just error.

c. use of either type of display

Either a pursuit or a compensatory display can be used when the following conditions are present:

1) The course is simple.

2) Machine dynamics are negligible.

3) The operator needs to know only the error and not the actual output.

d. use of compensatory display

A compensatory display should be used when either of the following conditions is present:

1) The system is quickened or aided.

2) The display must be kept small, but the output range is large and/or the precision requirements are high.

2.2 INTERMITTENT DISPLAY OF INFORMATION

2.2.1 Causes of Intermittency

a. general

In certain situations an operator receives information from a display intermittently rather than continuously. This condition may result from the nature of the system (from the method of instrumentation), from the requirements of his task, from behavior on his part which is undesirable and which is not required by the task, or from some combination of these three causes. Each cause is discussed below.

b. intermittency caused by nature of system

In some systems the display presents input information intermittently. A very common example is a PPI radar scope with a slow sweep rate and a low persistence phosphor: the picture which is painted on the scope during one sweep will decay before the next sweep.

In other systems, the input information is received directly from the external world by the operator (without requiring a special display). The nature of the input is such that the operator can only view it intermittently. A typical example is an aircraft being tracked visually through cloud formations.

c. intermittency caused by requirements of the task

In some systems information is presented continuously, but the operator can only receive it intermittently. In a typical case, the operator is required to view a number of displays; therefore, he must set up a scanning pattern which permits him to look at each display periodically but none continuously.

> Note: The relatively slow operator performance found in multi-display situations is due partly to the time taken by eye movements and partly to the mental lags associated with switching attention, the latter being on the order of 0.2 second.[13, 16]

In other cases, special considerations prohibit him from receiving the information which is always available. For example, under black-out conditions, he may be allowed to light his instrument panel only at infrequent intervals and for short durations.

d. intermittency caused by undesirable operator behavior

Regardless of the nature of the system and the requirements of the task, the operator is always capable of behaving in an undesirable and an uncalled for manner. Such behavior may be caused by failure to pay attention, distractions resulting from loud flashes and noises, involuntary eye blinks, etc.

Note: Eye blinks occur at a rate of approximately one per three seconds when a person is not attending to any task. Each blink can obscure vision up to 0.25 second. However, operators normally inhibit blinks when performing a difficult tracking task.[20]

2.2.2 Effects of Intermittency

a. general

In general, intermittency degrades tracking performance.[8, 64, 69, 93, 99] However, the operator may be unaware that he is performing more poorly with an intermittent display than with a continuous one.[64]

As the per cent of time which the operator can view his display decreases, his performance decreases in an approximately linear manner.[8] This holds true whether the intermittency results from: 1) a few relatively long looks at the display with a long period elapsing between looks, or 2) a number of relatively short looks at the display with a brief period elapsing between looks. In most cases, a system which provides for relatively short looks with brief periods between them is preferable.[8, 99]

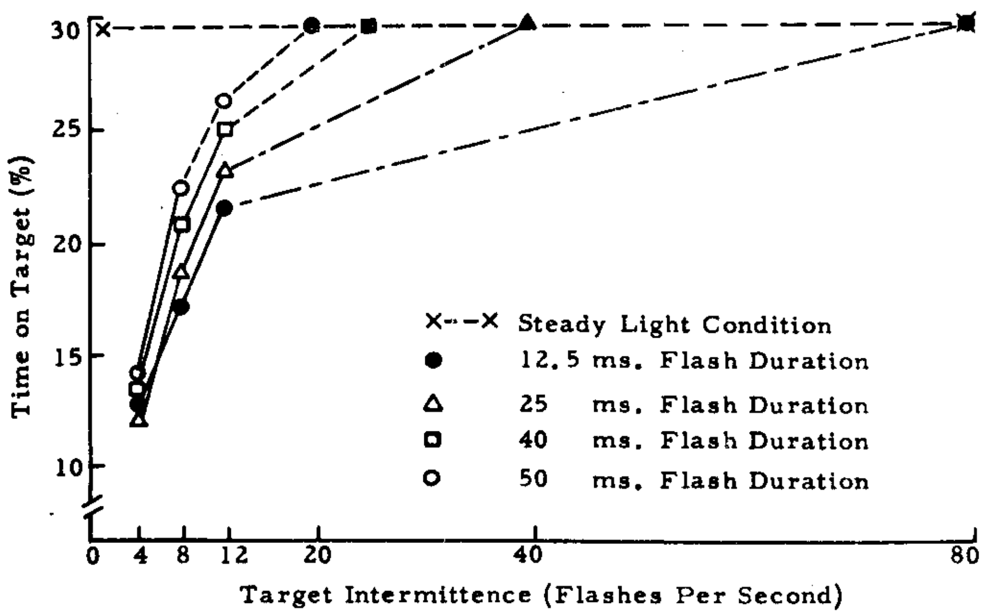
These general effects are modified by both input complexity and display brightness, as covered below.

b. input complexity

If the target moves slowly and changes course infrequently, the operator can predict its present and future positions relatively well with only occasional views of the display. However, as target course becomes more complex, he must observe the display more often in order to track satisfactorily. Therefore, the more complex the input, the more will be the degradation in performance caused by display intermittency.

c. display brightness

When the intermittency is caused by a flashing display, the flash duration usually affects target brightness.[110] When flash duration is short, brightness tends to be less than when flash duration is long. The decrease in brightness interacts with flash rate to further degrade performance.[7, 99]



In general, a brightness in the order of .005 ml results in poorer performance than a brightness of .05 ml, which in turn results in poorer performance than a brightness of 10 ml or above.[110]

2.2.3 Recommendations

a. general

If the inputs shown on the display(s) are simple in nature, and the operator need not respond to the inputs quickly and precisely, intermittent display(s) will not have harmful effects upon the system. However, if any display input is complex in nature (i.e., has high rates and frequent changes in direction) and the operator must track with a high degree of precision, intermittent display of this information will degrade performance. In the latter situation, all causes of intermittency should be eliminated whenever possible. If intermittency cannot be completely eliminated, its deleterious effects should be reduced by following the specific recommendations listed below.

b. specific

The harmful effects of intermittent displays should be reduced by carrying out as many of the following recommendations as are possible within the restrictions set by the over-all system design:

1) Anticipatory information should be provided by the display. Effective means include using a pursuit display (see Section 2.1) and alerting devices (see Section 3.2.5).

2) The brightness level of the display(s) should be kept high.

3) All sources of distraction should be eliminated.

4) When intermittency results from the operator's having to scan a number of displays, the displays should be designed and arranged to minimize the time required to view each display and to shift from one display to another. (Specific recommendations for display design and arrangement are covered elsewhere.[5,47])

5) When signals are displayed intermittently, the duration of each signal should be as long as possible and the rate of presentation as fast as possible.

6) Aiding or quickening should be used when applicable. (See Sections 2.4 and 2.5, respectively, for detailed coverage of these topics.)

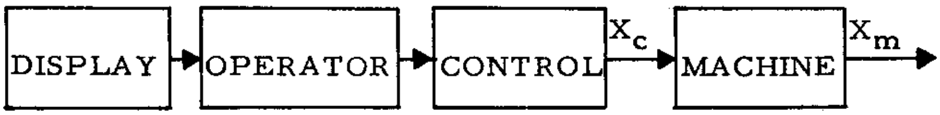
2.3 MACHINE DYNAMICS

2.3.1 General Background

a. definition

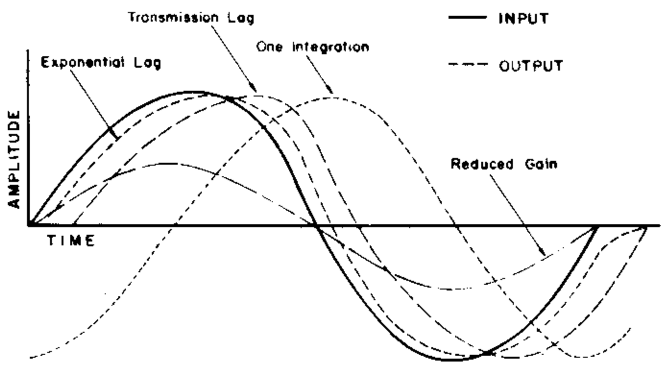
Machine dynamics, as used here, comprises the changes in machine output resulting from a control movement made by the operator. Mathematically, the dynamics of a machine can be described completely by one or a set of equations showing the relationship between machine input and output; this relationship is commonly called the transfer function.

Note: Since the operator's control output is the machine input, from a human engineering standpoint, machine dynamics involves the relationship between the operator's control output (X_c) and machine output (X_m).



b. important attributes of machine dynamics

In order to understand the dynamics of a machine, it is useful to examine the dynamics in terms of certain discernible attributes. Insofar as they affect performance, important ones are: 1) lag, 2) gain, 3) integration. (Each will be covered in the following sections.) The figure following shows the effects of each upon a simple sine wave input.



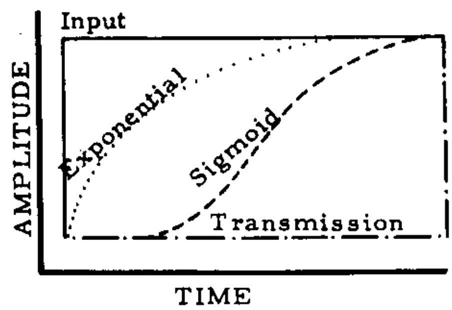
Note: There are other important attributes which are not covered in this section. For example, differentiation and analogue addition have not been studied sufficiently to be covered. Control resistance, which interacts with machine dynamics, is covered elsewhere.[46]

2.3.2 Effects upon Operator Performance

a. effects of lag

There are various types of lag, and these may appear in various parts of the system. An example of three types is shown below.

Example: Response to step input with three different kinds of lag: exponential, sigmoid and transmission.



Transmission lags normally degrade performance with a compensatory display, even though the lags may be so small (e.g., .06 second) that the operator is unaware of them.[111]

Note: Backlash (free play) and transmission lag are similar in their initial effects upon operator performance.[45] This is to be expected because both initially affect the system in a similar manner. With either present, a certain time period elapses before the system starts to respond to the operator's initial control movement.[100]

Exponential and sigmoid lags may either improve or degrade performance, depending upon their interactions with other parts of the machine dynamics. For example, when the gain is optimally set, the addition of an exponential lag between operator's control output and machine output will degrade performmance.[25,76] However, if the gain is too high (e.g., if it causes continual overshooting), the addition of a lag will serve to reduce output amplitude and, thereby, may improve performance.[95]

b. effects of gain

In zero-order control systems, the gain is one of the most critical factors affecting tracking performance. (A detailed discussion of its importance and of procedures for setting it is presented elsewhere.[46]) In higher-order control systems, the relative gain (or sensitivity) of each output term (viz., position, rate, acceleration, etc.) is also of prime importance. As explained in the preceding paragraph, gain interacts with other attributes of machine dynamics.

c. effects of integration

The number of integrations between operator's control output and machine output determines the control order of the system (e.g., no integration is zero-order control, one integration is first-order control, etc.). (See also Section 1.1.1.)

The optimum number of integrations depends upon: 1) the input frequency and 2) the availability of feed-back and feed-forward loops around each integrator. Under most circumstances the number of integrations should be minimized. However, for very slow input frequencies, first-order control (one integrator) is superior to zero-order control (no integrators).[24] Also, if feed-back or feed-forward loops can be supplied to "aid" or to "quicken" the system (see Sections 2.4 and 2.5 respectively), then at least two, and on occasion four or five, integrators are desirable.

2.3.3 Recommendations

a. general

The different attributes of machine dynamics all interact with each other and with control resistance in a complex manner. Hence, no recommendations can be made about any one without considering the others.

> Example: It may be necessary in some instances to increase lags and in others to decrease lags, depending upon the rest of the machine dynamics. Therefore, a general recommendation to the effect that all lags are detrimental to performance and should be minimized is incorrect.

In a very few cases, as enumerated below, some general statements can be made. In most cases, however, the designer should determine the optimum dynamics experimentally, and in so doing, he must evaluate all attributes concurrently and no one independently.

b. specific

1) Under most conditions, transmission lags should be minimized.

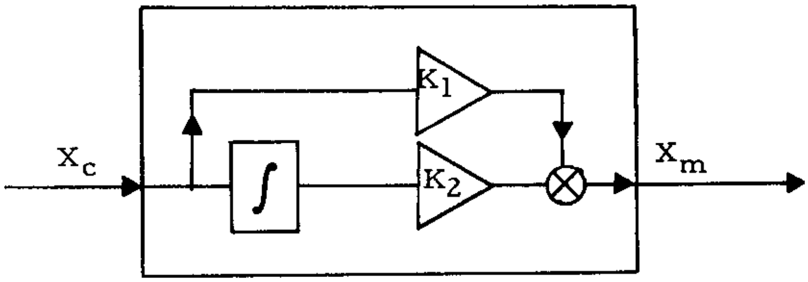
2) When the input is complex in nature, the number of integrations should be minimized unless the system is "aided" or "quickened."

2.4 AIDED TRACKING

2.4.1 General Concepts

a. rate aiding

Rate aiding is the simplest and most common type of aided tracking. It is a first-order system combining position control plus rate control. Thus, a change in the operator's control output (X_c) imparts a change in both position and rate to the machine output (X_m).



$$X_m = K_1 X_c + K_2 \int X_c dt$$

b. aiding constant

The fraction K_1/K_2 is known as the "aided tracking time constant" or "aiding constant." Since K_2 is a number divided by a time interval, usually seconds, the aiding constant is usually reported in seconds. Proper selection of this constant is critical for effective rate-aided tracking. (See also Section 2.4.3.)

2.4.2 Effectiveness of Aided Tracking

a. prime advantage

The prime advantage of aiding is that a simple operator response controls a complex machine output. For ramp inputs, rate aiding will reduce the number of responses made by the operator while improving system performance.

b. response complexity

A characteristic of aiding is that the operator must make more control movements in order to obtain a simple (step) machine output. Therefore, for step inputs, aided tracking is more difficult than simple position control. If, as has been suggested,[24] in tracking complex high frequency inputs "the operator's ability to follow continuously is taxed to the point where the tracking problem begins to resemble that posed by a course composed of a succession of step function changes," then aided tracking for such situations should result in poorer performance than position control. Evidence to date tends to confirm this hypothesis.[24]

c. type of display

The effectiveness of aiding is also a function of the type of display being used. For displays which enable the operator to estimate derivative information as well as error information, aiding loses its effectiveness. In order to be used most effectively, aiding requires that the operator make a response which is directly proportional only to the magnitude of error. If the operator's response is proportional to a combination of error plus error rate, the prime value of aiding is lost, and the operator may perform more poorly than if there were no aiding present.

2.4.3 The Aiding Constant

a. continuous inputs

For inputs which are presented continuously to the operator, the optimum constant has been estimated to range from 0.2 second to 0.8 second. Experimental evidence suggests that 0.5 second approaches the most satisfactory single value.[59, 97, 105] However, additional evidence indicates that the optimum constant is a function of input frequency and complexity[24, 89, 103] and of the type of display.[22, 77] (See Section 2.1 for descriptions of different types of displays.)

b. intermittent inputs

For inputs which are presented intermittently to the operator (e.g., radar displays), the optimum constant is the time interval between corrections.[84] Thus, for a radar with a sweep rate of six cycles per minute, the optimum aiding constant is 10 seconds if the operator makes corrections every sweep, 20 seconds if he makes corrections every other sweep. If he responds in an unpredictable manner, the constant should be set by a computer mechanism.

c. effects of degrading factors

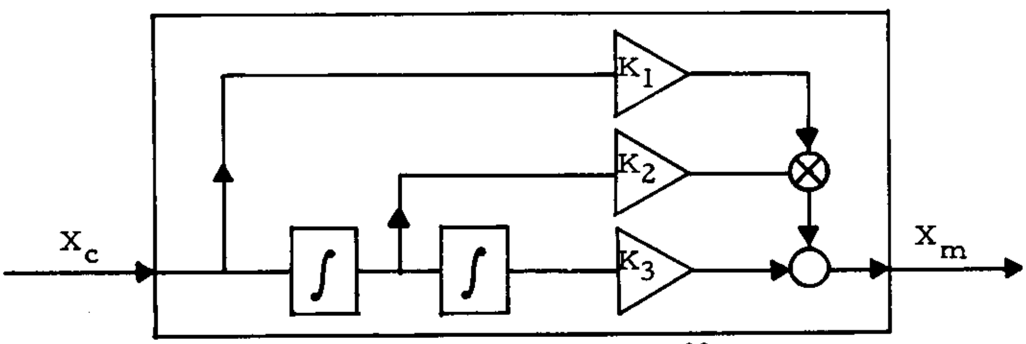
The above values are applicable only when there is no time lag, backlash or other degrading factor in the system. The introduction of lags at any point will result in interactions with other system parameters and will affect tracking performance.[95] Backlash has a somewhat similar effect as certain types of time lags, and thus, may also change the optimum aiding constant.[45, 59, 100]

CAUTION: BECAUSE OF THE NUMEROUS FACTORS AFFECTING THE OPTIMUM AIDING CONSTANT AND BECAUSE OF ITS IMPORTANCE IN IMPROVING TRACKING PERFORMANCE, THE CONSTANT SHOULD BE CONFIRMED EXPERIMENTALLY FOR EACH SPECIFIC SITUATION.

2.4.4 Addition of Higher Derivative Terms

a. course input

When course input changes very slowly, additional terms (beyond position and rate) will aid performance. For inputs with a constant rate, an acceleration term added to the position and rate terms will permit the operator to track with a minimum number of control movements.



$$X_m = K_1X_c + K_2\int X_c dt + K_3\iint X_c dt$$

In like manner, for inputs with a constant acceleration, a fourth term (viz., rate of change of acceleration) should be added.

b. constants

Under conditions of no lag or backlash, an optimum ratio in the range of 1: 2: 8 to 1: 4: 8 for the first three terms (K_1, K_2 and K_3) has been shown to be superior to others.[97] However, here again the designer should confirm the optimum ratio experimentally for his given conditions since they may depart significantly from those upon which the quoted ratios were determined.

2.4.5 Recommendations

a. when to use aiding

Aiding should be used when the input (desired output) has a constant rate, a constant acceleration, or some constant higher derivative.

b. how to use aiding

1) The number of terms used in aiding should exceed by one the derivative of the input which is constant. Thus, for a constant input rate there should be three terms in the aiding (viz., position, rate and acceleration); for a constant input acceleration there should be four terms in the aiding, etc.

2) Aiding constant should be determined empirically. (For discussion, see Sections 2.4.3 and 2.4.4.)

2.5 QUICKENING

2.5.1 General Concepts

a. problem of control in higher-order systems

Higher-order control systems comprised of pure integrations tend to be more difficult to control than lower-order ones.

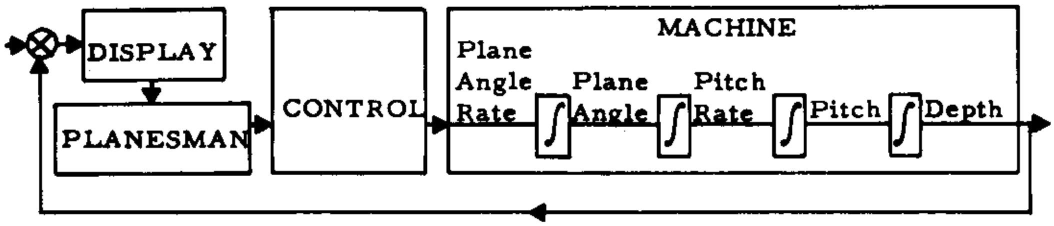
A third-order system, as exemplified by helicopter pitch control, is extremely difficult to control under conditions of instrument flight when the pilot is provided with only an attitude display.[3]

A fourth-order system, as exemplified by submarine depth control, is impossible to control when the operator (planesman) has only a depth gage.

In many systems, particularly those involving vehicular control, control order is determined by the relationship between the control surface(s) and the machine output. Since this relationship cannot be altered without completely redesigning the machine (e.g., changing the aerodynamic characteristics of an aircraft), the integrations present cannot be eliminated.

> Example: In fleet-type submarines with a single planesman controlling depth, the position of his control directly affects the rate of change

(first derivative) of plane angle (the control surface); plane angle directly affects the acceleration (second derivative) of pitch; and pitch directly affects the rate of change of depth. Hence, the planesman controls the fourth derivative of depth (i.e., there are four integrations between operator output and system output). One integration can be eliminated by redesigning the machine so that the operator directly controls plane angle rather than plane angle rate. However, as long as submarine depth is controlled primarily by planes, there will always be at least three integrations present.



b. general purpose of quickening

Normally the higher-order systems just described are controlled by providing the operator with an array of displays. One display gives output information and the rest provide derivative information about the output.

Example: For one-man depth control of a submarine, the operator might be provided with displays showing depth (output), depth rate or pitch (either being the first derivative of output), pitch rate (second derivative of output), and plane angle (third derivative of output).

With such an array, the operator's task is quite difficult: he needs to know how each indicator must move in order to achieve a desired output. To perform his task well, the operator must:

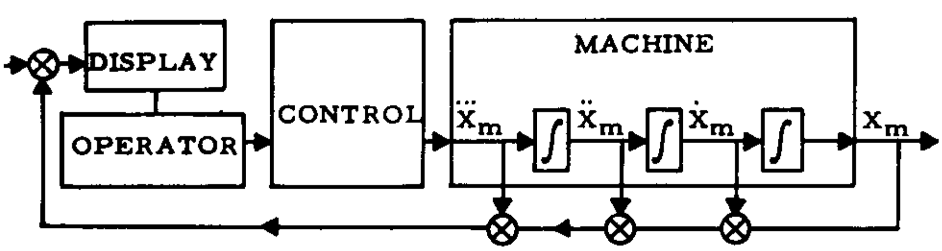
1) reach a high level of skill and 2) attend constantly to his displays.

The general purpose of quickening is to simplify the operator's task by providing him with a single display requiring a minimum of mental computation on his part in order to achieve the desired output.

2.5.2. Application

a. design of a quickened display

Complete quickening consists of a single display which provides the operator with immediate knowledge of the results of his own control actions before they become available from sensing of the system's actual output. The moving indicator on the display (X_d) represents the sum of the machine output (X_m) and its derivatives. This information (X_d) is obtained by placing feedback loops from the machine output and each of its derivatives back to the display.



$$X_d = K_1X_m + K_2\dot{X}_m + K_3\ddot{X}_m + K_4\dddot{X}_m$$

where: The K's are the weighting constants for the various terms.

$\dot{X}$ is the first time derivative of X, $\ddot{X}$ is the second time derivative of X, etc.

Although time derivatives of the machine output are often used, this procedure is not essential. Space derivatives (i.e., those showing how output changes per unit of distance rather than per unit of time) can also be used.

In a perfectly quickened system, the display tells the operator where to position his control. With a compensatory display, the magnitude of the error is directly proportional to the distance which he must move his control; and since his task is to minimize error, he behaves like a simple amplifier. The error indicator responds immediately to his control movement, thereby making his task very simple.[11]

Note: Simplifying the operator's task is not always the ultimate goal in design. (See Section 2.5.3 for a general evaluation of quickening.)

b. determination of weighting constants

The weighting constants (K_1, K_2, . . . , K_n, as described in the previous subsection) are very important in the proper design of a quickened display.[3] An improper selection of constants can result in an uncontrollable system.

To some extent, the selection of the constants determines the manner in which the machine achieves its desired output. For example, the constants may be such as to cause the machine to correct for a step-input very rapidly but with some overshooting, rather than slowly but with no overshooting.

The most desirable set of constants can vary with certain factors, such as speed. For example, the optimum set of constants for a vehicle moving at a slow speed may not be the optimum one for the same vehicle moving at a fast speed. It is frequently desirable to make such terms non-linear in order to improve system performance.

Note: In general, for quickened systems the weighting constants affect output in the same manner as they do for fully automatic systems.

There is, as yet, no simple but general analytical method which will permit the designer to determine these constants for all systems. With complex systems, the most effective method is an empirical one in which all weighting constants are varied simultaneously on a simulator (e.g., analogue computer) until the system responds in the desired manner.

c. partial quickening

Ideally, there should be one term in the quickened display for each order of the control system. Thus, for a third-order system, there should be four terms determining the quickened display (viz., machine output plus its first three derivatives). In some systems (e.g., certain guided missiles) it is impossible to sense directly some of the derivatives of output, and it is extremely difficult to obtain these derivative measures indirectly by such means as differentiating the output or installing rate gyros.

Such systems cannot be fully quickened, but there remains some advantage in partially quickening the display. The number of derivative terms which must be present in order for partial quickening to be effective has not been determined. In general, the more terms which are present, the better will be the partial quickening. The terms closest to the machine output (viz., position, then rate, etc.) are more essential than higher-order terms. Skipping any term (e.g., omitting the first derivative term but including the second) will generally result in system instability.

d. aiding and quickening

Aiding (see Section 2.4) and quickening are alike in that both: 1) simplify the operator's task, and 2) involve placing loops around the integrators in the machine. They differ in that aiding directly affects machine output while quickening is normally thought of as directly affecting the input to the operator.

With aiding the operator's display shows the actual state of the system. However, his output is changed so that he can control an aided system with simpler responses than those required to control the same system when unaided.

With quickening the operator's display shows what he should do with his control but not the actual state of the system. Quickening, in itself, does not affect output. To achieve a desired output, the operator should make the same set of responses, regardless of whether or not the system is quickened.

2.5.3. Evaluation

a. major advantages of a quickened display

1) It simplifies the operator's tracking task, and results in improved performance[3, 10, 63] except in those cases where either: a) the original task is very simple, or b) the operator has already reached a high level of skill in performing it.

2) It minimizes the time required to train an operator for the task.[63]

3) It frees some of the operator's time so that he can perform other duties concurrently.[10]

4) It eliminates most of the detrimental effects resulting from "reversal errors" (i.e., from the operator's starting to move his control in the wrong direction when correcting an error), thereby reducing the importance of such human engineering considerations as direction-of-movement relationships and frame of reference (inside-out vs. outside-in).[11]

5) It requires less ability to perform the tracking task, thereby facilitating the selection problem by permitting operators to be drawn from a larger population.

6) It permits the execution of a desired maneuver in a very short time, the limiting factor being the performance capabilities of the vehicle rather than the skill of the operator.

7) It permits repeatability so that a desired maneuver will occur in the same way each time it is performed.

8) It makes system performance much less dependent upon human performance; the designer rather than the operator determines what the performance characteristics of the system will be.

9) It permits "safety" terms to be incorporated into the display (e.g., in an aircraft a non-linear term from a g sensing mechanism can be fed into the display so that, in properly responding to his display, the pilot will never pull excessive g-forces).

b. major disadvantages of a quickened display

1) It does not provide the operator with information about the actual state of the system. (The system may be in a dangerous condition without the operator's being aware of it.)

2) In order to be useful when there are high frequencies present in the input, additional circuitry in the form of anti-bias networks must be provided.[11]

3) Under some conditions, it is less satisfactory than a fully automatic system, and the system can often be redesigned easily to become completely automatic.

4) Although theoretically it reduces to one the number of displays required by the operator, in actual practice it usually adds an extra display since the "normal" displays showing the actual state of the system will, in most cases, still be desired by operators.

5) If the operator does a perfect tracking job when using the display, he will always achieve his desired output in the same manner (e.g., by following the same flight path). However, the best manner for any one situation is not necessarily the best for others (e.g., under some conditions he must change his output very rapidly even though this results in overshooting, while under other conditions overshooting is intolerable).

Note: It is possible to use a quickened display and still vary the manner in which the final output is achieved. For example, the operator can deliberately cause his indicator to move beyond the desired position before correcting it in order to reach his desired output quickly. However, this type of operation requires additional training, and is risky because the operator does not know precisely what his control movement is making the system do.

2.5.4 Recommendations

a. when to use quickening

No general set of rules can be provided which will state the conditions under which quickening should be used. However, the list of advantages and disadvantages enumerated previously (Section 2.5.3) should aid the designer in determining whether quickening is appropriate for his particular problem.

b. how to use quickening

When a quickened display is to be used, the following requirements should be met:

1) As many derivative terms as necessary should be included, up to the n'th derivative in an n'th-order control system.

2) The weighting constants for all terms should be determined empirically.

3) If the operator requires information about the actual state of the system he is controlling, auxiliary displays should be provided.

PART 3

HUMAN TIME LAGS

This part presents detailed information about human time lags in both open-loop and closed-loop systems and recommendations for minimizing such lags. There are three main sections:

3.1 Basic information concerning human time lags.

3.2 Factors affecting human time lags.

3.3 Human time lags in watchkeeping situations.

3.1 BASIC INFORMATION CONCERNING HUMAN TIME LAGS

3.1.1 Introduction

a. definitions

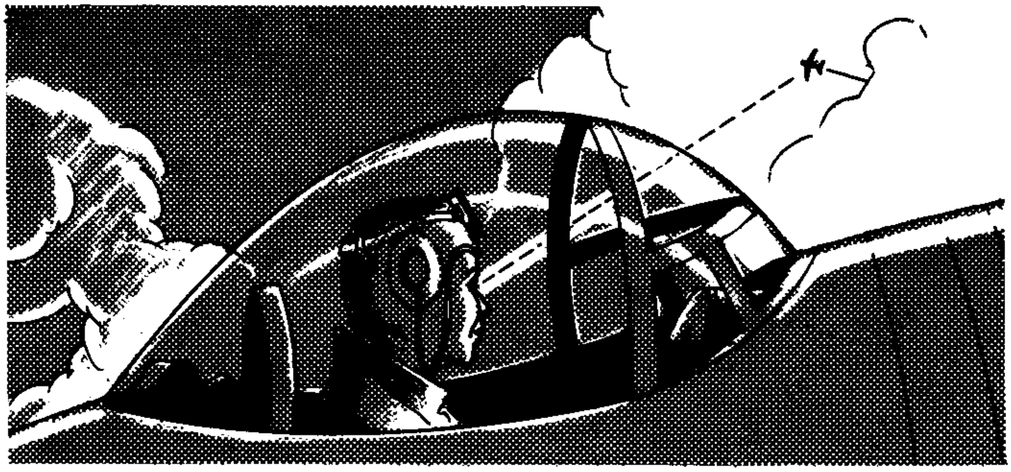
"Human time lag" is used synonymously with "reaction time" in this report. It is the time interval elapsing between the beginning of the signal (stimulus) and the completion of the operator's response. Hence, it includes the time required by the operator to sense the signal (sensing time), plus that required to decide what response to make (decision time or thinking time), plus that required to respond (movement time).

> Note: Care should be taken because various authors do not always define reaction time in the same way. Some define reaction time as ending when the operator starts to make his response rather than when he finishes making it. In this report reaction time includes completion of the response.

b. importance of human time lags

Human time lags contribute to the total operating time of man-machine systems. The importance of such lags depends upon the extent to which operating time affects the over-all goal or mission of the system. For some systems, time requirements are unimportant provided the assigned tasks are carried out with the required degree of precision (e.g., calibration of delicate measuring devices). However, in other systems (as exemplified below) total operating time is critical for the success of the mission, in which case human time lags can become very important and, on occasion, the determining factor of the mission's success.

Example: As an aircraft comes out of a cloud, its pilot sees another aircraft approaching it on a collision course. Under some conditions the approximate times involved in his taking corrective actions are listed in the table following.[20, 85, 106]



Event	Process	Approximate time (seconds)
Pilot detects object; eye moves to center and focuses on object. *	Awareness to fixation	0.3
Pilot sees object clearly and interprets image.	Perception	0.6
Pilot selects course of action.	Decision	0.5
Pilot makes control movement.	Response	0.3

*The object may have been in the visual field for some time without having been detected. Its probability of detection is affected by many factors, such as approach angle, size, contrast, operator alertness.[57]

Hence, a total of approximately 1.7 seconds transpires before the pilot moves the control plus some additional time (aircraft response time) before the aircraft changes its course and/or speed. If both aircraft are flying at 600 miles per hour, they will approach each other at a rate of one-third mile per second; at 1,800 miles per hour, at a rate of one mile per second. Since aircraft-to-aircraft visual detection range varies widely as a function of atmospheric and illumination conditions, a collision might occur without either pilot's being able to avoid it.

3.1.2 Sensing, Response and Decision Times

a. sensing time

The time required to sense a signal is a function of the properties of the signal (e.g., size, intensity, duration) and of the particular sense stimulated. (For details, see Sections 3.1.1 and 3.1.2.) Under simple conditions sensing time is a few hundredths of a second.

b. response time

The time required to respond to a signal is a function of the complexity of the response (e.g., force, displacement and precision requirements) and of the limb being used. (For details, see Section 3.2.6.) Very simple responses (e.g., pushing a button) involve a few hundredths of a second, but more complex responses (e.g., positioning a joystick precisely) take a few tenths of a second.

c. irreducible minimum

With the simplest types of tasks, where no decisions are required, the reaction time resulting from the sensing and response times has a minimum of approximately 0.06 second.[108, 114] Examples include involuntary eye blinks (0.06-0.08 second) and finger tapping (0.08 second).

d. decision time

Decision time varies widely, depending upon the complexity of the decision to be made. (For details, see Section 3.2.3.) When the decision is extremely simple, there is a slight increase in total reaction time (e.g., voluntary eye blinks take approximately 20 per cent longer than involuntary ones). In general, decision time is proportional to the logarithm of the number of alternative choices.

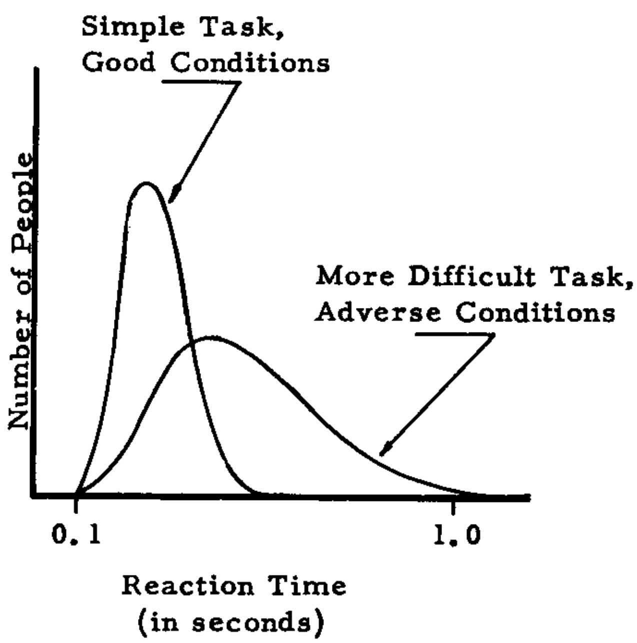
3.1.3 Variability in Reaction Time

a. general

No single value can adequately represent the reaction time for a given task. Given the identical task, there will be variations among individuals and within any one individual from one time to another.

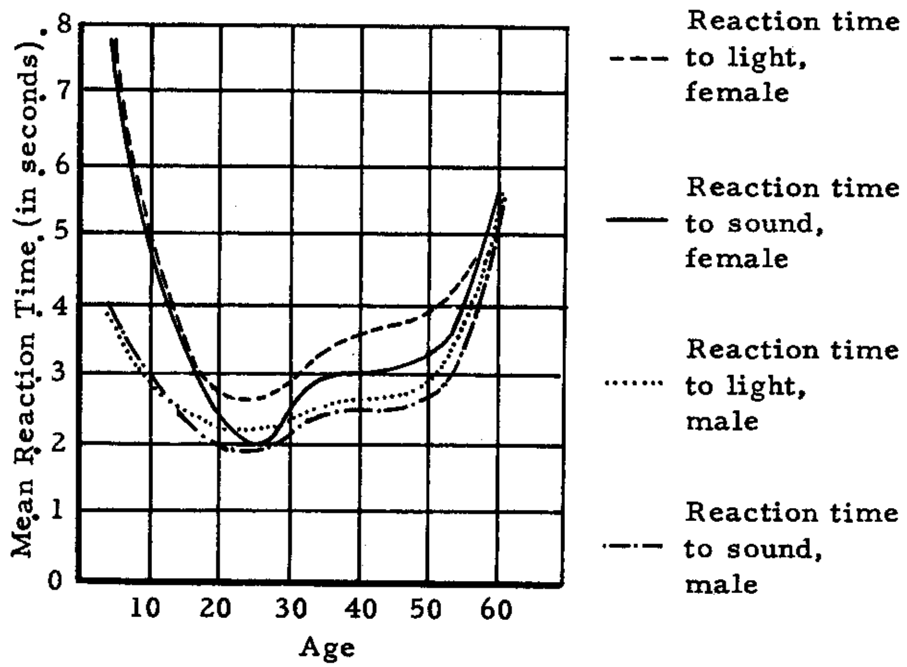
Example: The average time required by a group of men to make a simple response to an auditory signal was 0.170 second; however, the fastest man averaged 0.125 second and the slowest 0.215 second.[114]

Differences among people tend to increase as the task becomes more difficult or exacting and as the conditions of work become more adverse. The extent of this change in reaction time depends upon the particular conditions and individuals involved.[114]



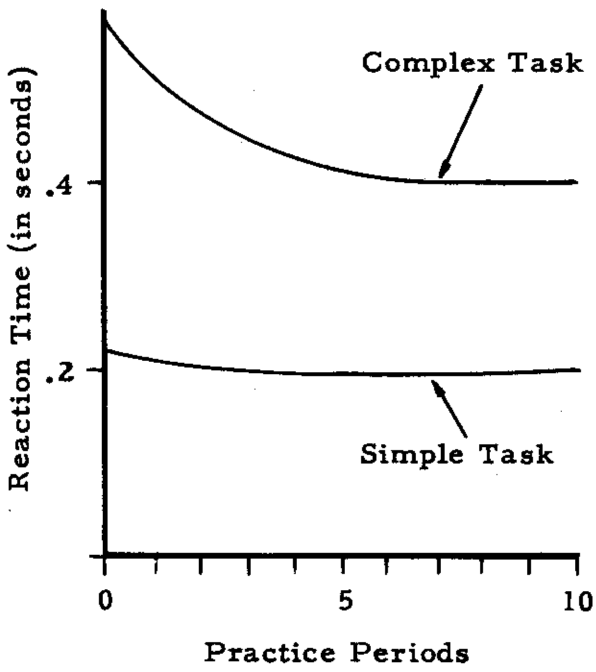
b. differences of age and sex

Older people (from the mid-fifties on) have a slightly longer reaction time than younger people (especially those in their twenties). Males have a slightly shorter and more consistent reaction time than females. The following figure shows the influence of age and sex upon the time required to make a simple response to a visual and an auditory signal.[116]



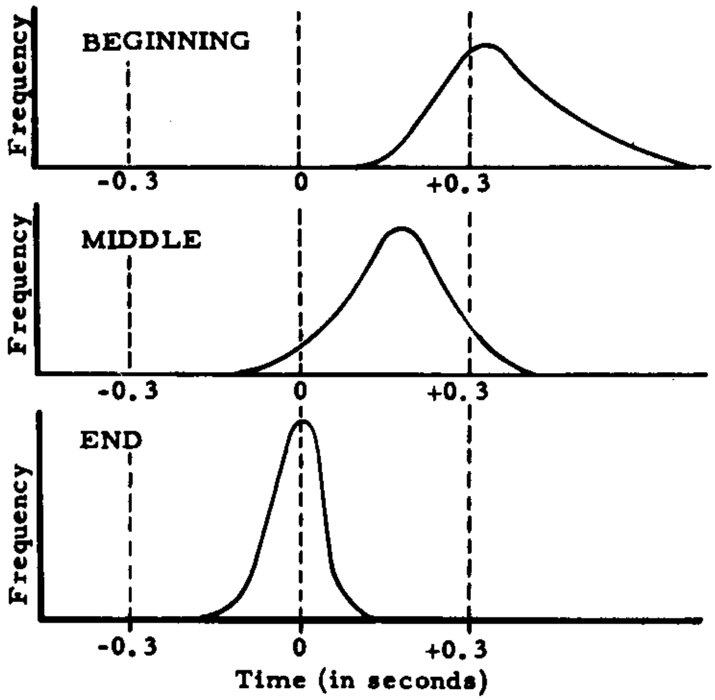
c. effects of practice

The general effects of practice depend upon the task and the conditions of work. (See also Section 3.2.7.) Simple tasks performed under good working conditions result in small time lags, which show little reduction with practice. Complex tasks, however, do show improvement, which results from a reduction in decision time, a dropping of irrelevant movements and a refining of essential movements.[114]



When the same signal occurs at a constant rate, with practice, the operator can learn to anticipate the occurrence of the signal and to reduce his time lag drastically.

Example: A light comes on every five seconds, and the operator must turn it off by pressing a button. Typical performance curves (time vs. frequency) for a group of operators, as a function of practice, are shown in the figure below.



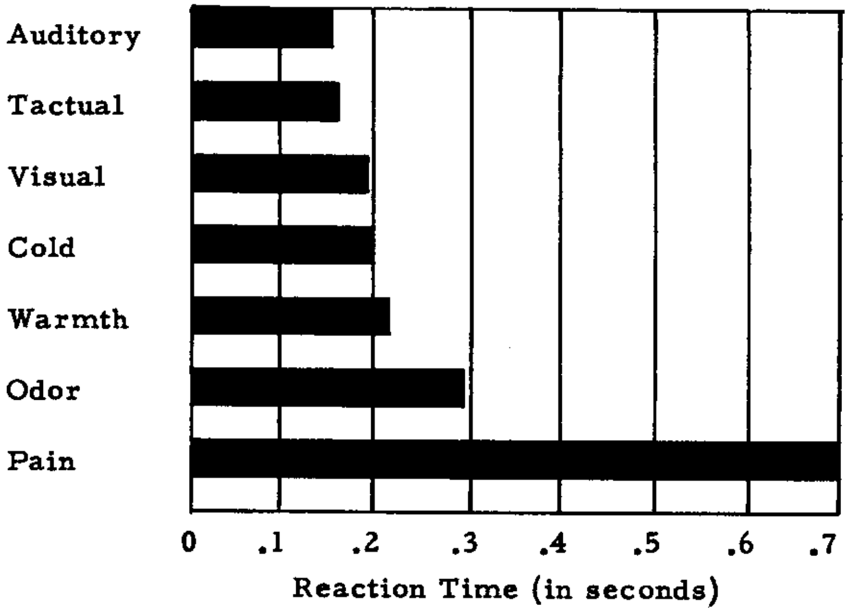
Note that at the beginning of the task, the average time lag is approximately 0.3 second. At the middle of the task, the average lag has decreased as operators learn to anticipate the signal, and there are a few "negative" lags (i.e., some operators have anticipated that the signal will appear before it actually does and have responded accordingly). At the end of the task, the average lag is approximately zero, and there are as many "negative" lags as there are positive ones.[26, 91, 113]

3.2 FACTORS AFFECTING HUMAN TIME LAGS

3.2.1 Sense Used

a. reaction time for each sense

The figure below shows the average simple reaction time for seven sense modalities.[108]



From the figure, note:

1) All signal-action processes have time lags.

2) For the three senses most likely to be used (viz., auditory, visual and tactual), the differences in time lags are small and probably insignificant for most, if not all, applications.

3) Odor and pain, which are physiological warning devices, have long reaction times.

Caution: Although these times are useful in making comparisons among senses, the times shown are not typical of those expected in practice because other factors are usually present which tend to increase reaction time. For example, in responding to a warning light, a pilot's reaction time may be much longer than 0.2 second because: 1) he is attending to other tasks and might not see the light immediately, and 2) once he does see the light, the decision he must make is quite complex and, therefore, takes additional time.

b. reaction time for combined signals

Reaction time for combined signals (signals going to two or more senses simultaneously) is no shorter than for the one signal giving the fastest reaction time.

c. recommendations

The value obtained from selecting the sense to be used solely on the basis of reaction time is small; other design considerations are nearly always more important. For example, auditory signals are poor when the ambient noise level is high; visual signals are poor when they may appear outside the normal viewing area of the operator.

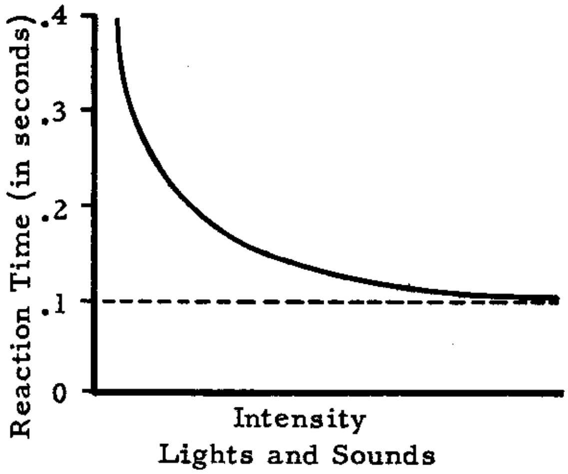
3.2.2 Signal Characteristics

a. size

The larger the size of a (visual) signal, the faster will be the reaction time, up to some limiting value.[108, 114]

b. intensity

The greater the intensity of a signal, the faster will be the reaction time, up to some limiting value. A typical curve for either light or sound is shown in the adjacent figure.[108, 114]



c. duration

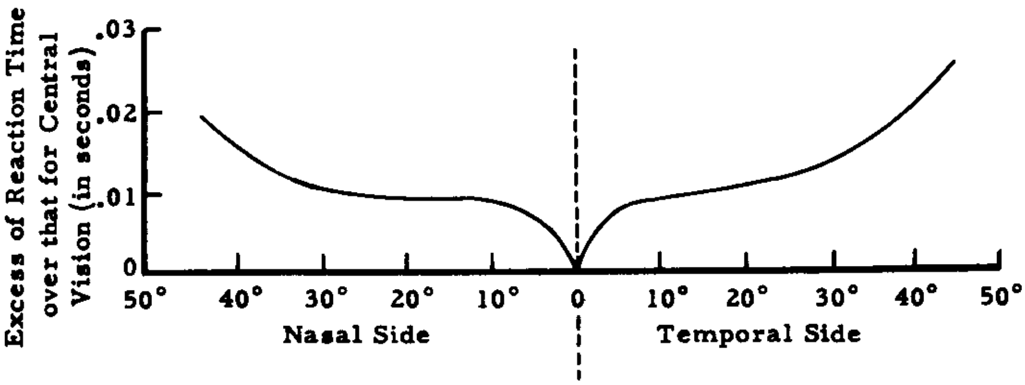
The duration of a signal has very little effect on reaction time provided the signal is easily visible or audible. Very short signals (0.1 second or less) may produce longer reaction times; however, their main disadvantage is the likelihood that they may not be noticed at all.[108] (See also Section 3.3.3.)

d. quality

Although no general relationships have been established, the quality of certain signals does evoke faster reaction times. For example, high frequency sounds have a slightly faster reaction time then low frequency ones.[15]

e. location

There is a faster reaction time to visual signals which strike the center rather than the periphery of the eye.[108]



f. intermittency

There is no difference in simple reaction time to flashing or steady signals. However, when one intermittent signal has to be distinguished from another by its flash rate, or when an intermittent signal has to be distinguished from a steady one, reaction time is directly related to the flash length of the intermittent signal, because flashing and steady signals are indistinguishable until the flash is ended.[52, 55]

g. recommendations

1) Visual Signals:

Visual signals should be of sufficient size, brightness and duration to be easily and obviously seen. (Detailed recommendations for their design are presented elsewhere.[5]) Duration should never be less than 0.5 second, and, where applicable, the signal should last until the appropriate response has been made.

Nothing is gained in speed of reaction by using a flashing signal rather than a steady one. However, in many applications a flashing signal is preferred to a steady one because of its greater attention-demanding value.[58]

Important signals should be placed directly in front of the operator or as close to this location as possible.

2) Auditory Signals:

Auditory signals should be sufficiently different from the prevailing noise background to be easily and obviously heard.

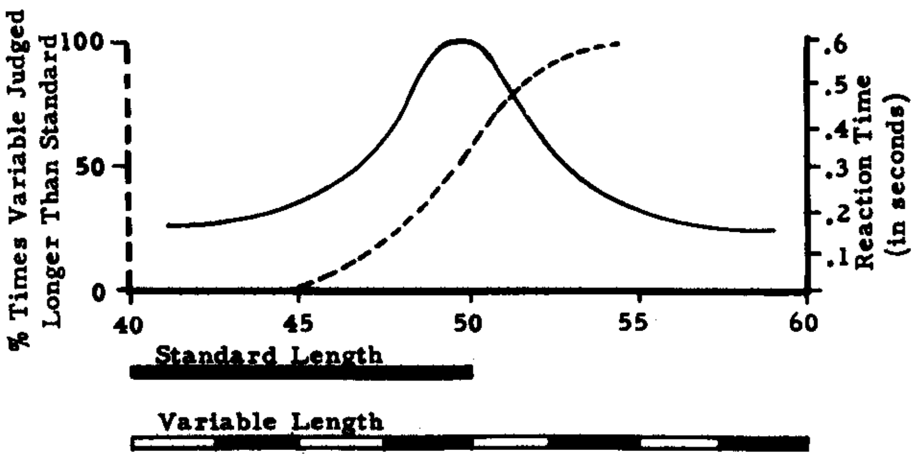
Signal duration should be at least 0.5 second, and, where applicable, the signal should last until the appropriate response has been made.

3.2.3 Signal Complexity

a. discriminability of signals

In some instances the signals which are to be responded to are not perfectly discriminable (distinguishable) from each other. The act of discrimination takes time: the more difficult the discrimination, the longer the time.[33, 94, 114]

The figure below demonstrates the change in reaction time when judging which of two lines is longer. Reaction time continues to decrease after the person is able to discriminate perfectly. Reaction time is a sensitive measure of the observer's uncertainty, so that when he is just barely capable of making a correct judgment, the extra effort is reflected in a longer reaction time.[114]



For signals which can be quantified in familiar and meaningful terms (e.g., area, size, length), the following formula approximates the reaction time (RT) to discriminate between two signals (S_1 and S_2):[33]

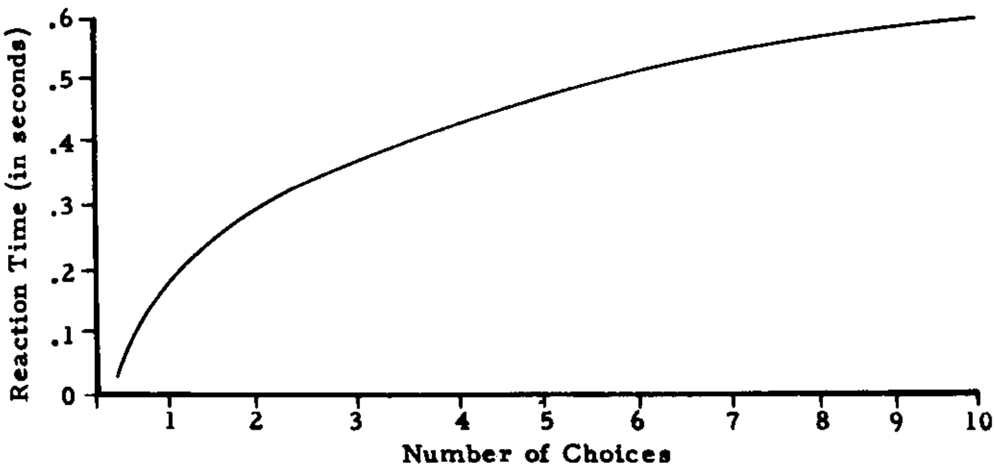
$$\text{RT (in seconds)} = \frac{C}{|\log_{10} S_1 - \log_{10} S_2|} + T_m$$

C is a constant which varies with the type of task and the type of signal. For a given type of task and signal, C may be determined from one or two trials, and the equation may then be used for all values of S_1 and S_2.

T_m is movement time, which may be difficult to separate from decision time since the decision may be continuing while the movement is being made. If the total reaction time is less than 0.2 second, movement time should be disregarded.

b. number of signals

As the number of available signals increases, the time required to respond to any one also increases.[61, 65] The following figure shows how reaction time increases as the number of signals increases when: 1) each signal and response are perfectly paired and distinct, 2) there are no variables or distractions in the situation except the array of signals, and 3) the operator is practiced and well motivated.



This curve is defined by the following formula:[61]

$$RT = C \log_{10} (N + 1) + T_m$$

RT: Reaction time, in seconds.

N: Number of choices.

C: Constant. For completely discriminable signals and ungraded responses, this will vary from 0.5 to 0.65 for different individuals.

T_m: Movement time. (See discussion in preceding paragraph.)

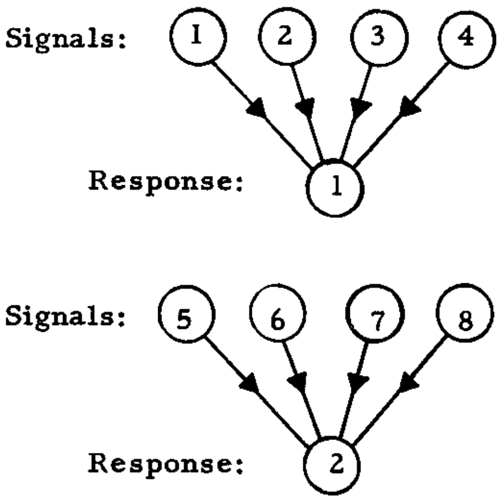
In practice, there will be limitations to the number of signals to be used because of the confines of the workplace.

There are three important cases when the above equation does not apply:

1) When all possible signals are not equally likely to occur. The most likely signals will have the shortest reaction time; the least likely signals will have the longest.[32]

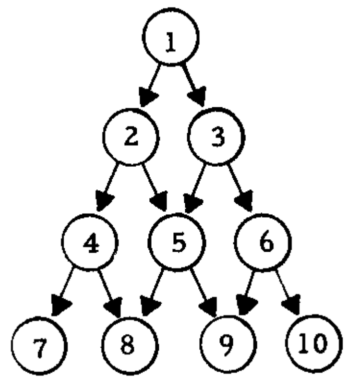
2) When the signals can be grouped in some meaningful way. Reaction time will tend to be proportional to the number of groups rather than the number of separate signals.[73]

The simplest example is when different signals require the same response. In the drawing below, each of the four signals within a group requires the same response. There is approximately the same reaction time for two <u>groups</u> of signals as for two individual signals.[49, 102]



3) When the signals are sequentially arranged. Once the operator learns the arrangement, reaction time will be a function of the number of signals which can occur at the next sequential step.

In the adjacent drawing, any of the 10 signals can occur at the outset. However, once signal 1 through 6 occurs, only two possible signals can follow (e.g., only signals 4 and 5 can follow signal 2).



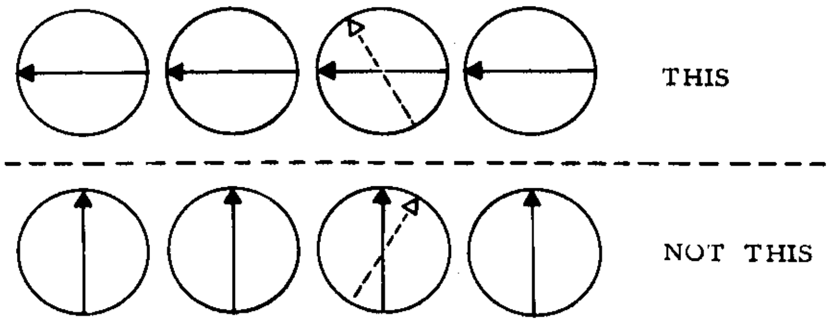
c. discriminability and number of signals

Reaction time is generally increased more when discriminability is reduced than when the number of signals is increased.

Example: In one situation the discriminability of an array of signals is reduced by 10 per cent (i.e., for a given time to react, operators make 10 per cent more errors in discriminating among the signals). In a second situation the number of signals is increased by 10 per cent. In order to bring about error-free performance, the time allowed for response has to be longer in the first situation than in the second.[12, 33]

d. spatial arrangement of signals

By suitable design and arrangement of displays, the time required to checkread a series of displays can be reduced to approximately that required to checkread a single display.[102] In the recommended array illustrated below, the operator has to decide only whether the pointers form a straight line or not, which is easier than deciding whether the pointers are all parallel.[5]



e. recommendations

1) The number of signals should be kept to a minimum for the required task; each additional signal will increase the time required to respond to any one.

2) When the signals are not independent, they should be arranged in such a way that the operator can easily see their relationships.

3) Instruments should be properly designed and arranged on a panel to facilitate reading signals. (Detailed recommendations for instrument design and panel layout are covered elsewhere.[5,47])

3.2.4 Signal Rate*

a. psychological refractory period

In tracking tasks the maximum rate of response by the operator is two to three times per second, regardless of how high the demand rate may be.[60, 109] This maximum rate is due in part to man's inability to respond to a new signal while the previous signal and its associated decision are being processed, i.e., man is in a "psychological" refractory period.[35, 112]

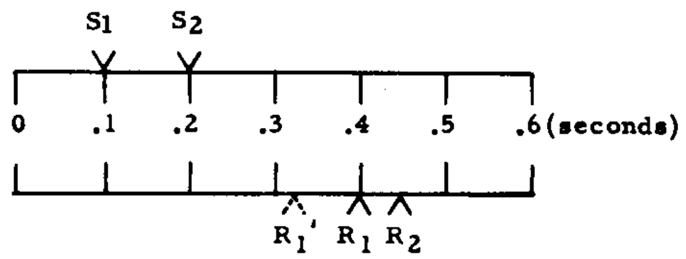
> Note: This differs from an "absolute refractory period" which results from neural impulses being limited in transmission to a rate of approximately one per millisecond.

b. intervals between successive signals [35, 112]

1) When two successive signals occur within 0.1 second, they are most likely to be treated as one signal requiring a double response. The double response takes longer to start than a response to the first signal alone would take.

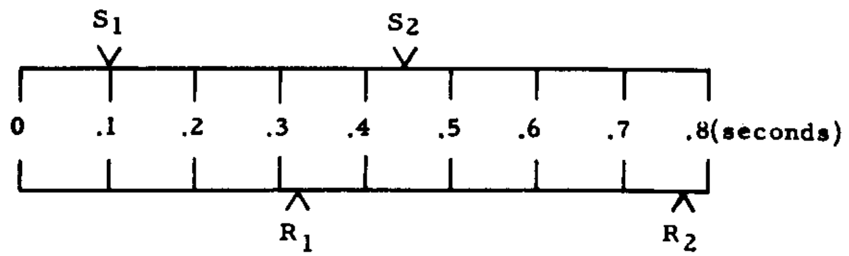
*This section covers only those situations in which signals are independent and are not "stored" by the operator for future response. Thus, tasks such as typing and piano playing are not considered.

Example: A green light calls for a control movement to the left; a red light, one to the right. If a green light appears and is followed 0.1 second later by a red light, the operator will probably respond as if he received one signal telling him to move his control left and then right. The time required to initiate his response will be longer than if he were responding to the green light by itself.



S_1 = First Signal (green light)
S_2 = Second Signal (red light)
R_1 = First Response (leftward)
R_2 = Second Response (rightward)
R_1' = Response to S_1 without S_2

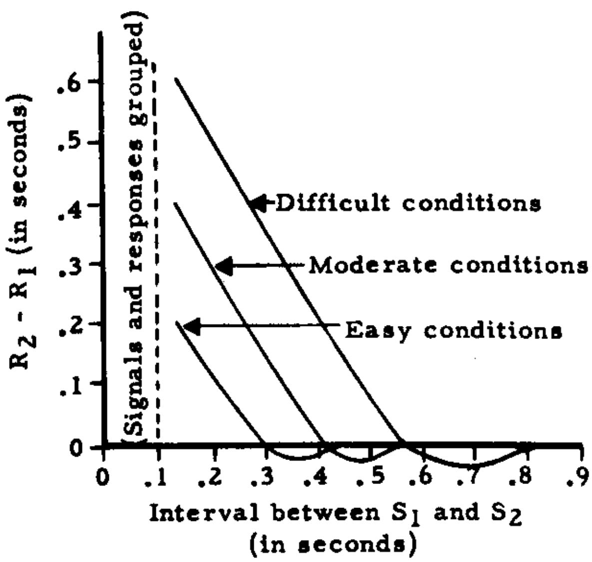
2) When the successive signals occur within approximately 0.1 to 0.5 second of each other, each is responded to individually. However, the psychological refractory period is present, and the second response takes appreciably more time than the first.



3) When the interval between successive signals is greater than approximately 0.5 second, the operator is capable of responding to each without exhibiting any refractory period. On occasion, there is a slight facilitating effect which results in the second signal being responded to somewhat faster than the first.

4) In addition to the time interval between signals, other factors affect the degree of refractoriness. Precision of response, number of choices, and other factors influencing the difficulty of the decision, all increase time lags. Anticipatory information reduces time lags.[74, 75]

The adjacent figure shows the general relations among: 1) time interval between successive signals, 2) response time to the second signal (R_2) as compared with that to the first (R_1), and 3) the general difficulty level of the task.



c. operator behavior when overloaded

If signals arrive at a rate too fast for the operator to handle, he can either: 1) keep himself current with new signals by omitting a certain percentage of responses, or 2) lag behind the current signals and, by relying on his memory, hope to catch up when the arrival rate slackens. The latter strategy is used commonly to overcome peak signal densities, such as those encountered in air traffic control operations, but is unsuccessful when the signal rate remains too high. Total failure often follows such a crisis; all contact with incoming signals is lost.[28, 29]

When any one signal source presents signals infrequently but a number of such sources are present, chances are high that at certain periods the signals will be bunched in time.[79] During these periods the operator's task is complicated further by the requirement that he switch his attention from one signal source to another, which takes a minimum of approximately 0.2 second.[79]

d. recommendations

1) Wide variations in signal rate should be avoided.

2) If bunching of signals cannot be avoided, some means should be provided whereby the operator can anticipate them, and/or the signals should remain on until each has been responded to. (See Section 3.2.5.)

3) Signals should not occur at a rate faster than two per second without providing some means of anticipation. (See Section 3.2.5.)

4) The use of many signal sources (channels) should be avoided. Operator performance will be better (i.e., the total number of signals which can be handled by the operator will be greater) with few channels and a relatively high signal rate rather than with many channels and a relatively low signal rate.[28]

5) It should be remembered that, if too much is demanded of the operator, system performance will be worse than if less is demanded but properly accomplished.

3.2.5 Anticipatory Information

a. alerting periods

A proper alerting signal preceding an action signal enables the operator to anticipate the occurrence of the action signal and reduces the time required for him to respond to it. Simple reaction times can be reduced by 40 per cent by an alerting signal.[108]

For a single signal, the alerting signal should come between 2 and 8 seconds before the signal, with preference given to the shorter period. If the time interval between the two signals is too long (beyond 8 seconds), the operator's ability to anticipate the precise time of arrival of the action signal is reduced. If the time intervals between the two signals is very short (less than 0.1 second), his lag time is greater than if no alerting signal were provided.[114]

Signals may occur in succession, in which case the action signal is also the alerting signal for the next action signal. When the interval between signals is constant, human time lags fall off until they approach zero. Most accurate performance occurs when the operator can impose a rhythm upon his movements; this is easiest when intervals are short (about 2 seconds), but intervals should never be less than 0.3 second.[74]

If the interval between the alerting and action signal is variable, the operator's reaction time is longer and more variable than if the interval is fixed. The operator learns to expect the action signal at some average interval after the alerting signal; hence, signals which occur distantly from the average one result in poorer performance.[71]

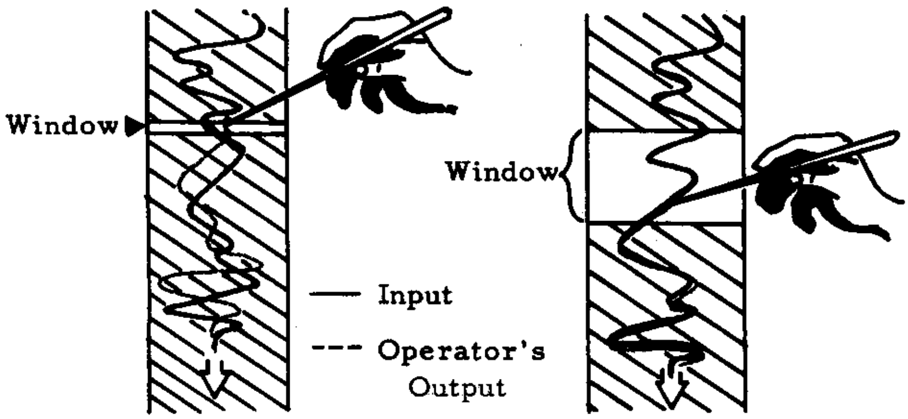
b. advance information

In some systems it is possible to provide complete or partial advance information to indicate where and/or when the action signal will occur. For example, eight action signals can be divided into two groups of four each; then a warning signal can be given to indicate the group in which the action signal will occur. Such advance information reduces the operator's reaction time to that equal to or, on occasion, even less than that of the subgroup if taken alone. [74]

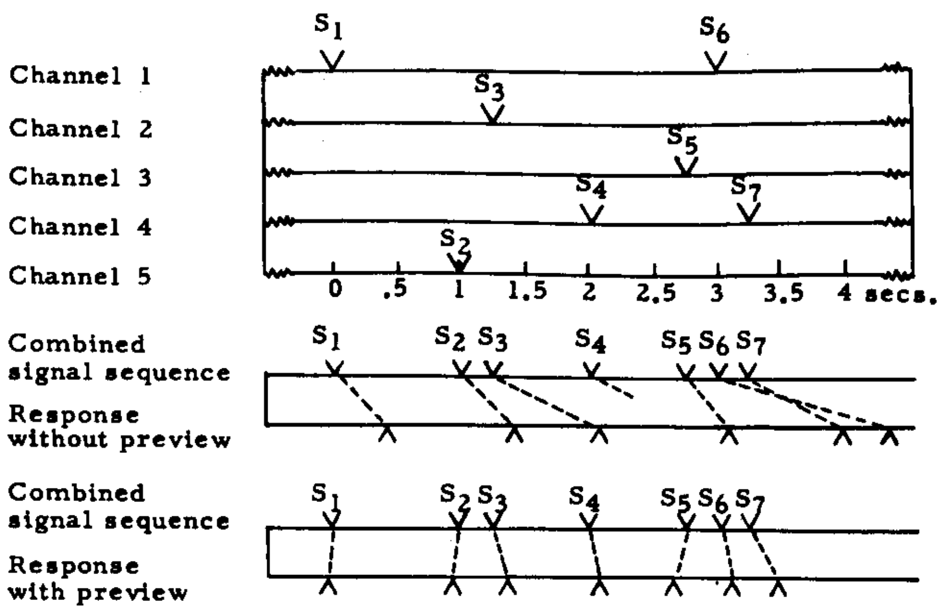
As with regular alerting signals, the time interval between signals which results in best performance is from 2 to 8 seconds for isolated tasks and from 0.3 to 2.0 seconds for serial tasks. Very short alerting signals (less than 0.1 second) are worse than none. [71]

For continuously varying signals or for successive discrete signals which occur in unpredictable patterns, advance information permits the operator to prepare a response before he must make it.

The illustration below shows a simple tracking task with and without some advance information. With a preview, there is little if any error and small time lags.



When responding to bunched signals coming from one or more channels, an operator with advance information can spread his responses over time but still respond to each signal. Without such information, he must respond to each signal as it appears.[28, 29]



c. **recommendations**

1) Alerting signals should be provided when it is necessary to reduce or eliminate human time lags.

2) Alerting signals should precede action signals by from 2.0 to 8.0 seconds for isolated signals and by from 0.3 to 2.0 seconds for signals occurring in sequence.

3) Very short alerting periods (less than 0.1 second) should be avoided.

4) Alerting periods should be kept as constant as possible.

5) Alerting signals should be used to restrict the number of choices whenever possible.

6) Advance information should be provided for tracking tasks and/or for bunched signals whenever possible.

3.2.6 Response Characteristics

a. limb used

There are only small differences in reaction time for various limbs. For simple tasks, it takes approximately 20 per cent longer to respond with the feet than with the hands. Response with the preferred limb (e.g., the right hand for right-handed people) is approximately 3 per cent faster than with the non-preferred limb.[108]

b. control design

As the required precision of adjustment increases, movement time also increases. This increase is due primarily to the fine positioning movement required.

If considerable force must be applied by the operator, response time will increase. Similarly, time will increase when the operator output is a removal of a holding force (e.g., lifting one's hand from a displaced spring-centered joystick).[108]

c. recommendations

1) When controls must be selected entirely on the basis of speed of activation, for right-handed operators the following should be the order of selection: right hand, left hand, right foot, left foot.

2) For detailed recommendations concerning control selection and design, see the special reports of this subject.[46, 47]

3.2.7 Operator Conditions

a. motivation

Although a general coverage of this topic is beyond the scope of this report, two points are in order. First, the value of improved motivation is dependent upon the degree to which man exercises control over the system output. If he has no opportunity to benefit from practice or to exercise any judgment concerning the machine, motivating factors will have little influence. Motivation is a significant factor only when system output is considerably affected by operator performance.

Secondly, the operator gains from knowledge about the goodness of his performance. This information not only aids in learning the job but also acts as an incentive toward improved performance.[54, 82] Feedback of such information should be provided as quickly as possible.

b. practice

Human time lags tend to be reduced with practice. If the operator's speed of response is very high initially (e.g., about 0.2 second), there will be little room for improvement. However, if it is relatively slow initially (e.g., 1 to 2 seconds), response speed will increase with practice because of: 1) reduction in "decision" time, 2) elimination of unnecessary movements, and 3) refinement of necessary movements, especially those of an adjusting (as opposed to a reaching) nature.[21, 114]

In highly complex tasks, response speed may continue to increase over a long period of time. However, most improvement will take place during the initial practice period of days or perhaps weeks.[21]

c. self-pacing vs. forced-pacing

When setting his own speed, man can either: 1) operate faster than when a regular pace is set by the machine, or 2) operate at the same speed but with fewer errors.[2, 27, 72] Man is variable; hence, his reaction time to the same signal will vary from time to time. When self-paced, such variations do not matter; he can benefit from an extra fast reaction time by not having to wait for the next signal to appear, and can avoid being penalized for an extra long reaction time. Self-pacing is particularly beneficial when the task is prolonged because the deleterious effects due to increased variability in performance are minimized.[14] (See Section 3.3.2.)

> Simple repetitive operations will benefit from self-pacing. For instance, in inspection operations, each item should move into the inspection point at an adjustable rate set by each inspector rather than at a permanently fixed rate.

d. recommendations

1) The operator should be provided with immediate knowledge of his own performance.

2) For best performance, practice periods should be allowed, particularly for complex tasks.

3) Each operator should be allowed, as far as possible, to work at his own pace. Rigid pacing of his task should be avoided.

3.3 HUMAN TIME LAGS IN WATCHKEEPING SITUATIONS

3.3.1 General Information

a. definitions

Watchkeeping situations are those in which man monitors some condition such as the state of automatic equipment. Typically, he is required to respond to signals which may occur at any time during the watch while the rest of the watch period is devoid of incidents and demands for action. When the signals occur infrequently, the task is called a "vigilance task" and, since performance tends to decline under such conditions, the term "vigilance decrement" has come into use.

b. vigilance decrement

Work on vigilance problems, as carried out on radar and similar apparatus, indicates that: 1) the longer the watch period, the more likely that some signals will be missed, and 2) when signals are detected, response time may be long and variable.[36, 78, 81] Further work confirms these findings, but it also shows that vigilance decrement is not inevitable and that it can be controlled to some extent by varying conditions of work.[6, 17, 18, 19, 36, 50, 51, 66, 67, 80, 81] (Specific factors affecting vigilance are discussed below.)

3.3.2 Factors Affecting Watchkeeping Performance

a. signal frequency

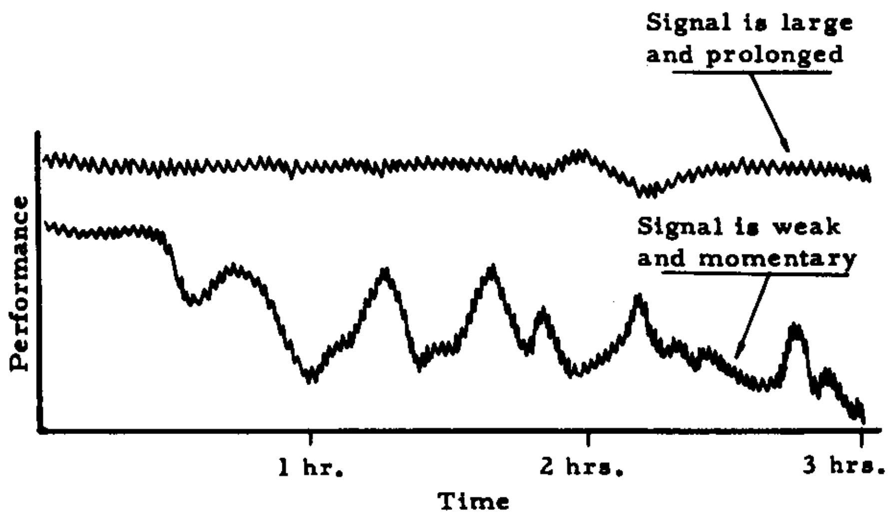
Variation of the number of signals within a watch period has a marked effect upon performance; the greater the number of signals, the better will be the average performance and the less will be the decrement with time.[12, 18, 36, 37, 66]

It appears that observers raise their level of attentiveness according to when they expect a signal to occur. It is easier to estimate short time spans; therefore, observers can estimate better the expected time of occurrence of the next signal when there are more signals in a given period of time.

b. signal magnitude and duration

Magnitude and duration of a signal have a marked effect upon performance; the more intense, bright, loud, or large the signal, the easier it is to detect and respond to rapidly.[1, 4, 14, 34]

Signals which are large in magnitude or prolonged in time are not only easier to detect initially but also lead to little or no deterioration of performance over long time periods. However, signals which are difficult to detect lead to relatively large vigilance decrements.



c. search area

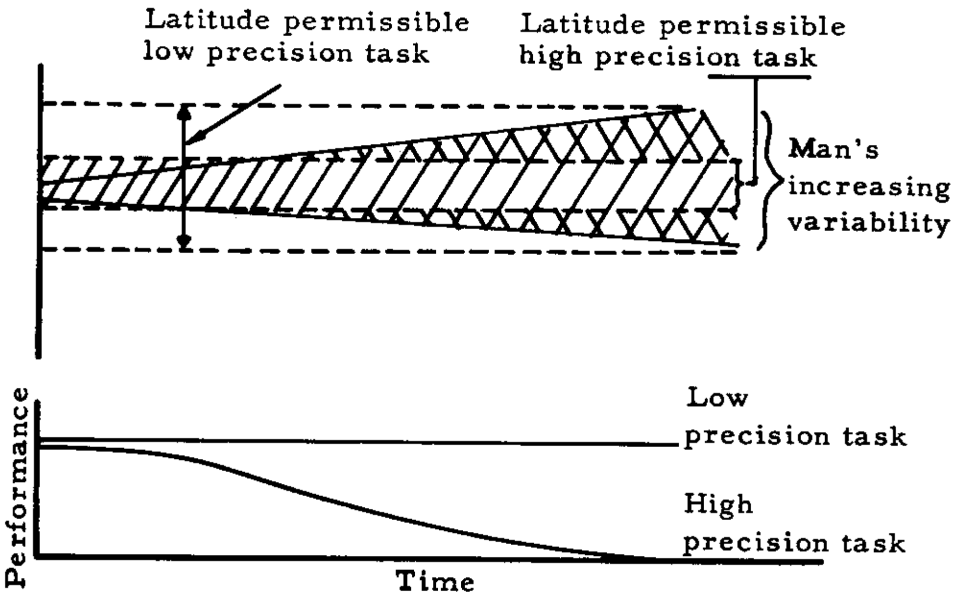
The area of search for a signal, while directly influencing the time required for a fresh observer to detect a signal, also interacts with his vigilance behavior.[19, 86] For instance, on a PPI radar scope there is a progressive tendency for operators to funnel their attention around the center of the sweep so that signals appearing on the periphery of the scope are either missed or a long time is taken to respond to them. Similarly, pilots, toward the end of a long mission, tend to focus their attention on their primary instruments to the exclusion of the remainder and to miss important indications on the latter instruments.[34, 67]

d. flashing signals

Flashing (repetitive) signals show no superiority over steady signals in terms of performance when the operator is fresh (see Section 3. 2. 2); however, flashing signals become superior as the task is extended in time. A fast flash rate (e.g., one signal per second) generally maintains performance better than a slow flash rate.[12]

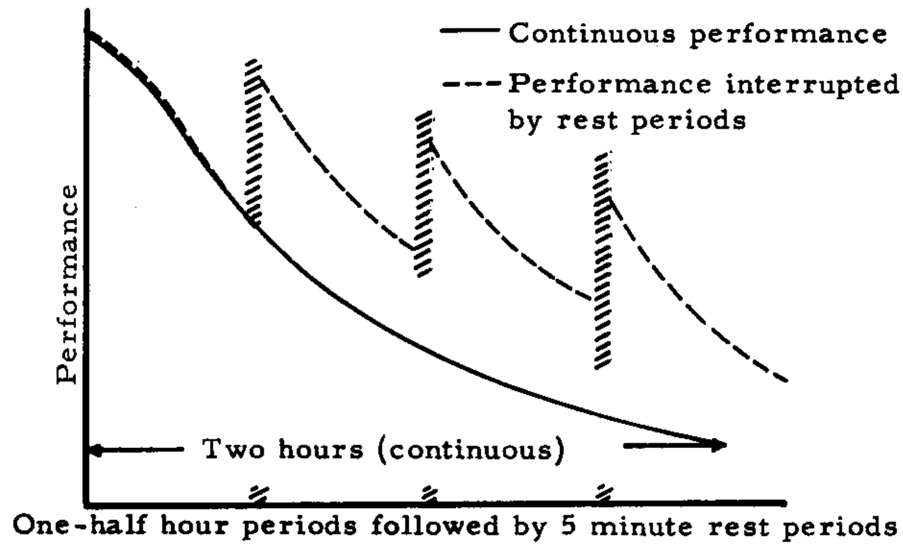
e. task precision

Tasks requiring a high degree of precision are degraded more with time than tasks requiring a low degree of precision. The reason for this effect is that the man tends to become more variable in his response with time.[21]



f. length of watch and rest periods

For at least some vigilance tasks, long watch periods are harmful. It has been customary to limit many vigilance tasks to approximately 30 to 45 minutes, and this practice has proved satisfactory in most cases. When conditions of work are good (as described in other parts of this section), a man may be able to continue for a number of hours without serious vigilance decrement. To aid his performance, the man should be informed about the length of his watch and should be allowed rest periods of up to five minutes every half-hour.[81] A typical example of performance on a difficult vigilance task with and without rest periods is shown in the figure below.



g. sense used

Under conditions of relative quiet, an auditory signal is more likely to be attended to than a visual signal. However, a visual signal is superior in terms of the amount of information which can be presented by a single signal. A combination of the two, e.g., the man's attention is attained by an auditory signal and quantitative information is presented visually, is effective and is superior to either one individually.

h. environmental factors

Environmental factors can degrade watchkeeping performance in two ways: by causing either too little or too much incidental stimulation of the man.

When there is too little environmental stimulation, the conditions are similar to those which individuals contrive for themselves just prior to sleep.[70] Such conditions encourage lack of attentiveness and bring about quickly deteriorating performance.[9,51] Therefore, a man should not be isolated in a dimly lit, soundless compartment when required to perform a vigilance task such as monitoring a radar scope.

Overstimulation may cause deterioration in performance. Various environmental conditions are noxious or distractive in their effects; in particular, noise (above 90 db) and excessive heat and humidity are conditions to be avoided.[17,68,80,81,90]

In general, it is desirable to place a man in a reasonably lit workplace, with some sounds in the background, in company with other men so that some occasional interactions can take place. He should also be permitted means of refreshment, such as cigarettes, coffee, etc.

i. individual differences

Performance in watchkeeping situations varies widely from person to person and, to a lesser degree, from day to day for the same person. The ability to be vigilant over prolonged periods does not appear to be strongly related to any measurable personality trait or ability, although there is some indication that good watchkeeping performance is positively related to an introverted disposition.[12]

When high penalty rates are attached to errors (viz., either reporting a signal which is not there or failing to report one which is there), vigilance is aided. However, the degree to which this is effective is very much dependent upon the person involved.

3.3.3 Summary and Recommendations

a. general summary

There is no characteristic decline in performance under all vigilance conditions. In some circumstances performance can improve during the watch; in other cases performance shows little change; but in the majority of cases there is a vigilance decrement.

Changes in performance are characterized either by failure to respond or by prolonged reaction time, most usually accompanied by increased variability of performance. In some cases reaction times of over three minutes have been observed toward the end of an hour's watch where the longest reaction time during the first quarter of the watch was six seconds.

The changes in performance for vigilance tasks cannot be traced to any one specific factor, but are a product of a complex of influences and factors which interact. These fall into four main groups which, in order of importance, are: 1) the individual, 2) the task conditions, 3) the rate of signaling, and 4) the environmental influences.

Although the performance of man in vigilance tasks is difficult to predict, there are certain steps which can be taken to minimize the vigilance decrement which accompanies prolonged watchkeeping activities. These are enumerated below.

b. specific recommendations

1) The signal should be as large in magnitude (e.g., brightness, size, intensity, length) as is reasonable under the conditions present.

2) The signal should persist in time either until it has been responded to or for as long as possible. The minimum signal period should be 2.0 seconds.

3) The area in which the signal can appear should be restricted.

4) For flashing signals, the flash rate should be high (at least one cycle per second with the ''on'' period at least 0.5 second).

5) Insofar as signal frequence is controllable, it should be kept high. As an approximate guide:

   For 1 to 10 signals per hour: expect considerable decrement.

   For 10 to 20 signals per hour: expect moderate decrement.

   For over 20 signals per hour: expect little decrement.

6) Some means for giving anticipatory information should be provided whenever possible.

7) Feed-back information concerning the man's proficiency should be provided.

8) The work environment (noise, temperature, humidity, etc.) should be maintained at a comfortable level.

9) The observer should not be isolated from other individuals nor deprived entirely of incidental stimulation (e.g., smoking, coffee, postural adjustments, minor interruptions).

10) When long watch periods are unavoidable, the observer should be provided with three to five minute rest periods every half hour.

11) Watch periods should ordinarily not exceed one hour, and, when working conditions are poor, should not exceed 30 minutes. Whenever possible, group members should be rotated among jobs every 30 minutes.

BIBLIOGRAPHY

1. Adams, J. A. Vigilance in the detection of low-intensity signals. J. exp. Psychol., 1956, 52, 204-208.

2. Anderson, N. H., Grant, D. A. and Nystrom, C. O. Performance on a repetitive key pressing task as a function of the spatial positioning of the stimulus and response components. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 54-76, March 1954.

3. Bailey, A. W. and Sweeney, J. S. Preliminary study of helicopter attitude display systems. Naval Research Laboratory, Washington, D. C., Memorandum Report No. 451, March 1955.

4. Bakan, P. Discrimination decrement as a function of time in a prolonged vigil. J. exp. Psychol., 1955, 50, 387-390.

5. Baker, C. A. and Grether, W. F. Visual presentation of information. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 54-160, 1954.

6. Bartlett, S. C., Bienert, R. L. and Graham, J. R. Study of visual fatigue and efficiency in radar observation. Rome Air Development Center, Human Factors Office, Griffis Air Force Base, N.Y., Report No. RADC TR 55-100, 1955.

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

8. Battig, W. F., Voss., J. F. and Brogden, W. J. Effect of frequency of target intermittence upon tracking. J. exp. Psychol., 1955, 49, 244-248.

9. Bexton, W. H., Heron, W. and Scott, T. H. Effects of decreased variation in the sensory environment. Canad. J. Psychol., 1954, 8, 2.

10. Birmingham, H. P., Kahn A. and Taylor, F. V. A demonstration of the effects of quickening in multiple-coordinate control tasks. Naval Research Laboratory, Washington, D. C., Report No. 4380, June 1954.

11. Birmingham, H. P. and Taylor, F. V. A human engineering approach to the design of man-operated continuous control systems. Naval Research Laboratory, Washington, D. C., Report No. 4333, April 1954.

12. Bowen, H. M. On the appreciation of visual displays. Doctor's dissertation, University of Cambridge, England, 1956.

13. Broadbent, D. E. Failure of attention in selective listening. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 168, 1951.

14. Broadbent, D. E. Noise, paced performance and vigilance tasks. Brit. J. Psychol. (Gen. Sec.), 1953, 44, 295-303.

15. Broadbent, D. E. Some effects of noises on visual performance. Quart. J. exp. Psychol., 1954, 6, 1-5.

16. Broadbent, D. E. Successive responses to simultaneous stimuli. Royal Air Force, London, England, Flying Personnel Research Committee Report No. 934, 1955.

17. Broadbent, D. E. The twenty dials and twenty lights tests under noise conditions. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 160, 1951.

18. Browne, R. C. Fatigue, fact or fiction? In Floyd, W. F. and Welford, A. T. (Eds.) Symposium on fatigue. London: H. K. Lewis and Co., Ltd., 1953.

19. Buckley, B. B., Hanes, R. M. and Deese, J. Slant area and target detectability on a P.P.I. cathode-ray tube. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 52-303, 1953.

20. Byrnes, V. A. Visual problems of supersonic speeds. Amer. J. Ophthal., 1951, 34, 169-177.

21. Chapanis, A., Garner, W. R. and Morgan, C. T. Applied experimental psychology. New York: John Wiley and Sons, Inc., 1949.

22. Chernikoff, R., Birmingham, H. P. and Taylor, F. V. A comparison of pursuit and compensatory tracking under conditions of aiding and no aiding. J. exp. Psychol., 1955, 49, 55-59.

23. Chernikoff, R., Birmingham, H. P. and Taylor, F. V. A comparison of pursuit and compensatory tracking in a simulated aircraft control loop. J. appl. Psychol., 1956, 40, 47-52.

24. 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.

25. Conklin, J. E. Effect of control lag on performance in a tracking task. J. exp. Psychol., 1957, 53, 261-268.

26. Conrad, R. Adaptation to time in a sensori-motor skill. J. exp. Psychol., 1955, 49, 115-121.

27. Conrad, R. Missed signals in a sensori-motor skill. J. exp. Psychol., 1954, 48, 1-9.

28. Conrad, R. Some effects on performance of changes in perceptual load. J. exp. Psychol., 1955, 49, 313-322.

29. Conrad, R. Speed and load stress in a sensori-motor skill. Brit. J. industr. Med., 1951, 8, 1-7.

30. Craig, D. R. Effect of amplitude range on duration of responses to step function displacements. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, Technical Report No. 5913, September 1949.

31. Craik, K. J. Theory of the human operator in control systems. II. Man as an element in a control system. Brit. J. Psychol., 1948, 38, 142-148.

32. Crossman, E. R. F. W. Entropy and choice time: the effect of frequency unbalance on choice-response. Quart. J. exp. Psychol., 1953, 5, 2.

33. Crossman, E. R. F. W. The measurement of discriminability. Quart. J. exp. Psychol., 1955, 7, 176-196.

34. Davis, D. R. Pilot error. London: His Majesty's Stationery Office, 3139 (a), 1948.

35. Davis, R. The limits of the "psychological refractory period." Quart. J. exp. Psychol., 1956, 8, 24-37.

36. Deese, J. Some problems in the theory of vigilance. Psychol. Rev., 1955, 62, 359-368.

37. Deese, J. and Ormond, E. Studies of detectability during continuous visual search. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 53-8, 1953.

38. Elkind, J. I. Characteristics of simple manual control systems. Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts, Technical Report No. 111, 6 April 1956.

39. Elkind, J. I. Tracking response characteristics of the human operator. Human Factors Operations Research Laboratories, Air Research and Development Command, Bolling Air Force Base, Washington, D. C., Memorandum No. 40, September 1953.

40. Ellson, D. G. and Gilbarg, D. The application of operational analysis to human motor behavior. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, Memorandum Report No. MCREXD-694-2J, 3 May 1948.

41. Ellson, D. G. and Gray, F. E. Frequency responses of human operators following a sine wave input. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, Memorandum Report No. MCREXD-694-2N, 21 December 1948.

42. Ellson, D. G. and Hill, H. The interaction of responses to step function stimuli. I. Opposed steps of constant amplitude. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, Memorandum Report No. MCREXD-694-2P, 19 November 1948.

43. Ellson, D. G. and Hill, H. Wave length and amplitude characteristics of tracking error curves. II. Individual differences and learning effects. USAF, Air Materiel Command, Engineering Division, Wright-Patterson Air Force Base, Ohio, Memorandum Report TSEAA-694-2H, 13 October 1947.

44. Ellson, D. G. and Wheeler, L. The range effect. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, Technical Report 5813, May 1949.

45. Ely, J. H., Schneider, R., Kelley, C. R. and Channell, R. C. Tracking training I: An approach. Office of Naval Research, U. S. Naval Training Device Center, Port Washington, New York, Technical Report NAVTRADEVCEN 1908-004-1, 29 May 1957.

46. Ely, J. H., Thomson, R. M. and Orlansky, J. Design of controls. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 56-172, November 1956.

47. Ely, J. H., Thomson, R. M. and Orlansky, J. Layout of work-places. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 56-171, September 1956.

48. Fitts, P. M., Marlowe, E. and Noble, M. E. The interrelations of task variables in continuous pursuit tasks. I. Visual-display scale, arm-control scale, and target frequency in pursuit tracking. Human Resources Research Center, Air Research and Development Command, Lackland Air Force Base, Texas, Research Bulletin 53-34, September 1953.

49. Flores, I. The effect of organization upon complex reaction time. J. Psychol., 1956, 41, 301-313.

50. Floyd, W. F. and Welford, A. T. (Eds.) Symposium on fatigue. London: H. K. Lewis and Company, Ltd., 1953.

51. Fraser, D. C. Relationship of an environmental variable to performance in a prolonged visual task. Quart. J. exp. Psychol., 1953, 5, 31-32.

52. Gerathewohl, S. J. Conspicuity of flashing lights. Effects of variation among frequency, duration and contrast of the signals. USAF, School of Aviation Medicine, Randolph Field, Texas, Project No. 21-1205-0012, Report No. 1, 1954.

53. Gibbs, C. B. Servo principles in sensory organization and the transfer of skills. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 218/54, July 1954.

54. Gibbs, C. B. and Brown, I. D. Increased production from the information incentive in a repetitive task. The Manager, May 1956, 3-8.

55. Gibbs, C. B., Brown, I. D., and Bilney, J. M. Reaction times to the "flashing light" signals of cars: The effects of varying the frequency and duration of the flash. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 245, 1955.

56. Goodyear Aircraft Corporation. Final report: Human dynamics study. Goodyear Aircraft Corporation, Akron, Ohio, Report No. GER-4750, 8 April 1952.

57. Grether, W. F. Eyes in the sky. Flying Safety, May 1957.

58. Hambacher, W. O. and Gallup, H. F. The effects of variation in temporal characteristics of warning lights presented against a heterogeneous background, whose onset occurs both within and outside the visual field. Air Crew Equipment Laboratory, Naval Air Materiel Center, Philadelphia, Pennsylvania, Report No. NAMC-ACEL-300, TEDNAM, E2-52004, Part 8, October 1956.

59. Helson, H. Studies in aided tracking. National Defense Research Council, Washington, D. C., Contract OEMsr-453, Memorandum No. 25 to Division 7, 31 August 1945.

60. Hick, W. E. Discontinuous functioning of the human operator in pursuit tasks. Quart. J. exp. Psychol., 1948, 1, 36-52.

61. Hick, W. E. On the rate of gain of information. Quart. J. exp. Psychol., 1952, 4, 11-26.

62. Hick, W. E. and Bates, J. A. V. The human operator of control mechanisms. Ministry of Supply, Permanent Records of Research and Development, London, England, Report No. 17-204, May 1950.

63. Holland, J. G. and Henson, J. B. Transfer of training between quickened and unquickened tracking systems. Naval Research Laboratory, Washington, D. C., Report No. 4703, February 1956.

64. Humphrey, C. E., Thompson, J. E. and Versace, J. Time-sharing and the tracking task. Applied Physics Laboratory, The Johns Hopkins University, Baltimore, Maryland, Report No. TG-201, July 1953.

65. Hyman, R. Stimulus information as a determinant of reaction time. J. exp. Psychol., 1953, 45, 188-196.

66. Jerison, J. H. and Wallis, R. Experiments in vigilance. II: One clock and three clock monitoring. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 57-206, May 1957.

67. Jerison, J. H. and Wallis, R. Experiments in vigilance. III: Performance on a simple vigilance task in noise and in quiet. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 57-318, June 1957.

68. Jerison, J. H. and Wing, S. Effects of noise and fatigue on a complex vigilance task. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 57-14, January 1957.

69. Katz, M. and Spragg, S. D. S. Tracking performance as a function of frequency of course illumination. J. Psychol., 1955, 40, 181-191.

70. Kleitman, N. Sleep and wakefulness. Chicago: University of Chicago Press, 1939.

71. Klemmer, E. T. Time uncertainty in simple reaction time. J. exp. Psychol., 1956, 51, 179-184.

72. Knowles, W. B., Garvey, W. D. and Newlin, E. P. The effect of speed and load on display-control relationships. J. exp. Psychol., 1953, 46, 65-75.

73. Krulee, G. K. and Weisz, A. Studies in the visual discrimination of multiple unit displays. Office of Naval Research, Washington, D. C., Report 1954-494-03-23, 1954.

74. Leonard, J. A. The effect of partial advance information. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. 217/54, 1954.

75. Leonard, J. A. Some experiments on the temporal relation between information and action. Doctor's Dissertation, Cambridge University, Cambridge, England, 1952.

76. Levine, M. Tracking performance as a function of exponential delay between control and display. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 53-236, October 1953.

77. Lincoln, R. S. and Smith, K. U. Systematic analysis of factors determining accuracy in visual tracking. Science, 1952, 116 (3008), 183-187.

78. Lindsley, D. B. Radar operator "fatigue." The effects of length and repetition of operating periods on efficiency of performance. Office of Scientific Research and Development, Washington, D. C., Report No. 3334, 1944.

79. Mackworth, J. F. and Mackworth, N. H. The overlapping of signals for decisions. Amer. J. Psychol., 1956, 69, 26-47.

80. Mackworth, N. H. High incentives versus hot and humid atmospheres in a physical effort task. Brit. J. Psychol., 1947, 38, 90-102.

81. Mackworth, N. H. Researches on the measurement of human performance. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 268, 1950.

82. MacPherson, S. J., Dees, V. and Grindley, G. C. The effects of K. and R. on learning and performance. II. Some characteristics of very simple skills. Quart. J. exp. Psychol., 1948, 1, 68-78.

83. McRuer, D. T. and Krendell, E. S. Dynamic response of the human operator. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 56-524, in preparation.

84. Mechler, E. A., Russell, J. B. and Preston, M. G. The basis for the optimum aided-tracking time constant. J. Franklin Institute, 1949, 248 (4), 327-334.

85. Milton, J. L., Jones, R. E., Morris, J. B. and Fitts, P. M. Pilot reaction time: The time required to comprehend and react to contact and instrument recovery problems. USAF, Air Materiel Command, Engineering Division, Wright-Patterson Air Force Base, Ohio, Memorandum Report TSEAA-694-13a, 1947.

86. Nicely, P. E. and Miller, G. A. Some effects of unequal spatial distribution on the detectability of radar targets. J. exp. Psychol., 1957, 53, 195-198.

87. Noble, M. E., Fitts, P. M. and Marlowe, E. The interrelations of task variables in continuous pursuit tasks. II. Visual-display scale, arm-control scale, and target frequency in compensatory tracking. Human Resources Research Center, Air Research and Development Command, Lackland Air Force Base, Texas, Research Bulletin 53-55, December 1953.

88. Noble, M., Fitts, P. M. and Warren, C. F. The frequency response of skilled subjects in a pursuit tracking task. J. exp. Psychol., 1955, 49, 249-256.

89. Pearl, B. E., Simon, J. R. and Smith, K. U. Visual tracking: IV. Interrelations of target speed and aided-tracking ratio in defining tracking accuracy. J. appl. Psychol., 1955, 39, 209-214.

90. Pepler, R. D. The effect of climatic factors on the skilled performances of young European men living in the tropics. 4. A task of prolonged visual search. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 156, 1950.

91. Poulton, E. C. Perceptual anticipation and reaction time. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 109, 1950.

92. Poulton, E. C. Perceptual anticipation in tracking with two-pointer and one-pointer displays. Brit. J. Psychol., 1952, 43, 222-229.

93. Poulton, E. C. and Gregory, R. L. Blinking during visual tracking. Medical Research Council, Unit of Applied Psychology, University of Cambridge, England, Report No. APU 152, 1951.

94. Reid, L. S. and Holland, J. G. The influence of stimulus similarity and stimulus rate. The third of a series of reports on experimental analysis of complex task performance. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 54-146, IV, 1954.

95. Rockway, M. R. The effect of variations in control-display ratio and exponential time delay on tracking performance. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 54-618, December 1954.

96. Searle, L. V. Psychological studies of tracking behavior. Part I. Rate and time characteristics of simple corrective movements. Naval Research Laboratory, Washington, D. C., Report No. R-3248, 3 March 1948.

97. Searle, L. V. Psychological studies of tracking behavior. Part IV. The intermittency hypothesis as a basis for predicting optimum aided-tracking time constants. Naval Research Laboratory, Washington, D. C., Report 3872, 29 October 1951.

98. Senders, J. W. The influence of surround on tracking performance. Part I. Tracking on combined pursuit and compensatory one-dimensional tasks with and without a structured surround. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 52-229, Part I, February 1953.

99. Senders, J. W. Tracking with intermittently illuminated displays. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 55-378, October 1955.

100. Senders, J. W. and Bradley, J. V. Effect of backlash on manual control of pitch on a simulated aircraft. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 56-107, March 1956.

101. Senders, J. W. and Cruzen, M. Tracking performance on combined compensatory and pursuit displays. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report No. 52-39, February 1952.

102. Senders, V. L. The effect of dials on qualitative reading of a multiple dial panel. USAF, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 52-182, 1952.

103. Simon, J. R. 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. appl. Psychol., 1956, 40, 367-370.

104. Slater-Hammel, A. T. and Brown, J. S. Discrete movements in the horizontal plane as a function of their length and direction. Office of Naval Research, U. S. Naval Training Device Center, Port Washington, New York, Report No. 57-2-2, October 1947.

105. Sobczyk, A. Aided tracking. Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, Report No. 430, 1943.

106. Strughold, H. The human time factor in flight. J. aviat. Med., 1949, 20, 300-307.

107. Taylor, F. V. and Birmingham, H. P. Psychological studies of tracking behavior. Part II. A study of the acceleration pattern of quick manual corrective responses. Naval Research Laboratory, Washington, D. C., Report No. R-3249, 3 March 1948.

108. Teichner, W. H. Recent studies of simple reaction time. Psychol. Bull., 1954, 51, 128-149.

109. Vince, M. A. The intermittency of control movements and the psychological refractory period. Brit. J. Psychol., 1948, 38, 149-157.

110. Voss, J. F. Effect of target brightness and target speed upon tracking proficiency. J. exp. Psychol., 1955, 49, 237-243.

111. Warrick, M. J. Effect of transmission-type control lags on tracking accuracy. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, Technical Report No. 5916, September 1949.

112. Welford, A. T. The "psychological refractory period" and the timing of high-speed performance--a review and a theory. Brit. J. Psychol., 1952, 43, 2-19.

113. Welford, A. T. Timing and organization of manual skilled performance. Acta. Psychol., 1955, 11, 185-186.

114. Woodworth, R. S. and Schlosberg, H. Experimental psychology. New York: Henry Holt and Co., Inc., 1954.

115. 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. Naval Research Laboratory, Washington, D. C., Report No. 3850, 20 August 1951.

116. Handbook of human engineering data. (Second Edition, Revised) Office of Naval Research, U. S. Naval Training Device Center, Port Washington, New York, Technical Report 199-1-2a, 1 November 1952.

INDEX