AN APPLICATION OF HIERARCHICAL CONCEPTS TO PERFORMANCE ASSESSMENT

A.N. Nzeako
CURRICULUM VITAE

ANTHONY NDUBUEZE NZEAKO

Born:  November 10, 1940, in Umukabia, Umuahia, Nigeria.

1948 - 1954  Attended the Central Elementary School, Umukabia, Umuahia, Nigeria.
            Obtained the First School Leaving Certificate.

            Obtained the West African School Certificate (with distinction).

1960 - 1961  A Radio Technical Officer-in-Training, at the Post and Telegraph Higher
            Technical School, Oshodi, Lagos, Nigeria; an employee of the Federal
            Ministry of Communication.

1961 - 1963  Attended the Federal Emergency Science School., Lagos, Nigeria; with the
            recommendation and sponsorship of my employer, the Federal Ministry
            of Communication.
            Obtained the University of London General Certificate of Education (GCE),
            "Advanced Level", in Science (Mathematics - Pure and Applied - and
            Physics). Gained the Nigerian Government Scholarship for further studies
            in USSR.

1963 - 1969  A student of Electrical Engineering, at the Faculty of Electro-Techniques,
            Leningrad Polytechnical Institute, Leningrad, USSR.
            Obtained a Master of Science Degree in Electrical Engineering, majoring in
            Automation and Telemechanics.

1969 - 1970  Joined the Chair of Automatic Controls, Department of Electrical Engineering,
            Twente University of Technology, Enschede, The Netherlands.
            Research interest: - Traffic Controls (Computer Simulation of Traffic Flows).

1971 - 1975  Joined the Chair of Industrial Psychology, Psychology Laboratory, Catholic
            University, Nijmegen, The Netherlands.

Now appointed a Lecturer in the Department of Electrical Engineering, University of Nigeria,
Nsukka, Nigeria.
PROMOTOR:

Prof. Dr. G. Brenninkmeijer
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To Kwame Enyinnaya
And
In deep memory of my beloved mother,
Nwayiocha

Patience Heals All Wounds
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Chapter One

The Problem Of Performance Assessment

1.1. Introduction

"Performance assessment is one of the most important and difficult areas of current research. It is important in its own right, as any supervisor who has been called upon to justify the ratings of his workers can attest. It is important also because it is the crux of the 'criterion problem' for so much other work: the final validation of selection and training techniques depends upon the assessment of the performances of men who have been differently selected and trained. The final validation of an improved, human engineered man-machine system depends upon it. The evaluation of the effects of various stresses, the measurement of performance decrements, the establishment of operational limits and even of optimum operational conditions and procedures—these, and many other tasks depend upon the measurement and assessment of performance" (Alluisi, 1967).

The concern with problems of performance assessment is by no means new in psychology, in engineering, and in other related fields concerned with the design and development of systems. The problem has been recognized as a difficult one (Inn, Hulin and Tucker, 1972; Glaser and Klaus, 1963; etc.). In the inquest of a solution, the typical researcher concen-
trates his research in the areas of his discipline's particular skill. For example, a physiologist might translate the problems of performance assessment into problems of measuring the output, impairment, or recovery of muscles. An industrial engineer might concentrate on time-and-motion study or on the measurement of productivity. A psychologist might concentrate his efforts in different ways: an industrial psychologist on the design (or re-design) of equipment, and an experimental psychologist on one or more of the traditional areas of learning, perception, psychomotor, etc. (Alluisi, 1967).

Direct attempts to solve the problems of performance assessment have been frustrated by the so-called "criterion problem" (Chiles, 1967). That is, what is the best way to define job performance? Another stumbling block to progress in these attempts, which grows out of the "criterion problem", is the uncertainty as to how best to proceed. The next section of this chapter will consider the general difficulties encountered in trying to define job performance, and the various approaches which have been employed to deal with this problem.
1.2. The Criterion Problem

The locus of the criterion problem may be sought in the definition of a system as a complex of interacting elements, in which the behaviour of any one element (man) is dependent upon, or inseparable from, the overall behaviour of the whole. According to Chiles (1967), "the greatest barrier to progress in developing (performance) criteria is that, for the most part, operator performance is inextricably confounded with system performance". Suppose, for instance, we are given the assignment to assess the performance of the driver at the end of training in a man-machine system consisting of a driver and his automobile, what would we do? What would be our criterion behaviour? Most of the measures that might be considered, such as speed, distance travelled, and ability to stop, are actually dependent upon the interactions between the human and the mechanical components in the system.

Total system performance is not only dependent on the skill of the operator, but on the capabilities of the machines in the system as well. To the extent that mechanical components can differ, the results of any comparison will be attenuated by factors independent of the human component. In this sense, it would not be realistic to contrast the performance of a driver using
a jalopy with that of another driver operating a modern, high-powered automobile. It would be almost equally unrealistic to measure the performance of both drivers in the same automobile, since one driver or the other will then be required to operate an unfamiliar mechanical component. Even if the problem is solved by giving both drivers extensive experience with the same automobile, many additional factors must be considered before the skills of the two drivers can be accurately assessed.

For instance, a decision must be made whether to use an actual performance test, to utilize information that might be obtained on past performance, or both. If an actual driving test is to be used, it is necessary to determine the importance and relevance of test conditions. Should the test include both icy and dry pavement? Should it measure skill in heavy traffic, or should it be conducted on a test course where the influence of non-participating drivers can be controlled? Should the drivers be examined on relevant job knowledge, such as skill in changing a tire, traffic regulations, and the design features of an internal combustion engine? How much weight should be given to these various kinds of performance? If the driver's past record is used to assess his proficiency, is it possible to equate for the number of miles driven, the environmental conditions experienced, or the
accuracy of the records themselves? (Glaser and Klaus, 1963).

Many would probably agree that there would be almost as many answers and approaches to any or all of these questions as there are attempts to solve them. Evidence has shown that there are almost as many measures of job performance as there are investigators utilizing such measures (Inn, Hulin an Tucker, 1972). Man tends to form his own criterion as to how well a given task should be performed and the task performer endeavours to meet it. Different measures have different components of validity. There is certainly no consensus as to which measure is most appropriate.

The numerous measures possible for a given task, and the lack of consensus, indicate a task definition problem: it is difficult to agree on just what a task is, and more specifically, "how big it is". As Bennet (1971) puts it: "Generally speaking, any set of behaviour which can reasonably be labelled with a verb can be called a task. Language structures our thinking to believe in the existence of a task because of the existence of a predicate".

Take the foregoing illustration, for example. For the driver whom we are testing, driving might

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* This illustration is abstracted from Glaser and Klaus, 1963).
be considered as a task of a larger job, like the job of a salesman. Alternately, for him, driving might be a sub-task, such as every person driving to and from work every day. This illustrates the variability of task definition. It then could be said that the first step towards a consensus on performance criterion is a consensus on the composition of a task.

1.3. APPROACHES TO PERFORMANCE ASSESSMENT

Various ways have been sought to describe job performance. Among these are:

I. **THE SINGLE CRITERION TECHNIQUE**

As the name implies, this approach employs a single criterion to assess a set of elicited behaviours. Rating scales, operator outputs, and system outputs/performances are examples of measures employed. Rating scales are more frequently used in social systems. For example, management rates each employee on the extent to which he meets the criterion of effective performance. Operator's output may be in the form of a motor response to a stimulus. This is often employed in laboratory experiments. In some instances (particularly in industrial situations), it is possible to measure some aspects of tangible products on the job as a means of assessing performance. It is often argued that the quality of a product is the most definitive indication
of the adequacy of performance in terms of the requirements of the system (Glaser and Klaus, 1963).

In other instances, tangible products are inaccessible in the task situation, and proficiency must be determined by assessing those responses which will ultimately contribute to a system's product. In such cases the process' or system's performance rather than human output is measured. The argument in support of the latter approach is that, for many purposes, demonstration of adequate (or inadequate) system's performance is all that is needed and the specification of the precise contribution of the human operator is, in a sense, irrelevant (see Alluisi, 1967).

This approach has, in a number of instances, many shortcomings. These include:

(i) Experience has shown that many different behavioural components define job performance. It is therefore difficult to conceive of a single measure which could adequately sample all of the relevant components of a behaviour. Such a measure would, according to Inn, Hulin and Tucker (1972), probably not be central to the nomological net defining the construct of job performance.

(ii) According to our definition of a system, the elements of a system interact and this interaction influences the performance of the operator, as one of the elements of the system in which he functions. Going back to elementary analysis of
variance concepts, one realizes that higher interactions typically defy interpretation. That is, the greater the number of interacting or potentially interacting elements of a system, the lesser our ability to interpret the meaning of an obtained outcome - the human and/or system's performance.

(iii) The trend toward automation of functions tends to require a greater proportion of man's activities to be devoted to intellectual functioning. This area is difficult to assess with a single measure, even under the best of conditions.

2. **THE SINGEL-COMPOSITE TECHNIQUE:**

This involves the combination of appropriately selected measures so as to form a single composite criterion. Any composite criterion is usually the sum of the weighted variables. The choice of weights is necessarily confounded with the psychological meaning of the criterion. The construction of a single composite criterion can also be achieved in several other ways; for instance, the computation of an unweighted sum of criterion variables expressed in terms of a common dimension (Brogden and Taylor, 1950).

The use of composite measures for performance assessment has some advantages over the single criterion technique. For instance, by carefully selecting his measures, an investigator can employ construct validation procedures to gain more
information on the correspondence between his measures and the construct. In addition, multiple measures allow for more effective sampling of the relevant behaviours on the job, and the investigator can be more confident that his measures are tapping the pertinent behaviour patterns or performance dimensions. For instance, it has been shown (Fleishman, 1962, 1964 and 1967) that such specific skills as control precision, multi-limb coordination, response orientation, reaction time, speed of arm movement, rate control, manual dexterity, finger dexterity, arm-hand steadiness, wrist-finger speed, and aiming, contribute to the common variance of such perceptual-motor tasks as tracking.

The single composite method also has its disadvantages. These include:

(i) The single composite methods lose information by combining measures. Even though each measure may reflect a different pattern of job behaviour or performance dimension, the composite score reduces these to a single dimension. The consequence is to mask both change in performance, say, over time, and the effects of individual differences on the job. Consider a job which has both quality and quantity dimensions of employee productivity with equally weighted measures which correspond to these dimensions. If, in his initial months on the job, an employee concentrates on quality rather than quantity and receives scores of 5 and 1, respectively, on these measures,
the composite score would be 6. But, if he were to reverse his emphasis from quality to quantity and the respective measures were now I and 5, the composite score would indicate no change. Individuals who view the job differently and adopt either a quality or quantity orientated behaviour pattern could receive identical scores on the composite criterion. This implies that discrimination between these individuals would be impossible and prediction of variables which are so global as to have little behavioural meaning may prove equally impossible (Inn, Hulin and Tucker, 1972).

(ii) Most methods of composite criterion construction assume that each measure obtained by the investigator represents an imperfect outcropping of the same underlying trait. Otherwise, while mathematically and statistically correct, the procedure makes no sense psychologically. Combining measures with zero covariance which measure independent traits will result in a composite measure of limited or no psychometric value (Horst, 1936; Edgerton and Kolbe, 1936; Ghiselli, 1956; etc.).

3. **THE MULTIPLE CRITERIA TECHNIQUE:**
This approach involves the use of multiple measures to assess job performance. Dunnette (1963) is among those who have advocated this. Dissatisfied with the single composite method, Dunnette suggests that instead of combining
multiple criteria to form a single performance measure, one could investigate and summarize the relationships among several predictors and several criteria. According to Dunnette, little information is lost by summarizing relationships among predictors and criteria. The multiple measures allow both construct validity and effective sampling of criterion dimensions. Behaviour changes over time as well as the effects of individual differences can be traced from the separate criterion measures.

However, the multiple criteria technique, like the other methods, is not without some disadvantages. The work of Inn, Hulin and Tucker (1972) has indicated that, while the correlations among predictors and criteria lose little information, multiple criteria and an analysis of patterns of interrelationships between predictors and criteria can be of little value in making decisions.

4. FACTOR ANALYTIC APPROACH:
Factor analysis is an empirical technique which may be used to investigate the dimensionality of performance measures due to a number of different modes or data sources. Through the use of factor analysis one could investigate the dimensionality of job performance and utilize the structure of the concept to derive his criterion scores. For example, in his work on multi-task performance, Alluisi (1966) had assessed vehicle operation performances of some mili-
tary men by factoring those activities involved in the dynamic control of a vehicle and in the manipulation of switches and controls. Fleishman (1966) had used the ability constructs to define proficiency measures on such laboratory psychomotor tests as the Rotary Pursuit and Discrimination Reaction Time Tests. The range of studies included analysis of fine manipulative performances, gross physical proficiency, positioning movements, and complex coordinated control responses. For a review of factor analytic investigations oriented towards the problem of performance assessment, see Fleishman (1967) and Chiles (1967).

The virtue of the factor analytic technique lies in its flexibility and limitless potential for meaningful performance assessment. For example, one could factorise a matrix of time periods to discover the dimensions which explain variance of performance due to time. One could factorise a matrix of individuals to discover the dimensions which represent characteristic patterns of behaviour. Alternatively, one could investigate and summarize the dimensionality of each source of performance variance simultaneously (see Fleisham and Hempel, 1955; Jones, 1966; Inn, Hulin and Tucker, 1972, etc.). However, the validity of this technique depends upon its application. Suppose for example, one has factorised objective performance measures taken at one point in time. In such a case, one could not account for changes in performances due to changes in time.
Fleishman and Hempel (1955) had reported that there is a change in the pattern of required abilities for psychomotor tasks at different stages of practice.

In summary, it can be said that, as long as the question of the criterion measure remains unresolved, there is no clear-cut approach to human performance assessment. As Grodsky (1967) puts it, "the choice of any method is dependent upon the type of question asked about the performance domain as well as the state of development of the system under consideration".

1.4. Purpose Of Study

In the present work, we want to examine the applicability of a hierarchical model to the problem of performance assessment. The basic assumptions in this model are (a) that human performance is complex and consists of many interrelated components (Fleishman, 1967), and (b) that to the extent that complex performances can be resolved into a number of more basic dimensions, the problems of performance assessment will be greatly simplified (Parker, 1967).

Essentially, this is a laboratory research in which certain task conditions are selected to reflect a set of elements and relations (or component behaviours) that contribute to an observed performance. As this is a preliminary study, which is restricted to a specific case (compensa-
tory tracking), we do not make any claim re-
garding the generality of the results obtained.
It is hoped, however, that, the conceptual
framework developed here can be extended into
other task situations.
CHAPTER TWO

THE CONCEPTUAL FRAMEWORK

2.1. Introduction

Hierarchical concepts are fundamental in the study of many kinds of complex problems (Warfield, 1973). The hierarchical approach, by decomposing the problem into subproblems at one level and coordinating the solution of the subproblems at one higher level and yet maintaining an overall optimum to the whole system, has provided solutions to the analyses of many complex problems: Water Resources Systems Managements (Haimes and Macko, 1973), Organizational Management (Mesarovic et al, 1970), Detection of Subsystems of Complex Systems (Conant, 1972), Design of Complex Equipments, such as the colour television (Love, 1972), and other kinds of human endeavours.

By virtue of decomposing the problem into subproblems, a conceptual simplification of the more complex system is achieved, and a more accurate and representative mathematical model may become both feasible and computationally tractable. Furthermore, a reduction in dimensionality is achieved and the total solution effort is reduced. In a sense, the idea of hierarchy is to understand a complexity by examining the working of its constituent parts. The parts being simpler, they are supposedly more amenable to understanding.

Usually, all skills involve the presentation of information from the environment, and the
return of this information to the environment in the form of a response. A successful performance, in any case, presupposes that the response information matches the input information. Disparity between the two may be due to the individual failing to detect the signal, for reasons of over-load or under-load or excessive noise associated with the signal. Other possibilities are: the individual may detect the signal but make an incorrect identification, because he is set for the wrong signal; there is a conflict of the various cues available or there is inadequate differentiation of the cues available. He may detect the signal and identify it correctly but then go wrong because he does not attribute to it the right importance. This is usually because of an undesirable vagueness in decision making.

He may get all of these things right but then go wrong because he selects the incorrect action. This is usually due to inadequate training. Perhaps, he may detect the signals, identify them correctly, attach the correct importance, decide on the correct action but still go wrong because the correct action does not emerge. This may be due to some ambiguities in the task environment; some of the physical actions may require fine coordination and accurate timing, or the action-control relationships are ambiguous.

The foregoing illustration typifies the nature
of task performance. The various modes of failure possible, and the existence of many causal reasons, outline the complexity of task performance and the need for subdivision. Thus, to the extent that we can recognize the complexity of task performance, there is no denying that the hierarchical approach could be effective in the investigation of human performance. As an illustration of this way of looking at the problem of performance assessment, we would like to consider here human behaviour in a compensatory tracking task. But before we go on, it might be reasonable to define very briefly the type of task that is known as tracking and its various forms.

2.1.1. Definition And Types Of Tracking Tasks

Tracking may be defined as the process of minimizing sensory perceived errors by exercising continuous control so as to match the presented input and output signals (McRuer and Krendel, 1959). *

Tracking tasks may conveniently be divided

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*The sensory mode of information perception (or presentation) may be visual, aural or tactual (Fenton, 1966; Wargo, 1967; and Mirchandani, 1972).
Fig. 2.1a Compensatory situation representing the initial phase

Fig. 2.1b Pursuit situation representing the second phase of the progression sequence

Fig. 2.1c Open outer loop representing the synchronous phase of the progressing sequence (adapted from Krendal & McRuel, 1960)
into two sub-classes, pursuit and compensatory tasks. Basically, the difference between the two lies in the nature of the display and the degree of accessibility of information about the state of the controlled system (element). In the pursuit task the operator has direct and sufficient information concerning the state of the controlled system as well as the input forcing function. That is, the effects of his own output motion are directly accessible, and his corrective responses can be distinguished from his input (see fig. 2.1b). But in the compensatory tasks the operator's information, though complete, is restricted, since the visual display is the system forcing function minus the modified control response (see fig. 2.1a). That is, the operator can only determine the effects of his control motion under zero input conditions.

Occasionally tracking, either pursuit or compensatory, approaches what is known as the "Precognitive Behaviour". This condition exists when the operator has complete information about the input's future and a stimulus can trigger off a repertory of practised, properly sequenced responses. With our interest focused on the compensatory type of tracking, we can now proceed to consider our problem of performance assessment.
2.2. The Conceptual Model

A hierarchical approach to the assessment of a complex performance, such as tracking, demands a thorough analysis of the various behavioural aspects of tracking, and accounting for the numerous interacting factors that contribute to effective or ineffective tracking performance. One way of doing this is through the "stratification" of the tracking behaviour. Stratification here simply means attempting to interpret an effective or ineffective tracking performance by interpreting the various dimensions of a tracking behaviour. In general, stratification arises in attempting to resolve the dilemma* in describing (modeling) a complex problem (system). The levels of abstraction involved in a stratified description are descriptive levels and are referred to as strata (see fig. 2.2., and Mesarovic et al. 1970; Haimes and Macko, 1973; etc). Lower strata involve more detailed and specialized descriptions of the problem than the higher strata. Each stratum has its own concepts, terms, elements/variables, etc., in terms of which the problem can be described, and may deal with

*The dilemma is basically one between the simplicity in description (solution), one of the prerequisites for understanding, and the need to take into account of the numerous aspects (dimensions) of the complex problem (Mesarovic et al., 1970).
different aspects of the problem. On any given stratum one describes (studies) the dimensions of the problem in terms of their internal evolution, while the description of how these dimensions (subproblems) interact so as to form higher stratum problem (subproblem) is done on that higher stratum.

Let us consider the task of tracking a continuous target, like the sinusoid, using the compensatory type of display and a simple control mechanism. The first step in the development of a proficiency measure is the specification of the behaviour (or performance criterion) to be observed and measured. Usually, in any tracking task, whether pursuit, compensatory or precognitive, the performance criterion is very often associated with the degree by which the output of the controlled element or system matches the input (to the system). In simple cases, where the mechanical devices of the controlled element (or simply the motor activity of the operator) can be described very simply, the output of the operator is taken to be that of the machine; provided, of course, the transfer function of the latter (machine = Yc = 1) is unity. This means that the degree by which operator's output matches his input could serve as a basis for assessing his performance.

In the present circumstance, let X(t) be the input signal which has to be matched by the out-
put Y(t), and let the transfer function (Yc) of the control mechanism (machine) be unity (see fig. 2.1a). If, as the case seems in practice, action (by the operator) is taken at discrete intervals, which may be assumed to be equal, the time functions X(t) and Y(t) can be replaced by finite sequences,

\[X_1, X_2, \ldots, X_n\]

and \[Y_1, Y_2, \ldots, Y_n\], respectively.

Consequently, the resultant error (assuming that at any control instance \(X_j \neq Y_j\)), \(e(t)\), could also be replaced by a finite sequence

\[e_1, e_2, \ldots, e_n\].

In discussing the tracking behaviour, we shall therefore be discussing the interconnection relations among \(X_j\), \(Y_j\), and \(e_j\), the principal, measurable, components (or characteristics) of this behaviour. One way of looking at such relations is as expressed by equation (2-1)

\[x(-)y = G \text{ var } e; \quad (2-1)\]

where \(x(-)y\) is an expression for the input-output \((X_j, Y_j)\) correspondence, \(\text{var } e\) is a measure of the extent of variability of the display, \(e_j\) (known otherwise as the error variance or the mean square
In the hierarchical approach, we presume $G$ to be a complex, "cause-and-effect", factor decomposable into a number of hierarchically related levels of more elementary factors (or variables). Expressed otherwise,

$$G = f(F_1, F_2, \ldots, F_n). \quad (2-2)$$

Of which

$$F_j = f(V_{1j}, V_{2j}, \ldots, V_{mj})$$
$$V_{ij} = f(U_{1ij}, U_{2ij}, \ldots, U_{1ij})$$
$$Z_{ij} = f(Q_{1p\cdot i}, \ldots, Q_{qp\cdot ij}); \quad (2-3)$$

where the variables $F_j, V_{ij}, \ldots, Q_{qp\cdot ij}$ may be physical, psychological, and/or physiological factors in the task environment. From equations (2-1) and (2-2), and by a simple transformation, whereby $x(-)y/var e$ is denoted by $\emptyset$, we can obtain a simplified mathematical model, as equation (2-4), for the present purpose; though it is somehow pretentious to term this a "model" at this stage of knowledge development.

$$\emptyset = f(F_1, F_2, \ldots, F_n). \quad (2-4)$$

In this expression, we refer to $\emptyset$ as the "general performance" measure (or criterion) against which the relative levels of performance by individual operators, as well as the relative
A MEASURE OF TASK PERFORMANCE

DETERMINANT

ATTRIBUTE

TASK STRUCTURE

DETERMINANT

ATTRIBUTE

TASK ELEMENTS

STRATUM 1

STRATUM 2

STRATUM 3

Fig. 2.2. Three-strata representation of a compensatory tracking performance.
contributions of the pertinent factors \( F_j \) to this performance, can be measured.

Another way of looking at this "model" is as shown in fig. 2.2., where, from eq. (2-4), \( n=2 \), and \( \emptyset, F_1, F_2 \) are equivalent to Stratum One (General performance criterion), Stratum Two (Task Structure), and Stratum Three (Task Elements), respectively. Put in other terms, the present tracking performance can be described from three levels of abstraction (descriptive strata) concerned respectively with the measurement of the observed performance (the performance criterion, \( \emptyset \)), with the analysis of the psychological process (or function, such as perception) involved in the task (Task Structure, \( F_1 \)), and with the definition of the variables that contribute to the variance of the observed performance (Task Elements, \( F_2 \)). The rest of this development will deal with the definition of the variables expressed in eqs. (2-1) through (2-4) and in figure 2.2.

2.3. DEFINITIONS

2.3.1. The Unit Measure Of The Performance Criterion

Earlier, it has been mentioned that, whatever the display configuration (i.e. compensatory or pursuit), the operator's task in the control loop is most essentially that of trying to match
the output of the controlled element, in this case his motor responses, \( Y(t) \), to the input, \( X(t) \), to the system (see fig. 2.1). In other words, whatever form of encoding or internal transformations the operator does by observing the display, i.e., the error information, \( e(t) \), he must establish some "correspondence" between the input forcing function and the (his) output. This correspondence or relatedness we define here by the parameter \( x(-)y \).

In the literature, there are many models for measuring this "correspondence". Of these, the transmission \( T \) (in information theory) and the correlation coefficient \( r \) (in statistics) have received popular application (see Conant, 1972). The properties of these models are well known (see Attneave, 1955; McGill, 1954; Edward, 1964; etc.). Among other things, Attneave and Edward (op.cit.) have established that, for some common (normal) distribution, \( T \) and \( r \) are related by

\[
T = \log \frac{1}{\sqrt{(1 - r^2)}}
\]  

(2-4a)

We also know that with measurements whose distributions are not normal, a simple transformation of the scale of measurement may induce approximate normality. The square root, \( \sqrt{X} \), and the logarithm, \( \log X \), are often used as
transformations in this way. Moreover, many models that are useful in statistical work, although strictly true only when the population is normal, hold well enough for "rough-and-ready" (ordinary) use when samples come from non-normal populations (Snedecor and Cochran, 1967). In other words, one might argue that the fact that expression (2-4a) is presumed to be true for normal (or "common") distributions does not necessarily decrease or preclude its applicability in non-normal conditions, since, as indicated above, any distribution can be transformed into "near-normality" by replacing the original scale of measurement \( X \) with \( \sqrt{X} \) or \( \log X \).

Now, let \( A_j \) and \( C_j \) be the transformed values of the sequences \( X_j \) and \( Y_j \), respectively, whose "correspondence" (or relatedness) is defined by \( x(-)y \). Let also \( R(a,c) \) be the correlation coefficient between \( A_j \) and \( C_j \). If the foregoing analysis is applied to the present development, it might then be possible to express the "correspondence" \( x(-)y \) by

\[
x(-)y = T(a,c) = \log_2 \frac{1}{\sqrt{(1 - R^2(a,c))}} \text{ bits (2-5)}
\]

The unit measure for \( x(-)y \) or \( T(a,c) \) may be expressed in bits, since a choice of a base (2 or 10) for the logarithm automatically means a choice of the unit measure for expression (2-5). However, since the argument underlying this development is

\* In rescaling future measurement data, we would like to use the transformation \( \log X \).
based on "approximate" rather than "absolute" normal conditions, this expression (2-5) can best be taken as a "near-estimation" of \( x(-)y \).

It might perhaps be worth-while to mention some of the properties of the "transmission" (\( T \)) that motivate its apparent use in this analysis. These properties may be summarized by quoting McGill (1954): "The transmission is a bivariate, positive quantity that measures the association between two variables, or sets of variables, in two separate event continua, e.g., the input and the output of a channel". Since the input-output relations that occur in many psychological contexts are certainly possible channels, it might be reasoned that the appropriate measure for the relationship between "the tracked (\( X \)) and the tracking (\( Y \)) signals" would seem to be that of the "transmission" (\( T \)).

A few more words about the parameter \( \varnothing \). If \( X(t) \), \( Y(t) \) and \( e(t) \) are in volts, it implies that the variance \( \text{var} \ e \) is in volt\(^2\). Then, from eqs. (2-4) and (2-5), the unit measure for \( \varnothing \) would be in bits/volts\(^2\). The latter (\( \varnothing \)) could also be seen as a multivariate measure, in informational/statistical metric, of the interconnection relation among the input forcing function, \( X(t) \), the response, \( Y(t) \), and the display, \( e(t) \). This relation is, as indicated above, a function of a variety of factors (\( F_j \)). For example, it is clear that tracking is a function of the sensory,
central nervous and motor systems, hence its ultimate explanation would require the understanding of the process by which the sensory information (X_j, e_j) is processed, stored, and used to determine the motor response (Y_j). This process is, in turn, a function of the more fundamental psychological factors (motivation, basic individual differences or abilities, etc.) which, though not readily amenable to description in physical terms (as X_j, Y_j, or e_j), nevertheless are of importance because of their influence on tracking performance. Other fundamental factors in the control situation include the characteristics (physical and dynamic) of the input forcing function (X), the display (e), and of the "controlled element" (Yc). In principle, then, the hierarchical approach may be considered as having the purpose of discovering and defining the various factors that contribute to the performance output (Ø), as well as the "content" and direction" of their interrelationships. Now, saving certain details for later consideration, let us consider a sample of these factors.
2.3.2 Task Structure

Information-processing concepts (Adams and Creamer, 1962; Fitts and Peterson, 1964; Crossman, 1964; Tilley, 1969; etc.) indicate that in perceptual-motor tasks, such as tracking, the different kinds of transformations which may be performed by the human operator (in turning his inputs, \( X_i \) and \( e_j \), into outputs, \( Y_j \)) may conveniently be classified into two major processes, perceptual and motor organizations. Perceptual organization has been described (Tilley, 1969; Krendel and McRuer, 1960) in terms of the way the operator detects and processes the sensory (visual and proprioceptive) information or signals; how he divides his attention among the signals; how he selects which signals or parts of a signal for special attention; and how he combines and relates the various informational "cues", and their sequential dependencies, to determine the immediate course of effector action and to build up a store of data for use in prediction (of tracked target, \( X \)). The motor organization involves, among other things, the direction and execution (in the form of motor responses) of the sequence of commands issued by the central process. It involves also the coordination of the kinaesthetic and proprioceptive information (feedback), arising from the response movements, with externally perceived
inputs; since the motor actions as well as the motor systems have to be matched with the input and perceptual systems, respectively. However, empirical evidence (Crossman, 1960 and Tilley, 1969) has also shown that although both processes are involved in almost all skilled performance, their relative importance varies from task to task. In cognitive skills, particularly where the motor activity and control mechanisms are considerably simple, the motor organization contributes relatively little to overall task difficulty. Rather much seems to depend upon the perceptual aspects of the control process, their complexity and characteristics. In other words, by choosing a tracking task wherein the motor activity can be described very simply, it may be reasonable to presume that performance is limited primarily by the perceptual function.

In the above context, let us presume that the perceptual function required to produce the observed performance ($\theta$) is characterized by (or is a function of) the following two factors, to be known hence forth as the "perceptual characteristics":

1. the statistical variability or "perceptual noise" ($\text{var} \ Z$) that is characteristic of this function; and

2. the amount of information ("mental information", MTWL) being gained by subject about
the pattern of target motion, with associated acts of selective attention (by subject) among the informational "cues" in the control loop; it is clear that perception involves the reception, storing (in the memory) and processing of information, which is, in turn, used to programme the motor activity.

In the sub-paragraphs that follow, we shall define the measures in terms of which the aforementioned factors can be described.

2.3.2.1. The Perceptual Noise

When the operator uses the compensatory display to track a continuous target, the only way he could learn to predict target motion is by continually comparing the proprioceptive feedback, arising from his own movement responses, with visually observed error information and by inferring target motion to the difference between these two sensory inputs (see fig. 2.1a). But as the tracking progresses and the operator is able to recognize the internal coherence of the input signal, he shifts his attention from the aforementioned information "cues" and tends instead to concentrate on the input signal itself and the visual feedback (see $x_j$ and $e_j$ of fig. 2.1b). Thus, having achieved "effective"
pursuit display re-structuring (Krendel and McRuer, 1960), the operator begins to sample and compare the sequential values of the input signal and the error information. This he does by alternatively switching his attention from one stimulus to another, in a ratio proportionate to their respective information contents. The culminating phase of this progression, known as "Successive Organization of Perception" (Krendel and McRuer, 1960), is the open-chain following (see fig. 2.1c).

According to Zaremba (1956), to achieve this open-chain following, the operator adopts a strategy which, at any control interval, could be expressed as

\[ Y_{j+1} - Y_j = X_{j+1} - X_j - B(Y_{j-1} - X_{j-1}). \] (2-6)

If the "noise", attributable to physiological, and/or psychological factors is to be taken into consideration, three random terms \( E_j', E_j'' \) and \( E_j''' \), have to be introduced; where \( E_j' \) represents the physiological error (i.e., the error in executing the intended movement), \( E_j'' \) the error in assessing \( X_{j+1} - X_j \), and \( E_j''' \) the error in assessing \( Y_{j-1} - X_{j-1} \). Thus, equation (2-6) becomes

\[ Y_{j+1} - Y_j + E_j' = X_{j+1} - X_j + E_j'' - B(Y_{j-1} - X_{j-1} + E_j'''). \] (2-7)
The first term of the right-hand side corresponds to the open-chain control, while the second represents the visual feedback element (the error display). Accordingly, the left-hand side term could be taken as the proprioceptive feedback information.

Owing to the linearity of equation (2-7) and to the mutual independence of the $E_s$, the culminating effects of $E_j'$, $E_j''$ and $E_j'''$ are additive and can be evaluated separately. However, there exists a relationship between the values of $\text{var } E_j''$ and $\text{var } E_j'''$, the operator having to divide, not necessarily equally, his attention between $X_{j+1} - X_j$ and $Z_{j-1} = Y_{j-1} - X_{j-1}$, and, in consequence, estimating each of these two terms with more or less accuracy. The locus of the aforementioned relationship could also be sought in the single-channel nature of attention (or perception). The fact is that even if two things are in the same place, both cannot be attended to strictly simultaneously without making some errors, as it is equally true that one cannot listen to meaningful material and look at meaningful material and process both simultaneously and effectively (Senders, 1966).

Thus, the fact that the subject cannot concentrate on the increments of $X_j$ (or under precognitive conditions on its future increments), and at the same time concentrate on the error display, at least without considerable loss of precision, outlines the relationship between the
values of var $E_j''$ and var $E_j'''$.

Now, assuming that the total amount of information (in Shannon's sense, 1949) gained by the operator during any control interval is constant, it is proposed to find an expression for the total amount of statistical variability (var $Z$), or "perceptual noise", that is characteristic of the control behaviour expressed by equation (2-7). Before going on, it is necessary to say a few words about the relative significance of the terms of this equation (2-7), in particular the visual and the proprioceptive stimuli (including the Es) in the control process.

Earlier, it has been indicated that although perceptual and motor organization, with their associated "exteroceptive and interoceptive" feedback loops, are involved in all skilled performance, their relative importance varies from task to task. In cognitive skills, for example, where the motor activity could be described very simply, the motor organization contributes relatively little to overall task difficulty. It is also evident (Baharick, 1957) that the proprioceptive cues, and apparently the motor organization, could be varied by manipulating the physical features of the control, in terms of such variables as mass, spring loading, friction, viscous damping, and amplitude of control displacement.
In a sense, the above overview implies that the physiological (motor) "noise" or error, which seems to be a product of the motor organization and/or the kineastatic control, could be controlled or, in the least, considerably reduced by a careful choice of a control with a particular physical feature. That is, the component of var Z due to \( E_j' \) could be considered to be of low significance for the prediction of the target and the way the operator selects his attention between the tracked course and the error display. Thus, for the purpose of the present investigation, the term \( E_j' \) can be omitted. This being the case, equation (2-7) may be rewritten as

\[
Z_{j+1} - Z_j + BZ_{j-1} = E''' - BE'''' \tag{2-8}
\]

This equation can be transformed into a linear differential equation of the form

\[
\frac{d^2 Z}{dt^2} - \frac{dZ}{dt} + BZ = 0,
\]

whose characteristic equation is

\[
P^2 - P + B = 0.
\]
Obviously, for the roots of this equation to be real, which in effect implies the stability of equation (2-8),

\[ 0 < B < 1. \]

This inequality being assumed, the coefficient \( B \) will be regarded as being constant. Conceptually, this coefficient may be considered as a measure of the so-called "temporal interval" between two consecutive control responses or error corrections.\(^\text{x}\)

\(^{\text{x}}\) Evidence has shown that, apart from the delay caused by the dynamics of the controlled element (\( Y_c \)), or "external dynamics" (as one may choose to call it), the speed of a continuous performance, such as tracking, is limited by what is known as the "temporal interval", which, in essence, is composed of (a) the visual reaction time, (b) the time needed to process the observed information (in this case the error display), (c) the decision time, and (d) the movement time. Although there are conflicting quantitative definitions for each of these times, it is, however, known that even in the simplest of cases the temporal interval is of the order of 0.2 to 0.6 sec. (see Craik, 1948; Licklider, 1960; Mashhour, 1969; etc.).
Mathematically, equation (2-8) can be considered as a particular instance of linear stochastic equation (Zaremba, 1956) with constant coefficients:

\[ Z_{j+1} + a_1 Z_j + a_2 Z_{j-1} = E_j \]

where \( a_1 = -1, \ a_2 = B, \) var \( E_j = \sigma''^2 + B^2 \sigma'''^2, \)

and \( \sigma''^2 = \text{var} \ E'', \ \sigma'''^2 = \text{var} \ E'''; \)

these variances being constant in time.

According to a well known formula (see Kendall, 1949, vol. 2, p. 393), we have, in the steady state,

\[ \text{var} \ Z = \frac{1 + a_2}{(1 + a_1 + a_2) (1 - a_1 + a_2) (1 - a_2)} \text{var} \ E. \]

Substituting for the "a's" and var \( E, \) var \( Z \) becomes

\[ \text{var} \ Z = \frac{(1 + B) (\sigma''^2 + B^2 \sigma'''^2)}{B(2 + B)(1 - B)} \quad (2-9) \]

It remains to define the quantitative values of \( E_j'' \) and \( E_j''' \). It is often said that while a signal is information which leads to the selection of a response, "noise" consists of information which obscures the "true" and proper
signal when it occurs, and results in the possible selection of the wrong response (Miller, 1963). Noise may be environmentally produced, as in the case of rain on the windshield, glare of lights at night, static in radio, radar, or television. Noise may arise from the sensing equipment itself, as through the electrical/electronic circuits of the display. Similarly, noise may arise from within the operator himself, as when he is distracted, is motivated by other activities or "projects" incorrect hypotheses about the cues presented to him. Any or all of these potential noise can be involved in the present task.

Let us presume that the operator, either through training and/or practice, has established a criterion, a frame of reference $X_c$ on the continuum of observations, to which he can relate any given observation $X_j$. If for instance, he finds for the $j$th observation, $X_j$, that $X_j > X_c$ he says "yes", there is a change; if $X_j < X_c$ he says "no". The situation can also be the other way round, so long as $X_j \neq X_c$.

*We presume that the task is precognitive, i.e., that the values of $X_j$ (the input) corresponding to a not too distant future are known to the operator.
evokes a response, positive or negative. Since the operator is capable of locating this criterion at any point along the continuum of observations, it is possible that at the \((j+1)\)th observation, he could also relate \(X_{j+1}\) to \(X_c\). It is, therefore, conceivable that in evaluating the change or difference between any two observations, at any control interval, the operator may be estimating the value, say, \(X_{j+1} - X_c\) instead of \(X_{j+1} - X_j\); which corresponds to a case of projecting an incorrect hypothesis about the tracked course.

In the light of this argument, we assert that the culminating error in this behaviour (estimation) could reasonably be equated to the discrepancy between the values \(X_{j+1} - X_j\) and \(X_{j+1} - X_c\). That is,

\[
E_{j'}' = (X_{j+1} - X_c) - (X_{j+1} - X_j) = X_j - X_c
\]

for \(X_j > X_c\)

or

\[
E_{j'}'' = (X_{j+1} - X_j) - (X_{j+1} - X_c) = X_c - X_j
\]

for \(X_j < X_c\)

Or, in a general case, \(E_{j'}' = |X_j - X_c|/\); since, saying "yes" or "no", the operator may in either case be correct or incorrect.

Then \(\text{var } E_{j'}' = \text{var } /X_j - X_c/= \sigma_j'^2\). \hfill (2-10)
Similarly, putting \( Z_{j-1} = Y_{j-1} - X_{j-1} \) or \( Z = X_{j-1} - Y_{j-1} = e_j \), the absolute value of the displayed information (the error display) at the same (jth) sampling point as \( X_j \), it can be shown that

\[
E_j''' = |e_j - e_c| \quad \text{and}
\]

\[
\text{var } E_j''' = \text{var } |e_j - e_c| = \sigma'''^2 \quad (2-10a)
\]

The choice of \( X_c \) and \( e_c \) can be based on the following considerations. Let us presume that as soon as the input (X) is encountered, when the display is effectively compensatory, the operator tries to establish its effective amplitude (A), by inference either from the amplitude of his own control movements or from the algebraic difference between the amplitude of his response displacements and that of the error display, or from a combination of both information sources. This done, he begins to infer subsequent amplitude distribution (\( X_j \)) from this "a priori knowledge" or "learned responses". In other words, we propose that, in the process of stimulus organization internal to the operator, he takes advantage of any redundancy, in this case the "effective" amplitude (A)\(^K\), that

---

\(^K\) The effective amplitude is defined here as the pre-set amplitude (of the input signal) which corresponds to the maximum displacement of the problem cursor to left or right of its center position.
is present in the input signal and uses this as a frame of reference \( X_c \) to enrich his stimulus input (the error display). On the other hand, we presume \( e_c \) to be the mean \( \bar{e} \) of the absolute values of the finite sequence, \( e_j \) \((j = 1, 2, \ldots n)\), of the error display (signal). That is,

\[
e_c = \frac{1}{n} \sum_{j=1}^{n} /e_j/ = \bar{e}.
\]

Substituting for \( X_c \) and \( e_c \) in expressions 2-10/10a, it could be said that

(i) for a given \( A \), which could be established by an experimental design, \( E_j'' \) is an environmentally induced error which, in effect, means that \( \sigma'^2 \) is dependent more on external factors (such as the statistical structure of the target) than on internal ones (such as internal "noise" resulting from the operator's behaviour);

(ii) \( E_j''' \), and apparently \( \sigma'^2 \), is an attribute of both external and internal factors (relative to the operator) in the task environment: since \( e_j \) as well as \( \bar{e} \) are functions of both the behaviour of the operator (i.e. the better his performance the smaller will be \( e_j \)) and the pattern of the tracked course (i.e., the less coherent the course is, the more difficult would be the task and, in consequence, the greater would be \( e_j \) and \( \bar{e} \)).
Both $\sigma_{11}^2$ and $\sigma_{12}^2$ being elements of $\text{var } Z$ (see eq. 2-9), the latter is therefore a function of both the characteristics of the target (which may be considered as being external with respect to the operator), and such psychological factors as the skill and disposition of the operator. Although both the external and the internal factors, and their associated "noise", are being considered separately, however, their effects are inseparable in the task environment. It could thus be suggested that the more predictable the target, the less the perceptual "noise" ($\text{var } Z$), and in consequence the better the tracking performance. Conversely, since human's internal organizing functions operate in a manner similar to the changes in the external environment, including external, experimentally feasible manipulations of the display, it could also be suggested that the better the stimulus organizations internal to the operator, the better his performance, and apparently the smaller would be his perceptual "noise" (or error).

The last suggestion brings us to an important question which was raised earlier. Assuming that the operator has predicted, and is taking advantage of the internal coherence of the input, $X(t)$, what quantitative measures indicate the mode of division of attention (by him) between the predicted input signal and the error display, and in what way is this attention division (se-
2.3.2.2 The "Mental Information" (MTWL) And Associated Acts of Selective Attention

Let us presume, as before, that the time functions $X(t)$, $Y(t)$ and $e(t)$ (see fig. 2.1b) can be replaced by the sequence $X_j$, $Y_j$, and $e_j$, respectively ($j = 0, 1, \ldots, n$). We also presume that (a) $A_j$, $B_j$, and $C_j$ are the "transformed scores" of the sequences $X_j$, $e_j$, and $Y_j$, respectively; (b) the operator has predicted the input signal and is progressively approaching the open-loop control, that is, the values of $X_j$ corresponding to a not too distant future are known to the operator; and (c) $X_j$, $Y_j$, and $e_j$ are correlated variables, where $X_j$ and $e_j$ are presumed to be information sources which are transmitting to $Y_j$, the human operator (see fig. 2.3).

Based on the foregoing presumptions, the analysis that follows uses the Multivariate Model of Information Transmissions introduced by McGill (1954). Fundamental in this model is the notion of the "Total Transmission", and its use as a measure of the total amount of association

\* An illustration of the procedure for obtaining these transformed values is given in page 27.
or "statistical dependence", among a set of variables or elements (of a system) which bear varying degrees of interconnection relations. A complete description of this model is given in McGill (1954). The various applications of the "Total Transmission" as a "useful tool" for
the study of complex problems are available in the literature. Here it suffices to indicate that our primary aim is (a) to find an expression for the "Total Transmission" $T(a,b,c)$, from the bivariate transmissions between $X_j$ and $Y_j$, $e_j$ and $Y_j$, and $X_j$ and $e_j$; and (b) to derive expressions for the relative weightings (by $S$) of the various "sources" of information in the control loop, by adopting $T(a,b,c)$ as a measure of operator's "mental information" (i.e., the total amount of "relative information" being gained by the operator at any control instant about the tracked target).

It is worthy of notice that since the technique for this analysis depends on relative rather than absolute values of transmissions/associations, based on the observed values of $X_j$, $Y_j$, and $e_j$ over a finite time, all quantities to be discussed in this presentation are best interpreted as estimations. As McGill puts it, "the kind of precision that obtains in many

---

Among them are: "Measuring the Internal Informational Exchange in Systems" (Ashby, 1965); "Information Flows within Co-ordinated Systems" (Ashby, 1969); "Detecting Subsystems of a Complex System" (Conant, 1972), to mention just a few.
applications of the transmitted information (particularly in Communication Theory) is seldom available in psychological contexts, since in the latter we generally do not know in advance how many sources are actually transmitting information to subject".

Let $T(a,c)$, $T(a,b)$, and $T(b,c)$ be the transmissions between $X_j$ and $Y_j$, $X_j$ and $e_j$, and $e_j$ and $Y_j$, respectively. As indicated above, these transmissions are positive, bivariate quantities that measure the associations (in psychological contexts) among the aforementioned variables.

It is necessary to mention that, since the transmission does not respect the direction of association (or in which the information is travelling, McGill, 1954), the indications of the arrows in fig. 2.3 are quite arbitrary, intended only for formal conceptual clarification. The calculation of $T(a,c)$, $T(a,b)$ and $T(b,c)$ is based on equation (2-5), by substituting $R(a,c)$, $R(a,b)$, and $R(b,c)$ for the correlation coefficients between $X_j$ and $Y_j$, $X_j$ and $e_j$, and $e_j$ and $Y_j$, respectively. These correlation coefficients are derived from the transformed "scores" $A_j$, $B_j$ and $C_j$ (see page 27), hence the use of the subscripts $a$, $b$, and $c$. It is also worthy of notice that the use of the same subscripts in relation to the transmissions is intended to stress that the latter are realized from the transformed values of the variables $X_j$, $Y_j$, and
e_j, and the notation "R" instead of the conventional "r" for the correlation coefficients is used for the convenience sake.

We now come to the basic postulate of this model. We assert that, if T(a,b), T(a,c) and T(b,c) exhaust all the associations among X_j, Y_j, and e_j, then, according to the "Three-Dimensional Transmitted Information Model" proposed by McGill (1954), the total amount of association (or transmitted information) among these variables (i.e. X_j, Y_j, and e_j) can be expressed as

\[ T(a,b,c) = T(a,c) + T(b,c) + T(a,b) \] (2-11)

In this expression we assume that the effect ("noise") of any one variable (say e_j) on the association between any other two variables (say X_j and Y_j) is constant and very negligible.

The operator, in a tracking task, has been described in the SOP model (proposed by Krendel and McRuer, 1960) as a data-organizing device. That is, to synchronize his control actions with the changes in his external environment, the operator must coordinate all the "cues" available to him in the control loop, weighting them in a manner most appropriate in the particular circumstances. Coordination, according to Ashby (1969), is essentially a heuristic phenomenon, discernible only over the whole, and all coordinations require that information be transmitted within the system.
Thus, since perceptual organization, which is a particular form of coordination behaviour, entails the receipt of information (from diverse sources) and the processing of this information, including the storage of this information in the memory (i.e. mental representation), it might be reasonable to suggest that the total Transmission/Association (expressed in eq. 2-11) is a measure of the total amount of "relative information" being gained and temporarily stored by the operator (from his surroundings) at any control instant. "Relative Information" in the sense that in compensatory tasks subject attempts to function "effectively" in an environment about which he receives only "equivocal information"; since, as already indicated here, the information about the real state of the tracked target is restricted. Here we choose to refer to $T(a,b,c)$ as a measure of the "Mental Information" (to be denoted by MTWL), on the basis of which the operator programmes/analyzes the selection of his motor activity; since every skilled performance takes place in a series of discrete steps, and on the basis of the information about the environment (Gagne, 1963; Crossman, 1964). Thus, replacing $T(a,b,c)$ by MTWL, equation (2-11) becomes

$$MTWL = T(a,b) + T(a,c) + T(b,c)$$

(2-12)
In the present instance, $T(a,c)$ can be interpreted as a measure of the "relative information" (or better relative amount of information)\(^\star\) which the operator seems to be gaining about the internal coherence of the input signal. Similarly, $T(b,c)$ denotes the relative information which the operator gains from the display (the error stimulus) about the pattern of course (input) behaviour. The transmission $T(a,b)$ we choose to term the "interaction information" between the input and the error information, which are considered as joint "inputs" to the response information (or the operator, see fig. 2.3). In the context of selective attention/perceptual organization, the latter is best interpreted as the relative information (owing perhaps to "peripheral visions") which the operator gains as he switches his attention from one stimulus event to another, i.e. between the input and the display. As expressed in equation (2-12), all these pieces of information are temporarily stored in the memory, and eventually processed and used to direct the motor activity.

The foregoing analysis leads us to the next and relatively more crucial postulate in this analysis. We contend that the operator selects (or divides) his attention among his information\(^\star\)

\(^\star\) For brevity, we shall be using the former, "relative information".
(or stimulating) sources, which may be overt (e.g. the display) and/or covert (e.g. the input forcing function), in a manner proportional to the ratios between the respective "relative information" gained from these sources and the total amount of information gained from all of the sources and temporarily held in the memory, i.e. the "mental information". Thus, if \( E(a) \), \( E(b) \), and \( E(a/b) \) denote the relative weightings of the input (being predicted), the display, and the interaction information, respectively, then

\[
E(a) = \frac{T(a,c)}{MTWL} \quad ; \quad E(b) = \frac{T(b,c)}{MTWL} \quad ; \quad \text{and}
\]

\[
E(a/b) = \frac{T(a,b)}{MTWL} \quad (2-13)
\]

In the above expression, the predicted input information and the observed error display are considered as the limiting factors in their respective associations with the response signal, i.e. the stimuli that initiate responses. In the association between the input and the display information, we consider the former to be the limiting factor upon which depends the latter. \( E(a) \), \( E(b) \), and \( E(a/b) \) could be considered as predictors of subject's "operative strategy"; where \( E(a) \) indicates the relative, covert attention fixation on input signal; \( E(b) \) the relative, overt fixation of attention on the dis-
play; while $E(a/b)$ indicates the covert (internal) alternation of attention between the input and error display. The relative values of these quantities lie between zero and unity. Unity when all attention seems to be focused on that particular stimulus, and zero when the "relative information" gained from the same source is zero. However, in future we would like to use the percentage (of MTWL) as the unit measure of these parameters, since it is relatively more convenient to handle whole numbers rather than fractions.

Conceptually, the above parameters may be looked at from the following points of view. $E(a)$ seems to indicate how well the operator could succeed in predicting signals of different degrees of coherence. Thus, it is expected that, as the operator progresses from the effective compensatory display control, through the pursuit display restructuring, to the open-chain following, $E(a)$ increases progressively, approaching unity during the latter mode of control. On the other hand, $E(b)$ would tend to decrease as $E(a)$ increases, approaching zero during the precognitive mode of tracking; since in this phase the operator seems to diminish his requirement of the display (Krendel and McRuer, 1960). However, $E(b)$ may likely assume its maximum value at the beginning of the task, or as the predicted motion (of the input) drifts off, or if the input is changed and made more intricate.
Similarly, it may be suggested that \( E(a/b) \) could hardly be totally zero even during the open-chain following, since without what may be termed intermittent (covert) switching of attention, between the course and the error, the operator can hardly take any corrective action or realize the effect of his control actions. It could also be predicted that \( E(a/b) \) would tend to increase with the increase in the input intricacy, as it is expected that the more intricate the task, the less the relative information the operator gains about the input internal coherence, and thus the more is the tendency to "hunt" for information by frequently alternating his attention between the display and the input.

Another way of looking at the above analysis is as follows. It seems logical to say that subject's attention selection (represented by the parameters of eq. 2-13), his "mental information" (denoted by MTWL), and tracking performance are in a permanent interdependence. The more appropriate his selective attention or perceptual organization, the more information he receives about the changes in his external environment (e.g. of the input signal), the more effective he can coordinate his responses to match these changes, and in consequence the better his tracking performance.
Since signal detection and identification involve some form of a "yes/no" decision process based upon the comparison of two inputs, the sensory input and the memory recall, and since the more redundant the latter, the more it can be called up with minimal sensory information, and the more is the effective signal-to-noise ratio of the sensory system, it may thus be suggested that the greater the "mental information" the smaller would be the human variability (the internal component, $\sigma'_{\text{int}}^2$, of var $Z$). Similarly, experience has shown that both the perceptual noise and selective attention can occur at many levels, internally and externally, and that "noise" consists of information which obscures the "true and proper" signal when it occurs, and allows a constant fraction rather than a constant absolute amount of "useful" information to be gained (Crossman, 1960). This seems to imply that the more the perceptual noise the less appropriate would be the selection of attention, and the less the information the operator would gain about the actual changes in his task environment, which, in effect, means the less effective would be his tracking performance.
2.3.3. Task Elements

2.3.3.1. Input Characteristics (I, A, w)

In order to track a moving target with an error display (e), subject must make accurate discriminations of stimulus magnitude and of stimulus rate. According to Walston (1953), effective tracking performance with a simple displacement control system and a coherent target course requires the discrimination of rate as well as position information. The rate information provides a basis for predicting future target position (Poulton, 1952 and 1957), and an "optimum" degree of display magnification seems probably to be one that affords a good compromise for the joint discrimination of position and rate information, given a particular type of target motion (Hartman and Fitts, 1955).

This seems to imply that it is possible to create an experimental situation wherein the characteristic patterns of performance by individual Ss could be varied over a wide range of display conditions (such as pattern, magnitude, rate), apparently by varying the intricacy (I), amplitude (A), and frequency (w) of the input forcing function (X). Continuous targets of varying degrees of coherence (I) can be obtained by a combination of two or more harmonics of different frequencies (w) and of the same or different amplitudes (A), of which either the average rates or amplitudes, or both, of the
resultant targets could be manipulated independently.

2.3.3.2 Learning (Psychological) Factors

Experience has shown that the state of a manually controlled system or a combination of systems depends upon a balance between the skill of the operator and the difficulty of his task. In other words, effective tracking performance calls for the operator to be competent and thoroughly familiar with the mechanism of the control process; he must be properly motivated for the task. More specifically, it could be said that whether subject would find the tracking task relatively difficult or easy may depend, among other things, upon (a) his basic abilities, (b) his training, and (c) perhaps upon the ways the tasks are organized and presented to him, i.e., the sequence of task content.

(a) Basic Abilities: The skills involved in complex activities can be described in terms of more basic abilities which an individual brings with him as he attempts to learn a new task or upon which he draws for ultimate proficiency in the task. Many of these abilities are a product of learning, such as those involved in the analysis of target motion, say, in a tracking task, while others depend more on genetic than on learning factors, such as the ability to make rapid
movements of the wrist and forearm (Fleishman, 1966 and 1967).

Adaptation, for example, is a well known ability of the human controller to adjust his behaviour to particular task characteristics, and can be any or all of the following types: (i) input adaptation - the method by which the operator adopts a control policy appropriate to the characteristics of the input forcing function; (ii) task adaptation - the behaviour whereby the controller adapts to changes in the gain or dynamics of the controlled system; (iii) biological adaptation - this is primarily concerned with sensory phenomena, for instance, the human visual and auditory senses are capable of adapting to a wide range of stimulus conditions, such as intensity and frequency; and (iv) learning adaptation - the process of developing skills based on past experience; it is well known that an operator improves his performance as he is trained for the job he is to perform.

(b) **Training Methods:** Subject may be given either (i) whole-task training (WTR), or (ii) part-task training (PTR); where the latter may, in turn, be either progressive-part (PP) or pure-part training method. Generally, either of these methods has been shown to interact with task characteristics to affect
achievement in a variety of ways (Naylor, 1962; Naylor and Briggs, 1963 and 1962; Trumbo et al., 1965 and 1968; etc.).

(c) **Sequence of Task Content:** There seem to be different ways of presenting the task content or the content of training. Given a set of task conditions of target patterns \( I_j \), the sequence and type of presentation may, in this case, be systematic - i.e., in progressive or regressive order of task complexity (in relation to the levels of intricacy, amplitude, and/or rate of target motion) - or random (i.e., with no regard to task-complexity levels). Either of these modes may affect the relative effectiveness of particular training methods (i.e., whole-task vs. part-task or progressive-part-task vs. pure-part-task training method), and probably the relative levels of individual performance in a number of ways.

For instance, subject may complicate the task he has to perform, by introducing a random element into what otherwise would be predictable events; apparently because, given a particular sequence of the content of training, he might not be able to learn to adapt his actions to the requirements of the task (i.e., task-relevant "cues"). Another subject may, on the other hand, find the same task relatively easier to perform;
perhaps, due to a different type of task presentation, he might have developed the techniques for selecting the "cues", filtering out much that the first subject would notice and noticing much that the latter would overlook.

2.4. Summary

Figure 2.4 summarizes, in a pictorial form, the foregoing discussion. This figure can also be seen as a rationalized version of the conceptual model (of fig. 2.2). Although there is no significant difference between these two terms, "strata" and "levels", the former refers to the three principal components in terms of which the tracking performance can be described, while the latter is used to indicate that each of the former can, in turn, be resolved into more basic components. In future, we would prefer to use the latter. Conceptually, fig. 2.4 indicates that compensatory tracking is a complex performance which can be described by a hierarchy of variables.
Fig. 2.4. A descriptive (hypothetical) hierarchy of the compensatory tracking performance.
CHAPTER THREE

THE SET-UP OF THE EXPERIMENT

3.1. Introduction

There are, at least, two ways of applying the conceptual framework developed in the last chapter. One may, for example, start by assuming that a skilled performance has a hierarchic structure and is nearly decomposable into a set of relevant components, each of the latter being, in turn, hierarchic in structure until one reaches some lowest level of the more basic (elementary) components. When this is the case, the problem of performance assessment then becomes, as implied by fig. 2.2., the process of:

(a) identifying the relevant components, or component parts of the skills, at each level of the "hierarchy"; which, in effect, implies

(b) determining the properties (or relative significances) and relations (or interactions) of the components, "within" and "among" the various levels; and

(c) relating a level to those immediately above and below it.

Such an approach has been suggested by Conant (1972), though in another but somehow related problem area. To quote him: "When faced with a complex system (or problem) which one is trying to understand, then, it is reasonable to start by testing the hypothesis that it has a hierarchic structure and is nearly decomposable into
sub-systems within which the interaction of the variables is relatively intense and between which the interaction is relatively weak, for if that is the case attention can be turned to the detailed workings of each sub-system".

Given only the basic assumption that human performance is complex and consists of many interrelated components, one may, on the other hand,

(a) start by sampling a number of elements (or variables) which seem to reflect the component behaviours required to produce a given (or observed) performance output (or measure); and then proceed to

(b) investigate the properties and relations of these elements; and

(c) categorize (or "stratify") them (the elements) into a number of descriptive strata, or hierarchically related levels, according to the nature ("direction" and "content", or strength) of the interactions of the elements, so as to obtain a descriptive "hierarchy" of the skilled performance (as shown in fig. 2.4).

The two processes are related in a number of ways. Each involves a great deal of trial and error. Various elements may have to be sampled and tested. The "stratification" of these elements (i.e., their encoding into a number of pertinent levels or strata) may take various
forms, in terms of the number of levels and hierarchies to be realized. At the same time, the stratification might involve the application of various techniques, such as "factor analysis" (Love, 1972), "graphic theory" or "signal-flow graphs" (Beishon, 1967; Warfield, 1973; etc.), "binary or subordination matrices", and by verbal descriptions of the elements and relations (see Warfield, 1973).

The main difference between the two approaches could be illustrated by the following two descriptions of a circle by Simon (1962): "A circle is the locus of all points equidistant from a given point". "To construct a circle, rotate a compass with one arm fixed until the other arm has returned to its starting point". According to Simon, the first sentence is a "state description" of a circle, the second a "process description".

The experiment described in this chapter is based on the second (aforementioned) approach. As an exploratory study, and with our interest focused on compensatory tracking, the scope of this experiment is limited to the investigation of the properties (or relative significances) and relations of a set of elements which seem to reflect the component behaviours (or dimensions) of a typical compensatory tracking performance (of the type shown in figs. 2.1a/b/c). These data are, in turn, used to determine the possible levels of abstraction of the variables.
3.2 Method

As indicated above, the task involves the tracking of continuous targets of varying patterns of motion, with compensatory type of display and a simple displacement control mechanism. Figure 2.1a illustrates the general nature of the set-up. The display is a scale pointer which presents only an indication of the difference, or error, \( e(t) \), between the input forcing function, \( X(t) \), and operator's response, \( Y(t) \). The operator's task is to minimize the error signal by trying to keep the scale pointer at a zero position, at the centre of the scale. To simplify the motor activity, a major factor which is experimentally controlled in this study, the dynamic characteristics of the display and the controlled element (in this case the device by means of which the operator exerts his control) are lumped into an effective control mechanism (knob), the transfer function \( Y_c \) of which is made unity. The control knob is light, without spring loading, and frictionless. Simple target patterns consist of simple harmonics. Varying complex target motion patterns are obtained by combining two or more simple harmonics of different frequencies.
3.2.1 Design

As the scope of the conceptual framework of this work is limited to only the perceptual aspects of the control process, the design of the present investigation is based on the so-called "limiting principle". That is, subjects are given tasks in which performance is assumed to be limited primarily by the perceptual process or system, the properties and interactions of the elements of which are then inferred from the pattern of the observed results.

3.2.1.1 The Experimental Variables

These may be classified into three sub-sets, (1) the "task elements", (2) the "perceptual characteristics", and (3) the "performance metric", according to stratification of the conceptual model (see fig. 2.2).

1. The "Task Elements": These include (i) the task coherence (I), (ii) training method (TR), (iii) the input amplitude (A), (iv) the input frequency (w), (v) the sequence of task content or presentation (TP), and (vi) basic individual differences or abilities (BID). These variables correspond to the elements of the third (last) stratum of this model, and may be considered, in psychological terms, as the
"main\textsuperscript{*}\textsuperscript{1} independent variables of this investigation.

According to figure 2.4, the aforementioned variables are further classified into two levels of significance, as shown below.

(i) Higher level variables:
1. task coherence (three levels);
2. training method (three levels).

(ii) Lower level variables:
1a. the input amplitude (three levels);
1b. the input frequency (three levels);
2a. the sequence of task content (three levels); and
2b. basic individual abilities.

In this classification the "higher level variables" could be considered as the more general or complex factors, decomposable into more elementary (or basic) factors, the "lower level variables". That is, an elementary (or lower level) variable is either a component of or nested under one "higher level variable" or the other. For instance, the input frequency ($w$)

\textsuperscript{*}

In the hierarchical approach, whether a variable is described as a dependent or an independent variable is determined primarily by its level (of abstraction), and in relation to which other variables and levels it is being considered.
The three levels of task coherence (I) are:

(i) coherent (I₁) - this consists of a simple harmonic;

(ii) less coherent (I₂) - consisting of two harmonics of different frequencies but of the same amplitude; and

(iii) least coherent (I₃) - made up of three simple harmonics of different frequencies but of the same amplitude.

Each level is further classified into three levels of task complexity, with respect to the average rate of motion of the resultant target (see table 3.1). Relative to the degree of their
predictability, these three target patterns could sometimes be referred to here as coherent (I_1), intricate (I_2), and more intricate (I_3) inputs, respectively.

The three levels of the input frequency (w) are:
(i) \( w_1 = 2 \text{ radians per second} \);
(ii) \( w_2 = 4 \text{ radians per second} \); and
(iii) \( w_3 = 8 \text{ radians per second} \).

These frequencies and their various combinations give nine different patterns (wave forms) of target motion (denoted by W(w)), three from each level of the input coherence (I_1). The three levels of the wave form under I_3 are obtained with the aid of the coefficient K_i (see table 3.1. and explanations below). In future, as the case may be, we will be considering these nine levels of the wave form in the place of the three levels of the input frequency, since the relative effect of the latter (w) is determined by the average rate of motion of the former (W(w)).

As indicated in the table, the wave form is nested under the input coherence.

The three levels of the amplitude are:
(i) \( A_1 = 2 \text{ volts} \);
(ii) \( A_2 = 4 \text{ volts} \); and
(iii) \( A_3 = 8 \text{ volts} \).

The choice of values for the three levels of both the frequency (w) and the amplitude (A) is based on Shannon's (1948) formula for the amount
of information, expressed in terms of possible states (n) of a source as \( I = \log_2 N \). According to this formula, the respective scale values of \( A_i \) and/or \( w_i \) can be transformed into information metric as \( A_1 ; w_1 = 1 \) bit; \( A_2 ; w_2 = 2 \) bits, and \( A_3 ; w_3 = 3 \) bits. As a matter of convenience, we shall adopt the latter unit (bits) in the description of the various levels of the independent variables, particularly the amplitude (A) and the frequency (w). Also, by assuming one simple harmonic as a source of information, imposing a unit amount of information-processing or memory-storage capacity upon subject, we can as well scale the three levels of the input coherence in the information metric; as \( I_1 \) (one simple harmonic) - 1 bit, \( I_2 \) (two simple harmonics) - 2 bits, and \( I_3 \) (three harmonics) - 3 bits, of task complexity, respectively.

According to Hartman and Fitts (1955), when two or more time-varying voltages are combined to produce a more intricate target motion pattern the peak voltage of the composite signal as well as its root mean square (RMS) is greater than that of any of the single component signals. Thus, in order to provide a basis of comparison between the three levels of the input coherence variable \( (I_1) \), the amplitudes of the composite signals are reduced until the peak amplitudes (plus or minus) are the same for all the task conditions \( (I_1, I_2, I_3) \). This is done with the
aid of the coefficients $K_i$ ($i = 1, 2, 3$), where $K_1$, $K_2$, and $K_3$ are assigned the values 0.2, 0.3, and 0.5 (all constants), respectively. These coefficients also enable us to obtain three different target patterns (wave forms 7, 8, and 9, see table 3.1) under the least coherent inputs ($I_3$). It is assumed that the average rate of the composite signal is shifted towards the component frequency that is least reduced by $K_i$.

In table 3.1, the combination, say,

$$A_1 (K_1 w_1 + K_2 w_3 + K_3 w_2)$$

is an equivalent (in a short form) of $K_1 A_1 \sin w_1 t + K_2 A_2 \sin w_3 t + K_3 A_3 \sin w_2 t$.

There are 27 combinations of $W(I) \times A$ input conditions of different levels of task complexity. These task conditions are shown in table 3.1, where they are arranged in a progressive order of the complex levels of the input characteristics $I$, $W(w)$, and $A$, respectively.

The three levels of training method are:

(a) simple part-task training schedule - the content of training (i.e., the training tasks) include only the nine coherent inputs of the $I_1$ - row of table 3.1;

(b) whole-task training schedule - the content of training involves all of the 27 task conditions ($I_1$, $I_2$, and $I_3$) in the table; and

(c) difficult part-task training schedule - the training tasks include only the nine, more intricate (i.e., least coherent) input conditions of the $I_3$ - row of the same table.
The three levels of sequence of task content or content of training (TP) are:

(a) progressive - this involves the arrangement and presentation of the task conditions (inputs) in a progressive order of task complexity, as defined in terms of the average rate (w) and amplitude (A), as well as of the degree of predictability (I), of the tracked target.

(b) random - that is, any of the task conditions may be selected and presented to S at random, with no regard to its level of complexity; and

(c) regressive - this sequence entails the arrangement and presentation of the content of training in a regressive order of task complexity, i.e., starting with the most difficult (hypothetically) down to the easiest, with respect to the complexity levels of all the input characteristics (I, A, and w).

2. The "Perceptual Characteristics": They are (i) the "mental information" (MTWL) and (ii) the perceptual "noise" (var Z). These variables constitute the elements of the second stratum (the "task structure") of the conceptual model, and thus provide the basic data for making inferences regarding the limitations of the perceptual process which, as mentioned above, is assumed to be the primary limiting function of the control process. A short description of each of these variables is as
(i) The mental information (MTWL): As indicated in chapter two, this may be described as a "summary description" of the pattern of motion of the tracked target by the perceptual system. Effective tracking performance seems to require the perceptual system to provide the central mechanisms with "enough" information about the tracked target, so as to determine the immediate course of action of the effector system and to build up a store of data for use in prediction. Described also as a function of some heuristic behaviours (i.e., the ways in which the human operator organizes his perception among competing "cues" in the control loop), MTWL is, in turn, a composite of the following three parameters:

(a) $E(a)$ - a measure of the relative attention fixation (by the human operator) on the input forcing function;

(b) $E(b)$ - relative attention fixation on the display; and

(c) $E(a/b)$ - relative (covert) attention alternation between the input forcing function and the display.

These three parameters have also been described as measures of the relative amounts of information which the human operator seems to gain by

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* For a more detailed description of these variables, and how they have been derived, see chapter two, section 2.3.2, eqs. (2-6) through (2-13).
anticipation (or precognition), from the display (by direct vision), and as he switches his attention from one stimulus event to another, respectively, about the tracked target.

(ii) The perceptual noise (var Z): This, it is presumed, characterizes the statistical aspect of the perceptual process, and has been described (in chapter two) in terms of the variabilities of (a) the tracked target ($\sigma'_1^2$), and (b) the human operator ($\sigma'_1^2$).

3. The Performance Metric: The principal performance measure is the "input-output correspondence" (or "transmission") divided by the mean square error. It is denoted by "$\theta$" and measured in bits/volts$^2$. A detailed description of this metric, and how it is derived, is given in the last chapter (see section 2.2 and equations 2-1 through 2-5). Known otherwise as the "general performance criterion" (or "task performance"), this metric provides the basic data, based on individual performance levels, for evaluating the relative significance (or effect) of each of the variables listed above as well as those of their interactions.

3.2.1.2. Subjects

Considering the number of variables being investigated, we have to employ either
(i) a large number of subjects to participate in the study, or
(ii) a large number of task conditions and test
sessions, whereby the variables could be manipulated in a variety of ways and with a limited number of subjects. The second alternative is considered to be more suited to the underlying concepts (near-decomposability of all the variables) and design of this investigation. Conceptually, each subject may implicitly be viewed as a complex element (or system) in the control loop which incorporates, and is nearly decomposable into, a number of manipulable components of behaviour. Besides, as this investigation is exploratory in nature, we deem it reasonable to start with a small number of subjects, enough to enable us see how far any attempt to manipulate one variable may reflect on the relative significances of the others in a future, more elaborate, study.

Thus, only three subjects participated in the experiment. They are two boys and a girl, designated $S_1$, $S_2$, and $S_3$, respectively. They are all undergraduate psychology students in their early twenties. None of the three subjects has had any "formal" training in this type of task. It is also worth noting that sex is not a factor in this investigation. Hence, for convenience sake, "he" instead of "he/she" is to be used when referring to any of the subjects.

These subjects are recruited as student assistants, and are paid as such according to the number of hours they put in. Both the training method and the actual test tasks assigned to
each subject are shown in table 3.2. Also shown in this table are the different sequences of task presentation to individual subjects both during training and test sessions.

3.2.2. Apparatus

The principal components of the apparatus are, as shown in figure 3.1a:

(1) AC - a two-component (the "master" and the slave") universal analog computer, type GP-6 of the Comdyna Inc.; (2) PP - programme selection panel; (3) CU - control unit; (4) TC - time clock; (5) AN-7 - analog-7 tape recorder (Philips); and (6) TP - the test panel (fig. 3.1d).

Given below is a short description of the function of each of these equipments. On the analog computers are synthesized three harmonic generators (fig. 3.1b), so that three coherent inputs of varying frequencies (w) and with the same or different amplitudes (A) can be obtained simultaneously. The summation of these harmonics, to obtain any of the intricate task conditions (I₁ and/or I₃) of table 3.1, is also carried out on these computers. Measures are taken to prevent the over-loading of the proportional amplifiers of the computers during the experimental runs. Zero integration errors of the integrators are also accounted for.

The programme selection panel (fig. 3.1c) facilitates the selection of the scale values for the input parameters, Aᵢ, wᵢ, and Kᵢ, without meddling with the programmed circuits on
Fig. 3.1a The apparatus

Fig. 3.1b Sinus generator

Fig. 3.1c The programme selection panel (PP)

Fig. 3.1d Subject test panel
the analog computers. The panel also contains the displays for the input, \(X(t)\), the response, \(Y(t)\), and the error, \(e(t)\), signals, and for each of the three harmonics, separately; so that the state of the on-going experiment can be observed.

The control unit serves the following purpose:
(a) automatic starting and stopping of the analog computers, the analog - 7 tape recorder, the time clock, and consequently each experimental run;
(b) programming and recording of such experimental digital information as: block session, subject, tape numbers, date, task condition, display and control scale factors; and
(c) serving as an interface between the computers and the recorder, for recording the analog information, \(X(t)\), \(Y(t)\), and \(e(t)\).

The test (subject's) panel (fig. 3.1d) incorporates the display (zero-centre scale pointer) and two - potentiometer knobs, one rotary and the other lateral. The rotary control knob is located in front, at the centre of the panel, while the lateral knob is fixed by the right-hand side of the panel. The scale factors of the display and both controls are in 1:1 ratio. Like the display, both controls are zero centred. Both extreme left and right for the rotary,
and backward and forward for the lateral, of the control range correspond to the minus (-10v) and plus (+10v) maximum displacements, respectively, from the centre of the display. Hence both display and control movements are spatially compatible. Dynamically, there is no visual or control time lag. The test panel allows for only one subject to be tested at a time. The displayed information (i.e. the stimulus) is the error, e(t), signal, which is the difference between the input, X(t), and the response, Y(t), signals.

3.2.3. Procedure

3.2.3.1. Administration

The control room (for the experimenter and equipment) and the experimenting cabinet are adjacent to one another. In the cabinet, there is only the test panel (fig. 3.1d) which rests on a table. By the table stands an adjustable stool. The panel is such that subjects can shuffle it about the table to suit their convenience. Hence subjects are advised to sit relaxed (i.e. to maintain any sitting posture that suits them), but to use only their right hand for control; the three subjects are right-handed.

An experimental (or training) trial (block) consists of only one out of the 27 input (task)
conditions of table 3.1, and this lasts 80 seconds. A session consists of 27 trials, involving a given set or all of the 27 task conditions. During both the training and the actual-test sessions, only one subject is tested at a time, for two successive sessions. Except for the starting, which is manual, all timing and scoring are automatic for every trial. A buzzer is sounded before each new trial.

There is a 15-min. rest period in between consecutive sessions, and about one minute intertrial intervals, devoted to programme each task condition by the experimenter. During the rest period, subjects are free to (and all did so now and then) leave the test cabinet. Each session lasts uninterrupted, except for the intertrial intervals mentioned above.

3.2.3.2. Training

According to table 3.2, the schedule of individual training can be summarized as follows:

$S_1$ - progressive simple-part-task ($I_1$) training
  - PSPT;

$S_2$ - random whole-task ($I_1, I_2, I_3$) training
  - RWTR;

$S_3$ - regressive difficult-part-task ($I_3$) training
  - RDPT;
Table 3.2: Experimental design of training and test conditions (See table 3.1)

<table>
<thead>
<tr>
<th>Group (Subjects)</th>
<th>Training Condition</th>
<th>Test Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Training Method</td>
<td>Sequence of Task Content</td>
</tr>
<tr>
<td></td>
<td>Training Task</td>
<td>No of Sessions</td>
</tr>
<tr>
<td></td>
<td>Sequence of Content of Training</td>
<td></td>
</tr>
<tr>
<td>S1 (G1)</td>
<td>Simple part-task</td>
<td>Whole task</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>Progressive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1, 2, 3)</td>
</tr>
<tr>
<td>S2 (G2)</td>
<td>Whole-task</td>
<td>Whole task</td>
</tr>
<tr>
<td></td>
<td>K1, K2, K3</td>
<td>Progressive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1 to 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Random</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(11 to 12)</td>
</tr>
<tr>
<td>S3 (G3)</td>
<td>Difficult part-task</td>
<td>Whole task</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>Regressive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1 to 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Random</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(11 to 12)</td>
</tr>
</tbody>
</table>

where "progressive", "random", and "regressive" refer to the sequence (mode) of task presentation to S. A detailed description of each of these arrangements has been given above, in section 3.2.1.1.

All Ss received 9 sessions of one hour training per session, two sessions a day for four and a half days. During each session, as implied in
the above scheme, each of the nine task conditions \((I_1 \text{ and } I_3)\) in which \(S_1\) and \(S_3\) received their respective training is repeated three times, as each training session consists of 27 trials. Of these nine sessions, the first eight are conducted with the rotary control, while the last (and only one) "introductory" session is with the lateral control. The reason for this arrangement is given below.

Basically, subjects are instructed to endeavour to maintain the scale pointer (i.e. the stimulus, which is an indication of the error signal, \(e(t)\)), at the zero position, at the centre of the scale, by exercising continuous control on the control knob (rotary or lateral, as the case may be). As subjects track, the input, \(X(t)\), the response, \(Y(t)\), and the error, \(e(t)\), signals are monitored on the programme selection panel, see fig. 3.1c. These signals are also recorded on paper recorders, to enable individual tracking behaviour to be studied at the end of each training day. What is particularly useful about these data is that they enabled us to determine at what stage of the training are the patterns of performance by the individual subjects very nearly stable. On the average, this was found to be after the ninth session.
3.2.3.3. The Experiment

The actual experiment consists of 12 scored sessions, conducted as shown in table 3.2. During these sessions, each subject tracked all the 27 input conditions of table 3.1. Before the beginning of every session, subjects are given 9 warm-up trials on 9 tasks that correspond, in all respects, to their respective training schedules, including the sequence of the content of training. These trials are conducted with the rotary control knob, and are not recorded. This is followed by a rest period of about five minutes before the session begins.

The various modes of task presentation to individual subjects as well as the type of control used during these sessions are as follows:

1. The first ten sessions:
   
   (i) the sequence of task content is for
       (a) $S_1$ and $S_2$ - in progressive, and
       (b) $S_3$ - in regressive order of task difficulty;
   
   (ii) the control used by all subjects is for
       (c) the odd numbers, i.e. sessions 1, 3, 5, 7, and 9 - rotary,
       and
       (d) the other five-even numbers - lateral.

And, of the two sessions per day, one session is with the rotary, while the other is with the lateral control.
2. The last two (control) sessions (11 and 12):
   (i) the sequence of task content is random
       for all the subjects; and
   (ii) they all used the rotary control during
       the two sessions in succession.

The reasons underlying the above scheme can be
summed up as follows:

1. Points 1:(i), a/b, and 2:(i) - It is anti-
   cipated that this arrangement may enable us to
   gain some insight into the relative significance
   of the various modes of task presentation employ-
   ed here for the pattern of individual tracking
   performances.

2. Points 1:(ii), c/d - This arrangement has
dual intentions:
   (a) to reduce, no matter how little, the bore-
       dom of doing the same thing (physically) for the
       two-1 hour sessions; and
   (b) to gain some information about the adaptive
       capabilities of individual subjects, on the basis
       of transfer of training phenomenon. Since sub-
       jects received most of their training (8 out
       of 9 sessions) with the rotary control, it is
       suspected that they may exhibit some sort of
       "positive" or "negative" transfer of training
       behaviour as they tracked with both controls,
       alternating their control modes between rotary
       and lateral displacements during every other
       session. For instance, if $\phi(R)$ and $\phi(L)$ represent
       the measures of individual relative performance
levels with the rotary and the lateral control knobs, respectively, it can be suggested that subject exhibits (i) the ability to adapt to some changes in the task environment (i.e. the control mode), and/or (ii) positive transfer of training behaviour, if, for a given task condition (i.e. $I_1$, $I_2$, or $I_3$),

$$\Delta \phi(L/R) = \frac{1}{N} \sum_{i=1}^{N} (\phi_i(L) - \phi_i(R)) \geq 0 \quad (3-1)$$

where $N$ is (5x9) number of observations from any of the two-five sessions for the nine inputs.

3. Point 2:(i) - These two sessions are considered to be the control of the other two forms (progressive and regressive) of task presentation.

Point 2:(ii) - In order to reduce, as far as possible, some effects (i.e., positive or negative transfer of training effects) attributable to any changes in the control mode, it was considered reasonable to conduct these two control sessions with the rotary control by which the Ss received most of their training.

As indicated above, the state of every trial is monitored on the programme selection panel, through the input, $X(t)$, the response, $Y(t)$, and the error, $e(t)$, signals which are displayed on this panel. These signals as well as the necessary detective-digital information (described above, under the apparatus) are recorded on
analog magnetic tape cartridges, by means of the analog-7 tape recorder. Should a random 'noise' occur during any trial, this is also noted and the trial is repeated forthwith.

3.2.4. Data Processing

This operation can be divided into two phases:

1. the conversion of the analog information, X(t), Y(t), and e(t), which are recorded in analog tape cartridges (see apparatus and procedure), into corresponding discrete sequences, X_j, Y_j, and e_j (j = 1, 2, 3, ..... 1024 samples); and

2. the processing of these sequences (or samples) to obtain the necessary parameters, as listed in section 3.2.1.1.

The first operation involves playing back (offline) the analog tapes, through an A/D convertor, into the PDP-9 digital computer, where the discrete, sampled, data are temporarily stored and eventually processed to obtain the necessary variables. This process is carried out with the aid of a programme (SAMPLE), written in a PDP-9 computer oriented language, and which is capable of handling a maximum of six signals simultaneously at 10 bit resolution or 1024 sampling levels. The operations performed by this programme can be summed up as follows:

(a) sampling and converting the analog information into discrete data;
(b) converting, and displaying on the scope, the sampled data back into analog signals, so that it might be possible to compare the sampled data with the original task (recorded) information;
(c) decoding the digital information, recorded along with the analog information during each trial and session and used to detect and identify the essential information or parameters of the design;
(d) detecting faulty trials and parameters to be skipped or modified; and
(e) controlling the sampling frequency, by printing out such error information as "NOT ENOUGH SAMPLES", or "TOO MANY SAMPLES", if $2TW \geq 1024$ (where $T = 80$ sec., the duration of a trial), thus ensuring the selection of a uniform sampling frequency ($W$) for all the trials.

The second phase is executed with the aid of another programme (PROCES), written in ordinary Fortran IV language. This programme works both on-line, on a time-sharing basis with the first one (SAMPLE), and off-line, separately. It functions as follows:
(f) converts the discrete quantities $X_j$, $Y_j$, and $e_j$ into transformed "scores", according to the familiar formula ($\log_2 X$) given in chapter 2 (see page 27);
(g) computes and prints out all the necessary parameters, indicated above, from the accumulated (sampled and perhaps standardized) data;
(h) stores (and retrieves, when necessary) both the sampled data and the processed information on dectapes.

Perhaps it is noteworthy to state the values, and the reason for the choice, assigned to the parameters \( B \) (see eqs. 2-6 through 2-9 of chapter 2), \( X_c \) and \( e_c \) (see eqs. 2-10 and 2-10 a), which enter in the calculation of the variables \( \text{var } Z \), \( \sigma''^2 \), and \( \sigma''''^2 \), respectively.

1. As indicated earlier, in chapter 2, we consider the coefficient \( B \) (a constant) as a measure of the "temporal interval" \( (t) \) between two subsequent error detection and correction; a phenomenon inherent in all continuous tasks, irrespective of the dynamics of the controlled element \( (Y_c) \). Since there is no clear-cut quantitative definition for this interval, our choice here of the value for \( B \) is quite arbitrary, based only on the condition (already stated here) that the roots \( p_{1,2} = \frac{1}{2}(1 \pm \sqrt{1-4B}) \), of the characteristic equation \( P^2 - P + B = 0 \), be real. Choosing the critical case in which these roots are not only real but also equal, we have \( B = 0.25 \).

2. The relative values of the criterion \( (X_c) \), defined here as being equivalent to the effective amplitude \( (A) \) of the input forcing function, are 2, 4 and 8 vts. The latter correspond to the three amplitude levels \( (A_1, A_2, \text{ and } A_3) \), respectively) being investigated here.
The value for $e_c = \bar{e}$, defined as the mean of the absolute magnitudes of the error information, is determined for every trial from the sampled data, since this value varies from trial to trial.

3.2.5. The Plan Of Results Analysis

The experimental variables will be treated under three major (functional) groups.

1. The input characteristics: These include the input coherence (I), amplitude (A), and frequency (w).

2. The learning (psychological) factors: They are training method, sequence of task content, and basic individual differences or adaptive capabilities; collectively, these factors will, for a number of reasons (see below), be denoted by the letter S (meaning subject).

3. The "perceptual characteristics", so called for conceptual convenience: These are the perceptual noise (var Z) and the mental information (MTWL), with associated components (see page 72).

This arrangement is particularly useful in at least one respect. It enables the analysis to be conducted in a considerable detail. The analysis will comprise of the descriptions and interpretations, where necessary, of (a) the main effects, (b) the interactions, and
(c) possible levels of abstraction (according to the nature of the interactions) of the experimental variables. Two different kinds of interactions can be distinguished here; (i) the interactions "within" the groups, and (ii) the interactions "among" the groups, i.e., the interactions among any two or more variables belonging to different groups.

The observations will be based on the relative levels of performance by the individual subjects, and will be measured in terms of the general performance criterion ($\varnothing$). Where necessary, the variables of any of the aforementioned groups will be treated as if they were one variable, whose relative effects will be assumed to depend in only an aggregated way on the relative effects of the variables of any other group. An example of such variables is the learning factors which, as indicated above, are usually denoted by $S$ (subject).
3.2.5.1. The Procedure For Determining The Possible Levels Of Abstraction Of The Variables.

The method to be adopted here is the "Subordination Matrix". A detailed description of this method is contained in Warfield (1973). The following is a modified (in the context of this analysis) description of this method. But before we go on, we would like to emphasize that the term "subordination" or "subordinated" is used here in a slightly different context from the usual sense. Here, a variable is said to be subordinated to any other variable when it is a function of and/or influenced by that variable, or when the latter is nested (by design) under it. For instance, any variable on a given level is assumed to be a function of, or dependent on, any other variable(s) on a level immediately below it. In other words, the "direction" of association is assumed to be upwards, the variables on the last (bottom) level being the most independent variables.

**Associating The Variables:** In this approach will make use of the following principles of association (of the variables).

1. All variables will be associated with the same type of mark, called a "vertex", and a number will be assigned to the vertex to represent the particular variable.
2. All relations will be associated with the same type of mark, called an "edge" (e), and a letter will be assigned to the edge to represent the particular relation.

3. Each edge will have associated with it a sense of direction representing some explicit distinction between the two variables connected by the edge.

Forming The Subordination Matrix: This will involve (i) determining which variables are in a subordination relations (in the sense in which the term is used here) to which other variables, and (ii) encoding the subordination relations in matrix form. The subordination relations will be determined (by inference and/or examination) from the relations among the various sets of data to be reported in the chapter, as well as from the design of the experiment.

The rules that will govern the formation of the matrix are as follows: Let us suppose that we have \( n \) variables numbered from 1-\( n \). This implies that we will construct a square \((n \times n)\) matrix, in the form shown in fig. 4.12. The entry \( e_{ij} \) in the jth column reflects the subordination relation between variables i and j from the set of variables. If variable i is not subordinate to (i.e., dependent on) variable j, the entry \( e_{ij} \) will be zero.
Other, more general, rules for this approach include:

1. **The Diagonal Entry Rule:** All entries on the main diagonal of the matrix, i.e., all entries of the form $e_{ii}$, are equal to 0.

2. **The Double Entry On 1 Rule:** If variable $i$ is subordinate to variable $j$, enter a 1 in position $e_{ij}$. Since variable $j$ is then not subordinate to variable $i$, one must enter a 0 in position $e_{ji}$.

3. **The Multiple Entry on Paired 1's Rule:** If variable $i$ is subordinate to variable $j$ (so $e_{ij} = 1$), and if variable $j$ is subordinate to variables $k_1, k_2, ..., k_r$ (so $e_{jkl} = e_{jk2} = ... = e_{jkr} = 1$), then variable $i$ is subordinate to the variables $k_1, k_2, ..., k_r$, and one must set $e_{ikl} = e_{ik2} = ... e_{ikr} = 1$. 
CHAPTER FOUR

RESULTS

4.1. Introduction

As indicated in the previous chapter, all the observations here are based on the relative levels of performance by the individual subjects, and are expressed in terms of the "general performance" criterion (\( \phi \)). The latter has been defined (in the last two chapters) as the "input-output correspondence" (as measured in information metric, "Transmission") divided by the mean square error, and is measured in bits/volts\(^2\). This metric is very often referred to here as "task performance".

In order to provide a basis for comparison among the relative effects of the various variables, and as a matter of convenience, the different scale values (in physical units) of most of the experimental variables are transformed into a uniform (information) metric (see chapter three, section 3.2.1.1.). For instance, by using the transformation \( \log_2 N \) (where \( N = 2, 4, 8 \)), the three levels of both the input frequency (in radians) and the input amplitude (in volts) are transformed into uniform units (task complexity levels) of 1, 2, and 3, respectively. These units correspond to the three complexity levels \( (I_1, I_2, I_3) \) of the input (task) coherence.
4.2. The Relative Significance Of The Variables.

Unless otherwise indicated, all the results to be reported in this section cover only the observations from the first ten sessions of the experiment. This implies that each point in the figures and tables illustrated here represents the average of ten observations with each of the 27 task conditions of table 3.1 (of chapter 3). As indicated in chapter three, the relative effects of the input frequency \((w)\) will be considered, where necessary, in terms of the waveform factor, \(W(w)\).

4.2.1. The Input Characteristics

4.2.1.1. The Coherence

According to figure 4.1, task performance tends to deteriorate with the decrease in the internal coherence of the input. However, comparing the relative values of \(\phi\) at the two intricate levels of I (I\(_2\) and I\(_3\)), it appears that the decrease in performance is not progressive with the corresponding decrease in coherence. Ss seem to experience less difficulty in what was considered here to be the more intricate inputs (I\(_3\)), than in the less intricate and complex tasks (I\(_2\)). In other words, those tasks that are composed of two harmonics appear to present,
Fig. 4.1 Task performance as a function of the input characteristics (I, A, W)
comparatively, the greatest difficulty to Ss. Among possible explanations that could be given for this phenomenon, the following appears to be more relevant to the present investigation.

**Training Effect:** We remember that unlike the other two classes of task ($I_1$ and $I_3$) on which two of the Ss ($S_1$ and $S_3$) received part-task training, none of the Ss received training specially on the $I_2$-class of task; $S_2$ was trained on all the 27 input conditions, as a whole, with the mode of task presentation being random. It thus appears that both $S_1$ and $S_3$, and perhaps $S_2$, might have experienced a sort of "negative transfer-of-training effect" with the $I_2$-class of task, on which they were not particularly trained.

**The Effect of Rate of Change of the Input:** That Ss did relatively better in $I_3$ than in $I_2$ task conditions may also be attributed to the relative effects of the components of $I$, particularly of the average rates of motion of both input classes. As can be seen from the relation between $\theta$ and the wave form factor, also illustrated in fig. 4.1, it appears that the average rate of motion of $I_2$ is relatively greater than that of $I_3$. To a certain extent, this difference might have contributed to the relatively poor performance by Ss in the former ($I_2$).
4.2.1.2. The Frequency

An examination of the relative values of $\phi$ at the simple harmonic inputs (i.e., wave forms 1, 2, and 3) in fig. 4.1 shows that task performance tends to decrease very progressively with the increase in the frequency (rate) of the input. This phenomenon is also noticeable in the other two classes of task ($I_2$ and $I_3$). Consider, for instance, the relative values of $\phi$ at wave forms 4, 5, and 6, of $I_2$. Wave form 4 is composed of two basic simple harmonics, $w_1$ and $w_2$. When the average rate of motion of this signal is increased, by replacing $w_1$ or $w_2$ with $w_3$ (where $w_1 < w_2 < w_3$) to obtain wave form 5 or 6, task performance is found to deteriorate correspondingly.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>MS</th>
<th>df</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>69,245</td>
<td>2</td>
<td>196.06</td>
</tr>
<tr>
<td>I</td>
<td>54,993</td>
<td>2</td>
<td>170.48</td>
</tr>
<tr>
<td>W (w1)</td>
<td>42,976</td>
<td>6</td>
<td>133.23</td>
</tr>
<tr>
<td>A</td>
<td>4,610</td>
<td>2</td>
<td>14.29</td>
</tr>
<tr>
<td>S x I</td>
<td>698</td>
<td>4</td>
<td>2.16</td>
</tr>
<tr>
<td>S x W (w1)</td>
<td>440</td>
<td>12</td>
<td>1.36</td>
</tr>
<tr>
<td>S x A</td>
<td>2,073</td>
<td>4</td>
<td>6.43</td>
</tr>
<tr>
<td>I x A</td>
<td>1,244</td>
<td>4</td>
<td>3.86</td>
</tr>
<tr>
<td>S x I x A</td>
<td>95</td>
<td>8</td>
<td>0.30</td>
</tr>
</tbody>
</table>

* $P < 0.05$; ** $P < 0.01$

Table 4.1 Variance analysis on task performance ($\phi$) for the first ten sessions.
4.2.1.3. The Amplitude

The relation between $\theta$ and $A$ in fig. 4.1 seems to indicate that tracking performance is not a monotonous function of the input amplitude. According to this relation, performance tends to improve at the initial stage of the increase in the complexity level of the amplitude, from $A_1$ to $A_2$, and then deteriorate as the latter ($A$) continues to increase, in this case to $A_3$. This observation can be explained by what Hartman and Fitts (1955) have described as the "visual and motor scale effects" on tracking performance.

According to the visual scale effect, relative accuracy in judging error magnitude (display) improves as the magnitude of the error display is increased from the "threshold" (the minimum recognizable value) up to some limit. Similarly, the motor system with its associated proprioceptive feedback loop is utilized most effectively when the full range of S's output capabilities is demanded by the task, rather than when only a restricted range of forces or movement amplitudes is required. However, beyond a certain limit, according to Hartman and Fitts, the advantages derived from these effects seem to decrease with the progressive increase in the complexity level of target's amplitude, and apparently of the amplitude of control movements.
4.2.2. The Learning (Psychological) Factors

Figure 4.2 illustrates the relative performance levels of individual Ss at all the 27 task conditions, where each point is the average of (10 x 27) observations. According to this figure, the tracking performance of $S_3$ appears to be better than that of either $S_1$ or $S_2$; the relative performance of $S_1$ being, in turn, better than that of $S_2$. Among other things, the following
three factors can be suggested as probable contributors to this result.

4.2.2.1. Training Method

The following observations are indicative of what may be considered as the relative contribution of the training factor (TR) to the characteristic patterns of performance by individual Ss (see figs. 4.2 and 4.6 and table 4.2).

1. As indicated in figure 4.6 (see page 114) both $S_1$ and $S_2$ did relatively better in those task conditions ($I_1$ and $I_3$, respectively) in which they were specially trained than in the other tasks in which they received no formal training (for the various modes of training of the subjects, see table 3.2 of chapter 3).

2. According to the same figure, the three Ss, particularly $S_1$ and $S_2$, did comparatively better in the more coherent tasks ($I_1$) than in either of the other less coherent inputs ($I_2$ or $I_3$).

3. As shown in table 4.2, the differences among individual performances seem to widen as one progresses from the most simple to the least coherent, and probably more difficult, tasks; this trend is much more pronounced between $S_3$ and either of the other two subjects ($S_1$ and $S_2$) than between the latter themselves.
<table>
<thead>
<tr>
<th>TASK CONDITION</th>
<th>$\Phi(S1)-\Phi(S2)$</th>
<th>$\Phi(S3)-\Phi(S1)$</th>
<th>$\Phi(S3)-\Phi(S2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.6</td>
<td>12.0</td>
<td>23.0</td>
</tr>
<tr>
<td>2</td>
<td>18.0</td>
<td>13.0</td>
<td>31.0</td>
</tr>
<tr>
<td>3</td>
<td>12.0</td>
<td>26.0</td>
<td>38.0</td>
</tr>
</tbody>
</table>

Table 4.2 The differences in the relative levels of performance by the individual Ss at the three task conditions (1)

The last two points are augmented by the following reasoning;
First, since the mode of behaviour at the more coherent tasks ($I_1$) is almost that of a simple open-loop response, the relative levels of Ss' performances here can be attributed less to such specific skills as perceptual organization, which may be acquired by training, and more to more general traits or basic abilities (such as fast, synchronous following), which Ss may bring along to the task environment. This being the case, the relatively high performance at $I_1$-tasks by all the subjects seems not surprising, particularly as the control mechanisms are simple and
linear.
Secondly, apart from general traits, the more intricate tasks, particularly $I_3$, also seem to demand the acquisition of more subtle perceptual and organizational skills, as demanded by their structure. In this relation, $S_3$, who received his training specifically on the $I_3$-class of tasks, most probably stands at a relatively greater advantage over $S_1$ and $S_2$, who were trained otherwise. This reasoning is supported by, or, on the other hand, explains, the fact that the difference between the relative performance of $S_3$ and that of either $S_1$ or $S_2$ is greater at $I_3$ than at $I_1$ and $I_2$-tasks, respectively. Similarly, that these differences are greater at $I_2$ than $I_1$ task levels can also be explained by this advantage, since such complex perceptual skills as demanded by the structure of $I_3$ are likely to be much more relevant in dealing with $I_2$ than with the $I_1$-class of tasks; the former being relatively more intricate and perceptually demanding than the latter.
Other indications of probable relations between the training factor and $S$s' tracking behaviours, as depicted here, are discussed below (in the next two paragraphs).
4.2.2.2. Basic Individual Differences

The characteristic patterns of performance by individual Ss (as illustrated in figs. 4.2 and 4.3) can also be attributed to their basic differences, such as their adaptive capabilities. The attributes of this factor could be sought in expression 3-1 of chapter three (see page 84). Tentatively, this expression suggests that a subject may:

(a) exhibit a sort of "task adaptation" (i.e., he adapts to any change in the control mode) when the average level of his performance with the rotary control, where he received most of his training (eight out of nine training sessions), is the same as that with the lateral control (with which he received only one, introductory, training session); and

(b) exhibit not only "task adaptation" but also other forms of adaptation (such as "input" and "learning" adaptations) if his performance is relatively better with the lateral than with the rotary control.

The definitions of the aforementioned forms of adaptation are given in chapter two, section 2.3.3.1 (a).

Figure 4.3 gives some clues as to the ways these suggestions are reflected by individual tracking behaviours; where positive sign (+) indicates a sort of learning process or what
is known as "positive transfer of training", while minus (-) indicates the opposite - "negative transfer of training" or "mal-adaptability". 1. The behaviour of S3 appears to conform with these suggestions, almost in all respects. Particularly interesting is the indication that his behaviour is (i) nearly consistent with the first suggestion (i.e., it is almost in an agreement with the first condition, $\Delta \Phi (L/R) = 0$, 

![Graph showing task complexity levels and Ss' adaptive capabilities](image-url)

**Fig. 4.3** A measure of Ss' adaptive capabilities:
- $\Delta \Phi (L/R) < 0$ - mal adaptability;
- $\Delta \Phi (L/R) > 0$ - high adaptive capability
of eq. 3-1), specifically at those task conditions \(I_3\) in which he received formal training, and (ii) almost that of "positive transfer of training" (i.e., it tends to agree with the second condition, \(\Delta \phi(L/R) > 0\), of eq. 3-1) at the other task conditions \(I_1 \) and \(I_2\) in which he was not trained.

2. Neither the behaviour of \(S_1\) nor that of \(S_2\) appears to conform with any of these suggestions; a comparison between the two shows that \(S_2\) tends to behave relatively more agreeably than \(S_1\).

In regard to the significance of these results, it is useful to point out that it is rather difficult to make any explicit inferences on the basis of these observations regarding any relationships between the adaptive capabilities and relative performance levels of the individual subjects. For one thing, the above results, though relevant, are not sufficiently substantive to permit proper identification and measurement of such relationships. For another, human adaptation is such a complex mechanism that we definitely cannot, by the present investigation, reduce its relationship with (or relative contribution to) tracking achievement into a clear picture. This is a subject that requires more extensive studies, and the accumulation of vast quantities of data.
4.2.2.3. Sequence Of Task Content

Another factor whose relative significance for the individual performance levels may not be ignored here is the varying modes of task presentation to Ss, during both the training and the actual test sessions. Consider, for instance, the relative performance of S₂. In principle, S₂ received whole-task training schedule, while the other two Ss both received part-task training schedules. By the virtue of his training, one would have expected that S₂ could do better than either of the other two (S₁ or S₃) in all the task conditions. For instance, many works (Naylor, 1962; Naylor and Briggs, 1962 and 1963; Trumbo et al. 1965 and 1968; etc.) have shown that the whole-task training is comparatively more effective than part-task training methods, particularly in those task situations (as considered here) that emphasize the acquisition of complex perceptual skills in dealing with the total task. That the reverse appears to be the case here can lead one to argue that the random manner by which the tasks (whole) were sampled and presented to S₂, during the training sessions, offered him no opportunity to grasp the cross-dimensional relationships (among the constituent components of I) that distinguished the various task conditions, particularly I₂ from I₃, and/or to perform as well as (or better than) either S₁ or S₃. As indicated in figs. 4.4 and 4.6, the
relative performances of S$_2$ at the two intricate tasks (I$_2$ and I$_3$) are the same, while the other two SSs, whose modes of task presentation were not random, behaved differently at both task conditions.

The mechanism of transfer-of-training seems to operate here too. Whereas the sequence of task content to either S$_1$ (progressive) or S$_3$ (regressive) is the same during both the training and the actual test (i.e., the first ten) sessions, to S$_2$ it differs in both cases, being random during the training but systematic (progressive) during the test sessions. It thus makes some sense to suggest that another possible reason why S$_2$ performed worse that S$_1$ or S$_3$ is because he, unlike the latter, transferred from one task organization and sequence of content to another.

![Fig. 4.4 Individuals' levels of performance at the three task conditions (I) during the last two (control) sessions.](image-url)
4.2.3. The Perceptual Characteristics

The data summarised in tables 4.3a/b illustrate the regression of the general performance criterion ($\phi$) on the "perceptual characteristics", var $Z$ and MTWL. The description of this result is as follows. Table 4.3a contains two main rows, labelled:

1. Single Predictors: Here are shown the relationships between $\phi$ and each of the aforementioned variables independently;
2. Two Predictors: This illustrates the prediction of $\phi$ from the two variables (var $Z$, MTWL) together.

According to these results, it appears that

(a) almost in all the options considered, $\phi$ is highly and positively related to MTWL: indicating the tendency of the former to increase with the latter (see parameters $p$; $b_x$, $y$; $R^2$; etc. of the table). This result is not surprising, at least for the obvious reason that the two parameters ($\phi$ and MTWL) are related in some way, by the presence of a common parameter, $T(a,c)$, in their respective expressions (see eqs. 2-4, 2-5 and 2-12 of chapter two).
### Table 4.3a The regression of task performance (Φ) on the perceptual characteristics (MTWL, var Z).

<table>
<thead>
<tr>
<th>independent variables</th>
<th>dependent variable y=Φ</th>
<th>regression parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>beta β</td>
</tr>
<tr>
<td>1 - MTWL</td>
<td></td>
<td>MTWL</td>
</tr>
<tr>
<td>2 - var Z</td>
<td></td>
<td>var Z</td>
</tr>
<tr>
<td>single predictors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTWL</td>
<td>0.640</td>
<td>37.247</td>
</tr>
<tr>
<td>var Z</td>
<td>0.147</td>
<td>3.712</td>
</tr>
<tr>
<td>double predictors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTWL</td>
<td>1.178</td>
<td>68.544</td>
</tr>
<tr>
<td>var Z</td>
<td>-0.726</td>
<td>-18.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>dependent variable</th>
<th>multiple corr. R²</th>
<th>std. error of estimate</th>
<th>df</th>
<th>F value</th>
</tr>
</thead>
<tbody>
<tr>
<td>y=Φ</td>
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<td>0.147</td>
<td>0.805</td>
<td>4.858*</td>
</tr>
<tr>
<td>MTWL</td>
<td>0.741</td>
<td>11.616</td>
<td>8</td>
<td>0.154</td>
</tr>
<tr>
<td>var Z</td>
<td>1.000</td>
<td>14.954</td>
<td>8</td>
<td>5.507*</td>
</tr>
</tbody>
</table>

### Table 4.3b The correlation matrix of Φ, MTWL, and var Z.

<table>
<thead>
<tr>
<th>variable</th>
<th>Φ</th>
<th>MTWL</th>
<th>var Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTWL</td>
<td>0.640</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>var Z</td>
<td>0.147</td>
<td>0.741</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 4.3a The regression of task performance (Φ) on the perceptual characteristics (MTWL, var Z).

Table 4.3b The correlation matrix of Φ, MTWL, and var Z.
(b) the weighting of \( \theta \) by \( \text{var} \ Z \) is relatively very small and in most of the cases negative, indicating some tendency of \( \theta \) to decrease with \( \text{var} \ Z \), and inversely;

(c) the two parameters (\( \text{var} \ Z \), MTWL) are highly correlated, indicating their mutual dependence or relationship (see table 4.3b).

We will like to reserve the interpretation of these results until we come to consider the interactions of these variables with the other experimental variables (see section 4.3.3.), since these results are functions of such interactions.

4.3. The Interactions Of The Variables

4.3.1. Within-Group Interactions: The I x A Interaction

From an inspection of the data summarized in fig. 4.5, it appears that the relative effects of the amplitude variable discussed above (in section 4.2.1.3.) depend, to a great extent, upon the internal coherence of the tracked target. For instance, whereas for the more coherent tasks \( (I_1) \) tracking performance tends to decrease
in progression with the increase of the amplitude, at the other two, less coherent classes ($I_2$ and $I_3$) of task, the picture appears to be comparatively different. The relation between task performance ($\phi$) and the amplitude ($A$) at the latter task conditions has the same pattern as that shown in fig. 4.1. That is, tracking performance first tends to increase with the initial increase in $A$, and then decreases as $A$ continues to increase. It is also interesting to note that, although the difference in task performance among the three task conditions is quite noticeable at the lower amplitude levels ($A_1$ and $A_2$), at the highest amplitude ($A_3$) considered here, this difference is almost indistinguishable.

![Graph showing the relationship between task performance and amplitude](image)

Fig. 4.5 Task performance as a function of $I \times A$ interaction
The above observation is reminiscent of the phenomenon of human selective attention, between the visual and the proprioceptive cues, in continuous tracking tasks of different configuration; a phenomenon which correlates with the visual and motor scale effects mentioned earlier. According to Rethlingshaffer (1943), Helson (1949), Hartman and Fitts (1955), the proprioceptive feedback arising during a movement response is most effective when the movement pattern is simple and highly repetitive. But Ss seem to find it difficult to utilize proprioceptive cues when executing the more intricate movement patterns, and tend to shift their attention relatively more to the visual cues. It has also been shown (by Hartman and Fitts, 1955) that optimum visual stimulus magnitude is relatively more important than optimum response magnitude (or optimum proprioceptive feedback) for complex target courses; hence the improvement in Ss' relative performances with the initial increase in the amplitude of the more intricate inputs ($I_2$ and $I_3$).

On the other hand, the background of the relatively poor performances by Ss at the highest amplitude ($A_3$) considered here, which is uniform in all the three task categories, could be traced more to physical (such as the duration of control movements) than to sensory
limitations. For instance, Fitts (1954) had found the response variability (i.e. the noise associated with the output) to increase with the increase in the duration of the control movement, following the increase in the average movement amplitude, which is, in turn, a function of the amplitude of the input forcing function.

4.3.2. Among-Group \((S \times (I, A, w))\) Interactions

As indicated at the end of chapter three, the learning factors are assumed to interact in an aggregated way, and are thus considered as if they were one variable denoted by \(S\) (subject).

4.3.2.1. The \(S \times I\) Interaction

As illustrated in figure 4.6, Ss seem to exhibit different modes of behaviour at different conditions of task coherence \((I)\). Considering how individual Ss fared at the various complexity levels of \(I\), one realizes, as already indicated in section 4.2.2.1, that

(a) all the Ss performed relatively well at the simple harmonic inputs \((I_1)\);

(b) the performance of \(S_1\) tends to deteriorate in progression with the decrease in task coherence;

(c) the performance of \(S_2\) first decreases, sharply, with the decrease in task coherence between \(I_1\) and \(I_2\), and then levels off between
I₂ and I₃;

(d) S₃ seems to encounter more difficulty at the I₂-class of tasks than at the other two, I₁ and I₃, the latter being the least difficult for him. In general the performance of S₃ in all the task conditions is relatively superior to that of either S₁ or S₂.

The interpretation of these results in terms of the learning factors are given above, in sections 4.2.2.1 through 4.2.2.3.

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Fig. 4 6. Task performance (φ) as a function of the learning factors (S) x input characteristics (I, A, W, ) interactions.
4.3.2.2. S x A Interaction

The subjects also seem to react differently to the variation of the input amplitude (see fig. 4.6 and table 4.1). The "visual and motor scale effects", mentioned earlier, appear to be highly manifested by the $S_2 \times A$ interaction. As illustrated in fig. 4.6, the performance of $S_3$ first increases with the initial increase of the amplitude, between $A_1$ and $A_2$, then reverses and decreases as $A$ is further increased, up to $A_3$.

$S_1 \times A$ interaction indicates that up to $A_2$, the performance of $S_1$ is insensitive to any change in the amplitude of the target, i.e., his behaviour remains the same as $A$ varies between $A_1$ and $A_2$. However, like $S_3 \times A$ interaction, the performance of $S_1$ tends to deteriorate between $A_2$ and $A_3$. Comparing the behaviours of $S_1$ and $S_3$ with the variation of the input amplitude, it appears that the sensory discrimination of position (displacement) by $S_1$ is relatively lower than that of $S_3$. The same assessment can also be made about the appropriateness of their respective attention selection between the visual and the proprioceptive cues, a phenomenon that is akin to the sensory discrimination of stimulus position (magnitude).

On the other hand, $S_2$, whose performance seems to decrease with the progressive increase in task's amplitude, appears not to take an advantage of either the visual or the motor scale effect, or both.
4.3.2.3.  $S \times W(w)$ Interaction

Figure 4.6 also indicates the ways the individual Ss interacted with the input frequency. It appears that the three Ss seem to share the same fate relative to the variation of w, the progressive deterioration of tracking performance with the increase in the average rate (frequency) of target motion.

Putting this observation in other terms, it appears that the informational stress imposed by the input frequency on Ss is independent of their respective dispositions (motivation, ability or skill, etc.). That the latter might be the case is indicated by the closeness of the relative levels of Ss' performances at the simple harmonic tasks ($I_1$), where the influence of the frequency factor could be felt separately. Here one realizes that the differences among Ss' performances are relatively smaller than at the other two task conditions ($I_2$ and $I_3$), where Ss' modes of behaviour might have been influenced not only by this factor (w) but also, to some extent, by the input coherence and other related factors, such as the inter-component relationship between w and A.
4.3.3. The Interactions Among The Three Groups Of Variables

The relationships among the three groups of variables are illustrated in fig. 4.7. Also illustrated in this figure are the functions \( \phi(S) \), \( \phi(I) \), \( \phi(A) \), and \( \phi(w) \), so as to indicate the ways in which these interactions are related to task performance. The variance analyses for some of these relationships are shown in table 4.4.

Here, as illustrated in the figure, only three levels of the waveform factor, \( W(w) \), are considered to be of significant interest. In each of these interactions, the input characteristics and/or the learning factors (denoted by \( S \)) are considered to be the "limiting factors". To distinguish this kind of relationship (with the perceptual characteristics) from the other interactions considered here, we use the notation "vs." instead of the usual "x", indicating that the "latter" is a function of the "former".

\begin{table}
\begin{tabular}{|c|c|c|c|c|}
\hline
Source of Variation & MS & \text{df} & F Ratio & \\
\hline
\text{MAIN EFFECTS} & & & & \\
S & 4.08 & 1 & 100.06 & 5.31 \\
I & 0.59 & 7 & 2.99 & \\
W & 2.74 & 1 & 12.09 & 117.59 \\
A & 16.95 & 122.43 & 214.29 & 116.2 \\
S \times I & 0.35 & 0.09 & 0.15 & 0.25 \\
S \times W & 5.73 & 0.02 & 1.75 & 1.01 \\
S \times A & 0.11 & 0.01 & 0.00 & 0.00 \\
\hline
\text{INTERACTION EFFECTS} & & & & \\
S \times I & 0.14 & 0.14 & 0.32 & 3.56 \\
S \times W & 0.01 & 0.02 & 0.01 & 1.21 \\
S \times A & 0.01 & 0.02 & 0.32 & 1.01 \\
\hline
\end{tabular}
\caption{Variance Analysis on MTWI and var Z for the first ten test sessions.}
\end{table}
Fig. 4.7 The relationships between the perceptual characteristics (MTWL, var Z), the input characteristics (I, A, W), and the learning factors (S).
4.3.3.1 The (S, I, A, w) vs. MTWL Interactions

The variation of the "mental information" (MTWL) with the input characteristics, the input coherence (I), amplitude (A), and frequency (w), respectively, is found to be significant at the $p < .01$ level of confidence (see table 4.4). According to fig. 4.7, MTWL tends to decrease with the increase in both the intricacy (I) and the frequency (w) of the tracked target, but to increase with the amplitude (A). It also varies from one subject to another, at the ($p < .01$) level of confidence.

Regarding the relative significance of each of these relationships for task performance, one finds a high degree of correlation (about 0.6, see table 4.3b) between the relative values of $\phi$ and MTWL in relation to each of the limiting factors (S, I, A, and w). In most of the instances, $\phi$ tends to increase or decrease with MTWL.

To be able to interpret these results, we shall go on to consider the (S, I, A, w) vs. (E(a), E(b), E(a/b)) relationships, given the assumption that $MTWL = f(E(a), E(b), E(a/b))$.  

*Hypothetically, the parameters E(a), E(b), and E(a/b) have been described (in chapters two and three) as the relative amounts of information (continued on the other page)
These relationships are illustrated in figs. 4.8 and 4.9a/b. Their variance analyses are reported in table 4.5. The parameters are expressed (in these figures) as percentages of MTWL, and each point represents the mean of the first ten test sessions.

4.3.3.2. The I vs. (E(a), E(b), E(a/b)) Interactions

In figure 4.8, the increase in the relative values of both E(a) and E(a/b) with decreasing coherence (I) of the target tends to reflect some about the pattern of target motion which Ss seem to acquire (a) by precognition, (b) from the display, and (c) as they switch their attention between the display and the input forcing function, and which they use to build up a store of data (the "mental information", MTWL) for predicting the target and for determining the immediate course of the motor response. These parameters also provide the basis for making inferences regarding the modes of perceptual organisation or selective attention by the individual operators; since E(a), E(b), and E(a/b) serve as the measures for the relative attention fixation (by the Ss) on the input forcing function, the display, and what is here known as the "interaction" (or "peripheral") information, respectively.
Fig. 4.8 The relationships between the components of MTWL (E(a), E(b), E(a/b)), the input characteristics and the learning factors (S).
sort of departure from the relationship between MTWL and I, where, as shown in fig. 4.7, MTWL tends to decrease with I. This trend is apparently counterbalanced by corresponding decrease of the relative values of $E(b)$, since as mentioned in chapter two (see also the foot note), the cumulative effects of the three parameters are additive. One way of interpreting these results is as follows.

There is evidence (Hartman and Fitts, 1955) that when an intricate (i.e., less coherent) target, such as $I_3$, is obtained by the addition of one or more lower harmonics (such as $w_1$ and/or $w_2$) to a basic signal of higher frequency (such as $w_3$), the average rate of the resultant signal is usually less than that of the original (basic) target. If this is the case, it could be said that the reduced rate of motion of the less coherent targets, such as $I_2$ and $I_3$, might have enabled the Ss (by giving them sufficient time) to anticipate and acquire more information (by precognition), and apparently to pay more attention to the pattern of target motion, than it is possible when tracking the more coherent, higher frequency, targets, such as wave form three ($w_3$).

The I vs. $E(a)$ relationship could also be interpreted in terms of the relative importance of the perceptual (visual and/or precognitive) vs. the proprioceptive (motor) cues in tracking targets of varying degrees of coherence.
According to Hartman and Pitts (1955), the proprioceptive cues are utilized less effectively when executing the more intricate movement patterns. In other words, it could be that the difficulty encountered by the Ss in the utilization of the proprioceptive cues at the more intricate targets forces them to rely and concentrate on the precognitive information, E(a), more than they do when tracking the less intricate targets.

The I vs. E(b) relationship may be interpreted to mean that once Ss have predicted the target, and adopted a pattern of attention switching, they tend to reduce their need of the display. That is, it appears that during precognitive tracking, which apparently evolves from increased utilization of the precognitive information, E(a), Ss tend to rely less on the information from the display, E(b), to facilitate their performance.

As indicated by the I vs. E(a/b) relationship, it appears that as the predicted motion of the target drifts off (since precognitive tracking is very nearly an intermittent behaviour) or as the input is changed and made more intricate, and with reduced attention on the display (as indicated above), Ss tend to switch their attention between the input forcing function and the display more frequently, presumably in search of more information to supplement the one available from the display.
### Table 4.5 Variance Analysis on E(a), E(b), E(a/b), $\sigma''$, and $\sigma'''$ (for the First Ten Test Sessions)

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>df</th>
<th>F Ratio</th>
<th>E(a)</th>
<th>E(b)</th>
<th>E(a/b)</th>
<th>$\sigma''$</th>
<th>$\sigma'''$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAIN EFFECTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>62 16**</td>
<td>65 15**</td>
<td>43 38''</td>
<td>119.46**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>238.94**</td>
<td>66 12**</td>
<td>386 0''</td>
<td>588.26**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W (w)</td>
<td>6</td>
<td>49 62**</td>
<td>59 35*</td>
<td>28 04''</td>
<td>93.38**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>3 38*</td>
<td>19 91**</td>
<td>3 10</td>
<td>3.935**</td>
<td>38 06**</td>
<td></td>
</tr>
<tr>
<td><strong>INTERACTION EFFECTS</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S x I</td>
<td>4</td>
<td>26 35**</td>
<td>20 10**</td>
<td>26 96**</td>
<td>18.57**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S x W(w)</td>
<td>12</td>
<td>6 06**</td>
<td>6 03**</td>
<td>4 55''</td>
<td>4.17*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S x A</td>
<td>4</td>
<td>2 88*</td>
<td>1 81</td>
<td>3 32*</td>
<td>1.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I x A</td>
<td>4</td>
<td>0.47</td>
<td>3 57**</td>
<td>3 73''</td>
<td>9.56**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I x w</td>
<td>4</td>
<td>12.39**</td>
<td>10 34**</td>
<td>11 15''</td>
<td>20 04**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

4.3.3.3. The A vs. (E(a), E(b), E(a/b)) interactions

As indicated in fig. 4.8, E(a) tends to increase (the same way as MTWL), while both E(b) and E(a/b) decrease, with the input amplitude (A). According to the visual scale effect mentioned in section 4.2.1.3, it appears that the magnification of the input amplitude tends to increase not only the
relative magnitude of the display (error) but also the relative amount of information regarding target's pattern of movement (i.e., E(a) and MTWL). Thus, availing themselves of this information, Ss tend to rely more on "perceptual anticipation" than on either the "peripheral" or the displayed (error) information. In a sense, the A vs. (E(a), E(b)) relationships tend to reflect the same kind of behaviour as that evolving from I vs. (E(b)); that is, a sort of precognitive tracking, with less attention to the error display.

4.3.3.4. The W(w) vs. (E(a), E(b), E(a/b)) Interactions

Looking at the more coherent targets, wave forms 1, 2, and 3 (as shown in fig. 4.8), one sees that E(a) tends to decrease, while both E(b) and E(a/b) increase, as the frequency of the input forcing function is increased. This result seems to suggest that with the increase of the average rate of target motion, Ss tend to rely more on the displayed and the "peripheral" sources of information than on perceptual anticipation for their performance. A comparison between the relative values of E(b) and E(a/b) at different task conditions indicate that, whereas the former is greater and increases faster than the latter at the more coherent inputs, at the less coherent tasks the reverse is the case; E(a/b) is relatively greater and tends to increase faster than E(b).
It thus seems that Ss' tendency to alternate their attention between the input and the display becomes not only more frequent with the increase in input intricacy (I), but also increasingly exaggerated as the average rate of target motion is increased as well.

Fig. 4.9 a/b MTWL, E(a), E(b), and E(a/b) as functions of SxI interaction.
4.3.3.5. The (S x I) vs. (E(a), E(b), E(a/b)) Interactions

The data illustrated in figs. 4.8 and 4.9a, seem to provide some insight into the different modes of "perceptual organization" by the individual subjects at the various task conditions. Judging from the relative values of E(a/b) at the three target conditions, for instance, it appears that S\textsubscript{3} tends to alternate his attention (between the input forcing function and the display) more frequently as the target becomes more intricate; a phenomenon which is consistent with the general trend observed earlier (in section 4.3.3.2.). The behaviour of S\textsubscript{1} differs from that of S\textsubscript{3} at the two intricate targets; his attention alternation tends to be less frequent at I\textsubscript{3} than at I\textsubscript{2}. S\textsubscript{2} seems to adopt yet a different strategy from those of S\textsubscript{1} and S\textsubscript{3}; his attention alternation tends to be less frequent with increasing intricacy of the target.

From the (S x I) vs. E(a) interaction, it appears that S\textsubscript{3} tends to concentrate on the tracked target more than either S\textsubscript{1} or S\textsubscript{2} does. On the other hand, while the relative concentrations on the target by both S\textsubscript{1} and S\textsubscript{2} appear to increase with target's intricacy, that of S\textsubscript{3} is not a direct function of I; attention fixation on the target by the latter (S\textsubscript{3}) is relatively more at the less (I\textsubscript{1} and I\textsubscript{2}) than at
the more \(I_3\) intricate targets. According to \((S \times I) vs E(b)\) interaction, all the subjects seem to rely less on the display as the target becomes more intricate; that is, they tend to pay less attention on the error display at the more intricate targets.

In general, comparing the relative values of MTWL of the three subjects at the different task conditions, as illustrated in fig. 4.9b, one may be tempted to say that the organization of perception by \(S_3\) is relatively more appropriate than that of \(S_1\) or \(S_2\); granting that the assumption that the "mental information" is a direct function of individual's mode of perceptual organization is correct. The superiority of \(S_3\)'s performance, over that of either \(S_1\) or \(S_2\), in all the task conditions tends to lend some support to this reasoning.

4.3.3.6. The \((S, I, A, w) vs. var Z\) Interactions

The various ways in which the perceptual noise \((var Z)\) is related to the input characteristics \((I, A, w)\) are illustrated in fig. 4.7 (see page 118). According to this figure, \(var Z\) is an increasing function of the amplitude, but tends to decrease with the coherence \((I)\), of the target. On the other hand, the variation of \(var Z\) with the frequency, though statistically significant (as shown in table 4.4), is not quite noticeable in this figure (4.7).
Var $Z$ also varies from one subject to another, this variation being significant at ($p < .01$) level of confidence (see table 4.4, page 117). The relative values of var $Z$ seem to bear some relationships with the relative levels of performance by the individual Ss; the latter is inversely proportional to the former.

Fig. 4.10 The components of var $Z$ ($\sigma^m, \sigma^{\text{mix}}$) as functions of the input characteristics and the learning factors ($S$).

Fig. 4.11 var $Z, \sigma^m$ and $\sigma^{\text{mix}}$ as functions of $S \times I$ interaction.
In interpreting these results, we would like to refer to the (mathematical) definition of var Z, in chapter two. Hypothetically, var Z has been described as a composite of two variabilities, \( \sigma'^{2} \) and \( \sigma''^{2} \), attributable to two major factors, "random noise" in the task environment, such as the variability of the tracked target, and "noise" from within the subject, as from his perceptual and/or sampling behaviour (see eqs. 4-6 through 4-10a of chapter two). The relationships between these variabilities and each of the aforementioned limiting factors (S, I, A, w) are illustrated in figs. 4.10/11. Let us take each of these parameters (in relation with var Z) in turn.

First, the decrease in var Z with target's coherence (I) may be explained in terms of corresponding relationship between \( \sigma'^{2} \) and I, where the latter relationship can, in turn, be explained on the basis of expression (2-10) of chapter two. In this expression, \( \sigma'^{2} \) has been equated to \( \text{var}/X_{j} - X_{c}/ \); where, conceptually, \( X_{c} \) was described as the frame of reference (or criterion) to which Ss relate individual values of \( X_{j} \), the sequence of the input forcing function. This frame of reference, it was assumed, could be acquired by Ss through practice and/or training in the task. In practice, \( X_{c} \) had been assigned the "effective amplitude" (A) of the various targets, which correspond, in the experiment, to the maximum displacements of the problem cursor to left and right of its centre position on the display.
This seems to imply that for a given $A$, $\sigma''^2$ is a function of the amplitude distribution ($X_j$) of the input. Mathematically, being the variance of the difference (separation) between $X_j$ and $A$, $\sigma''^2$ might be taken as the quantitative measure of the noise level in the input. If this is the case, then the decrease in $\text{var } Z$ with target's coherence may be taken as to mean that when two or more time-varying signals (in voltages) are combined to produce a more intricate target pattern, the amplitude distribution of the resultant target changes in such a way that its noise level is relatively lower than that of either of the component signals. Apparently, the more intricate the target, the smaller is the noise level.

The increase in $\text{var } Z$ with $A$ could also be explained in terms of the same expression, $\sigma''^2 = \text{var}/X_j - Xc/$, as well as from the corresponding relationship between $\sigma''^2$ and $A$ (as illustrated in fig. 4.10); given that $Xc = A$ and $\text{var } Z = f (\sigma''^2)$.

Secondly, since $\sigma''^2$ has no relationship, by definition, with target's frequency, the variation of $\text{var } Z$ with the latter (frequency) can only be explained in terms of $\sigma''''^2$. As illustrated in fig. 4.10, $\sigma''''^2$ is an increasing function of the input frequency. This result seems to suggest some sort of relationship between human sampling behaviour and the rate of information propagation. It appears that human sampling variability tends to increase with the information rate.
4.4. The Possible Levels Of Abstraction

It remains to indicate possible levels of abstraction of the experimental variables. In doing this, we will employ the "subordination matrix" method described at the end of chapter three. The decision as to whether there are subordination relations among the variable pairs will be based on (a) the design of this experiment, (b) the relations among the various sets of data reported above, and (c) judicious reasoning.

4.4.1. Forming The Subordination Matrix

Applying the first principle of association of this method (see description in the last chapter, page 91), we will begin by numbering the experimental variables as follows.

1. The general performance metric ($\emptyset$).
2. The mental information (MTWL).
3. The perceptual noise (var $Z$).
4. The input coherence ($I$).
5. The input amplitude (A).
6. The input frequency (w).
7. Training method (TR).
8. Sequence of task presentation (TP).
9. Basic individual differences (BID).

The parameters \( E(a) \), \( E(b) \), \( E(a/b) \), \( \sigma''^2 \), and \( \sigma'''^2 \), which are mathematically related to MTWL and var \( Z \), respectively, see equations (2-6) through (2-12) of chapter two, are not entered in this list. Their relations with any of the other variables are, by definition, already determined by the relations between such a variable and MTWL or var \( Z \).

There are several possibilities of constructing the subordination matrix of these variables. Two of these are: By one-step approach; this involves one square 9 x 9 matrix as implied by this list. The other is by multi-step approach, which involves the use of more than one matrix, according to the number of groups in which this list could be sub-divided. We will adopt the second alternative, as this is easier to follow and may apparently lead to the understanding of the result more readily.

Sub-dividing, arbitrarily, the above list into three groups, we have

**A. The learning-factors group:**

1. Training method.
2. Sequence of task presentation.
3. Basic individual differences.

As has often be done here, this group will be represented in the main (third) group by the
variable "subject" (S).

B. The input-characteristics group:
1. The coherence.
2. The amplitude.
3. The frequency.
This group will be represented in the main group by the variable "the input coherence (I)".

C. The main group:
1. The general performance criterion.
2. The mental information.
3. The perceptual noise.
4. The input coherence.
5. Subject.

In associating any variable of either of the first two groups (A and B) to any other variable of the main group, we will apply the "multiple entry in paired 1's rule" (see the description of this method at the end of chapter three). This implies two things: (a) what applies to any of the "representative" variables (the input coherence and subject), in relation with any other variable of the main group, also holds for each variable within the group; which, in turn, means (b) that, when necessary, any of the variables within the ("minor") group will be linked (diagramatically) with any other variable of the main group through its representative variable (see fig. 4.15a). The matrices of these three groups of variables will be known here as A-Matrix, B-Matrix, and C-Matrix, respectively.

The matrix is 3 x 3 square as shown in fig. 4.12, according to the above list. Applying rule 1, the diagonal entry rule, the diagonal is filled with zeros as shown in fig. 12. Next, arbitrarily select variable 1 (training method) for analysis of its subordination relation to the other variables of the group. This means that row 1 of the matrix will be completed.

Entry $e_{12}$: According to the design of this experiment (see page 66 of chapter three), training method is subordinate to sequence of task presentation, the latter being nested under the former. The results of this experiment also appear to indicate that the effectiveness of training method could be influenced by the mode of task presentation; as seems apparent in the training (whole-task training) given to $S_2$, of which the mode of task presentation is random. Therefore, by rule 2, we set $e_{12} = 1$, and $e_{21} = 0$.

Entry $e_{13}$: Although not explicitly indicated by the results of this experiment, implicitly it appears that the effectiveness of any training method could be influenced by the basic ability of the trainee. As Tilley (1969) puts it: "Training will be ineffective if it fails to take account of the knowledge and skills which men entering training already possess". This implies that $e_{13} = 1$, and by rule 2 $e_{31} = 0$. Having completed row 1, we turn to row 2 which is already
partly filled.

Entry $e_{23}$: From the data reported here, as well as from the design of the experiment, there seems to be no subordination relation between the effectiveness of sequence of task presentation and basic individual differences; although the existence of this may not be ruled out in reality or in a more predictive experiment. That is, $e_{23} = 0$. We can as well enter $e_{32} = 0$, since basic individual difference is not subordinate to sequence of task content. This automatically fills row 3, and consequently completes the matrix.

By a simple rule, that where there is a 1 in the matrix, there will be a connection between the associated variables, we can construct, from this matrix, the hierarchy shown in fig. 4.12a. We shall come back to this diagram later.

Fig. 4.12 "A"-matrix (The learning factors)

Fig. 4.12a "A"-hierarchy (The learning factors)
4.4.1.2. Filling The B-Matrix.

This is also a square $3 \times 3$ matrix, as shown in fig. 4.13. We start by filling the diagonal with zeros, according to the diagonal entry rule. Next, we go to row 1, by selecting variable one (the input coherence).
Entry $e_{12}$, $e_{13}$, $e_{21}$, $e_{31}$: According to the design of the experiment, as well as by definition, the input coherence (I) is a function of both the input amplitude and frequency. This means that $e_{12} = e_{13} = 1$, and also by rule 2, $e_{21} = e_{21} = e_{31} = 0$.

Entry $e_{23}$ and $e_{32}$: The input amplitude is not a function of the input frequency, neither is the latter of the former. This implies that $e_{23} = e_{32} = 0$, thus completing the matrix. Applying the same simple rule as above, i.e., where there is a 1 in the matrix there will be a connection between the associated variables, we have the hierarchy shown in fig. 4.13a.

4.4.1.3. Filling The C-Matrix

The matrix is $5 \times 5$, as shown in fig. 4.14. As usual we start by filling the diagonal with zeros. Since the first variable, the general performance metric ($\emptyset$), is a function of all the other experimental variables, as indicated by the various sets of data reported here, we can automatically fill the first row with 1, except of course entry $e_{11}$ which is equal to 0, by the diagonal entry rule. This means, by the second (double entry on 1) rule, that the entries $e_{21} = e_{31} = e_{41} = e_{51} = 0$. The next step is filling row 2, two entries ($e_{21}$, $e_{22}$) of which are already filled.

Entry $e_{23}$: Although interrelated, as indicated
1. $\emptyset$
2. MTWL
3. var $Z$
4. $I$
5. $S$

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Fig. 4.14 "C"-matrix.

Fig. 4.14a "C" hierarchy.
by the correlation matrix of table 4.3b, there seems to exist (from the results reported here) no subordination relation between the mental information (MTWL) and the perceptual noise (var Z). This means that $e_{23} = 0$. Although this decision does not automatically determine the entry $e_{32}$, the latter can as well be equated to zero, since var Z is not subordinate to MTWL.

Entry $e_{24}$, $e_{25}$: All observations here (see figs. 4.7 through 4.9a/b) indicate that MTWL is a function of both the input coherence (I) and the learning factors; the variation of MTWL with both I and S is found to be significant at $p < .01$ level of confidence (see table 4.4). That is, we can set $e_{24} = e_{25} = 1$, and thus $e_{42} = e_{52} = 0$. The next row is 3, the perceptual noise (var Z), three entries ($e_{31}$, $e_{32}$, $e_{33}$) of which have already been filled.

Entry $e_{34}$: var Z is subordinate to the input coherence (I); as illustrated in figs. 4.7 and 4.11, var Z is a decreasing function of I. This means that $e_{34} = 1$, and hence by rule 2 $e_{43} = 0$.

Entry $e_{35}$: The relative values of var Z vary from one subject to another, the variation being significant at $p < .01$ level of confidence. This implies that var Z is subordinate to S (the learning factors). That is $e_{35} = 1$, and consequently $e_{53} = 0$. The next row is 4, the input coherence (I). The only entry, $e_{45}$, that is not yet filled can automatically be equated to zero, since I is not a function of the learning factors (S).
The last row, 5, can as well be completed by setting $e_{54} = 0$, since, by the design of this experiment, the learning factors (S) are not functions of the input characteristics. However, according to the results obtained here, these factors ($S, I$) interact with one another in a variety of ways. We shall come back to the consideration of this kind of relationship.

The hierarchy resulting from this matrix is illustrated in fig. 4.14a. In constructing this hierarchy, we make use of "direct" and "indirect" connections between associated variables. For instance, 1 (Ø) is directly connected with 2 (MTWL) and 3 (var Z), but indirectly connected with 4 (I) and 5 (S), respectively.

4.4.2. The Resultant Hierarchy

Fig. 4.15 illustrates the final subordination matrix of the overall list of the variables, which is a combination of matrices "A", "B", and "C", as shown in figs. 4.12, 4.13, and 4.14, respectively. The resultant hierarchy is illustrated in fig. 4.15a, which is also a combination of figs. 4.12a, 4.13a, and 4.14a. The "dummy" variable (S) of fig. 4.12a is not included in this figure; since this seems superfluous. The two-way connection (broken lines) between the variables MTWL (2) and var Z (3), and TR (7) and I (4) indicate that these variables, though not subordinate to one another, nevertheless,
are interrelated, i.e., they interact with one another. Their mutual interactions have been illustrated in a number of places here.
Fig. 4.15a  Realized (descriptive) hierarchy of the tracking performance.
4.5. Discussion

Several methods exist to give form and hierarchic structure to the elements of a problem. Each method has its own merits and disadvantages, and may produce different kinds of results. One important aspect of the subordination matrix procedure which makes it particularly attractive here, is that one needs only to specify for each element pair, whether one element is subordinate to the other or not. The matter of levels in the hierarchy is resolved automatically by the mentrix. That is, the procedure permits the automatic development of the graphic structure that portrays the hierarchy.

In general, the selection of levels, in terms of which a given problem can be described, is dependent mainly upon the investigator, his knowledge and interest. In the present circumstance, for instance, if one is not familiar with the psychological process (perception) involved in the performance, he might be restricted to the level of the input coherence and training method. He can develop a proficiency measure on the ability to predict and act on targets of varying degrees of coherence, and how this behaviour is related to the different training schedules, without being aware of the specific internal function required to produce the observed performance. Afterwards, in the intact normal subject it is not all that necessary to observe
directly the functions performed in the middle of the network (by the human nervous system), since they can be inferred from the performance output. Conversely, the tracking performance can be studied in terms of only the more basic performance variables, such as the amplitude and frequency of the tracked target, the basic individual abilities and the sequence of task content, without regard to either the nature of the training schedule or the degree of target's coherence, or both.

For many problems, there are, however, some levels which appear as natural or inherent. Real life problems tend to have dominant elements which mask the form of the problem. In performance assessment, for example, the dominant element is the performance criterion, and the first step in the development of a proficiency measure is usually the specification of the behaviour to be observed and measured. According to Leuba (1964): "It is awkward enough to quantify the wrong thing when a criterion exists, but it is a sham of the most unprofessional sort to quantify in the absence of a criterion. If a criterion does not exist it must be created".

This brings us to the two possible ways of looking at the results of this investigation, as portrayed by the hierarchy shown in fig. 4.15a. First, they indicate that it is possible to describe a skilled performance, such as compensatory tracking, by a hierarchy of variables
each concerned with the behaviour of the human operator as viewed from a different level of abstraction. As mentioned above, the highest level of abstraction can be the specification of the performance measure, while the descriptions at lower levels may entail a more detailed analysis of how this measure is related to the other, more basic, elements (or variables) of the performance. Secondly, they indicate that these variables are not independent but rather interact with each other. Thus, in going up the hierarchy, one can obtain an understanding of how these variables interact so as to produce the observed performance.

The difference between the hierarchy resulting from this investigation (as shown in fig. 4.15a) and the hypothetical model (of fig. 2.4) can be explained in a number of ways. For one thing, this model was constructed almost arbitrarily; that is, without the application of any specific procedures or principles of association regarding the relations between the performance variables. For another, the present investigation is conducted with the modification and development of this conceptual model in mind. In this sense, fig. 2.4 may be seen as characterizing the tracking performance as sensed (or conceived); it provides the basic concepts for the design of this study. On the other hand, fig. 4.15a seems to characterize this performance as observed in actual task environment; it provi-
des the relevant data for modifying some of the assumptions of this model. For instance, in constructing fig. 4.15a, on the basis of the data generated here, some of the variables and levels of fig. 2.4 turned out to be superfluous: they seem to provide no substantive information regarding the tracking performance. Finally, it can be said that this is what one would expect in a study like this. The development of a proficiency measure can be likened to the task of discovering the proof for a difficult theorem or to a search through a maze; it involves a great deal of trial and error. One starts by operating in some context wherein there is a concern with a complex of variables and relations with respect to the activity. These are modified in turn until, with persistence and good fortune, one might come up with some substantive measures.

There are two sources of criticism in the design of this investigation. The first concerns the hierarchical nature of the design; that is, the nesting of some of the experimental variables, one under the other. The other is the decision to trade a small number of subjects for many test sessions and task conditions (inputs). Taken together, these two factors have turned out to be very detrimental to the results of this experiment. Notably, it has not been possible to isolate properly the relative contributions (or effects) of the three psychological
factors, training method, sequence of task content and basic individual differences. Neither could we compare very reliably the relative effectiveness of the three levels of training schedules and/or sequence of task content.

A study should be performed in a manner that would provide data which would permit proper measurements and comparisons of the relative effects and interactions of the variables. The inclusion of a number of control or secondary task conditions in such a study would be very useful. For instance, basic individual differences could be studied in terms of a simple reaction time, control precision or sensory (visual) discrimination performance, in a secondary or pre-task situation; since these activities are involved in tracking. It might also be reasonable to restrict both the training schedules and the sequence of task content to two levels, that is, part-task vs. whole-task training and random vs. systematic sequence, respectively. This might simplify the design, and analysis of the results, of the experiment.
Summary

Performance assessment has been recognized as a difficult area of current research. The problem is not only one of finding an objective measure of job performance. It also involves finding the "right" approach. Several attempts to solve these problems have been made. Some of these have been discussed here. The hierarchical approach described here received its major impetus in the work of Parker (1967), which states that: "To the extent that complex performances can be resolved into a number of more basic dimensions, the problems of performance assessment will be greatly simplified".

Thus, the most important aspect of this approach is that it breaks down a complex performance into a number of more basic component parts of skills, each concerned with the behaviour of the human operator as viewed from a different level of abstraction. It also recognizes that the components are not independent, but rather interact with each other, and that a direction can be associated with any interaction between any pair of these components. Hence in a hierarchical description, one can obtain an understanding not only of the properties of the individual behavioural components of the task, but also of how these components interact so as to produce the observed performance.
How a complex performance could be described by a hierarchy of variables was illustrated with the aid of a compensatory tracking performance involving a continuous target and a simple control mechanism. Conceptually, this performance was viewed in terms of three descriptive strata. The first stratum entailed the derivation of the performance metric ($\phi$), in terms of which the properties and interactions of the other variables of the performance were studied. The second stratum (the "task structure") dealt with the psychological process (perception) involved in the performance; it was assumed that the tracking performance was limited primarily by the perceptual process (or system). This process was characterized by two variables, the perceptual noise (var $Z$) and the mental information (MTWL). On the third stratum (the "task elements") were described the physical characteristics (the internal coherence, the amplitude and the frequency) of the tracked target, as well as the psychological factors (basic individual defferences, training method and sequence of task content) which seem to elicit the observed behaviour. This conceptual model was further elaborated, so as to illustrate the hypothetical relationships between the aforementioned variables.

In actual application of this conceptual framework, two possibilities were considered. Based on the assumption that the tracking performance
has a "formal" hierarchic structure, the first procedure might have entailed identifying and measuring the relevant component parts of the tracking performance at each level of the hierarchy, and then relating a level to those immediately above and below it. The second involved investigating the properties and interactions of a sample of task-relevant variables, and on the basis of these data to determine the possible levels of description of the tracking performance - that is, to construct the descriptive hierarchy of the tracking performance. The experiment reported here was designed on the basis of the second procedure.

As indicated above, the task involved the tracking of continuous targets of varying patterns of motion. The display was a scale pointer which presented only the indication of the difference, or error, between the tracked target and operator's response. The control mechanism consisted of two potentiometer knobs, one (rotary) in front, and the other (lateral) by the side, of the test panel. These control knobs were used alternatively, one session after the other. Simple target patterns consisted of simple harmonics. Varying (intricate) target patterns were obtained by combining two or more simple harmonics of different frequencies. The experimental variables included (1) the input characteristics: the input coherence (I), the amplitude (A) and
the frequency (w), three levels each; (2) the perceptual characteristics: the perceptual noise (var Z) and the mental information (MTWL); and (3) the learning (psychological) factors: training method (simple-part-task, difficult-part-task, and whole-task training schedules), sequence of task content (regressive, progressive, and random), and basic individual differences.

Three subjects participated in the study, each assigned to any one of the three training schedules and sequences of task content. The sequence of task content was nested under training method. One test session consisted of 27 task (stimulus) conditions, and lasted one hour. Each of the Ss tracked 12 test sessions or 12 x 27 trial blocks. The subjects received most (eight out of nine training sessions) of their training with the rotary control, and tracked five out of the twelve test sessions with the lateral control; in a transfer of training paradigm. The observations (i.e., the properties and interactions of the aforementioned variables) were based on the relative levels of performance by the individual subjects, and were measured in terms of the performance metric (Ø).

The variation of task performance (Ø) with each of the input characteristics (I, A, w) was very significant (at p < .01 level of confidence). The relationship between tracking performance and the internal coherence of the tracked target appeared to depend upon other
related factors, notably the training schedule and the frequency of the target. The subject who received his (part-task) training in the more intricate target forms \((I_3)\) performed relatively better here than at the more coherent (less intricate) tasks. On the other hand, the other Ss who received other training schedules did relatively better at the more coherent target forms than at the intricate ones. On the whole, Ss seemed to experience greater difficulty at the target pattern \((I_2)\), which consisted of any two of the three harmonics \((w_1 < w_2 < w_3)\), than at either the simple harmonic \((I_1)\) or the more intricate target pattern \((I_3)\); apparently because (a) unlike the last two target forms, none of the Ss received special training in the former \((I_2)\); and (b) the average rate of \(I_2\) was comparatively greater than that of \(I_3\). Tracking performance was found to be a decreasing function of the input (target) frequency. Performance tended to improve as the input amplitude was increased from an initial level of \(A_1\) (two volts) to \(A_2\) (four volts), but deteriorate as \(A\) was magnified to still a higher level of \(A_3\) (eight volts). In other words, tracking performance was found to be a fluctuating function of the amplitude of the tracked target.

The correlations between task performance \((\phi)\) and the mental information \((MTWL)\), on one hand, and between the latter and its constituent components \((E(a), E(b), E(a/b))\), on the other, seem
to suggest some form of relationships among (effective) tracking performance, the amount of information which Ss could acquire about the tracked target, and the act of perceptual organization. How far an individual could succeed in tracking a moving target of any degree of coherence was postulated to depend upon the amount of information he could gain about the pattern of motion of the target, the latter being, in turn, dependent upon how the individual organized his perception among the relevant cues in the control loop. On the other hand, tracking performance appeared to be an inverse function of the noise (\( \text{var } Z \)) associated with the variabilities (\( \sigma''^2, \sigma'''^2 \)) of both the tracked target and the human operator.

Although the present experimental procedure did not permit the independent study of the relative effectiveness of the individual training schedules and sequences of task content, however, the characteristic patterns of performance by the individual subjects at the various task conditions provided a basis for inferences regarding the relative effects of these factors on the tracking performance. The subjects who received part-task training schedules performed relatively better at those tasks in which they were trained than at the other ones where they received no formal training. The paucity of the performance of the subject (\( S_2 \)) who received whole-task training,
as compared to those who had part-task training, was, to a large degree, attributed to the random sequence of the content of training to him. The mechanism of transfer of training seemed to operate here too. The relative performances of the subjects who received part-task training tended to deteriorate in the same direction as their respective sequence of task content. There were also some indications of the relative contributions of the individual basic differences to their respective performance levels; a control test on the adaptive capabilities of the individual subjects indicated that much of the differences in their relative performance levels could be attributed to their personal characteristics.

The relations among the various sets of data provided considerable insight into the interactions among the experimental variables and how these interactions affect the tracking performance. An increase in the amplitude of target motion was found to be as beneficial for tracking the more intricate targets as the increase in coherence was relevant when tracking targets of relatively low amplitude of motion. The mental information (MTWL) and the perceptual noise (var Z) were found to be correlated, although they seemed to have opposite influences on tracking performance. The relative values of MTWL at the various task conditions seemed to suggest that the more intricate the target pattern, the less is the information which Ss could obtain about its motion, and apparently the
less predictable is the target. It appears that when two or more time-varying harmonics (or signals) are combined to obtain a more intricate target pattern, the amplitude distribution of the resultant target changes in such a way that its noise level (or variability) is comparatively less than that of either of the constituent harmonics. Ss' variabilities \( (\sigma')^2 \) tended to increase, while their mental information decreased, as target's frequency was increased. On the other hand, Ss seemed to receive more information about target's pattern of motion as the amplitude was increased.

The relative values of both the mental information (MTWL) and the perceptual noise (var Z) were found to vary from one subject to another. The variability of the subject whose sequence of task content was random was comparatively higher than those of the other two subjects, to whom the content of training was presented in a systematic order. A comparison of the relative values of MTWL by the individual Ss suggested that the subject who trained in the more intricate, perceptually demanding task conditions could more readily learn to organise his perception more appropriately than either of the other two subjects who received different training schedules.

These results provided the data for the construction of the descriptive hierarchy of the tracking performance. In doing this, we made use of the subordination matrix method developed by
Warfield (1973). This hierarchy was seen as a modification of the hypothetical model. It also reflected our earlier point of view, that a skilled performance, such as compensatory tracking, can be described by a hierarchy of variables, each concerned with the behaviour of the human operator as viewed from a different level of abstraction. However, since this hierarchy could also be seen as one out of several ways of representing this performance (in hierarchical context), it was emphasized that the selection of levels and variables, in terms of which a particular task could be described, is a matter of individual's interest and knowledge.

Finally, some time was devoted to mention two major inhibiting aspects of the experimental procedure, the hierarchical nature of the design and the trading of a small number of subjects for many test sessions and task conditions. One of the implications of these (the aforementioned aspects) was, as indicated above, that it was not possible to identify and measure precisely the relative effects and interactions of some of the experimental variables. A number of recommendations was also suggested for further studies. Among them were the inclusion of some relevant control or secondary task conditions in the design of the experiment and the use of more limited levels (preferably two) of both the training schedules and the sequence of task content.
It must be conceded that the data generated here do not provide sufficient basis for reaching any conclusions regarding the potential of this approach for meaningful performance assessment. Nevertheless, it is hoped that this work will stimulate more interests and concerted efforts in this direction. Properly used, hierarchical concepts can be a valuable aid to the understanding of human performance complex.
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Poulton, E.C. (1952) The Basis of Perceptual An-


Samenvatting

Prestatiebeoordeling wordt beschouwd als een moeilijk gebied van hedendaags onderzoek. Het probleem omvat zowel het vinden van een objec­tieve maat voor het verrichten van een taak als ook het zoeken naar de 'juiste' benadering. Verschillende pogingen om deze problemen op te los­sen zijn reeds ondernomen; sommige ervan worden in dit proefschrift bediskussieërd. De door ons beschreven hiërarchische benadering werd het sterkst gestimuleerd door het werk van Parker (1967), die van mening is dat: "To the extent that complex performances can be resolved into a number of more basic dimensions, the problems of performance assessment will be greatly simplified".

Het belangrijkste aspekt van deze benadering is dus, dat een complexe verrichting uiteenge­legd wordt in een aantal meer fundamentele kom­ponenten van een vaardigheid, die elk voor zich vanuit een wisselend abstraktieniveau betrekking hebben op menselijk gedrag. Deze benadering stelt de komponenten niet onafhankelijk van elkaar zijn maar een onderlinge wisselwerking hebben, en dat een bepaalde richting geassocieërd kan worden met een interaktie tussen ieder paar van de gedrags­komponenten. Vandaar dat men door een hiërar­chische beschrijving inzicht kan verwerven niet alleen in de eigenschappen van de afzonderlijke gedragskomponenten van de taak, maar ook hoe deze komponenten interacteren bij het voortbren­gen van de waargenomen handeling.
Hoe een complexe verrichting met hiërarchisch geordende variabelen beschreven kan worden, wordt geïllustreerd aan de hand van een compensatoire trackingtaak, bestaande uit een continu target en een eenvoudig regelmechanisme. Konceptueel wordt deze taak beschouwd in termen van drie niveaus van beschrijving (strata). Het eerste stratum betreft het afleiden van de prestatiemaat (\(\theta\)), waarmee de eigenschappen en interacties van de andere taakvariabelen verder worden bestudeerd. Het tweede stratum (de 'taakstructuur') handelt over het psychologische proces, t.w. de perceptie, betrokken bij de verrichting; aangenomen werd, dat het trackinggedrag voornamelijk beperkt wordt door het waarnemingsproces (of systeem). Dit proces wordt gekarakteriseerd door twee variabelen, de perceptuele ruis (variabele Z) en de door het individu opgeslagen informatie (MTWL). Op het derde stratum (de 'taakelementen') worden de fysische eigenschappen van het te volgen target beschreven (de interne samenhang, de amplitude en de frequentie), alsmede de psychologisch factoren (elementaire individuele verschillen, trainingsmethode en taakinhoud), die het geobserveerde gedrag waarschijnlijk oproepen. Dit konceptuele model is verder uitgewerkt om de veronderstelde relaties tussen de hierboven genoemde variabelen te illustreren. Bij de feitelijk toepassing van dit konceptuele raamwerk werden twee mogelijkenheden overwogen. Uitgaande van de veronderstelling dat het
trackinggedrag een 'formele' hiërarchische structuur bezit, zou de eerste werkwijze hebben kunnen bestaan uit het vaststellen en meten van de relevante componenten van het trackinggedrag op ieder niveau van de hiërarchie om vervolgens aan iedere daar direct boven en onder gesitueerde component een niveau te relateren. De tweede procedure zou dan een onderzoek inhouden naar de eigenschappen en interakties van een bepaald gedeelte van de voor de taak relevante variabelen om daarna op basis van de verkregen gegevens de mogelijke beschrijvingsniveaux van het trackinggedrag te kunnen vaststellen; m.a.w. om een beschrijvende hiërarchie van het trackinggedrag op te kunnen bouwen. Het hier beschreven experiment werd overeenkomstig de laatste procedure ontworpen.

Zoals reeds vermeld bestond de taak in het volgen van continue targets met wisselende bewegingspatronen. Als display fungeerde een wijzer op een schaal, die slechts het verschil of de fout aangaf tussen het gevolgde target en de responsie van de operator. Het regelmechanisme bestond uit een potentiometer met twee knoppen: een draaiknop vóór op het testpaneel, een schuifknop aan de zijkant. Deze regelknoppen werden bij de testzittingen om beurten gebruikt.

De gemakkelijke targetpatronen bestonden uit eenvoudige harmonischen. Wisselende (komplexe) patronen werden verkregen door twee of meer eenvoudige harmonischen met een verschillende frequentie te combineren.
De experimentele variabelen betroffen allereerst de kenmerken van de input: samenhang (I), amplitudo (A) en frekwentie (w), elk met drie niveaus; ten tweede de kenmerken van de waarneming: perceptuele ruis (variabele Z) en de opgeslagen informatie (MTWL); en op de derde plaats de (psychologische) leeffactoren: trainingsmethode (schema's voor een eenvoudige resp. moeilijke deeltaak en voor de gehele taak), volgorde van de taakinhoud (in moeilijkheidsgraad toe- of afnemend dan wel random) en elementaire individuele verschillen.

Aan het onderzoek namen drie proefpersonen deel, ieder afzonderlijk toegewezen aan een van de drie trainingsschema's en volgorden in taakinhoud. Deze laatste waren gegeven met de trainingsmethode. Een testzitting had als stimuli 27 taakcondities en duurde een uur. Met iedere proefpersoon werden 12 testzittingen belegd. De proefpersonen oefenden hoofdzakelijk (acht van de negen trainingsessies) met de draaiknop en werkten gedurende vijf van de twaalft testzittingen met de schuifknop. Een en ander overeenkomstig het transfer of training principe. De observaties (t.w. de eigenschappen van en interakties tussen de eerder genoemde variabelen) waren gebaseerd op de relatieve prestatieniveaux van de afzonderlijke proefpersonen en werden gemeten in termen van de prestatiemaat $\varnothing$.

Variaties in de prestaties op de taak ($\varnothing$)
als gevolg van het manipuleren van de inputeigenschappen (l, A, w) zijn hoog signifkant ($p < .01$). Het verband tussen trackingprestatie en de interne samenhang van het gevolgde target blijkt door andere factoren te worden bepaald, met name door het trainingsschema en de frequentie van het target. Die proefpersoon, die (voor zijn deelstaak) geoefend werd in de ingewikkelder targetvormen ($I_3$), presteerde daarop relatief beter dan op de meer koherente, minder ingewikkkelde opdrachten. Daartegenover deden de proefpersonen die andere trainingsschema's volgden, het relatief beter bij de eenvoudiger targetvormen dan bij de ingewikkeld. Over het geheel genomen schenen de proefpersonen meer moeilijkheden te ondervinden met targetpatroon $I_2$ (dat steeds bestond uit twee van de drie harmonische ($w_1 < w_2 < w_3$)) dan met ofwel de eenvoudige harmonische ($I_1$) ofwel het ingewikkelder targetpatroon ($I_3$). Dit moet kennelijk aan twee factoren worden toegeschreven: 1) in tegenstelling tot voor de laatste twee targetpatronen, werd geen van de proefpersonen speciaal getraind voor de eerste ($I_2$) en 2) de gemiddelde snelheid van $I_2$ was in vergelijking met die van $I_3$ groter. Het trackinggedrag blijkt een afnemende functie te zijn van de frequentie van de targetinput. De prestatie werd beter bij een verhoging van de inputamplitudo van een aanvangsniveau van $A_1$ (twee volt) naar $A_2$ (vier volt), maar verslechterde wanneer $A$ opgevoerd werd tot een nog hoger
niveau A₃ (acht volt). Met andere woorden: het trackinggedrag blijkt een wisselende functie te zijn van de amplitudo van het gevolgde target. De korrelaties tussen taakverrichting (Ø) en de opgeslagen informatie (MTWL) enerzijds en tussen het laatstgenoemde en zijn componenten (E(a), E(b), E(a/b)) anderzijds schijnen te duiden op een zekere vorm van samenhang tussen (doelmatig) trackinggedrag, de hoeveelheid informatie welke proefpersonen over het gevolgde target konden verwerven en het proces van perceptuele organisatie. In hoeverre een proefpersoon erin zou kunnen slagen een bewegend target met een bepaalde mate van samenhang te volgen werd afhankelijk verondersteld van de hoeveelheid informatie, welke hij kon vergaren omtrent het bewegingspatroon van het target. Dit laatste zou op zijn beurt dan weer afhankelijk van de wijze, waarop de proefpersoon zijn waarneming van de relevante cues in de regelkring zou organiseren. Verder bleek het trackinggedrag een inverse functie te zijn van de ruis (var. Z), verbonden met de variaties (σ², σ'²) van zowel het gevolgde target als de menselijke operator.

Ofschoon de gevolgde experimentele procedure geen onafhankelijke bestudering toeliet van de relatieve doelmatigheid van de individuele trainingsschema's of van de volgorden in taakinhoud, verschaften de karakteristieke prestatiepatronen van de verschillende proefpersonen in de wisselende taakkondities toch een basis voor gevolg-
trekkingen t.a.v. het relatieve effect van deze faktoren op het trackinggedrag. De proefpersonen, die voor deeltaken getraind werden, presteerden relatief beter op de taken waarvoor ze getraind waren dan op de taken, waarvoor ze formeel geen training ontvingen. De, in vergelijking met hen die getraind werden voor deeltaken, gebrekkige prestatie van proefpersoon S₂, die voor de gehele taak getraind werd, kon in belangrijke mate toegeschreven worden aan de willekeurige volgorde in de inhoud van zijn training. Ook hier schijnt het mechanisme van transfer of training werkzaam te zijn. De relatieve prestaties van de proefpersonen die voor deeltaken getraind werden, hadden de neiging in dezelfde richting te verslechteren als de overeenkomstige volgorde van hun taakinhoud. Er waren ook enkele aanwijzingen voor de relatieve bijdrage van de elementaire individuele verschillen tot de respektievelijke prestatieniveaus; een kontroletest op het aanpassingsvermogen van de proefpersonen toonde aan, dat verschillen in hun prestatieniveaus voor een belangrijk gedeelte konden worden toegeschreven aan persoonlijke eigenschappen.

De relaties tussen de verschillende datasets verschaffen een goed inzicht in de interakties tussen de experimentele variabelen en hoe deze interakties de trackingprestatie beïnvloeden. Het blijkt, dat een toename in de bewegingsamplitude van het target bij complexere targetpatronen het trackinggedrag in eenzelfde gunstige
zin verbeterd als bij targets met een betrekkelijk lage bewegingsamplitudo een toename in de mate van samenhang. De opgeslagen informatie (MTWL) en de perceptuele ruis (var. Z) blijken met elkaar samen te hangen, ofschoon de indruk bestaat dat ze een tegengestelde invloed uitoefenen op de trackingprestatie. De waarden van MTWL in de verschillende taakkondities schijnen erop te wijzen, dat naarmate het targetpatroon ingewikkelder wordt, de hoeveelheid informatie, welke de proefpersonen over de beweging ervan kunnen verwerven, afneemt evenals blijkbaar de voorspelbaarheid van het target. Het blijkt, dat wanneer twee of meer tijdafhankelijke harmonischen (of signalen) gekombineerd worden om een ingewikkelder targetpatroon te verkrijgen, de amplitudo-verdeling van het resulterende target zo- danig verandert, dat het ruisniveau (of de variantie) ervan in verhouding lager ligt dan dat van beide samenstellende harmonischen. Bij een toen- name in de frekwentie van het target hebben de varianties van de proefpersonen ($\sigma'$ en $\sigma^2$) de neiging ook toe te nemen, terwijl de door hen opgeslagen informatie afneemt. Daartegenover schij- nen de proefpersonen meer informatie te ontvangen over het bewegingspatroon van het target, naarmate de amplitudo wordt verhoogd.

Vastgesteld werd, dat de relatieve waarden van zowel de opgeslagen informatie (MTWL) als de waarnemingsruis (var. Z) van proefpersoon tot proefpersoon verschilden. De variantie
van de proefpersoon, wiens volgorde van taakinhoud random was, was groter in vergelijking met die van beide andere proefpersonen, aan wie de trainingsinhoud systematisch werd gepresenteerd. Een vergelijking van de relatieve waarden van MTWL bij de verschillende proefpersonen wijst erop, dat de proefpersoon die getraind werd in de complexere en perceptueel gezien veeleisender taakkondities, gemakkelijker leerde zijn waarneming adequaat te organiseren dan de beide andere proefpersonen, die afwijkende trainingsschema's ondergingen.

Deze resultaten verschaften de gegevens voor de opbouw van een deskriptieve hiërarchie van het trackinggedrag. Hierbij werd gebruik gemaakt van de subordinatiematrix methode, ontwikkeld door Warfield (1973). Genoemde hiërarchie wordt beschouwd als een verandering in het hypothetische model. Het weerspiegelt tevens ons eerdere uitgangspunt, dat een vaardigheidsverrichting (zoals kompensatoir tracking) beschreven kan worden door een hiërarchie van variabelen, elk voor zich op een verschillend abstraktieniveau betrekking hebbend op het gedrag van de menselijke operator. Aangezien men deze hiërarchie echter ook zou kunnen beschouwen als slechts één van de verschillende mogelijke manieren om dit gedrag in een hiërarchische kontekst te plaatsen, werd benadrukt dat de keuze van de niveaus en variabelen in termen waarvan een bepaalde taak kan worden beschreven, een
Kwestie is van persoonlijke voorkeur en kennis. Tot slot is enige tijd en aandacht besteed aan het bespreken van twee belangrijke remmende aspecten van de experimentele procedure, te weten het hiërarchische karakter van het design en het gebruiken van een klein aantal proefpersonen voor veel taaksessies en -kondities. Een van de consequenties van genoemde aspecten was de onmogelijkheid om, zoals al eerder vermeld, op een precieze manier de relatieve effecten en interakties van enkele van de experimentele variabelen vast te stellen en te meten. Tevens wordt een aantal aanbevelingen gedaan voor verdere bestudering. Daaronder de opname van enige relevante regel- of sekundaire taakkondities in het experimentele design en het gebruik van een beperkter aantal niveaus (liefst twee) voor zowel de trainingsschema's als de volgorde van de taakinhoudens.

Toegelaten moet worden, dat de door ons gevonden data geen voldoende grond verschaffen op basis waarvan conclusies getrokken kunnen worden m.b.t. de mogelijkheden, die onze benadering heeft voor een vruchtbare prestatiebeoordeling. Niettemin valt te hopen, dat deze studie een stimulans zal zijn voor een grotere belangstelling voor en een gezamenlijke inspanning in deze richting. Mits op juiste wijze aangewend, kunnen hiërarchische concepten een waardevolle hulp zijn bij het begrijpen van complexe menselijke verrichtingen.
To the extent that complex performances can be resolved into a number of more basic dimensions, the problems of performance assessment will be greatly simplified.

Hierarchical concepts are one of several basic concepts needed in dealing with complex problems; properly applied, they can be a useful aid to the understanding of human performance complex.

Many learning theories are devoid of any concern about task dimensions, and it is this deficiency which makes it so difficult to apply these theories in the real world of tasks and people.

It seems to be a distasteful task for the methodologists in scientific psychology to attempt to study human behaviour in any other manner than those methodological approaches and experimental designs which have worked in the past and are generally accepted in psychological circles.

As technology becomes more complex, so does human nature, and this phenomenon has precipitated the need for system developers (or engineers) to correct the view that "if only the hardware sub-system can be made to run, somehow human beings with the proper characteristics can be found and fitted into the system".

One reason why much of existing technology and its application is without the "human face" is the overspecialization of the hard (engineering) sciences as well as the general lack of exposure of the engineering community to the sciences of psychology and sociology.

If advances in technology are not to threaten humanity, engineers and technologists must learn that the value of a technology lies not only in its economic viability and technical soundness, but also in its social and cultural values and consequences.

The transfer of technology must proceed on a much larger scale if increase in the production of material necessities is to meet the basic aspirations (hunger) of the industrializing countries; the universities of the industrialized nations have not only the facilities to promote technology transfer, but also fundamental responsibility of awakening public conscience and developing guidelines.

Since man is a self-realizing organism capable of considerable achievements given the right environmental conditions, but who becomes refractory when placed in a dependency situation, an appropriate concept (or policy) of aid would seem to be that of helping one to help oneself.

The use of Third World (orsimilar diminutive terms) does not only beg the issue of development, but also diverts attention from much meaningful ways of characterizing countries on the basis of their common cultural, social and historical elements, all of which have major implications for the nature of their economic development.