NASA TECHNICAL NOTE

NASA TN D-8365

NASA TN D-8365

PILOT WORKLOAD AND FATIGUE: A CRITICAL SURVEY OF CONCEPTS AND ASSESSMENT TECHNIQUES

Walter B. Gartner and Miles R. Murphy

Ames Research Center
Moffett Field, Calif. 94035

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1976

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-8365		

4. Title and Subtitle
PILOT WORKLOAD AND FATIGUE: A CRITICAL SURVEY OF CONCEPTS AND ASSESSMENT TECHNIQUES

5. Report Date
November 1976

6. Performing Organization Code

7. Author(s)
Walter B. Gartner* and Miles R. Murphy

8. Performing Organization Report No.
A-6630

9. Performing Organization Name and Address
Adex Systems, Los Gatos, Calif. 95030
and
NASA Ames Research Center, Moffett Field, Calif. 94035

10. Work Unit No.
504-09-32

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code

15. Supplementary Notes
*Presently with Stanford Research Institute, Menlo Park, Calif. 94025.

16. Abstract

This study addresses the principal unresolved issues in conceptualizing and measuring pilot workload and fatigue. These issues are seen as limiting the development of more useful working concepts and techniques and their application to systems engineering and management activities. A conceptual analysis of pilot workload and fatigue, an overview and critique of approaches to the assessment of these phenomena, and a discussion of current trends in the management of unwanted workload and fatigue effects are presented. Refinements and innovations in assessment methods are recommended for enhancing the practical significance of workload and fatigue studies.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Pilot workload Pilot fatigue Biotechnology	Unlimited STAR Category — 54

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	60	$4.25

*For sale by the National Technical Information Service, Springfield, Virginia 22161

Page
Intentionally
Left Blank

CONTENTS

PILOT WORKLOAD AND FATIGUE: A CRITICAL SURVEY OF CONCEPTS AND ASSESSEMENT TECHNIQUES

Walter B. Gartner*
Adex Systems

and

Miles R. Murphy
Ames Research Center

SUMMARY

This study addresses the principal unresolved issues in conceptualizing and measuring pilot workload and fatigue. These issues are seen as limiting the development of more useful working concepts and techniques and their application to systems engineering and management activities. A conceptual analysis of pilot workload and fatigue, an overview and critique of approaches to the assessment of these phenomena, and a discussion of current trends in the management of unwanted workload and fatigue effects are presented. Refinements and innovations in assessment methods are recommended for enhancing the practical significance of workload and fatigue studies.

INTRODUCTION

In ordinary uncritical discourse, the phenomena referred to by "pilot workload" and "fatigue" are easily distinguished. In its broadest and simplest aspect, pilot workload refers to how much a pilot must do to perform a specified flight operation. Fatigue is widely understood as a feeling of tension or weariness, often accompanied by an obvious unwillingness or inability to continue. However, when attempts are made to quantify the workload imposed on a pilot by a particular aircraft design or operational procedure or to assess the effects of fatigue on system performance, important unresolved issues arise in regard to the more precise specification of workload and fatigue concepts and to the adequacy of assessment criteria and techniques.

Pilot workload and fatigue are considered here in the context of commercial flight operations and applications to system development studies, and to operational activities concerned with the management of workload and fatigue. The orientation of the study is practical, that is, interest is centered on the potential impact of workload and fatigue on pilot well-being and performance capability and on system effectiveness and operating constraints. The study addresses the principal unresolved issues in conceptualizing and measuring pilot workload and fatigue, which are seen as limiting the development of more useful working concepts and techniques.

---

*Presently with Stanford Research Institute, Menlo Park, Calif. 94025.

The need for more sensitive and practicable techniques for assessing pilot workload is widely recognized. In a study of the relationship between workload and aircraft handling qualities, Westbrook et al. (ref. 1) provide a generic requirement statement:

> "If a reliable method were available to obtain a measure of workload or stress, it is undoubtedly true that many of the anomalies in handling qualities data could be explained. . . . The implications on criteria for the design of new aircraft, their control systems and their display instrumentation are obvious . . . . And yet this capability of measuring, and understanding overall pilot workload and thereby being able to utilize this knowledge in vehicle design continues to elude us."

Such straightforward expressions of need are not as readily available for fatigue. Following an extensive survey of medical and operational factors that allegedly contribute to fatigue in commercial jet pilots, Schreuder (ref. 2) acknowledged the complexity of the problem and the many difficulties encountered in assessing its severity and extent. His conclusions, however, were that "fatigue as ordinarily thought of and defined is not peculiar to the pilot" and that "the occurrence of pilot fatigue as defined is not a common occurrence in the airline pilot, that in the same age bracket, the airline pilot is healthier than the general male population, and that there is nothing to indicate that flying the turbojet is deleterious to health. . . ."

In contrast to Schreuder's findings, studies of actual flight operations (refs. 3-6) indicate that significant fatigue effects are often seen in commercial airline operations. Mohler (ref. 7) has taken a more neutral position suggesting that "fatigue should neither be dismissed as an unimportant entity nor conveniently embraced as the culprit in various untoward situations in air-carrier activities."

A review of the recent literature on workload and fatigue supports the contention that there are important unresolved conceptual and practical issues that currently limit the utility and acceptance of available data and assessment techniques. The general intent here is to use excerpts from this literature to clarify these issues and to identify current trends toward their resolution. The report begins with a consideration of the major differences in the way workload and fatigue have been conceptualized. The ambiguity of these concepts and their use in a variety of contexts to refer to clearly different phenomena have often been noted. The resulting semantic confusion has led to a diversity of investigative methods and to the publication of apparently contradictory data.

The presentation of alternative workload and fatigue concepts ends with a delineation of concept indicators, that is, the observable and measurable variables that have been adopted or devised by various investigators to serve as operational definitions for workload and fatigue or as measures for assessing their effects. This delineation of concept indicators is followed by a discussion of the important issues of operational relevance and practical significance in contemporary studies of pilot workload and fatigue. This section of the report contains a general critique of current trends in workload and fatigue assessment techniques and is concerned with such assessments in the context of system development studies.

In the next portion, the focus of the discussion shifts to the application of assessment techniques to the management and control of unwanted workload and fatigue effects that may occur after the system is operational. The role of additional operational factors that may interact with workload and fatigue to affect system effectiveness or individual well-being is also considered.

The report concludes with a synopsis of the issues discussed and a statement of the conclusions reached regarding the factors contributing to the limited utility and acceptance of workload and fatigue studies. Recommendations are presented for the development of more useful working concepts, for refinements and innovations in assessment methods which would enhance their practical significance, and a broader consideration of factors contributing to fatigue.

CONCEPTS AND INDICATORS

There is no consensus among scientists or practitioners in the conceptualization of either workload or fatigue. Ratcliffe's (ref. 8) reaction to this lack of agreement with respect to workload was to state that he was prepared to accept "any definition of workload not in conflict with common English usage and which lends itself to measurement." The vague, multiple, and conflicting usages of the fatigue concept have encountered even less acceptance. Following an unsuccessful effort to devise a simple and effective test for fatigue, Musico (ref. 9) concluded that there was no simple condition or state that could be clearly distinguished and labeled as fatigue. He then suggested that the term be abandoned altogether and that each component of the fatigue concept be labeled and referred to with its own word.

In this report, we are obviously not abandoning the terms workload and fatigue and we will not argue for the adoption of any particular conceptualization. One of the central concerns of the study, however, is to distinguish the principal differences in the way workload and fatigue phenomena are conceptualized and to identify the more specific phenomena referred to when these terms are used, that is, the concept referents. To facilitate the discussion, "workload" and "fatigue" are used as shorthand names or labels for the potentially specifiable sets of referents which serve to define these concepts; different sets of referents are thus construed as different ways of conceptualizing (or defining) workload and fatigue.

This section simply identifies the major differences represented in both the traditional and more contemporary uses of these terms. The workload and fatigue concepts presented here represent alternative ways of focusing on phenomena of interest to an investigator. While these alternative foci are deliberately chosen by investigators, they are not always explicitly identified when the concept labels are used; relationships between the concept and the phenomena examined here are often not clearly established.

The phenomena actually examined in studies purporting to deal with workload and fatigue, that is, the observable variables on which data are taken, are here referred to generally as indicators. Klausner (ref. 10) defines an indicator as "a term which gives an instruction about where to look for observable evidence about the concept referent." For example, the overt and observable slowing or disorganization of performance may be used as an indicator of a comparatively inaccessible central or subjective state conceptualized as fatigue. As an elaboration of the workload and fatigue concepts distinguished here, a set of indicators associated with each concept is extracted from the literature to further illustrate their range and character.

Excerpts from the literature are used only to provide examples of concept referents and indicators. A full exposition of any particular author's conceptualization of workload or fatigue is beyond the scope of this discussion. (For a more complete discussion of these concepts, the interested reader should consult the references cited.)

Workload

At a recent interagency conference on aircraft crew system design, Jahns (ref. 11) surveyed the origins of operator workload concepts and found it useful to characterize workload as "an integrative concept for evaluating the effects on the human operator associated with the multiple stresses occurring within man-machine environments." Jahns proposed to partition this broad conception of workload into three functionally related components: input load, operator effort, and work result. With some minor changes in terminology, this classification scheme is adopted for workload here.

Not surprisingly, the broader and more inclusive conceptualizations of workload are most visible at conferences and symposia. For example, Benson (ref. 12) emphasized the integrative nature of workload concept and was willing to include such factors as environmental stressors and sleep loss, as well as the flying task, as components of workload. While these broader conceptions are considered useful for indicating the range and diversity of workload referents, the purpose here is to outline the principal ways in which investigators have elected to restrict the use of the term, and these more limited notions are discussed below.

Workload as a set of task demands— The common attribute of task demand concepts of workload is the use of the term to refer to requirements for task performance which can be specified without reference to any operator response or effort actually applied to satisfy these requirements. The distinction between demands, as such, and any actual operator response (or any operator capabilities, readiness, etc., considered necessary for an effective response) is a very important one. One approach to the treatment of workload as demand is exemplified by Klein's (ref. 13) attempt to quantify and predict "'design specific' instantaneous workload levels imposed upon the pilot while in flight." In distinguishing this approach from traditional workload quantification methods, Klein emphasized that "workload is addressed from the standpoint of predicting human performance *requirements* as demanded by the system in its operational environment rather than from the standpoint of *measurement* of human responses to those demands."

The application of task analysis techniques within a designated system-mission-environment context to determine task performance requirements is a familiar and widely used human factors practice. A less familiar approach to the specification of task demands has been suggested by Gartner et al. (ref. 14) in their study of the requirement for providing more realistic representations of crew workload in flight simulation studies. This approach calls for a stimulus-oriented definition of crew workload which does not allow demands to be stated in terms of the crew performance required to meet a demand or of any related task characteristics (such as the time required for task completion).

Gartner et al. proposed that demands be more strictly distinguished as *inputs* to the crew, which serve, directly or indirectly, to establish crew performance objectives or to represent operational conditions and events which, in an actual flight situation, would be expected to initiate crew activity or modify ongoing crew responses. Task demands are identified using functional criteria, that is, they are inputs that operate as response programs or as action requirements for the crew, as illustrated by the following examples:

> "Response programs may be construed as preplanned or previously established performance objectives and/or guides which govern the execution of anticipated crew tasks. Two obvious examples are (1) flight plans specifying route segments, headings to be flown, etc., and (2) precalculated climb profiles in the form of altitude vs. airspeed schedules. Action requirements are the more immediate, and often more dynamic, conditions and events which 'demand' some sort of crew response when they occur in the ongoing flight situation. Some general examples here include specific ATC control instructions, command instrument readouts, and aircraft and/or subsystem operating states."

The foregoing distinction between response and stimulus-oriented expressions of task demands has been stressed because it is considered to underlie some of the problems in workload assessment and practical application discussed later, and because different kinds of demands are often confounded. For example, system-oriented and situation-specific demands are often confused with perceived demands (an operator response) or with the behavioral or psychophysiological demands imposed on an operator by an assigned task. The task demand concept is closely related to Jahn's (ref. 11) input load component of workload, which he defines, operationally, as "a vector (L) of input data which must be transformed by the operator into a vector (P) of output data to satisfy a specified performance criterion function and/or maintain a homeostatic operator state." This input load characterization of task demands would also seem to fit a variety of operator-loading concepts that distinguish one or more sensory channels or modalities as important to task performance, and address such concerns as channel capacity, perceptual overload, etc. For example, in his review of task load, Hartman (ref. 15) defined load as "the sum of all requirements imposed on the operator at any instant by the system," and later distinguished load as the number of information channels affecting operator performance.

The defining feature of demand-oriented expressions of workload, for purposes of this discussion, is simply that they be free of any dependence on considerations of operator response or response capabilities. In view of the apparent difficulties in sustaining this distinction in practice, it would seem advisable to associate demand only with input or stimulus-oriented variables and to reserve workload for the response-oriented variables.

Workload as effort— The focus of this conceptualization of workload is on how much an operator has to do and/or how hard he must work to satisfy a specified set of demands. A general characterization of this concept of workload has been given by Cooper and Harper (ref. 16): "The term 'workload' is intended to convey the amount of effort and attention, both physical and mental, that the pilot must provide to attain a given level of performance." The focus on operator effort and the apparent necessity to distinguish between physical and mental effort are widely accepted elements of the workload concept. Jenny et al. (ref. 17) use the concept to refer to "the level of effort required to perform a given activity or complex of tasks." In their study, the level of effort is regarded as "an imprecise term denoting an internal condition or process which, with the exception of purely muscular activities, cannot be measured directly."

A somewhat different emphasis is provided by Welford (ref. 18, p. 262) in characterizing effort as "the *intensity* with which action is carried out. A man may work either more or less hard at a job." Here the emphasis shifts from effort required to a consideration of the effort a human operator actually does exert in the performance of a task. As a unique variant of this approach to effort, Ryan (ref. 19) insists on an experiential focus:

> "By *effort* I mean first of all the experiences of the individual as he works. He feels at one time that he is 'working hard', at another that he is 'working slowly and easily.' Effort also includes the experience of difficulty in maintaining one's attention upon a boring task, and the strain or stress in performing an unpleasant or distasteful job. However, Ryan then notes that the degree of effort reported by a worker would not provide an accurate or reliable assessment of effort, and considered muscular potentials during task performance to be a more useful indicator."

Note the readiness with which effort is redefined in terms of an internal state or neuromuscular condition. In his elaboration of the operator-effort component of workload, Jahns (ref. 11) emphasizes the operator's readiness to respond and identifies such factors as "experience, motivation and set, physiological readiness, psychophysical factors, as well as the general background and personality of the operator" as determinants of this operator state. However, the narrower focus is on the overt expression of this readiness in an undefined effort expenditure. Associations to energy expenditure, level of activation, or the costs of meeting task demands are commonly found in effort-oriented formulations of workload, and these associations account for the close tie-in to the use of physiological indicators.

The concept of effort is most often used simply to refer to how hard a man is working and not to actual task performance or to the difficulty or demands of the task. Singleton (ref. 20) has argued for the separation of performance and effort by invoking the familiar observation that "an operator may be performing better in one of two tasks compared in an experiment because he is trying harder rather than because one task is easier than the other." Whatever it is that occurs when a man works harder is referred to as effort.

Workload as activity or accomplishment— This conceptualization of workload applies to actual task performance or the products of this activity. It is often used in operational studies of the effects of operating procedures or system design on aircrew performance. An example is provided by a work-sampling study of flight-crew activities during short-haul jet transport operations (ref. 21). After characterizing pilot workload as an elusive and nebulous term, the approach adopted was to define workload in terms of the total activity of the captain and copilot in performing such tasks as flight-path control, vigilance, communications, navigation, and system operation during each phase of an actual flight.

The actual activities engaged in by crew members have also been used as workload referents in long-term studies of crew performance factors. For example, Cantrell and Hartman (ref. 22) recorded typical flight-crew activities over 20 consecutive days, including off-duty and administrative activities, as well as those carried out in flight. Howitt (ref. 23) found it convenient to distinguish three time periods in his classification of workload:

> "(i) immediate workload: i.e., the workload experienced over any particular short period of time. . . .; (ii) duty-day workload: i.e., the sum total of the short-term workload experienced during a working day; (iii) long-term workload: i.e., the effect of sequences of working days over a particular roster pattern which would include such things as sleep patterns and time zone changes."

Fatigue

At the close of a symposium on fatigue, Welford (ref. 24) presented a good summary statement of the recurring theme that the central difficulty in dealing effectively with the problem of fatigue is one of definition. To the man in the street, according to Welford, fatigue means a subjective state following some kind of physical or mental strain; to the physiologist, it means some kind of reduction of response following more or less prolonged activity. The psychologist is placed in the middle and charged with the responsibility of tackling the problem of fatigue in practical human affairs. Unfortunately, the psychologist often evades this responsibility by dismissing fatigue as unscientific or by redefining the phenomenon of interest.

Many contemporary investigators have elected to accept Musico's (ref. 9) proposal to abandon the use of the fatigue concept, but others continue to view it as necessary and useful. Welford (ref. 18, p. 241) notes that "difficulties have led some to wish to abandon the term 'fatigue.' Yet there is a need for a term to cover those changes in performance which take place over a period of time during which some part of the mechanism, whether sensory, central, or muscular, becomes chronically overloaded." Bartley (ref. 25) develops the position that the inherent utility of the concept will be realized only when it is clearly distinguished from such considerations as the situations in which it occurs, the bodily mechanisms underlying the expression of fatigue, and the effects of fatigue on performance, work output, etc. However, it will be apparent in the following overview of fatigue concepts that such phenomena have not been excluded from more restrictive definitions of fatigue and that considerable diversity in the contemporary use of the term remains.

Fatigue as a feeling of weariness or tiredness— This conceptualization of fatigue has been characterized by Bartley (ref. 25) as experiential or sensory-cognitive. Factor analytic studies (refs. 26 and 27) indicate that the sensation of fatigue has three major components: (1) bodily tiredness and drowsiness, (2) weakened motivation or concentration toward the tasks, and (3) a group of physical complaints pertaining to psychosomatic disorders. Experiential concepts seem to be favored in operational studies of fatigue wherein extensive use is made of subjective assessments (refs. 28 and 29).

In his review of operational studies, Schreuder (ref. 2) elaborates on the subjective aspects of fatigue to suggest that "the ordinary sense of weariness which the pilot subjectively feels after a hard day's work should not be labeled as fatigue." Schreuder would insist on a level of intensity of this feeling of weariness "which is in excess of the expected normal fatigue and which is cumulative and of such amount as to alter the pilot's judgment and ability." Other investigators are satisfied with more global and unqualified definitions. For Yoshitake (ref. 30), "the feeling of fatigue signifies overall unpleasantness experienced by workers, and is not quite the same as complaints of symptoms of fatigue."

Fatigue as a clinical syndrome— In clinical practice, subjective complaints (as behavior rather than feeling) and/or specified sets of signs and symptoms are regarded as useful working definitions for fatigue. Mohler (ref. 7) has outlined an extensive list of signs and symptoms for both physical and mental fatigue, with the physical signs expressed primarily in terms of physiological functions (e.g., decreased blood glucose, increased lag in pupillary response, instability of neuromuscular coordination) and the mental symptoms in terms of psychogenic and emotional dysfunction (e.g., increased irritability and intolerance, tendency to depression and withdrawal, decreased sex drive). The familiar distinctions between acute and chronic fatigue also derive primarily from clinical practice.

Hartman (ref. 31) suggests a three-category classification of fatigue, characterizing acute fatigue as that normally occurring between a pair of sleep periods, and cumulative fatigue as occurring over a period of days or weeks as a result of inadequate recovery from successive periods of acute fatigue. Hartman adopts a description of chronic fatigue as a "psychoneurotic syndrome characterized by difficulty in committing oneself to an active or aggressive course of action, and by a generalized withdrawal or retreat from conflict which is intolerable for situational or personality reasons."

Fatigue as performance decrement or skill impairment— Concept referents in this category, like the clinical signs and symptoms just cited, are often treated as indicators or effects of fatigue rather than a distinguishable state. Some investigators feel that it is unnecessary to postulate the existence of hypothetical states and processes that underlie or mediate fatigue phenomena, and prefer to use the term to refer to observable changes in task performance or behavior. An example is provided by Bartlett (ref. 32):

> "Fatigue is a term used to cover all those determinable changes in the expression of an activity which can be traced to the continuing exercise of that activity under its normal operational conditions, and which can be shown to lead, either to deterioration in the expression of that activity, or, more simply, to results within the activity that are not wanted."

A more formal expression of these changes in performance is provided by Hull's development of the reactive-inhibition construct. His behavioral restatement of Spearman's general law of fatigue (ref. 33) and Pavlov's concepts of conditioned inhibition (ref. 34) is as follows: "Whenever any reaction is evoked in an organism there is left a condition or state which acts as a primary, negative motivation in that it has an innate capacity to produce a cessation of the activity which produced the state . . . we shall call this state or condition *reactive inhibition*" (ref. 35, p. 278).

Subsequently, Hull (ref. 35) noted that fatigue was to be understood in this context as "denoting a decrement in action evocation potentiality, rather than an exhaustion of the energy available to the reacting organ." Contemporary treatments of fatigue in terms of performance decrement, diminished readiness or capacity to respond, or impaired efficiency may be construed as variants of this basic process.

One of the more interesting variants is Bartlett's concept of skill fatigue. On the basis of studies of pilot performance in the Cambridge Psychological Laboratory, Bartlett (ref. 36) suggests that "it is necessary to draw a broad distinction between fatigue produced by continued hard physical work and that produced by work which calls for little continuous muscular effort, but demands persistent concentration and a high degree of skill." Skill fatigue, also distinguished from mental fatigue, was said to occur when a task, such as piloting a plane, required complex, coordinated, and accurately timed activities. In later Cambridge studies (ref. 37), deterioration of skilled performance was apparent after about 2-1/2 to 3 hr of simulated flying, manifesting primarily as a progressive lowering of standards of performance, missing important information displays, and gross miss-timing of interrelated control actions.

Fatigue as a neurophysiological condition or state— In traditional or classical studies, fatigue was referred to a particular neuromuscular site (i.e., to specific motor units, muscle groups, organs, tissue structures) and then defined in terms of specific biochemical and/or response capability changes. This comparatively narrow focus is now generally recognized as only one aspect of fatigue, as indicated by Basmajian (ref. 38, p. 81) in a discussion of neuromuscular fatigue as a special instance of a more general condition:

> "I shall observe, at once, the traditional and necessary warning that fatigue is a complex phenomenon and perhaps a complex of numerous phenomena. The fatigue of strenuous effort is probably quite different from the weariness felt after a long day's routine sedentary work. Undoubtedly, the following types exist: emotional fatigue, central nervous system fatigue, 'general' fatigue, and peripheral neuromuscular fatigue of special kinds."

Examples of the focus on peripheral fatigue mechanisms are provided by the work of Tsaneva and Markov (ref. 39) on permeability changes in synaptic membranes (presumably governed by feedback regulation originating in metabolic changes in the working organ) and by Welford's (ref. 18, p. 261) concept of fatigue as local neural impairment. Welford's theory is based on the traditional assumption that "some group of nerve cells concerned with the performance that fatigues, or with some essential link in it, becomes insensitive or unresponsive through continued activity." When fatigue is considered as a more complex phenomenon, the question arises as to where fatigue actually occurs, that is, should it be referred to the total person (or organism) or localized in some specific neurophysiological structure or function?

Grandjean (ref. 40) shares the view of many investigators that fatigue is a central neurophysiological condition and would locate it in the central nervous system—more specifically, in the brain-stem reticular activiation system: "In the light of present neurophysiological knowledge, we may consider fatigue as a state of the central nervous system induced by a prolonged activity and fundamentally controlled by the antagonistic activity of the activating and inhibitory systems of the brain stem."

Grandjean's conceptualization of fatigue as a condition of the central nervous system is based on early studies of the role of the brain-stem reticular formation in producing and maintaining various levels of inactivity, arousal, and activation (refs. 41-43). Beginning with Duffy (ref. 44), other investigators have assembled evidence that the degree of activation of an organism is a major variable in a wide range of behavioral processes related to fatigue (refs. 45 and 46). Duffy has reviewed a number of studies indicating that activation level affects the speed, intensity, and coordination of responses, but notes that "the effect of any given degree of activation upon performance appears to vary with a number of factors, including the nature of the task to be performed and certain characteristics of the individual" (ref. 47, p. 194).

Welford (ref. 18, p. 247) has also suggested that fatigue is a central phenomenon and attempts to integrate the comparatively less accessible condition of mental fatigue with the more readily observed neuromuscular fatigue condition:

> "It appears that in the intact organism changes in the muscles brought about by prolonged or repeated contractions can, according to circumstances, have one of two limiting effects. Either the muscles themselves become temporarily incapable of further contraction or the condition of the muscles produces afferent stimuli and these in turn affect the central mechanisms and lead to the cessation of efferent impulses. . . . If the term 'mental fatigue' is to have a meaning in line with that of neuromuscular fatigue, it must denote the impairment of some brain mechanism as a result of long continued use. The impairment must be reversible in the sense that it disappears with rest, and may take the form of lowered sensitivity or responsiveness of capacity."

Welford suggests that this definition permits a distinction to be made between mental fatigue and such other central conditions as adaptation, habituation, and monotony or boredom, which also lead to a decrement in performance over time. However, Thompson and Spencer (ref. 48) see no significant differences in operational definitions of reactive inhibition, habituation, and central fatigue. Tidwell and Sutton (ref. 49) note the relationship of monotony and boredom to fatigue and cite the different viewpoints of investigators concerning these phenomena. Some consider boredom to be a component of fatigue, and others treat it as a distinct phenomenon with distinctive causal factors. Grandjean (ref. 50) expresses the popular view that monotony and boredom are components of the fatigue condition and are related to the task situation: "if the work load is too heavy, fatigue due to physical or mental effort is to be expected; if the worker is underloaded or forced to conduct repetitive work, fatigue due to monotony will be produced."

Hartmann (ref. 51) distinguishes between physical and mental fatigue and hypothesizes a relationship to sleep: physical fatigue represents a need for slow wave sleep (SWS) and mental fatigue represents a need for desynchronized (D), or REM, sleep. Physical fatigue typically follows a day of "physical activity, sport, or mixed physical-intellectual activity without worry or anxiety." Mental fatigue typically follows a day of "emotional stress or a day of hard, not entirely pleasant, intellectual work or intellectual plus emotional work" (ref. 51, p. 125). Hartmann indicates that, although physical fatigue produces no definite mental changes, mental fatigue produces discomfort, irritability, anger, lack of energy, inability to concentrate, loss of social adaptiveness, and loss of ability for careful patterning or long-term planning. After reviewing a large data base (e.g., on the physiology and chemistry of sleep, sleep deprivation, dreaming, age changes, and long and short sleepers), Hartmann concludes that the function of synchronized (S) sleep is anabolism and synthesis of macromolecules to be used partially in the functions of D sleep; the functions of D sleep are repair, reorganization, and formation of new connections in the cortex and the catecholamine systems ascending to the cortex required for optimal attention mechanisms, secondary process, and self guidance during waking.

Fatigue as a level of energy expenditure— The energistic approach to fatigue focuses on the costs of protracted effort, whether mental or physical, in terms of the energy investments or transformations required to sustain it. This approach is both traditional and contemporary. Janet (ref. 52) used the concept of *force mentale*, roughly equivalent to a form of mental energy, to account for the individual's capacity for making decisions and facing new situations. According to this concept, decision-making becomes difficult and imposed choices lead to functional disorder as fatigue develops.

A more recent formulation of the energistic approach characterizes fatigue as a psychophysiological process of energy utilization (ref. 53):

> "The term fatigue is applied in this review to denote a normal psychophysiological process, which starts immediately after the beginning of any physical or mental activity and consists of the utilization of the body's energy stores, the accumulation of the breakdown products, and the activation of adaptive mechanisms which maintain the homeostasis of the organism."

In his work, Dukes-Dobos (ref. 53) sets aside subjective feelings of fatigue (which can occur in the absence of activity or stress) and performance effects (which cannot be reliably associated with the fatigue process) and chooses to focus on the urinary excretion of proteins, electrolytes, simple compounds, and hormones as indicators of energy expenditure. An energy utilization approach has also been applied to studies of muscular fatigue. The energy utilization process during muscular work has been summarized as follows:

> "The energy for muscular activity can be supplied either by the anaerobic process with the accumulation of lactic acid, the product of glycogen breakdown; or by the aerobic process, when the oxygen intake balances the extra oxygen requirements for the given work-load. Short bursts of high intensity work are done anaerobically and prolonged, sustained work is done aerobically. . . . At the onset of the exercise, the aerobic work prevails first, which is evidenced by very low lactic acid in the blood. During progressive increase in the work load, energy is released to cope with this extra amount of work, and the anaerobic process begins to compensate for this, thus causing oxygen debt" (ref. 54, p. 71).

Cameron (ref. 29) considers the term fatigue to be no more than a useful descriptive term for a generalized stress response over a period of time:

> "The human stress response is generalized in character, involving the whole system of biological emergency mechanisms. Since it implies, by definition, an abnormal demand on the energy resources of the system, it is fatiguing. The degree of fatigue experienced

may depend to some extent on the level of the stress response, but will depend primarily *on its duration*."

Cameron emphasizes that he is not recommending conceptualization of fatigue in simple energistic terms—which he considers inappropriate for dealing with a complex biological process. The duration of the stress response, not necessarily the duration of the stressful conditions, is considered to be the critical variable, and he argues that the length of time needed to return to a normal arousal level (of biological emergency mechanisms) is an index of the severity of fatigue resulting from the state.

McFarland (ref. 55) has criticized the focus on physiological factors in fatigue, citing the familiar arguments that effects observed in the laboratory (e.g., high lactic acid levels in the blood) are not always found in actual work situations, that other factors often influence energy reserves and utilization capacities (e.g., physical condition and motivation), and that the metabolic costs of mental work are very slight. Characterizations of the pilot's job as predominantly cognitive, and not physical or muscular, are frequently cited to question the relevance of physiological factors, especially those derived from studies of heavy physical work.

In the preceding discussion of fatigue as a neurophysiological condition, a number of investigators have argued that the degree of activation of an individual plays a major role in a wide range of behavior processes (cf. ref. 56). Here it is relevant to note that in 1962, Duffy (ref. 47) defined the level of activation as the extent of release of the stored energy of the organism through metabolic activity in the tissues. However, in an earlier formulation, she provided a more wholistic characterization of energy levels and one better suited to the energistic approach being distinguished here:

> "By 'energy level' I refer to the degree of mobilization of energy within the individual which Cannon found to be very high during the excited 'emotions'; or to what Freeman has defined as 'the general organic background (neuro-glandular-muscular) which operates to sustain and energize overt phasic response. . . .' Changes in energy level, in degree of organization of responses, and in conscious state occur in a continuum. . . . Extremes in the continuum are readily identifed as 'emotion'; intermediate points offer difficulty in identification" (ref. 57).

Scott's review (ref. 56) of applications of activation theory to task design provides a good overview of how Duffy's (ref. 57) continuum of changes in energy level can be used to account for and integrate an impressive number of empirical observations of fatigue phenomena (e.g., performance decrement, motivational drift, impairment of efficiency, low productivity, subjective complaints of exhaustion and boredom). A clear focus on the higher order construct of energy mobilization and channeling in the individual, rather than the localization and reduction of this process to metabolic activities in particular muscles or tissues, is considered essential to the achievement of this integration.

The further development and explication of this focus on energetic processes in the individual should not be misconstrued in terms of the outdated controversy between "vitalist" and "mechanistic" viewpoints in science; a renewal of the search for the *elan vital* is not being suggested. However, an unbiased review of the controversial notions of life energy developed by Wilhelm Reich (ref. 58) might prove stimulating, especially in light of recent developments in bioenergetics (ref. 59). As a biological discipline, bioenergetics is currently focused on cellular and molecular processes. However, the implications are clear that all organic structures and functions can potentially be modeled and understood as energy transformations. "Energy is required to create the very complexity of form of a living organism. . . . Living organisms are rich in information, which can be regarded as a form of energy" (ref. 59, p. 13).

Delineation of Workload and Fatigue Indicators

The different ways of conceptualizing workload and fatigue outlined in the foregoing discussion can be construed as the filters through which various investigators prefer to view phenomena of interest. When such higher order constructs as task demand, effort, central neurophysiological state, level of energy expenditure, etc., are adopted in empirical studies of these phenomena, it becomes necessary to further elaborate these concepts in terms of observable events and processes, that is, to identify the observable and measurable variables accepted by the investigator as indicators of workload or fatigue.

In this section, the consideration of alternative workload and fatigue concepts is concluded with a delineation of the concept indicators that have been used in contemporary studies. Indicators for workload are listed and categorized in table I. A reference to the literature is given (in parentheses) for each indicator listed to direct the interested reader to a published study that will provide an example or a discussion of how the indicator has been used.

Observable variables used to indicate fatigue are listed in table II, using the same general format. One of the common features in the conceptualization of workload and fatigue is that fatigue is often seen as a consequence of prolonged activity or exertion. It is not surprising, then, that in some instances fatigue indicators are similar to those listed for workload. The task requirement/input category is not applicable to fatigue; however, some elements common to both workload and fatigue are apparent in task performance, behavioral, psychophysiological, and affective indicators.

The treatment of fatigue as a consequence or concommitant of workload has been noted by Welford (ref. 18), who views both mental and neuromuscular fatigue as effects of loading. Bartley (ref. 25, p. 15) also implies this relationship. While insisting that "fatigue is a condition of the individual and is not to be defined in terms of external situations or even work products," he considers energy expenditure, paced performance, prolonged activity, and demands on particular body mechanisms to be typically fatigue-producing. There is, however, a difference in emphasis (see the indicators listed in

TABLE I.- DELINEATION OF WORKLOAD INDICATORS

Task requirements input	Task performance	Behavioral	Psychophysiological	Affective
1. Task requirements by flight segment (ref. 60).	1. Record of actual crew activities by flight segment (ref. 21).	1. Finger tremor (ref. 68).	1. Heart rate (ref. 73).	1. Self ratings of perceived exertion (ref. 86).
			2. Electrical activity of the brain, EEG (ref. 74).	
2. Task completion time vs. time available (ref. 61).	2. Accuracy of quality of primary task performance (ref. 63).	2. Critical fusion frequency (ref. 69).	3. Muscle activity or tension, EMG (ref. 73).	2. Operator-preferred levels of work intensity (ref. 86).
3. Task-time stress index (ref. 13).	3. Speed and task completion time (ref. 64).	3. Eye movements and fixations (ref. 70).	4. Skin resistance, GSR (ref. 75).	3. Direct estimates of task difficulty and tension (ref. 17).
4. Crew task demand elements (ref. 14).	4. Average duration of task elements (ref. 62).	4. Intonations of speech (ref. 71).	5. Blood pressure (ref. 76).	
			6. Sinus arrhythmia (ref. 77).	
5. Number of input channels and signal rate (ref. 15).	5. Accuracy or quality of secondary task performance (ref. 65).	5. Pilot evaluation of handling qualities (ref. 16).	7. Evoked cortical potential (ref. 64).	
6. Amount of task information available and index of quality (ref. 62).	6. Probability of target acquisition (ref. 66).	6. Pilot evaluation of task difficulty (ref. 72).	8. Urinary excretion of catecholamines, metabolites, electrolytes, and simple compounds (ref. 78).	
	7. Threshold for detectable error (ref. 67).	7. Cognitive, perceptual, psychomotor, and sensory task performance (ref. 17).	9. Parotid fluid excretions (ref. 79).	
	8. Completeness and accuracy (ref. 17).		10. Pupil size (ref. 80).	
			11. Relative metabolic rate (ref. 81).	
			12. Oxygen uptake (ref. 81).	
			13. Ventilatory rate (ref. 82).	
			14. Level of activation (ref. 47).	
			15. Combination of patterns of 1-13 above (refs. 83-85).	

TABLE II.- DELINEATION OF FATIGUE INDICATORS

Task performance	Behavioral	Psychophysiological	Affective
1. Production rate or productivity (ref. 87).	1. Sensory or perceptual changes (ref. 18).	1. Excretion of urinary metabolites (ref. 53).	1. Self ratings of fatigue feelings (ref. 103).
2. Irregularities in timing of actions (ref. 18).	2. Slowing of psychomotor performance (ref. 18).	2. Circulatory strain (ref. 97).	2. Complaints of irritability, depression, vague psychosomatic disorders, etc. (ref. 2).
3. Disorganization of skill or proficiency (ref. 37).	3. Blink value or ratio (ref. 89).	3. Lactic acid levels in the blood (ref. 54).	3. Feelings of impotence (ref. 104).
4. Reduction of speed of task performance (ref. 20).	4. Critical fusion frequency, CFF (ref. 90).	4. Rectal temperature (ref. 98).	4. Complaints of eye strain or discomfort (ref. 105).
5. Decrease in precision or accuracy of performance (ref. 7).	5. Handwriting pressure, tapping pressure, and speed of finger movement (ref. 91).	5. Muscular tension or contraction (ref. 99).	5. Direct estimation of fatigue state (ref. 17).
6. Accuracy or quality of secondary task performance (ref. 88).	6. Disintegration of complex action patterns (ref. 92).	6. Ocular muscle strain (ref. 100).	
	7. Sustained concentration of attention (ref. 93).	7. Percentage of alpha rhythms in EEG (ref. 101).	
	8. Tapping rates (ref. 50).	8. Blood condition (ref. 3).	
	9. Eye movements (ref. 94).	9. Neuromuscular excitability (ref. 3).	
	10. Finger tremor (ref. 68).	10. Disturbances of visual function (ref. 102).	
	11. Blocking (ref. 95).		
	12. Withdrawl, decreased sexuality, insomnia, etc. (ref. 7).		
	13. Personality traits of extroversion or surgency (ref. 96).		

table II). Generally, fatigue indicators are more clearly and directly focused on the condition of the individual, and the range of conditions of interest is extended, notably in the behavioral category, to include long-term or chronic effects on the individual's well-being and social adjustment, as well as effects on task-related performance capabilities. This difference in emphasis may be related to different conceptions of the connection between fatigue and workload. Cameron (ref. 29), for example, contends that "changes within the individual which are independent of workload appear to be of greater significance than the effects of continued performance." The role of factors other than task demands or task loading on system operations and pilot well-being is discussed later.

ASSESSMENT OF WORKLOAD AND FATIGUE IN PILOT-SYSTEM INTEGRATION STUDIES

In the preceding conceptual analysis, the complex and multi-dimensional character of pilot workload and fatigue phenomena was clearly indicated. In turning to the practical concerns of measurement and the interpretation of workload and fatigue assessment data, this complexity will be seen to underlie many difficulties in the applicability of workload and fatigue studies to operationally meaningful task performance. Kelley and Prosin (ref. 106) characterized the attempt to assess human performance for complex operational tasks as "an exceedingly difficult and frequently impossible undertaking." They then stated the central issue as follows:

> "The fundamental question is what to measure and why. . . . The more knowledgeable the investigator the more formidable the problem appears. Those unsophisticated in the measurement field gather measurements by some available means, assuming that the variance in the scores they gather represents a meaningful variation in task performance. The experienced investigator knows that such measurement variance need not and frequently does not represent the truly significant parameters of variation in a complex task."

In consideration of the assessment problem, the focus here is on practical applications, and the fundamental question of "what to measure and why" is addressed in that context. In this section, workload and fatigue assessments are considered with regard to the objectives and requirements of research studies conducted in support of system development and operational evaluation. An examination of workload and fatigue assessment techniques applicable to management practices applied after the system is operational is presented under "Management of Workload and Fatigue."

The major practical concerns during system development are to make the conceptual distinctions that achieve the clearest focus on the phenomena of interest, and to adopt or develop assessment techniques that will satisfy the requirements, resource constraints, and data interpretation objectives of a particular study. Criteria are needed for the selection of workload and fatigue indicators, for judging the utility or suitability of alternative measurement techniques, and for assessing the applicability of the data obtained. This section begins with a brief discussion of the criteria adopted for establishing the usefulness or applicability of workload and fatigue concepts and techniques. An overview and a critique of current trends in the assessment of pilot workload and fatigue are then presented.

Assessment Objectives

The development studies of interest here are those that attempt to establish or evaluate system design concepts on the basis of pilot factors (i.e., their capabilities, limitations, acceptance attitudes, well-being). These pilot factor studies may also be concerned with the pilot roles, skills, attitudes, performance aids, etc., required to achieve an optimum matching of pilot characteristics with already established system design and operating constraints. Within the context of such studies, the assessment of workload and fatigue has been directed toward such diverse objectives as: (1) establishing or contrasting the demands imposed on an individual pilot or crew by alternative system or component designs, flight plans, environmental conditions, operating procedures, regulatory practices, etc.; (2) relating observed or projected levels of workload or fatigue to theoretical or empirically established limits on pilot or crew performance capabilities or to their ability to cope with additional or unexpected task demands; (3) determining the immediate and long-term effects of sustained, effective task performance on pilot proficiency, morale, health, personality, etc.; and (4) establishing functional relationships between task demands and effort required or the effectiveness of various effort investment strategies.

In these studies, the basic issue of "what to measure and why" is often resolved by selecting concept indicators and measures, not because they are specific to a particular workload or fatigue concept but because they are theoretically interesting, or simply because they are easy to record and seem to be sensitive to independent variables of interest to the investigator. It is likely that indicator and measure selections will continue to be made on the basis of *ad hoc* criteria and to be greatly influenced by differences in the preferences and interests of individual investigators until more formal assessment criteria are established. In the practical context of pilot task performance, the prospects for achieving any sort of consensus on such criteria are not good. At the close of a conference on methodology in the assessment of complex operator performance in aerospace systems, Chiles (ref. 107) reported the general conclusions of the conferees that meaningful criteria for judging the predictive validity of concepts and measures have not yet been identified in "all but the conceptually simplest of operational systems" and that "we generally lack the empirical or theoretical structure necessary to specify what system variables should be measured."

The criteria adopted for the subsequent critique of assessment techniques are simply the characteristics of these techniques which are important to the achievement of assessment objectives. Four major criteria were distinguished: (1) clarity of focus, (2) operational relevance, (3) practical significance, and (4) pilot acceptance. Such considerations as feasibility, state of the art in measurement technology, costs, convenience, etc., are also acknowledged as important criteria but are not given special emphasis here.

Clarity of focus— This attribute refers generally to how well the selected indicators or measures serve to clearly distinguish the phenomena of interest. The filters through which we choose to view workload and fatigue are established initially by the concept referents we are willing to accept, that is, by the way we resolve the semantic issues raised in the Introduction. The concept indicators listed in tables I and II further elaborate these concepts necessary to identify measurable events and processes.

Using clarity of focus as a criterion for distinguishing useful workload and fatigue assessment techniques does not require that the selected indicators and measures, whether used singly or in combination, be widely accepted or formally established as operational definitions for these concepts. However, it does require that clear distinctions be made among the alternative concept referents considered under "Concepts and Indicators" (e.g., task demands, effort, feelings, energy levels) and between these phenomena and such related phenomena as conditions in the task environment, situational stressors, personality variables, or the wide range of acute and chronic effects attributed to workload or fatigue.

Operational relevance— Chapanis (ref. 108) recently addressed this issue, and his remarks provide an appropriate statement of emphasis for discussion: "In our attempts to relate experimental criteria to systems criteria, I do not think that we should be persuaded by logic, intuition or appeals to our common sense. If there are connections between our experimental variables and the things that we want to measure about systems, these connections should themselves be demonstrable and measurable."

Chiles (ref. 109) also noted that explicit consideration of these connections is not often attempted in the context of interest here: "When the topic of interest is the real world of work as represented by systems such as those found in aviation, the extrapolative chain that must be constructed to get from the typical experimental situation to the task confronting the pilot or air traffic controller is truly formidable . . . and probably seldom justified."

Chiles offers two reasons for this unfortunate state of affairs. The first relates to the often-noted problem that many researchers of human factors and ergonomic problems find it difficult to break away from the traditional concerns and methodologies of the academic environment which do not clearly relate to operational situations. However, more pertinent to this discussion is Chiles' second reason: "the reluctance on the part of the researcher to deal with experimental tasks that approximate the level of complexity of *the demands placed on the human operator as a part of the man-machine system*."

In most instances, the inadequate representation of operational demands is primarily a matter of limitations in the analysis of system functions and pilot tasks of interest, and may be due to inadequacies in available system data (e.g., for new systems) or simply to resource constraints (time and money) imposed on the study. However, operational relevance is considered to be an essential criterion for the assessment of pilot workload and fatigue, and this requires both the identification of actual task demands *and* the specification of functional relationships between these demands and the concepts, indicators, measures, and procedures employed in the research setting.

Practical significance— This criterion requires that the selected workload and assessment techniques be sensitive to operationally meaningful differences in independent variables and produce data that are clearly related to the practical issues addressed in pilot factor studies.

A directly related issue is the question of how the practical significance of the data is to be established — that is the second component of this criterion. It is suggested, with De Jong (ref. 110), that potential contributions to system effectiveness or to the well-being of individuals participating in system operations are the appropriate basis for judging practical significance. This criterion reaches beyond the question of operational relevance to consider the actual impact of measured levels of workload or fatigue on the quality of system performance and on the psychological and physiological well-being of individuals affected by system operations.

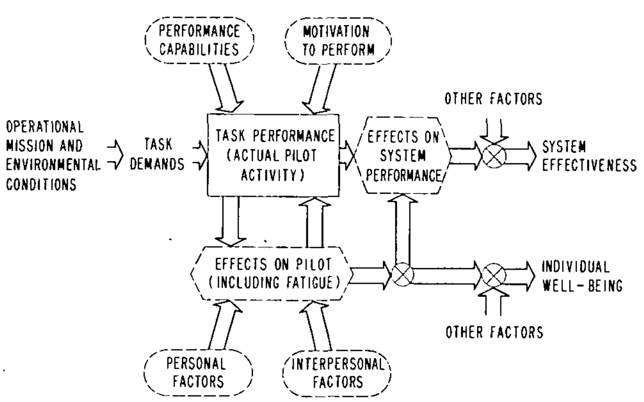

Figure 1.- Schematic overview of factors affecting system effectiveness and individual well-being.

The intended distinctions between clarity of focus, operational relevance, and practical significance are illustrated in figure 1. Task performance is shown as being responsive to a set of task demand inputs specific to a particular operational mission and flight situation; task-specific performance capabilities (i.e., skills and proficiency) and motivation are represented as the principal variables affecting task performance (actual pilot activity in response to task demands). Note that fatigue is shown here as only one of the potential effects of task performance on the pilot and that it is directly affected by personal (e.g., fitness, personality) and interpersonal (e.g., role concepts, management policies) factors.

The clarity-of-focus criterion is concerned with how clearly workload and fatigue variables are isolated for study, without losing sight of their interactions with other variables operating in the system context of interest. Operational relevance would then address the questions of how well the phenomena examined in the research setting correspond to those occurring in actual system operations and environments. However, the consideration of relevance does not necessarily extend to effects on system performance or the interactions of these effects with an unspecified set of other factors that also contribute to system effectiveness and well-being. Practical significance thus begins where clarity of focus and operational relevance typically end, that is, with the effects of pilot performance and his condition on what the system actually does (or can do) and the consequent impact on system effectiveness and individual well-being.

Figure 1 is of interest as much for its identification of factors that typically are *not* considered in workload and fatigue studies as it is for distinguishing those that are. The intent of this broad characterization is simply to interrelate the factors underlying practical significance and to illustrate the complexity of the problem of establishing functional relationships between workload and fatigue variables. Methodological studies addressing the general issue of relating human-performance assessment to the larger context of system performance have been undertaken (e.g., ref. 111), but presently this issue is largely unresolved.

Pilot acceptance— The final criterion to be considered establishes two important constraints on the equipment and procedures used to assess workload and fatigue: (1) the measurement technique must not interfere with ongoing primary task performance and (2) the techniques applied must not evoke negative pilot acceptance attitudes. These constraints are especially important where data are taken in actual flight situations, and they are also important in flight simulation and laboratory studies where pilots are asked to participate as experimental subjects or evaluators.

The noninterference constraint is important not only for obvious safety-of-flight considerations but also to assure that the assessment process does not itself operate to modify or disturb the phenomena of interest. Interference can range from the subtle effects of the pilot's awareness that his performance is being evaluated to the more obvious distortions in task performance which can arise when, for example, a control technique or style is imposed on the pilot by the study design, or when side tasks are added for assessment purposes. The use of encumbering or uncomfortable data-collection devices (e.g., head-mounted cameras, posture-restraining apparatus, intrusive physiological sensors) are also obvious as potential sources of interference.

Since interference with task performance or the use of encumbering measurement apparatus may also be a source of negative acceptance attitudes, the criterion being distinguished here is generally referred to as pilot acceptance. Other potential sources of negative acceptance must also be considered and include such factors as unrealistic task demands, inadequate simulation of aircraft handling qualities or environmental effects, the use of operationally meaningless psychological tests or questionnaire items, annoying preflight preparation procedures, and difficult or tiresome data-recording requirements. These potentially troublesome conditions cannot always be avoided, of course, but the possibilities for significant influence on the pilot's behavior or condition which might confound the data obtained must be carefully considered.

Overview and Critique of Workload Assessment Techniques

Using the criteria just discussed, the utility and applicability of current trends in the assessment of pilot workload are now presented. An in-depth presentation and critique of specific applications is beyond the scope of this study, and the reader is referred to the references cited. For example, a good overview of the advantages and limitations of workload assessment techniques applied to the comparison of alternative system design concepts is available in Beyer's (ref. 112) review of display evaluation studies. The intention here is to identify the major assessment techniques currently in use and to provide a general critique of their suitability for pilot-system integration studies.

Analytic determinations of task demands— Any attempt to delineate system, flight operation, situation-specific pilot performance requirements, or stimuli governing task performance may be construed as an analysis of task demands whenever it satisfies one important constraint: task demands must not be confused with actual task performance or with assumptions regarding the psychological or physiological effort or resources required to satisfy such demands. This constraint is often ignored, but when it is observed, the delineation of task demands represents a direct attempt to achieve clarity of focus and operational relevance in workload studies. Task demand analyses are typically carried out within the context of a flight profile (or mission) structure and entail an analysis of the pilot's participation in such system functions as flight management, vehicle control, navigation, subsystem control, and communications (ref. 14).

Computer simulations of flight operations and crew activity (refs. 13, 60, and 113), based on mission analysis, have greatly expanded the number and complexity of system performance parameters that can be treated in deriving workload or task loading estimates and predictions. The limitations of the analytic approach are those of any modeling or simulation technique which necessarily entails the selective extraction of system characteristics or environmental phenomena for representation in the model. However, this selection process is deliberate and the connections to the system can, in principle if not in practice, be made explicit.

In applications to pilot-factor studies, the attempt to distinguish demands as system attributes that are independent of pilot-task performance factors is considered essential to both the operational relevance of such studies and to the clear interpretation of study results. For example, demands may be held constant while specific system features intended to reduce workload (e.g., display design, procedures, control techniques) are varied. Moreover, when demands are distinguished from pilot performance factors, studies can be carefully controlled so that the separate and interacting effects of these two variables can be assessed.

Task performance assessments of pilot effort— The focus of system design evaluations and, indeed, of attempts to assess the demands imposed on the pilot or crew by alternative design configurations or operational employment concepts is often on effort, that is, on how hard the pilot has to work or how much of his total capacity he must apply to a task or system function. In the study cited earlier (ref. 60), for example, workload was assessed as the total time a given operator channel (visual, cognitive, motor, etc.) or combination of channels is used during a flight segment of interest. The most direct approach to the assessment of pilot effort would appear to be the measurement of system-relevant task performance in the context of actual flight operations or a high-fidelity simulation of task demands. However, Cooper and Harper (ref. 16) noted the difficulties with this approach:

> "A significant difficulty arises here in that, first, the tasks selected for measuring performance may not demand of the pilot all that the real mission demands, especially in items of distractions, auxiliary tasks, and pilot stress . . . (second) the pilot is an adaptive controller whose goal (when he is so instructed) is to achieve good performance. In a specific task he is capable of attaining essentially the same performance for a wide range of vehicle characteristics, at the expense of significant reductions in his capacity to assume other duties. . . . In the third place, it is difficult, if not impossible, at the present time to measure all important aspects of pilot performance. Encouraging results have been obtained in specific instances — wherein good correlation has been obtained between measurement of *physical* effort executed by the pilot (i.e., integral of pilot control displacement, force, etc.) and pilot ratings. In such cases, it must be assumed that differences in *mental* effort and attention were not significant."

The familiar argument that task performance measures provide an inadequate basis for evaluating alternative system design concepts was taken by Spyker et al. (ref. 85) as a point of departure for their attempts to develop an improved index of pilot workload:

> "An evaluation procedure which relies exclusively on performance measures in inadequate. That is, a pilot with one configuration may work twice as hard as he does with another, yet achieve equal performance for both. Thus, one can conclude that the pilot's capabilities were unequally taxed and that his inequality was not detected by a performance measurement."

The central limitation here appears to be sensitivity, that is, task performance measures do not readily distinguish operationally meaningful differences in the effort associated with variations in task demand. Moreover, the costs of acceptable and sustained task performance in terms of either energy investment or spare capacity are not disclosed by such measures. Finally, cognitive strain (mental effort) occurring during task performance is not assessed. As a general consequence, the pilot's ability to deal with nonroutine events or emergency situations cannot be assessed and the onset of serious performance decrement cannot be predicted.

Psychophysiological assessment of effort— Many investigators (refs. 20 and 83) are willing to accept psychophysiological reactions as more or less direct reflections or concommitants of variations in physical and mental effort. With respect to physical work, highly direct relationships have been demonstrated. Citing numerous studies conducted since 1962, Streimer (ref. 114) finds:

"that in self-paced aerobic work which is not thermally, environmentally or psychologically stressed, direct and linear relationships exist between energy input levels and work output levels. . . . The reliability of these relationships has been such that, despite alterations produced in the oxygen-pulse ratio by various muscle group involvements, a number of relationships have been posited which may be employed in the evaluation of such factors as work load levels, relative task difficulties, operator physical condition, equipment comparisons. . . ."

When the perceptual-cognitive character of flight management tasks is considered, these relationships are not so clearly and directly established. As Kelley and Prosin (ref. 106) noted:

"Psychophysiological parameters also hold promise for measuring a single task variable that permits one to compare and scale very different kinds of tasks. As yet, psychophysiological parameters have not proved highly sensitive to task variables other than physical work and to motivation, emotion or stress, but this may just mean that the appropriate measuring instruments or techniques are not yet developed."

Kalsbeek (refs. 77 and 115) reported on one parameter that appeared to overcome this sensitivity limitation and to provide an improved clarity of focus for mental effort. This parameter — sinus arrhythmia — is described by Kalsbeek (ref. 115) as follows:

"The normal heart rhythm of healthy subjects during rest is irregular. This irregularity can show a beat variation equal to ten beats per minute and more. This phenomenon is referred to in the medical literature as *sinus arrhythmia*. Physical workload such as walking on a treadmill or stretching out an arm increases the mean heart frequency and diminishes the irregularity of the rest value. Mental workload also diminishes the irregularity of the rest value but does not change the mean heart frequency."

Laboratory studies (ref. 77) have shown that the irregularity of the heart-rate pattern tended to disappear as a function of the number of signals per minute subjects were required to cope with in a perceptual-motor task. In a flight simulation study (ref. 115), the suppression of sinus arrhythmia clearly differentiated flight segments representing varying task demands (e.g., level flight, holding, approach).

A series of papers presented at a recent symposium on heart-rate variability indicates the difficulty, however, in quantifying the change in cardiac response and relating it to mental load. Rolfe (ref. 116) contends that the problem is in the development of techniques to process and analyze the data. Sayers (ref. 117) and others suggest that heart-rate variability is not a reliable measure. Sayers related spontaneous variability of heart rate to three major physiological factors: quasi-oscillatory fluctuations thought to arise in blood-pressure control, variable frequency oscillations due to thermal regulation, and respiration. Sayers concluded that "it seems likely that the positive conclusion will be reached that recourse to simpler measures of sinus arrhythmia should be regarded as no longer adequate or appropriate."

Benson et al. (ref. 84) cited individual differences in physiological reaction as an important qualification in their attempts to distinguish task demands, and found it necessary to use combined measures:

> "In situations where intra-subject comparison of the physiological response to a change in task variables is possible, and when several physiological measures, rather than a single one, can be employed, then it is likely that relatively small differences in task load can be detected . . . in certain situations (e.g., pilot aircraft control) where it is undesirable to introduce a secondary task and quantification of overall performance presents considerable difficulty, measures of physiological activity may allow a relative, if not absolute, assessment of task load to be made."

Their position is not a very strong endorsement, but probably is a representative view of the general utility of most psychophysiological techniques. Additional qualifications that must be considered, however, are the complexity of data recording and interpretation, the response time of the measure relative to task demands, and the convenience and acceptance of the technique.

Wisner (ref. 64) has reviewed the often-noted equipment limitations and data interpretation difficulties in obtaining useful EEG, ECP (evoked cortical potentials), EMG, and eye movement data. Biochemical measures are ruled out by Cumming and Corkindale (ref. 83) because they do not reflect short-term (minute-by-minute) responses, although they are considered useful for detecting long-term effects. Pilot acceptance problems can be expected whenever uncomfortable, cumbersome, or intrusive sensor attachments are required and when preparation or post-flight procedures are excessively time-consuming and inconvenient.

Pilot opinion and subjective assessments— When experiential conceptualizations of workload are accepted, the pilot's direct perception or estimation of his feelings, exertion, or condition may provide the most sensitive and reliable indicators. Jenney et al. (ref. 17) reported "encouraging findings as to the usefulness and validity of subjective magnitude estimates." In their study of workload using an information-processing task relevant to air-traffic control, they used hourly subjective estimates of fatigue, tension, and task difficulty to assess workload levels. These estimates were obtained using the direct estimation techniques developed by Stevens (refs. 118 and 119). Stevens demonstrated that for many sensory qualities, including such complex qualities as whole-body vibration and ride comfort, the subjectively perceived magnitude of the phenomenon being observed is a power function of the physical magnitude of the sensation-producing stimulus.

Using a simple rating scale, Borg (ref. 86) reported good agreement between perceived exertion or difficulty and physiological indicators of effort (stress). For the most part, these results were obtained on physical tasks performed in the laboratory, although similar results were reported for one study of intellectual work. Good predictions of working capacity were also reported for such non-laboratory activities as skiing competitions and cross-country running. In an interesting variation of this technique, Borg established preferred workload levels by having subjects judge the intensity of exertion required in a laboratory task as "just about right" for a 1-hr effort on a familiar task in the field.

In a somewhat different application of subjective assessment techniques, Cooper and Harper (ref. 16) present the following argument:

> "Pilot evaluation still remains the only method of assessing the interactions between pilot-vehicle performance and total workload in determining the suitability of an airplane for the mission. It provides a basic measure of quality and serves as a standard with which pilot-airplane system theory may be correlated, and significant airplane design parameters and characteristics may be determined and correlated."

In the development of their rating scale, Cooper and Harper emphasize that such rating categories as "acceptable" and "satisfactory" relate *only* to the individual pilot's own assessment, and not to any existing standards, specifications, or other acceptance criteria. However, the focus of these pilot evaluations is on handling qualities, defined as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role." And workload is seen as inextricably involved in assessments of such characteristics as precision of control, and separate judgments of physical or mental effort are not attempted. Thus, the influence of perceived exertion or task difficulty, if it enters into the pilot's rating at all, is not explicit.

The use of pilot opinion and rating scales is positively accepted by pilots according to Westbrook et al. (ref. 1); it is the technique preferred by handling-qualities engineers for workload assessment. It also seems to satisfy requirements for operational relevance, convenience, and unobtrusiveness. Its principal limitation is that it has little or no clarity of focus with respect to either task demands or effort and, without this focus, its sensitivity cannot be assessed.

A major limitation in the use of experiential indicators of direct perceptual assessments of effort or exertion is that the pilot's awareness of neuromuscular states or of energy transformations in his body may be severely limited. Based on extensive clinical studies, Lowen (ref. 120, p. 57) has characterized both adequate and inadequate self perception as follows:

> "All feelings are body perceptions. If a person's body does not respond to the environment, he feels nothing. Self-awareness is a function of feeling. It is the summation of all body sensations at any one time. Through his self-awareness a person knows who he is. He is aware of what is going on in every part of his body; in other words he is in touch with himself. For example, he senses

> the flow of feelings in his body associated with breathing, and he senses all other spontaneous or involuntary body movements. But he is also aware of the muscular tensions that restrict movements. . . . In the unaware person there are areas of his body that lack sensation and are therefore missing from his consciousness. For example, most people are generally unaware of the expressions on their faces. . . . Other areas of the body of which people are commonly unaware are the legs, the buttocks, the back, and the shoulders."

Various techniques are currently being explored, most of them still too new or unorthodox to be adequately represented in the literature, which are directed toward a retraining of individuals in sensory awareness and sensitivity to bodily feeings (refs. 121-123). However, this kind of sensitivity is difficult to assess objectively and, more pertinent to this discussion, it tends to diminish during periods of intense concentration on task performance or external demands. These are precisely the conditions under which pilot workload assessments must be made.

Assessment of reserve capacity— According to Rolfe (ref. 65), the use of this workload assessment technique has its roots in theoretical issues relative to the number of channels an operator might have available during task performance and the limitations, if any, on his channel capacity, especially those associated with perceptual processes. The concept of limited channel capacity has been summarized by Garvey and Henson (ref. 124) as follows: "It is reasonable to suppose that, with all other conditions equal, the greater the error the subject perceives the more effort he expends in attempting to reduce it and the less of his capacity remains available for simultaneously contending with secondary tasks or other circumstances which demand his attention."

The usual characterization of this surplus capacity for attending to other task demands as reserve capacity derives from arbitrary notions of a man's total channel capacity, that is, it represents the difference between some assumed limit and the actual effort expended on a primary task of interest (ref. 125). A lack of clarity of focus in the use of this technique is indicated in a recent overview of measures of reserve capacity (ref. 85, appendix A) wherein three kinds of measures are distinguished: (1) loading tasks — intended to stress primary task performance and performed, if necessary, at the expense of degraded primary task performance; (2) subsidiary tasks — performed by the subject only when he feels he can respond with no decrement on primary task; and (3) information-sampling tasks — a primary task performed under varying conditions of information availability (e.g., time, sampling rate) based on the dubious assumption that if an operator can perform adequately when important information is available only x percent of the time, he can direct 100-x percent of his attention to other demands.

As Rolfe (ref. 65) noted, this technique is primarily a laboratory tool and "there is an absence of any indication that results obtained in the laboratory (the term includes the use of simulators) actually relate to performance in the actual environment of utilization." Westbrook et al. (ref. 1) expressed the typically low acceptance of this technique by handling-qualities engineers: "Experiments have been run with various side tasks and problem solving situations. Many of the experiments offer relatively little realism to the actual flight situation and the piloting job. Consequently, much of this work has had limited application to practical system design other than in establishing trends or limits."

A more positive view has been expressed by Roscoe (ref. 63) and his use of the technique illustrates its potential applicability to actual aircraft operating problems:

> "When a pilot makes a blunder, it may be assumed that he does not do so intentionally; the blunder occurs because the perceptual, judgmental, and motor demands of the moment exceed his momentary attention capacity . . . . During routine flight operations a pilot's attention capacity exceeds the moment-to-moment demand by varying amounts, and the continual measurement of his *residual attention* provides an inferential index, not only of the pilot's ability, but also of the relative blunder proneness of the equipment he is using."

In a flight-simulation study of manual-control-system dynamics (ref. 126), an adaptive information-processing task was used to maintain workload at the pilot's maximum momentary capacity. Since the rate of information inputs governing the performance of this side task was increased or decreased automatically as primary task performance (a complex area navigation task) improved or deteriorated, the display rate with which the pilot could cope served as a measure of residual capacity. When the side-task demands were applied, the number of blunders recorded was more than twice as high. Moreover, the measure of residual attention was reported to be sensitive to differences in airborne systems design after the effects of pilot ability and training were sorted out.

The two most damaging limitations of the secondary task assessment technique are interference with primary task performance (obtrusiveness) and poor clarity of focus when it is used to assess task demands or effort. Kelley and Wargo (ref. 127) reviewed instances where decrement in both primary and secondary task performance occur when the technique is used and "when this occurs, it is impossible to determine the extent to which conditions differ, since the two sets of units reflecting the difference (i.e., primary and loading task scores) are incommensurable. Further, if one score is better and the other worse under the two conditions, there is no way to know which condition is more difficult." Their recommended solution is the use of a cross-adaptive technique, such as the side task used in reference 126. However, in a recent study of adaptive technique, Kelley and Prosin (ref. 106) concluded:

> "It seems there is no simple way that the technique of adaptive performance measurement, so effective in the specific areas previously studied, can be generalized to complex tasks *as such* . . . If there are clearcut *general* rules that can be formulated that will permit any investigator facing a problem of measuring complex performance to obtain better measurement by using adaptive techniques, these

rules were not uncovered in the present project. It is our conclusion that complex performance per se is too heterogeneous a category of performance to provide a good approach to the development of adaptive techniques."

The poor clarity of focus is apparent in attempts to apply secondary task techniques to the assessment of effort. For example, Brown (ref. 128) has argued that when a subsidiary task is used to measure the relative difficulty of alternative primary tasks, the level of effort applied to the primary tasks will be affected, and that this effect will be confounded with the task performance factors of interest (e.g., equipment design variables). In the comparison of difficult tasks, Brown points out that the difficulty can be due to many factors (e.g., information load, input rate, response rate, stimulus compatability) and that any assumption that changes in primary task difficulty due to these factors will be comparable to those due to the subsidiary task demands is not justified.

Overview and Critique of Fatigue Assessment Techniques

In view of the many difficulties in defining fatigue, it is not surprising that very few studies of fatigue *per se* have been conducted in the context of system development studies. Interest in fatigue is most often seen in operational studies such as those reviewed in references 2, 7, and 31. Earlier, it was shown in figure 1 that fatigue can be treated as a consequence or concommitant of workload or effort, and that there are many elements common to both fatigue and workload indicators. Indeed, fatigue is sometimes used as a dependent variable in workload studies (e.g., ref. 17), and it is often included as a secondary interest in studies of pilot performance. In many instances, then, the limitations of workload assessment techniques also apply to fatigue.

The principal difficulty in applying fatigue concepts and assessment techniques more explicitly in pilot-factor studies is clarity of focus. In studies where the phenomena of interest are clearly distinguished, it would often seem best, as Bartley (ref. 25, p. 4) has suggested, not to use the term fatigue. "When the ability to perform is actually the central concern it should be studied as such without pretending that it is fatigue." With the exception of direct reports of feelings of fatigue, Bartley's suggestion would seem to be applicable to all of the fatigue indicators listed in Table II.

In view of the limited applications of fatigue assessment to pilot-factor studies, the summary of these techniques will be brief. For a more complete survey of current trends in the assessment of fatigue, the reader is referred to reference 129. A 1953 symposium of fatigue (ref. 130) is also relevant. In the discussion below, the major approaches to fatigue assessment are identified and elaborated only where they appear especially suitable for the context of interest here.

Performance decrement— Degradation of task performance over time or in response to changes in task demands is perhaps the most widely used indicator of fatigue. Welford (ref. 18) distinguished four kinds of changes that might occur: (1) impairment of sensory or perceptual functions, (2) slowing of sensory-motor performance, (3) irregularity of timing, and (4) disorganization of performance. Measures of performance decrement may be taken on primary task performance while it is in progress, on separate fatigue tests during interruptions of the task (or before and after), or on secondary tasks in the manner previously discussed for assessing reserve capacity. The general criticism of performance decrement indicators for fatigue is that alternative ways of accounting for the decrement may be preferred (e.g., boredom, anxiety, motivation, excessive task demands) and that fatigue effects may not be disclosed when subjects compensate by exerting greater effort.

One application of the performance decrement approach to the study of fatigue appears to have considerable clarity of focus and to be particularly applicable to the evaluation of system-design concepts and pilot workload. This approach is based on Bartlett's (ref. 36) conceptualization of skill fatigue; it is distinguished by its focus on observable changes in behavior which are taken as a direct reflection of the quality of pilot performance. Some examples of the observable breakdown of pilot skills are provided by McFarland (ref. 55) in his summary of the Cambridge "Cockpit Studies" conducted by Bartlett (examples are italicized).

> "A large number of R.A.F. pilots were studied under simulated flying conditions in a standard Spitfire cockpit with full controls and instruments. The pilots "flew" for at least two hours, some continuing until exhaustion after six to seven hours . . . As the subjects became more fatigued *they were willing to accept lower and lower standards of accuracy and performance.* Furthermore, *they failed to interpret the various instrument readings as being part of a single integrated system,* but paid attention to one or the other of them as individual, isolated instruments. As fatigue increased, *the pilot's range of attention decreased,* and forgetting or ignoring the more distant instruments was common. Possibly the most significant *finding was a general tendency for a sudden increase in errors at the end of the flight.* A tired airman, it seems, has an almost irresistible tendency to relax when he nears the airport."

This focus on the actual occurrences of pilot behavior clearly and directly related to the accomplishment of flight management and/or control objectives provides a straightforward way out of the conceptual and methodological difficulties that characterize more indirect fatigue assessment techniques. It derives from Bartlett's proposal to adopt, as indicators for fatigue, "all those *determinable changes in the expression of an activity* which can be traced to the continuing exercise of that activity *under its normal operational conditions*, and which can be shown to lead, either immediately or after delay, to deterioration in the expression of that activity, or, more simply, to *results within the activity that are not wanted*" (ref. 32, italics added).

In addition to its refreshing clarity of focus, this approach is inherently relevant to operational situations, it is unobtrusive, and it does not appear to involve any characteristics that would evoke negative pilot acceptance attitudes. The general limitation noted above, that performance decrement may not be specific to fatigue, has been noted by Davis (ref. 131). After repeating some of the Cambridge studies, Davis

> "came to the view that the disorders of skill observed were more readily explained as due not to fatigue but to what I then called 'anticipatory tension' . . . . My thesis is that skills tend to become disordered, and errors to be made, in conditions in which the outcome of a task is in doubt. In such conditions uncomfortable emotions are aroused, to which I shall hereafter refer as 'fear' or 'anxiety', although the term 'anxiety' is often used in a rather different sense."

Cameron (ref. 29) also agreed that measures of performance decrement are not specific to fatigue effects, noting that

> "the various fatigue phenomena reported by research workers can reasonably be assigned to a simple inhibition effect known to occur with extended activity, to an emotional variable similar to anxiety or fear, and to sleep deficit. Nothing is left to be accounted for by a fatigue effect, and the term itself is unnecessary except as a convenient label for a generalized response to stress over a period of time."

Cameron went on to develop the familiar argument that fatigue must be construed as a complex biological phenomenon, that direct attempts to quantify fatigue effects in performance terms are unlikely to prove fruitful, and that the fatigue problem is imbedded in the whole life pattern of the individual.

Note, however, that such broader notions regarding alternative explanatory mechanisms for fatigue represent diversions into theory and the postulations of such hypothetical constructs as anxiety and stress. This would lead back into the unresolved semantic issues discussed earlier and to a muddying of the clear focus on the phenomena of interest provided by Bartlett's analysis. An appreciation of additional contributing factors to changes in the expression of an activity and, especially, to results within the activity that are unwanted is important, both for controlling these factors in systems studies and for the effective management of fatigue in operating environments. These additional factors are considered later.

Behavioral indicators— The use of behavioral indicators of fatigue is closely associated with the focus on performance change or decrement, especially whan the behavioral events of interest occur as components of task performance (e.g., eye movements, speech quality, postural changes). However, changes in behavior unrelated or only indirectly related to task performance have also been used as fatigue indicators. The latter include personal and social behaviors such as increased irritability, increased use of alcohol or tobacco, and withdrawal from avocational social activities (ref. 7). Other behavioral indicators that may accompany or follow from fatigue include such conditions as inattention or impairment of vigilance (ref. 132).

In their summary of behavioral changes attributable to fatigue in airmen, Hartman and Fitts (ref. 133) cite loss of fine motor control, variability in performance, equivalence of stimuli, stereotyping of movements and responses, and disjunction of discriminations. Visual fatigue is often treated as a separate phenomenon (ref. 105); however, Murphy and Randle (ref. 102) recently studied its relationship to the flying task. They used four behavioral indicators of flight-induced fatigue: (1) the ability to maintain focus on stationary and moving targets, (2) the speed of monocular accommodation to abrupt (step) changes in target distance, (3) the ability to voluntarily control monocular accommodation, and (4) the range of focus.

As the foregoing examples suggest, persuasive arguments can often be advanced to support the contention that selected behavioral indicators represent critical elements of effective performance on complex operational tasks. The problems that remain are the large intersubject differences typically found in behavioral measures, their low correlations with other fatigue indicators, and the previously mentioned difficulties in establishing the specificity of behavioral events to fatigue rather than related states.

Psychophysiological assessment of fatigue— The general critique of psychophysiological techniques presented earlier for workload assessment is applicable here. A more thorough treatment of the strengths and weaknesses of this approach is available (ref. 134). The principal difficulties discussed are : (1) response generality — measures are not specific to various states conceptualized as fatigue or anxiety (or any other hypothetical construct); (2) response patterning — patterned physiological reactions are often stimulus-specific and/or peculiar to an individual; (3) response intensity — poor correspondence between the intensity of psychological (behavioral) reactions and associated physiological changes; and (4) temporal relationships — some physiological responses occur almost instantaneously (e.g., heart rate, GSR) whereas others can be observed only after periods of hours or even days (e.g., excretion of urinary metabolites).

The consensus seems to be, as McFarland (ref. 55) concluded, that "fatigue cannot be considered a simple physiological condition resulting from sustained activity. Furthermore, if one thinks of the body as a whole, fatigue cannot be defined solely in terms of biochemical changes in the muscles or nerves, or by the exhaustion of energy reserves." And so the problem of clarity of focus presents itself again. The many difficulties in data collection and interpretation notwithstanding, many investigators have found psychophysiological indicators to be useful for distinguishing fatigue states in operational studies, especially where biochemical analysis of blood and urine were performed (refs. 3, 73, 79, and 135).

Subjective reports— Again, the difficulties in applying subjective assessment techniques already discussed for the measurement of workload are applicable for fatigue, especially the limitations in body awareness.

Interviews, questionnaires, and subjective rating techniques are in wide use; however, they are most often used in combination with other measures that are given more emphasis. A checklist developed by Pearson and Byars (ref. 136) provides a good example of a subjective assessment technique widely used in operational studies of flight fatigue. The use of direct estimation techniques is exemplified in studies conducted by Grandjean (ref. 50) and Jenney, et al. (ref. 17).

In his analysis of the concept of mood, Nowliss (ref. 137) observes that the current usefulness of subjective reports is essentially limited to the realm of everyday discourse and suggests that their low scientific usefulness stems, in part, from a scientific Zeitgeist that fosters analytical and experimental investigations of only a few categories of behavior at a time. He is optimistic about the promise of combining a neurophysiological approach with more disciplined subjective reporting to achieve more reliable data on private events. In particular, he cites the work of Kamiya (ref. 138) as providing "a powerful convergence on private event, trainable verbal report and neurophysiological process, such that facts about all three are obtained at a single level of observation."

Clinical assessment of fatigue— This assessment technique is often simply a selective synthesis of the techniques already discussed. The distinguishing characteristic here is the imposition of the medical model of a fatigue syndrome (ref. 7), and the focus on the physician's clinical judgment of individual occurrences of pilot fatigue. Clinical assessment is widely used in aviation medicine (ref. 2) and is probably an indispensable procedure for the ongoing assessment and management of fatigue in operational situations. The latter application is discussed in the next section.

Applications of clinical technique to studies of fatigue in commercial flight operations are extensively reviewed in references 2 and 7. As noted earlier, these studies have produced conflicting data on the incidence and severity of fatigue effects in flying personnel. The central problem, again, seems to be one of clarity of focus. For example, Schreuder (ref. 2) insists on a special definition of fatigue to support his general conclusion that "pilot fatigue *as defined* is not a common occurrence in the airline pilot. . ." On the positive side, the clinical approach provides direct assessments of the effects of the flying task on the well-being of individual pilots reacting to particular circumstances and conditions.

MANAGEMENT OF WORKLOAD AND FATIGUE

In the foregoing discussion of workload and fatigue assessment in system development studies, the emphasis was clearly on workload. A major objective of human engineering activities and ergonomic studies carried out during system development is to minimize or optimize the demands imposed on the flight crew in an attempt to preclude any serious impairment of pilot performance capabilities or well-being. Fatigue has been treated as one of the mediating conditions that can lead to the impairment of pilot performance capabilities or well-being which accompanies task performance in the actual operational situation. After the system is operational, then, study emphasis shifts to the effects of ongoing system operations; fatigue, as a sort of all-inclusive term for unwanted effects, tends to replace workload as the central concern.

According to Schreuder (ref. 2), the broad aims of operational studies of fatigue are "to analyze the various ramifications of pilot fatigue in an attempt to come to some conclusions as to the severity of the problem." However, Mohler (ref. 7) suggested a more aggressive approach and emphasizes positive management control and preventive programs:

> "Since no serious person would dismiss potentially detrimental consequences of fatigue to aviation, continuing studies of fatigue are being conducted. Times change, equipment changes, and responsible monitoring of altered conditions in relations to fatiguing factors is a "communal" requirement of those engaged in aviation. Where fatigue may jeopardize safe operations remedial action is mandatory."

We will now consider the practical concerns of the management segment of the aviation community rather than the system design and supporting research interests of the system developers. With respect to workload and fatigue, the broad objectives of management activities may be stated as the deliberate effort to control their unwanted effects and to control the implicit threat these effects pose for flight safety, operational effectiveness, and individual well-being. A more explicit statement of management objectives would entail a delineation of unwanted effects, an elaboration of the corresponding requirements for their early detection, and the implementation of preventive or corrective action. The principal categories of unwanted effects are distinguished below. Current trends in the detection of these effects and in the application of preventive or corrective techniques are then briefly considered.

In the preceding discussion of practical significance as a desirable attribute for workload and fatigue assessments, interactions between pilot workload, fatigue variables, and other factors were cited as some of the central difficulties in sorting out the relative contribution of workload and fatigue to system effectiveness and individual well-being. A full delineation of the interaction of these additional factors with task demands, actual task performance, and the many effects associated with fatigue is beyond the scope of this study. However, before moving on to the more specific objectives and concerns of management activities, it will be helpful to consider briefly the general character of these other factors and their functional relationship to workload and fatigue.

The Role of Other Factors

Some investigators report that factors other than task demands or task loading seem to have the stronger and more direct impact on system operations and pilot well-being. For example, Billings and Eggspuehler (ref. 139), in a study of task loading and fatigue in helicopter pilots, reported that differences between subjects were much greater than any differences in performance associated with fatigue or task loading. Cantrell et al. (ref. 135) suggested that "the problem of task loading seems to have been largely human-engineered out of the present aerospace system — insofar as the actual operation of air-transport systems is concerned." They also cite an earlier study of workload in military transport pilots (ref. 22) which found that "neither the task load nor the flying hours required were the major sources of frustration to these pilots, but rather such factors as lack of planned free time, excessive ramp pounding time, and avoidable enroute delays." The major categories of other factors and their roles in affecting system effectiveness and pilot well-being are outlined below.

Personal factors— Schreuder (ref. 2) has set the tone for considering this class of other factors in the following comments:

> "In any study of pilot fatigue it is mandatory to also take into consideration the non-operational aspects of this problem. Among these are the psychological factors, professional attitudes or motivation, off-duty activities and the possibility of fear of flying. With reference to psychological factors, there are mental conflicts, frustration or anxiety resulting from domestic difficulties, financial or social insecurity, and thwarted ambitions. Other psychological factors which may cause increased stress are deterioration in skill or a lack of aptitude for increased responsibility and emotional instability. Also, it is a known fact that monotony and boredom in performing a task can also cause a sense of tiredness or weariness."

With regard to motivation, Zeller (ref. 140) considers that one of the few general conclusions warranted by our current understanding of fatigue is that "*motivation* has a powerful influence on the effects of fatigue and must always be considered in any evaluation . . . ." Cameron (ref. 29) identifies the danger in generalizing from experimental studies, where high motivation may overcome small performance decrements, to practical situations where a high motivation level cannot be assumed.

Following an extensive examination of flight crew and ground personnel of a French airline, Blanc et al. (ref. 141) emphasize that "occupational fatigue seems to be favored by the inadequacy of the subject's personality in respect to the work performed and, in particular, by the absence of affective investments in the job." Eysenck (ref. 96), in his systematic study of the biological basis of personality, contends that fatigue is a direct correlate of the central personality dimension of extroversion-introversion: "in the case of extroversion-introversion, clearly the concept in experimental and theoretical psychology corresponding to the personality dimension is that of fatigue."

Personal factors that have received less emphasis in the literature include physical fitness (ref. 2), age (ref. 142), experience and training (ref. 36), genetic factors such as sex and physical constitution (ref. 96), and even the pilot's life style. With respect to the latter, Schreuder (ref. 2) noted that the pilot is in a select socioeconomic stratum and this often leads to his participation in fatigue-producing, off-duty activities, such as private business ventures, excessive social activities, and long commutes by car or air to reporting bases.

Interpersonal factors— Bartley (ref 25. p. 40) related this set of factors to the motivation for performance that derives from interactions with other people:

> "The fact that we must reckon with is that much of the influence of the surrounds upon the individual operate at a verbal level, or at least at the social level, i.e., between the individual and other people in the many ways they have of interacting as persons. This means fatigue may be induced or alleviated by things that people may say to each other."

Welford (ref. 18) points out that, in many practical applications, it is not necessary to know *a priori* what it is that ultimately gives direction to a subject's dealings with his environment, but that "it is enough to examine the precise ways in which they control behavior." Social interactions associated with management-employee relationships are more accessible for the study of such controlling influences than those occurring in more personal interactions (e.g., family or marital). They may both represent significant sources of interpersonal problems affecting individual motivation. Communication failures in the exercise of management functions and the trends toward depersonalization of work were cited by Cantrell et al. (ref. 135) as important and understudied factors contributing to long-term, military aircrew effectiveness: "Management factors are perhaps the least studied of all areas discussed in this report. It is not clear whether this limited study is due to the highly sensitive and threatening nature of research in this area, or to implicit faith among many that problems in this area will 'work out by themselves.'"

Operational conditions and environmental factors— Cantrell et al. (ref. 135) also reviewed studies of the effects of task conditons and environmental stressors (e.g., the human engineering aspects of flight deck design and such conditions as humidity, ozone, atmospheric and microwave radiation, visual problems, acceleration, climatic changes, hypoxia, noise, and vibration). With the possible exception of humidity, noise, and vibration, these investigators tend to minimize the influence of these factors in producing either fatigue or performance decrement.

Such factors are the scheduling of work-rest cycles and the effects of disrupting established biorhythms (in both crew and passengers) may be of greater significance. Based on his study of aircrew fatigue, Cameron (ref. 143) concluded:

> "Fatigue, as recognized by aircrew, is associated with disturbed sleep, the causes of such disturbance being: (a) an irregular pattern of night and day work with insufficient opportunity for adaptation; (b) variations in local time due to rapid traversing

of time zones, again with insufficient opportunity for adaptation; (c) a chronic stress reaction among the aircrew, clinically of a relatively mild nature, but important as a determinant of sleeping difficulties."

Cameron (ref. 29) also discussed the relevance of sleep-deprivation research to the fatigue problem.

A factor receiving increasing attention and interest is the disruption of circadian rhythms. Hauty and Adams (refs. 5 and 144) studied phase shifts in these day-night rhythms and associated effects on aircrew performance during a westward, an eastward, and a southward flight. They found that, whereas the latitudinal flights resulted in a primary phase shift in rhythms, manifested by physiological functions, the longitudinal flight did not, although significant increments in subjective fatigue were reported on all flights. Some impairment of performance occurred in westward flights, but not in the reverse eastward flight, nor in the southward flight.

"Other explanations could be attempted, particularly in retrospect, but the data obtained from the three flights provide a basis for the following conclusion: Rapid translocation through many time zones does effect impairment of "well-being" but this is not accompanied by a commensurate change in the efficiency of basic psychological functions" (refs. 5 and 144).

In contrast to the conclusions of Hauty and Adams, Klein et al.(ref. 28) found significant decrement in flight simulator performance after an eastward and a westward flight of 8-hr time shift:

"The change in the performance level following transit, in dependence of the coincidence of old and new clock time, was unequal during the course of the day, but in general the level was significantly decreased (up to 40%) at daytime and increased during the late night hours. A performance decrement seen for the 24-hours total average, in comparison to the preflight control, was significant only after the eastward (-8.5%) but not after the westward (-3.3%) flight. The reason for this difference is mainly seen in a greater fatigue due to an unfavorable flight schedule and the more severe sleep loss connected with eastward travelling."

Klein et al. then consider lowering of total performance level of the day "to be a result of fatigue caused by preflight activity, the stress of long distance transportation, and sleep loss mostly connected with external desynchronization." They did find, however "highly significant *mean* performance decrements of almost 20% . . . at approximately the same day-times; *individual* changes even reached more than 50%." They suggest that the discrepancy between their results and the results of Hauty and Adams (ref. 5) was due to a difference in the complexity of the performance tests used in the two studies. "As already supposed by Hauty and Adams their negative results may be due to the low demand of their tests."

A subsequent study by Klein et al. (ref. 145) gave similar results using a complex psychomotor task, other than a flight simulator, after an eastward and a westward flight of 6-hr time shift. Results of this study and evidence from other studies led to the conclusion that "there is reason enough to assume that the decline of the 24-hour means of temperature and performance circadian rhythms is provoked by flight stress, sleep loss and fatigue rather than being a dysrhythmic symptom in itself" and that "impairment of performance at certain times of the day and elevation at others must be seen as a consequence of a persisting rhythm of sleep-wakefulness with a displacement in light and deep sleep periods during the night.

Unwanted Effects of Excessive Workload or Fatigue

The term "unwanted" is clearly inadequate for characterizing such extreme outcomes as aircraft accidents involving fatalities or severe impairment of individual health or well-being. However, workload and fatigue are seldom cited as a direct cause or even major contributing factors in producing these tragic circumstances. Hartman (ref. 31) reported that fatigue is not often identified as a major factor in aircraft accidents, citing USAF statistics that identify fatigue as a factor in only 2.7 percent of the accidents occurring in a recent 5-yr period. But Hartman also noted that "the practicing flight surgeon knows, however, that fatigue is frequently a secondary factor, and that it stands in the background ready to make its contribution to pilot error far more often than we, as passengers, might care to consider."

There are reported instances when fatigue does seem to be a major factor, and when the consequences of even one such incident are too costly to dismiss in any statistical analysis of the relative contributions of other factors. For example, Barlay (ref. 146) describes an accident in which tiredness was ranked as the second of 11 causes of pilot errors involved in a crash involving the death of 36 people. "The pilots were well within the officially permitted limits of duty and rest times, but they were at the end of a long, tiring day which already included two inevitably alerting or even tension producing overshoots" (ref. 146, p. 171).

In most instances, however, the role of fatigue in aircraft accidents or the serious impairment of the pilot's health is unclear. Barlay (ref. 146) reiterated the difficulties in distinguishing fatigue as a contributory factor in an accident when existing flight-time regulations are not violated and when no one knows what the acceptable maximum for safety should really be. However, in discussing accidents in general, others contend that "fatigue, although less dramatic, is undoubtedly the most universal cause of alteration in one's state of consciousness. Because of its lack of drama, its effects on accident causation are probably underestimated. Yet the manifestations of fatigue are tailor-made to produce accidents" (ref. 147, p. 372).

Scucchi and Sells (ref. 148) reviewed several airline accidents in which they attribute information overload of crew members to be a major causal factor.

"In these and most other accidents there is some decision point in time and space at which an incident is determined and becomes irrevocable, even though it has not yet occurred. In most cases such incidents are products of inaccurate perceptions and decisions or of failure to make timely critical decisions, rather than of improper control application. . . . This incident. . .and other numerous incidents not listed in this paper which involved sound mechanical systems, emphaizes the ease with which the human component, as an information processor, may be overloaded, and hence, may fail."

The decision function is not usually emphasized in workload nor in fatigue studies, as is, for example, psychomotor performance. Hartmann (ref. 51), however, contends that mental fatigue produces cognitive changes that include difficulties in concentrated thinking and the loss of ability for careful patterning or long-term planning.

With respect to severe impairment of pilot health or well-being, Schreuder (ref. 2) reports that there is no evidence that flying turbojet aircraft in scheduled airline operations is excessively fatiguing, deleterious to health, or conducive to premature aging. For the most part, then unwanted effects will refer to the more immediate and less extreme consequences of sustained pilot effort. They are effects that are clearly undesirable and can lead to more serious consequences, albeit in ways that are probabilistic and not readily foreseeable. Listed roughly in an increasing order of criticalness with regard to their potential operational impact, the major categories of unwanted effects are:

(1) Motivation decrement — including negative feelings and attitudes toward assigned tasks or equipment (ref. 149), diminished vigor or aggressiveness, and disturbances in aircrew morale (ref. 31) — all occurring without observable decrement in performance or proficiency.

(2) Skill or proficiency decrement — noticeable deterioration in virtuosity, precision, timing, coordination, etc. (ref. 32) or reserve capacity (ref. 125), with no significant degradation of system performance (in terms of mission or operational criteria).

(3) Psychological stress — detectable impairment of perceptual, cognitive, or psychomotor function and/or disorganization of regulatory or adaptive mechanisms required for effective task performance (refs. 18, 51 and 150).

(4) Performance decrement — operationally significant blunders (ref. 63), erratic behavior, errors, delays, omissions, etc., which are clearly related to system performance.

Effective management techniques are needed to monitor indicators of the first three categories of unwanted effects and, hopefully, to anticipate the occurrence of either performance decrement or the more severe consequences of psychological stress soon enough to take corrective action.

Current Trends in Detection, Diagnosis, and Control

The general requirements for an effective management program for controlling unwanted workload and fatigue effects have been outlined by Mohler (ref. 7):

> "(1) accurate monitoring of pilots for stress-related symptoms and conditons (identified in relation to aircraft, routes and schedules), (2) human engineering of cockpits, (3) the individualization of scheduling regimens to minimize susceptibility to disruption of circadian rhythms, (4) close rapport on the subject of fatigue between pilots, managers, flight surgeons and airframe manufacturers, (5) the continuation of interdisciplinary research on fatigue in aviation activities, (6) more detailed assessments of the role of fatigue in accidents, and (7) the specific assignment, within each airline, of key personnel to workload and fatigue management."

The preferred concepts and techniques for dealing with pilot workload and fatigue in the operational context appear to be clinical judgment and field studies directed by specialists in aviation medicine. Airline management activities specific to such objectives as optimizing task demands, controlling environmental stressors, or minimizing fatigue are probably widely practiced but are not highly visible. Perhaps, as Cantrell et al. (ref. 135) noted, this reflects "the highly sensitive and threatening nature" of studies of management factors.

To deal with long-term stress factors, Cantrell et al. (ref. 135) find that the management-oriented approach to aircrew effectiveness adopted by USAF for the C-5 program will be required far into the future. This approach calls for (1) a projection of attrition rates based on prior experience under comparable stress situations, (2) an estimation of aircrew requirments for future operations, (3) estimates of training failures (wash-out rates), and (4) the selection of enough aircrew candidates to ensure that a sufficient number will be available despite the operation of all potential attrition factors. However, for economic and other reasons, this military management policy may not be applicable to commercial operators.

The detection and diagnosis of excessive task demands or pilot fatigue entails all of the conceptual difficulties and assessment methodology problems discussed previously. It is likely that pilot complaints, often voiced most persuasively through labor organizations (ref. 151), are the principal indicators heeded. Ashkenas and McRuer (ref. 152) characterized pilots as vocal-adaptive controllers who, up to some limit, maintain adequate task performance under adverse conditions, but who are not likely to remain silent about the conditions they find objectionable.

The need for a multidimensional approach to fatigue assessment is widely recognized. "In the measurement of fatigue it would seem that the best approach would be to combine the measurement of the amount of stress by biochemical means with the measurement of level of proficiency after either a flight or simulated flight" (ref. 2). And, indeed, the use of combined measures is typical in operational studies (refs. 23 and 135). At most, however, these combined measurements represent multidimensional assessments of fatigue effects *after* they occur; they are of little or no value for *predicting* these effects.

The traditional approach to preventing fatigue has emphasized adequate rest, physical fitness, weight control, nutrition and diet, and moderation in the use of alcohol and tobacco (ref. 2). Studies of the efficacy of fatigue-preventive or relieving drugs are ambiguous. For example, Haward (ref. 153) reported that "modern concepts of aerospace medicine favor the belief that operating efficiency can be maintained by the administration of amphetamine-like drugs" and presents evidence for the effectiveness of Pemoline, a mild stimulant, in sustaining performance on an air-traffic-control task. However, Haward then makes the following observation on the wide use of amphetamine by service pilots in England: "To many flight surgeons, the use of stimulant drugs in such a widespread way is viewed with some degree of disfavor, partly because of the consequences attendant upon their misuse, but chiefly because the after-effects impair complex behavioral skills long after the beneficial effects have been exhausted."

The extent to which cultural hypocrises and prejudgments still operate to distort studies of psychopharmacological techniques is difficult to assess. Bartley (ref. 25) has presented a comprehensive review of the use of chemical agents for relieving fatigue. Positive effects were noted for substances ranging from aspirin and caffeine, through mood elevators and psychic energizers, to injections for correcting metabolic deficiencies. Apart from the usual caution as to the desirability of medical supervision in their use, Bartley noted only the indiosyncratic effect as a limiting consideration: "There is none of the medicines in the groups to be discussed but which has helped or failed to help depending upon the particular nature of the case."

A promising technique for preventing the occurrence of severe fatigue effects has been suggested by Haward (ref. 154) on the assessment of stress tolerance in commercial pilots. Briefly, this technique calls for an in-flight evaluation of the pilot's stress response and flying proficiency at the same time. These evaluations would be required only after the occurrence of some overt indication of psychological stress, (e.g., a nonflying accident or an incident involving suspect judgment or proficiency). They are planned on the basis of prior psychological testing and a confidential review of the difficulties the pilot has experienced on the job. Moreover, they are conducted, if possible, in the aircraft the pilot typically flies and on carefully selected flight maneuvers.

An important feature of this technique is that the evaluation is conducted by an "independently consulted specialist who has the pilot as his first and exclusive responsibility. He acts for and on behalf of the pilot and not of the pilot's employers . . . his role is to furnish the pilot with the medical and psychological facts and to provide a professional opinion on these" (ref. 154). The procedure is reported as being reasonably inexpensive and acceptable to pilots. The acceptance attitudes of airline management to this procedure were not addressed by Haward, and the potentially troublesome issue of any requirements imposed on the evaluator to report opinions that an active pilot was considered to be unfit to fly to regulatory agencies such as the FAA was cited as an unsettled question.

Cantrell et al. (ref. 135) reported that environmental stressors are typically seen as already under adequate control, and there is little pressure for new technological developments for their management. However, improved management of flight schedules and of numerous nuisance factors does seem to merit more attention. As examples of these nuisance factors, Cantrell et al. cited the following conditions as significant contributors to acute fatigue in military jet transport operations: monotonous tasks, extraneous duties, length of a flight, length of time on duty before takeoff, lack of planned free time, excessive ramp pounding time, poor cockpit layout, administrative practives, the things aircrewmen say to each other and how they say them, lack of sleep and disturbed sleep, inability to maintain a schedule, and irregular hours.

CONCLUSIONS AND RECOMMENDATIONS

This report has presented a conceptual analysis of pilot workload and fatigue, an overview and critique of various approaches to the assessment of these phenomena, and a discussion of current trends in the management of unwanted workload and fatigue effects in the operational environment. The orientation of this study was said to be practical in that the consideration of alternative concepts and approaches to the assessment problem was intended to support the development of more useful working concepts and measurement techniques for applications to systems development studies and to management activities. The major conclusions of the study are enumerated below. Recommendations are then outlined for research directed toward improvements in the assessment of pilot workload and for a broader consideration of factors contributing to fatigue.

Conclusions

1. Workload and fatigue must be viewed, from the outset, as constructs that do not clearly and unambiguously distinguish phenomena of interest without the addition of more explicit terms of reference. The alternative concepts reviewed here may be construed as highly interrelated components of more inclusive conceptualizations of workload and fatigue which must be separated and clarified to clearly denote specific phenomena of interest in a particular study.

2. More explicit referents were sought in the observable and measurable events and processes various investigators have used as indicators for workload and fatigue (tables I and II). The central difficulty noted was the lack of any widely accepted and applied criteria for establishing the functional relationships between indicators and concepts. Consequently, measures are often selected or devised, not because they are specific to a particular conceptualization of workload or fatigue, but because they are of theoretical interest to an investigator or because they are comparatively easy to obtain and seem to be sensitive to independent variables of interest.

3. For the applications to commercial flight operations considered here, a concern for operational relevance, that is, the degree of correspondence between the phenomena examined in the research setting and those occurring in actual system operations, must be accepted as an essential feature of selected measurement procedures. Serious inadequacies in the representation of system-specific task demands and operational conditions were cited as the major factors acting to degrade the operational relevance of many studies of pilot workload and fatigue.

4. The critical review of workload assessment techniques in this report indicates that, despite conceptual and practical difficulties, the attempt to develop and apply useful measures of pilot workload is being vigorously pursued. The workload techniques examined included task-demand analyses, measures of task performance, psychophysiological measures, and subjective reports. None of these assessment techniques were found to be free of significant limitations in their sensitivity to differences in task difficulty, in distinguishing between physical and mental effort, and in the reliability of data acquisition and interpretation procedures.

5. The concept of reserve capacity was considered to be directly applicable to pilot-factor studies. However, measurement techniques associated with this concept were found to be severely limited by the confounding of primary and secondary task performance factors.

6. Explicit studies of fatigue were found to be infrequently applied to system development studies. The primary difficulty in applying fatigue assessment techniques more explicitly is the multidimensional character of fatigue phenomena and their interaction with even more complex phenomena of individual motivation and stress tolerance. An approach to fatigue assessment, particularly useful for evaluations of systems design concepts and pilot workload, was Bartlett's (ref. 36) application of the concept of skill fatigue. Bartlett's approach on observable changes in pilot behavior during primary task performance can be clearly and directly related to the accomplishment of flight management and/or aircraft control objectives.

7. Many investigators have concluded that factors other than task demands or protracted effort are more significant in the occurrence of fatigue. These other factors include individual differences in personality, motivation, physical fitness, and lifestyle, as well as such situational factors as operational management policies, disruption of established biorhythms and sleep patterns, and exposure to various environmental

stressors. The relative contribution of personal versus task-specific fatigue factors is an important unresolved issue.

8. The review of current trends in the management of unwanted workload and fatigue effects indicates that (1) there is considerable disagreement with respect to the incidence and severity of the problem, (2) the preferred concepts and techniques for dealing with pilot workload and fatigue appear to be clinical judgment and field studies directed by specialists in aviation medicine, and (3) the focus of preventive and corrective measures is more often on the individual pilot rather than on such factors as task design, performance aids, management practices, flight scheduling, or progrmas for enhancing stress tolerance.

Recommendations

The survey of conceptual and assessment issues presented here does not clearly support recommendations for the adoption of any particular working definition of workload or fatigue or for the application of any particular measurement techniques. It is expected that the terms workload and fatigue will continue to be used to refer to multidimensional phenomena. An investigator may choose to focus on only one of the alternative concept referents considered here, or he may attempt a more inclusive, multidimensional assessment. In every instance, however, it is essential that more explicit terms of reference be provided if serious communication problems and the confusing of study results are to be avoided.

To achieve the desired clarity of focus, a rigorous distinction between task demands, pilot effort, and performance effects is recommended. Task demands are regarded as *system attributes,* derived from the consideration of such factors as aircraft control and subsystem managment requirements, mission and flight segment objectives, environmental conditions, and external constraints imposed on the conduct of the flight. Effort encompasses both predicted and actual pilot (or crew) responses and reactions to a specified set of demands and is thus construed as a *pilot attribute,* heavily influenced by inter- and intraindividual differences. Performance effects are the consequences or concomitants of effort and may have impact on either system performance or individual well-being; fatigue is thus treated as one kind of performance effect.

With respect to workload, significant improvements in both measurement and management can best be accomplished by refinements and innovations in the analysis and measurement of pilot effort. Human-factors engineering activities are already being applied to task demand analysis, and effective techniques are available for this application. However, systematic attempts to assess effort *per se* are considerably less in evidence, despite the fact that such assessments are needed for the empirical evaluation and adjustment of task demands. Innovations in the direct assessment of effort would also provide a basis for developing more effective "effort control" techniques. For example, special training programs could be designed to enable pilots to minimize the effort required to satisfy a given set of demands or to enchance the pilot's tolerance of the acute and long-term effects of protracted or intense effort.

A synthesis of conventional energistic approaches and contemporary developments in the voluntary regulation of psychophysiological processes using biofeedback techniques (refs. 155 and 156) is regarded as offering a promising basis for defining more effective effort assessment and control procedures. For example, directly accessible neuromuscular tension patterns, which can be reliably related to both central neurophysiological states (ref. 157) and task-relevant phenomena of attention and perception (ref. 158), could provide a basis for modeling and measuring pilot effort.

It is also recommended that greater emphasis be placed on cognitive processes underlying decision-making and procedural tasks in future studies of pilot task loading and fatigue effects since aircraft accidents have been attributed to information overload and since degraded cognitive functioning has been attributed to fatigue.

Finally, a more systematic integration of recent developments in sleep research (ref. 51) and studies of fatigue effects is recommended. In particular, the role of such qualitatively different sleep states as synchronized and desynchronized sleep, as both an important antecedent condition for fatigue states and as a more or less effective restorative process, should be investigated.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035, June 7, 1976

REFERENCES

1. Westbrook, C. B.; Anderson, R. O.; and Pietrzak, P. E.: Handling Qualities and Pilot Workload. AFFDL-FDCC TM-66-5, AF Flight Dynamics Lab., Wright-Patterson AFB, Sept. 1966.

2. Schreuder, O. B.: Medical Aspects of Aircraft Pilot Fatigue with Special Reference to the Commercial Jet Pilot. Aerosp. Med., Special Report Pub. 37, (4) 1966, pp. 1-44.

3. Juin, G.: Protocol and Results of Medical Inquiry on the Fatigue of Aircrews Flying On Board the Boeing 707. Pilots de Ligne, Paris, Dec. 1961.

4. Ruffell Smith, H. P.: Independent Investigation of Workload and Working Conditions of British European Airways Pilots. Air Ministry, FPRC/1177, Flying Personnel Research Committee, Farnborough, England, Nov. 1961.

5. Hauty, G. T.; and Adams, T.: Phase Shifts of the Human Circadian System and Performance Deficit During the Periods of Transition: I. East-West flight. II. West-East flight. III. North-South flight. Aerosp. Med., vol. 37, 1966, pp. 668-674, 1027-1033, 1257-1262.

6. Beaty, D.: The Human Factor in Aircraft Accidents. Secker and Warburg, London, 1969.

7. Mohler, S. R.: Fatigue in Aviation Activities. Aerosp. Med., vol. 37, 1966, pp. 722-732.

8. Ratcliffe, S.: Mathematical Models for the Prediction of Air Traffic Controller Workload. REE Memo 2532, Royal Radar Establishment, Malvern, England, Feb. 1969.

9. Musico, B.: Is a Fatigue Test Possible? British J. Psychol., vol. 12, 1921, pp. 31-46.

10. Klausner, S. Z.: Concepts and Indicators in Studies of Behavior Under Stress. AFOSR-640137, Bureau of Social Sciences Res. Inc., Oct. 1964.

11. Jahns, D. W.: Operator Workload: What Is It and How Should It Be Measured? in Cross, K. D. and McGrath, J. J. (ed.) Crew System Design. Proceedings of an Interagency Conference on Management and Technology in the Crew Systems Design Process, Los Angeles, Calif., Sept. 12-14, 1972.

12. Benson, A. J.: Technical Evaluation. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance, Brooks AFB, Texas, 14-15 May 1969.

13. Klein, T. J.: A Workload Simulation Model for Predicting Human Performance Requirements in the Pilot-Aircraft Environment. Paper presented to the Human Factors Society's 14th Annual Convention, San Francisco, Oct. 13-16, 1970.

14. Gartner, W. B.; Ereneta, W. J.; and Donohue, V. R.: A Full Mission Simulation Scenario in Support of SST Crew Factors Research. NASA CR-73096, 1967.

15. Hartman, B. O.: Time and Load Factors in Astronaut Proficiency. Symposium on Psychophysiological Aspects of Space Flight, B. E. Flaherty, ed., Columbia Univ. Press, N.Y., 1961, pp. 278-308.

16. Cooper, G. E.; and Harper, R. P. Jr.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

17. Jenney, L. L.; Older, H. J.; and Cameron, B. J.: Measurement of Operator Workload in an Information Processing Task. NASA CR-2150, 1972.

18. Welford, A. T.: Fundamentals of Skill. Methuen and Co., London, 1968.

19. Ryan, T. A.: Muscular Potentials as Indicators of Effort in Visual Tasks. Symposium on Fatigue, W. F. Floyd and A. T. Welford, eds., H. K. Lewis and Co., London, 1953.

20. Singleton, W. T.: Prologue to Section 1: Man. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 15-16.

21. Anon: Some Workload and Environmental Characteristics of an Air Carrier Short Haul Turbo-Jet Operation. Summary report on a UAL-ALPA joint project to evaluate pilot workload on B-737 flight operations, United Airlines, March 1969.

22. Cantrell, G. K.; and Hartman, B. O.: Application of Time and Workload Analysis Technics to Transport Flyers. SAM-TR-67-71, AFSC, Brooks AFB, Texas, April 1967.

23. Howitt, J. S.: Flight Deck Workload Studies in Civil Transport Aircraft. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance, Brooks AFB, Texas, 14-15 May 1969, pp. 1 to 1-7.

24. Welford, A. T.: The Psychologist's Problem in Measuring Fatigue. Symposium on Fatigue, W. F. Floyd and A. T. Welford, eds., H. K. Lewis and Co., London, 1953, pp. 183-191.

25. Bartley, S. H.: Fatigue: Mechanisms and Management. Charles C. Thomas, Springfield, Ill., 1965.

26. Wolf, G.: Construct Validation of Measures of Three Kinds of Experiential Fatigue. Perceptual and Motor Skills, vol. 24, 1967, pp. 1067-1076.

27. Saito, Y.; Kogi, K.; and Kashiwagi, S.: Factors Underlying Subjective Feelings of Fatigue. J. Sci. of Labour, vol. 46 (4), 1970, pp. 205-224.

28. Klien, K. E.; Bruner, H.; Holtman, H.; Rheme, H.; Stolze, J.; Steinhoff, W. D.; and Wegman, H. M.: Circadian Rhythm of Pilots' Efficiency and Effects of Multiple Time Zone Travel. Aerosp. Med., vol. 41, 1970, pp. 125-132.

29. Cameron, C.: A Theory of Fatigue. Ergonomics, vol. 16, 1973, pp. 633-648.

30. Yoshitake, H.: Relations Between the Symptoms and the Feelings of Fatigue. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 175-186.

31. Hartman, B. O.: Psychological Factors in Flying Fatigue. Psychiatry in Aerospace Medicine, vol. 4, C. Perry, ed., Little, Brown and Co., Boston, 1967, pp. 185-196.

32. Bartlett, F. C.: Psychological Criteria of Fatigue. Symposium on Fatigue, W. F. Floyd and A. T. Welford, eds., H. K. Lewis & Co., London, 1953, pp. 1-5.

33. Spearman, C.: The Abilities of Man. Macmilliam, London, 1927.

34. Pavlov, I. P.: Conditioned Reflexes (Trans. by G. V. Anrep). Oxford Univ. Press, London, 1927.

35. Hull, C. L.: Principles of Behavior. Appleton-Century-Crofts, N.Y., 1943.

36. Bartlett, F. C.: Fatigue in the Air Pilot. Rept. 488, Air Ministry, Flying Personnel Research Committee, 1942.

37. Bartlett, F. C.: Fatigue Following Highly Skilled Work. Proc. Roy. Soc. Ser. B, vol. 131, 1943, pp. 247-257.

38. Basmajian, J. V.: Muscles Alive: Their function revealed by electromyography. The Williams and Wilkins Co., Baltimore, 1974.

39. Tsaneva, N.; and Markov, S.: A Model of Fatigue. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 11-16.

40. Grandjean, E.: Fatigue: Its Physiological and Psychological Significance. Ergonomics, vol. 11, 1968, pp. 427-436.

41. Moruzzi, G.; and Magoun, H. W.: Brain Stem Reticular Formation and Activation of the EEG. Electroenceph. Clin. Neurophysiol., vol. 1, 1949, pp. 455-473.

42. Lindsley, D. B.; Bowden, J. W.; and Magoun, H. W.: Effect Upon the EEG of Acute Injury to the Brain Stem Activating System. Electroenceph. Clin. Neurophysiol., vol. 1, 1949, pp. 475-486.

43. Akert, K.; Koella, W. P.; and Hess, R., Jr.: Sleep Produced by Electrical Simulation of the Thalamus. Am. J. Physiol., vol. 168, 1952, pp. 260-267.

44. Duffy, E.: The Concept of Energy Mobilization. Psycholog. Rev., vol. 58, 1951, pp. 30-40.

45. Malmo, R. B.: Activation: a Neurophysiological Dimension. Psycholog. Rev., vol. 66, pp. 367-386.

46. Berlyne, D. E.: Conflict, Arousal and Curiosity. McGraw-Hill Book Co., N.Y., 1960.

47. Duffy, E.: Activation and Behavior. John Wiley & Sons, N.Y., 1962.

48. Thompson, R. F.; and Spencer, W. A.: Habituation: a Model Phenomenon for the Study of Neuronal Substrates of Behavior. Psycholog. Rev., vol. 73, (1), 1966, pp. 16-43.

49. Tidwell, J.; and Sutton, J. H.: Fatigue: an Introduction to a Concept. Contract NONR-126801, San Diego State College, 1954.

50. Grandjean, E.: Introductory Remarks. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. xvii-xxx.

51. Hartmann, E. L.: The Functions of Sleep. Yale Univ. Press, New Haven and London, 1973.

52. Janet, P.: Principles of Psychotherapy. The Macmillan Co., N.Y., 1924.

53. Dukes-Dobos, F. N.: Fatigue from the Point of View of Urinary Metabolites. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 31-41.

54. Maitra, S. R.; and Koyal, S. N.: Experimental Studies of Muscular Fatigue of Bengalees with Increasing Work-loads under Different Environmental Conditions. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 71-84.

55. McFarland, R. A.: Understanding Fatigue in Modern Life. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 1-10.

56. Scott, W. E.: Jr. Activation Theory and Task Design. Organizational Behavior and Human Performance, vol. 1, 1966, pp. 3-30.

57. Duffy, E.: An Explanation of "Emotional" Phenomena Without the Use of the Concept "Emotion." J. Gen. Psychol., vol. 25, 1941, pp. 283-293.

58. Raknes, O.: Wilhelm Reich and Orgonomy: The Controversial Theory of Life Energy. Penguin Books, Baltimore, 1971.

59. Lehninger, A. L.: Bioenergetics. W. A. Benjamin, N.Y., 1971.

60. Zipoy, D. R.; Premselaar, S. J.; Gargett, R. E.; Belyea, I. L; and Hall, S. J.: Integrated Information Presentation and Control System Study. AFFDL-TR-70-79, vol. I, Air Force Flight Dynamics Lab., 1970.

61. Price, H. E.; Honsberger, W. D.; and Ereneta, W. J.: A Study of Potential Roles of Supersonic Transport Crews and Some Implications for the Flight Deck. NASA CR-561, 1966.

62. Leplat, J.; and Pailhous, J.: The Analysis and Evaluation of Mental Work. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 51-56.

63. Roscoe, S. N.: Assessment of Pilotage Error in Airborne Area Navigation Procedures. Tech. Rep. ARL-72-24/AFOSR-72-13, Univ. of Illinois Institute of Aviation, Savoy, Ill., Oct. 1972.

64. Wisner, A.: Electrophysiological Measures for Tasks of Low Energy Expenditure. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 61-74.

65. Rolfe, J. M.: The Secondary Task as a Measure of Mental Load. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 135-148.

66. Zaitzeff, L. P.: Aircrew Task Loading in the Boeing Multimission Simulator. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance, Brooks AFB, Texas, 14-15 May 1969, pp. 8 to 8-3.

67. Buckner, D. N.; and McGrath, J. J.: A Comparison of Performance on Single and Dual Sensory Mode Vigilance Tasks. Tech. Rep. 8, Human Factors Research, Inc., Los Angeles, 1961.

68. Nicholson, A. N.; Hill, L. E.; Borland, R. G.; and Ferres, H. M.: Activity of the Nervous System During the Let-down, Approach and Landing: a Study of Short Duration High Workload. Aerosp. Med., vol. 41, 1970, pp. 436-446.

69. Rey, P.: The Interpretation of Changes in Critical Fusion Frequency. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 115-120.

70. Shackel, B.: Electro-oculography: the Electrical Recording of Eye Position. Proceedings of the Third International Conference on Medical Electronics, 1966, pp. 322-335.

71. Luk'yanov, A. N.; and Frolov, M. V.: Signals of Human Operator State. NASA TT F-609, 1969.

72. Krzanowski, W. J.; and Nicholson, A. N.: Analysis of Pilot Assessment of Workload. Aerosp. Med., vol. 43, 1972, pp. 993-997.

73. Corkindale, K. G; Cumming, F. G.; and Hammerton-Fraser, A. M.: Physiological Assessment of Pilot Stress During Landing. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance, Brooks AFB, Texas, 14-15 May 1969, pp. 9 to 9-4.

74. Haider, M.: Comparison of Objective and Subjective Methods of the Measurement of Mental Workload. Displays and Controls, R. K. Bernotat and K.-P. Gärtner, eds., Swets & Zeitlinger, Amsterdam, 1972, pp. 17-27.

75. Murrell, K. F. H.: Temporal Factors in Light Work. Measurment of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 45-50.

76. Ettema, J. H.; and Zielhuis, R. L.: Physiological Parameters of Mental Load. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 137-144.

77. Kalsbeek, J. W. H.: Sinus Arrhythmia and the Dual Task Method in Measuring Mental Load. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 101-114.

78. Hale, H. B.; Williams, E. W.; Smith, B. N.; and Melton, C. E.: Excretion Patterns of Air Traffic Controllers. Aerosp. Med., vol 42, 1971, pp. 127-138.

79. Warren, B. H.; Ware, R. W.; Shannon, I. L.; and Leverett, S. D.: Determination of Inflight Biochemical Responses Utilizing the Parotid Fluid Collection Technique. Aerosp. Med., vol. 37, 1966, pp. 796-799.

80. Kahneman, D.; Tursky, B.; Shapiro, D.; and Crider, A.: Pupillary, Heart Rate, and Skin Resistance Changes During a Mental Task. Exptl. Psychol., vol. 79, no. 1, pp. 164-167.

81. Bonjer, F. H.: The Contribution of Work Physiology to the Evaluation of Man-Machine Systems. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London , 1971. pp. 93-100.

82. Sharkey, B. J.; McDonald, J. F.; and Corbridge, L. G.: Pulse Rate and Pulmonary Ventilation as Predictors of Human Energy Cost. Ergonomics, vol. 9, 1966, pp. 223-227.

83. Cumming, F. G.; and Corkindale, K. G.: Physiological and Psychological Measurements of Pilot Work Load. Tech. Memorandum HFG 101, Royal Aircraft Establishment, Nov. 1967.

84. Benson, A. J.; Huddleston, J. H. F.; and Rolfe, J. M.: Psychophysiological Study of Compensatory Tracking on a Digital Display. Human Factors, vol. 7, no. 5, 1965, pp. 457-472.

85. Spyker, D. A.; Stackhouse, S. P.; Khalafalla, A. S.; and McLane, R. C.: Development of Techniques for Measuring Pilot Workload. NASA CR-1888, 1971.

86. Borg, G.: Psychological and Physiological Studies of Physical Work. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 121-128.

87. Chambers, E. G.: Industrial Fatigue. Occupational Psychol. vol. 35 (1-2), 1961, pp. 44-57.

88. Brown, I. D.: Measuring the Spare Mental Capacity of Car Drivers by a Subsidiary Auditory Task. Ergonomics, vol. 5, 1962, pp. 247-250.

89. Fukui, T.; and Morioka, T.: The Blink Method as an Assessment of Fatigue. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 23-30.

90. Kogi, K.; and Saito, Y.: A Factor Analytic Study of Phase Discrimination in Mental Fatigue. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 119-127.

91. Komoike, Y.; and Horiguchi, S.: Fatigue Assessment on Key Punch Operators, Typists and Others. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 101-109.

92. Hamar, H.; and Novak, E.: A Telemetric Method for Assessing Mental Performance. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 129-135.

93. Takakuwa, E.: Maintaining Concentration (TAF) as a Measure of Mental Stress. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 145-158.

94. Ohtani, A.: An Analysis of Eye Movements During a Visual Task. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 167-174.

95. Bills, A. G.: Blocking: a New Principle of Mental Fatigue. Am. J. Psychol., vol. 43, 1931, pp. 230-245.

96. Eysenck, H. J.: The Biological Basis of Personality. Charles C. Thomas, Springfield, Ill., 1967.

97. Donoso, H.; Apud, E.; and Lundgren, N. P. V.: Direct Estimation of Circulatory Fatigue Using a Bicycle Ergometer. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 53-60.

98. Welch, R. B.; Longley, E. O.; and Lomaev, O.: The Measurement of Fatigue in Hot Working Conditions. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 85-90.

99. Hemingway, A.: The Physiological Background of Fatigue. Symposium on Fatigue, W. G. Floyd and A. T. Welford, eds., H. K. Lewis and Co., London, 1953, pp. 69-75.

100. Weston, H. C.: Visual Fatigue with Special Reference to Lighting. Symposium on Fatigue, W. F. Floyd and A. T. Welford, eds., H. K. Lewis and Co., London, 1953, pp. 117-135.

101. Kennedy, J. L.: Some Practical Problems of the Alertness Indicator. Fatigue, W. F. Floyd and A. T. Welford, eds., H. K. Lewis and Co., London, 1953, pp. 149-153.

102. Murphy, M. R.; and Randle, R. J.: Effects of Fatigue on Visual Accommodation in Air Crew Members. Paper presented at the 42nd Annual Meeting of the Aerospace Medical Association, Houston, Texas, 1971.

103. Kashiwagi, S.: Psychological Rating of Human Fatigue. Methodology in Human Fatigue Assessment, H. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, pp. 17-21.

104. Luongo, E. P.: Work and Physiology in Health and Disease. J. Am. Med. Assoc., vol. 188, 1964, pp. 27-32.

105. Bartley, S. H.: The Basis of Visual Fatigue. Am. J. Optometry Arch. Am. Acad. Optometry, Monograph 30, 1947, pp. 1-12.

106. Kelley, C. R.; and Prosin, D. J.: Adaptive Techniques in Measuring Complex Performance. NR 196-050, Dunlap and Assoc., Santa Monica, Calif., 1969.

107. Chiles, W. D.: Methodology in the Assessment of Complex Performance: Discussion and Conclusions. Human Factors, vol. 9, no. 4, pp. 385-392.

108. Chapanis, A.: The Search for Relevance in Applied Research. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 1-14.

109. Chiles, W. D.: Complex Performance: The Development of Research Criteria Applicable in the Real World. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 159-164.

110. De Jong, J. R.: The Applicability of Physiological and Psychological Techniques. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 171-176.

111. Finley, D. L.; Muckler, F. A.; Obermayer, R. W.; Bertone, C. M.; and Meister, D.: Human Performance Prediction in Man-Machine Systems: vol. I. A Technical Review. NASA CR-1614, 1969.

112. Beyer, R.: Efficiency Studies on Cockpit Displays. NASA TT F-14,846, 1973.

113. Siegel, A. I.; and Wolf, J. J.: Man-Machine Simulation Models; Psychosocial and Performance Interaction. New York: John Wiley, 1969.

114. Streimer, I.: Considerations of Energy Investments as Determinants of Behavior. Measurement of Man at Work, W. T. Singleton, J. G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, pp. 35-40.

115. Kalsbeek, J. W. H.: Objective Measurement of Mental Work-load; Possible Applications to the Flying-Task. Proceedings of the 55th AGARD Conference, Problems of the Cockpit Environment, Amsterdam, 1968, pp. 4-1 to 4-6.

116. Rolfe, J. M.: Symposium on heart rate variability. Ergonomics, vol. 16, 1973, p. 1.

117. Sayers, B. McA.: Analysis of Heart Rate Variability. Ergonomics, vol. 16, 1973, pp. 17-32.

118. Stevens, S. S.: The Surprising Simplicity of Sensory Metrics. Am. Psychologist, vol. 17 (1), pp. 29-39.

119. Stevens, S. S.: On the Operation Known as Judgment. Am. Scientist, vol. 54,(4), 1966, pp. 385-401.

120. Lowen, A.: Pleasure: A Creative Approach to Life. Coward-McCann N.Y., 1970.

121. Gunther, B.: Sensory Awakening and Relaxation. Esalen Inst., Big Sur, Calif., 1967.

122. Lowen, A.: The Betrayal of the Body. Collier, McMillan, London, 1967.

123. Kelly, C. R.: Education in Feeling and Purpose. Interscience Research Institute, Santa Monica, Calif., 1970.

124. Garvey, W. D.; and Henson, J. B.: Interactions Between Display Gain and Task-Induced Stress in Manual Tracking Systems. U.S. Naval Res. Lab. Rep. 5204, 1958.

125. Brown, I. D.: The Measurement of Perceptual Load and Reserve Capacity. Trans. Assoc. Industrial Medical Officers, vol. 14, 1964, pp. 44-49.

126. Kraus, E. F.; and Roscoe, S. N.: Reorganization of Airplane Flight Control Dynamics. Tech. Rep. ARL-72-22/AFOSR-72-11, Univ. of Illinois Institute of Aviation, Savoy, Ill., Sept. 1972.

127. Kelley, C. R.; and Wargo, M. J.: Cross-Adaptive Operator Loading Tasks. Human Factors, vol. 9, no. 5, pp. 395-404.

128. Brown, I. D.: Some Alternative Methods of Predicting Performance Among Professional Drivers in Training. Ergonomics, vol. 11, 1968, pp. 13-21.

129. Hashimoto, K.; Kogi, K.; and Grandjean, E.: Methodology in Human Fatigue Assessment. Taylor and Francis, Ltd., London, 1971.

130. Floyd, W. F.; and Welford, A. T., Eds.: Symposium on Fatigue. H. K. Lewis & Co., Ltd., London, 1953.

131. Davis, D. R.: Psychological Mechanisms in Pilot Error. Flight Safety, vol. 1, no.1, 1967, pp. 18-21.

132. Mast, T. M.; and Heimstra, N. W.: Effects of Fatigue on Vigilance Performance. J. Engineering Psychol., vol. 3, 1964, pp. 73-79.

133. Hartman, B. O.; and Fitts, P. M.: The Development of Techniques and Procedures for the Study of Alertness in Aviation Personnel. NRC Commission on Aviation Psychology, 1950.

134. Averill, J. R.; and Opton, E. M. Jr.: Psychophysiological Assessment: Rationale and Problems. Advances in Psychological Assessment, P. McReynolds, ed., vol. 1, Science and Behavior Books, Palo Alto, Calif., 1968, pp. 265-288.

135. Cantrell, G. K; Trimble, R. W.; and Hartman, B. O.: Long-Term Aircrew Effectiveness: A Literature Study. Aeromedical Reviews, SAM-TR-71-4; SAM-REVIEW-1-71, 1971.

136. Pearson, R. G.; and Byars, G. E. Jr.: The Development and Validation of a Check-List for Measuring Subjective Fatigue. Rep. 56-115, School of Aviation Medicine, Randolph AFB, Texas, 1956.

137. Nowliss, V.: Mood: Behavior and Experience. Feelings and Emotions, M. B. Arnold, ed., Academic Press, N.Y., 1970, pp. 261-277.

138. Kamiya, J.: Conditioned Discrimination of the EEG Alpha Rhythm in Humans. Abstract of paper presented at the Western Psychological Association, San Francisco, Calif., 1962.

139. Billings, C. E.; and Eggspuehler, J. J.: Studies of Pilot Performance in Helicopters. Progress Rep., Ohio State Univ., June 1, 1966-May 31, 1967.

140. Zeller, A. F.: Accidents and Safety. Systems Psychology, K. B. DeGreene, ed., McGraw-Hill Book Co., N.Y., 1970.

141. Blanc, C.; Lafontaine, E.; and Laplane, R.: Psychological and Psychiatric Problems in Aviation (1). Flight Safety, vol. 1, 1968, 1,(3) pp. 15-18.

142. Klumpp, T. G.: The Problem of the Aging Population. World Med. J., vol. 8, 1961, pp. 425-427.

143. Cameron, C.: A Questionnaire Study of Fatigue in Civil Aircrew. ARL/H.E. 24, Aeronautical Res. Labs., Melbourne, Australia, 1968.

144. Hauty, G. T.; and Adams, T.: Phase Shifting of the Human Circadian System. Circadian Clocks, J. Aschoff, ed., North-Holland Publishing Co., Amsterdam, 1965, pp. 413-425.

145. Klein, K. E.; Wegman, H. M.; and Hunt, B. I.: Desynchronization of Body Temperature and Performance Circadian Rhythm as a Result of Outgoing and Homecoming Transmeridian Flights. Aerosp. Med., vol. 43, 1972, pp. 119-132.

146. Barlay, S.: The Search for Air Safety. William Morrow and Co., N.Y., 1970.

147. Kastenbaum, R.; and Aisenberg, R.: The Psychology of Death. Springer Publishing Co., N.Y., 1972.

148. Scucchi, G. D.; and Sells, S. B.: Information Load and Three-Man Flight Crews: an Examination of the Traditional Organization in Relation to Current and Developing Airliners. Aerosp. Med., vol. 40, 1969, pp. 402-406.

149. Price, H. E.; Smith, E. E.; and Gartner, W. B.: A Study of Pilot Acceptance Factors in the Development of All-Weather Landing Systems. NASA CR-34, 1964.

150. Gorham, W. R.; and Orr, D. B.: Research on Behavior Impairment due to Stress. Final Rep., Contract AF 41(657)-39, Project 7707, American Institutes for Research, 1958.

151. Anon.: International Labor Organization, Ad Hoc Civil Aviation Meeting on Hours of Duty and Rest Periods of Flight Personnel, Report II, Geneva, 1960.

152. Ashkenas, I. L.; and McRuer, D. T.: The Vocal Adaptive Controller - Human Pilot Dynamics and Opinion. Systems Technology, Inc., Hawthorne, Calif., 1960.

153. Haward, L. R. C.: The Effects of a Stimulant Drug on an Air Traffic Control Task. Flight Safety, vol. 2, 1967, pp. 3-7.

154. Haward, L. R. C.: Assessment of Stress Tolerance in Commercial Pilots. Flight Safety, vol. 1, 1967, pp. 12-17.

155. Barber, T.; DiCara, L. V.; Kamiya, J.; Miller, N. E.; Shapiro, D.; and Stoyva, J., ed.: Biofeedback and Self Control. Aldine-Atherton, Chicago, 1971.

156. Green, E. E.; Green, A. M.; and Walters, E. D.: Voluntary Control of Internal States: Psychological and Physiological. J. Transpersonal Psychol., vol. 2(1), pp. 1-26.

157. Jacobson, E.: Biology of Emotions. Charles C. Thomas, Springfield, Ill. 1967.

158. Meldman, M. J.: Diseases of Attention and Perception. Pergamon Press, London, 1970.

NASA-Langley, 1976 A-6630

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546