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34. Application of Manual Control Theory to the Study of Biological Stress

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Current techniques used to evaluate the effects of stress on the human operator may be generally divided into two classes: man-machine systems effectiveness models and factor-analytic techniques using test batteries. Each of these methods have inherent difficulties which may be solved by manual control techniques. The use of mission effectiveness metrics provide the essential estimate of system performance but due to the broad range of human operator adaptation, the effects of stress are not observed until catastrophic failure. On the other hand, task batteries can be constructed which are sensitive to changes induced by stress but from which little extrapolation to system effectiveness can be made. It is desirable, therefore, to have a task sensitive to stress induced changes in the human operator while measuring quantities which can be used in an analysis of mission effectiveness and reliability.

A study was run using both a stable, third-order task and an adaptive first-order unstable task singly and in combination to test the effects of 2 min hypoxia (22 000 ft). The results indicate that the RMS error in the stable task does not change as a function of hypoxic stress whereas the error in an unstable task changes significantly. Models involving human operator parameter changes and noise injection are discussed.

INTRODUCTION

This report discusses an experiment the purpose of which is to deminstrate that measurement of human operator parameters is a sensitive technique for evaluation of human operator performance under stress. The task consisted of an adaptive unstable compensatory tracking task and a stable third-order plant compensatory tracking task. The stresses used consisted of three simulated altitudes utilizing oxygen-nitrogen mixtures equivalent to sea level, 12 000 ft, and 22 000 ft.

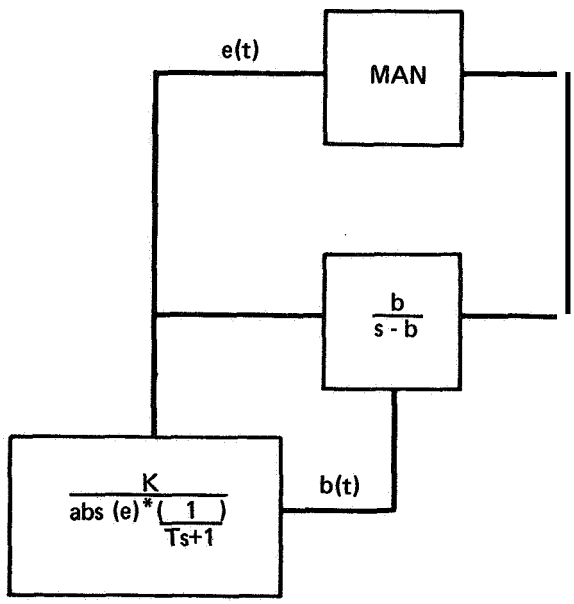
Research into the effect of stress on the human operator may, in general, be broken into three classes: systems effectiveness evaluation for mission oriented tasks, behavior testing for changes in the operator, and physiological examination. Substantial difficulties have risen in the ability to predict a decrement in operational capability from all three approaches. The general pattern found in heat, hypoxic, acceleration, vibration, vestibular, toxic, and workload stresses is physiological and operator compensation to some limit and then rapid decreases in systems effectiveness. The man in a control situation will utilize his maximum capability to reduce or minimize closed loop error until the environment, task, mission goal or psychological factors, overwhelm him or terminate the control task. For this reason, measurement of system effectiveness alone, while providing necessary mission capability information, is not predictive of the decrement. Behavioral and physiological measures are more sensitive to changes in the human operator but only with great difficulty (if at all) can be related back to changes in operational errors. The task of identification of compensation and limits of human operator control parameters then falls to the control engineer. Not all of the techniques used to study manual control may be adapted to this area. The duration of many stresses may be as short as 30 sec to 1 min. Further the degree of compensation or adaptation may be large in this time frame. Techniques which need a 30 sec

analysis period or which must be done off-line have at best limited uses.

To evaluate the performance of a man in a control situation, the investigator is obligated to evaluate how the man is achieving effective control. If the stresses upon the man are affecting his ability to control the weapons system and the man can switch to alternative modes of control while maintaining closed loop error at a minimum, then evaluation of the man as an input-output processor will show the changes in his operating behavior while analysis of closed loop error will be uninformative. If changes in the man's mode of control are correlated with the stresses upon the man then they ought to be correlated with the psychological and physiological changes induced by the stresses.

TASK DESCRIPTION

The unstable tracking task is a first-order system with a single pole to the right of the imaginary axis. The first-order unstable tracking task as described by Jex et al. (ref. 1) was modified in the following manner (fig. 1). The absolute value of the displayed error was filtered with a first-order linear filter and then divided into a constant K. This provides a real time function called b. The function b is always positive and is used as the pole in the unstable element. By appropriate choices of the values for the constant K and the time constant in the first-order filter, one can prevent skilled trackers from losing control of the task while at the same time forcing him to maintain a low mean squared error.



UNSTABLETASK

FIGURE 1.—Modified unstable tracking task.

The above modification of the unstable tracking task provides the following advantages. The operator while controlling such a system can optimize one of two variables. He can either optimize the displayed error which he is instructed to do or he can optimize the difficulty of the controlled element by operating at a point which provides a manageable unstable element. In either case in order for the operator to effectively control the system, he must either adjust his internal gain or he must maintain an effective time delay which is smaller than the value of the unstable pole at all times. Jex et al. have observed that the unstable tracking task forces a mode of controlling by the operator which is consistent with pure gain controlling. This is true as long as the operator maintains an effective time delay shorter than the value of the unstable pole. The distribution of the moving pole b or the distribution of the displayed error therefore provides a measure of either the operator's gain or his effective time delay. Jex has shown that in his formulation of an unstable element the critical value of the unstable pole is proportional to the effective time delay of the operator and Leviston has demonstrated an increased sensitivity in the unstable task to injected noise.

The stable tracking task was chosen to be representative of the pitch axis dynamics of a high performance aircraft. The dynamics of this stable tracking task are typical of a third-order system with a pole at the origin. The forcing function used in the stable tracking task consisted of the sum of five sine waves whose frequencies were chosen to simulate Gaussian white noise buffeting (fig. 2).

If the operator's performance at 22 000 ft is different than his performance at sea level, then the modification of the unstable tracking task as described above should indicate either a change in the mean value of the signal b or a

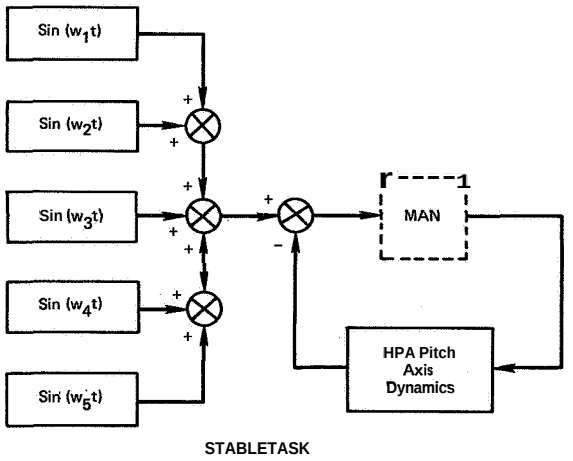


FIGURE 2.—Stable tracking task representative of the pitch axis control system of a high performance aircraft.

change in his rms error. Either of these changes or both in combination indicate that there is an internal change in the structure of the human operator. The operator has no control over the dynamics represented in the stable tracking task. It is, therefore, anticipated that at altitude no effect on rms error will be observed. If the operator is forced by the affects of altitude to change his internal structure as an operator, he can do so while operating the stable task and maintaining identical or similar mean squared error distribution.

EXPERIMENTAL DESIGN

The experiment is designed to evaluate the performance of an operator in a compensatory tracking task at sea level followed by the same task at a simulated altitude of either *12000* or *22 000* ft. Each run of the experiment consisted of two periods of tracking. Each period was preceded by one minute of prebreathing at the indicated altitude followed by one minute of tracking. Randomization of the order of presentation of the simulated altitudes and tasks to the subjects was done in order to minimize the effects of learning and anticipation of experimental factors.

Six subjects were evaluated. Each subject performed the same task on two different occasions. Three Compensatory tracking tasks were employed. The first was a single axis stable tracking task. The dynamics of the stable tracking tasks were representative of a high performance aircraft pitch axis control system. The second task was an unstable single axis tracking task modified as described below. The third task consisted of a dual axis tracking task combining the stable tracking task on the vertical axis and the unstable tracking task on the horizontal axis. The data were sampled at a rate of 50 samples per sec. The data were reduced by calculating the mean error and the variance of the error for the displayed error signals, and the mean unstable pole and the variance of the unstable pole in the unstable tasks. In addition, empirical probability entity functions were generated for the displayed error and the unstable pole-signals. The mean squared error scores and the variance of the mean squared error scores were subjected to analysis of variance utilizing a random variable design.

RESULTS

The results are straightforward and require little interpretation. Referring to table *1*, it is

TABLE *1.—Results of Analysis of Variance Comparing the Differences in the Various Scores at Ground Level and 22 000 ft Altitude Across Subjects*

Task	Score	Main effect $df = 1$	Interactions $df = 5$	F ratio
Stable	Rms error	1.69	11.99	.8457
Unstable	Rms error	0.01	64.97	.00092 *
Combined	Mean $b(t)$	6.98	5.54	7.56†

* $p > 0.99$
† $p > 0.95$

apparent that the RMS error in the stable axis was not affected by the 22000 ft altitude. The RMS error in the unstable tracking task is significantly affected by altitude, and the mean operating point b in the combined task unstable axis is significantly affected by the altitude **of 22 000** ft.

Further analysis of the data will include identification of the linear portion of the human operator as a function of altitude. The analysis of variance will be repeated on the parameters of the operators. It is anticipated that examination of the internal parameters of the operator while performing the stable tracking task will demonstrate an effect due to the simulated altitude. Support **for** this statement arises as a result of examining the data for the unstable tracking task at **22** 000 ft. It is apparent that the majority of the operators in the unstable axis attempted to maintain the average operating points b at an identical point irrespective of altitude while allowing mean squared error to change.

Examination of the empirical probability density curves (figs. **3** through 8) verifies that the

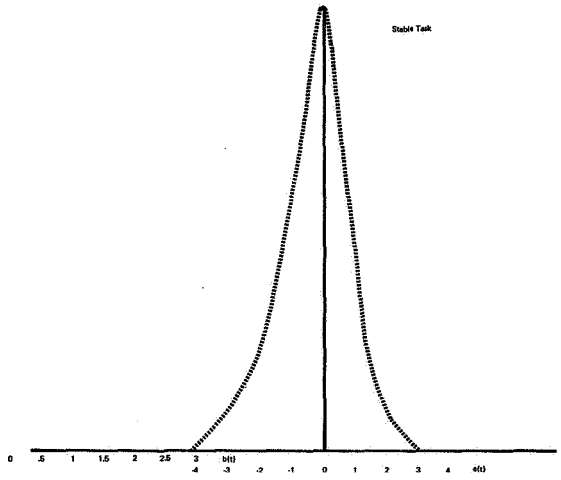


FIGURE 3.—Representative empirical probability density function of closed loop error in the stable task at sea level.

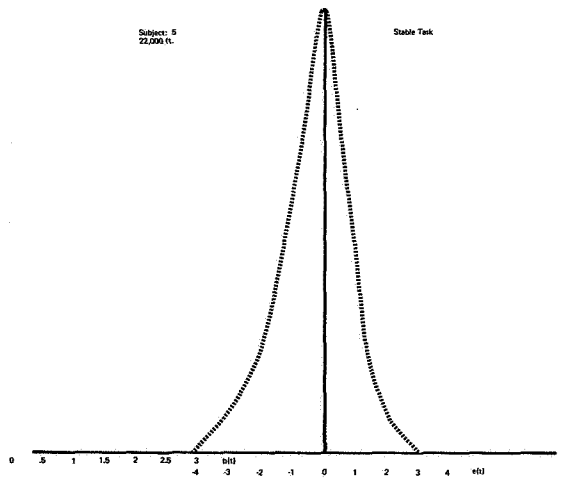


FIGURE 4.—Representative empirical probability density function of closed loop error in the stable task at 22 000 feet.

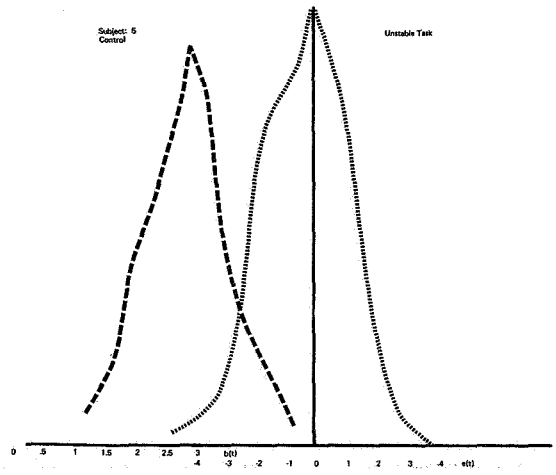


FIGURE 5.—Representative probability density functions for $b(t)$ and closed loop error $e(t)$ in the unstable task at sea level.

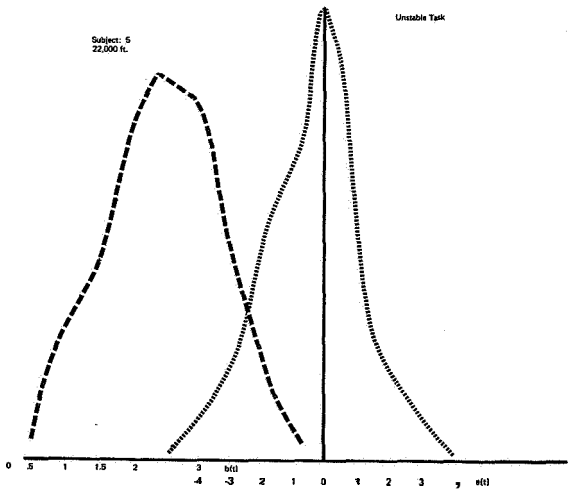


FIGURE 6.—Representative probability density functions for $b(t)$ and closed loop error $e(t)$ in the unstable task at 22 000 feet.

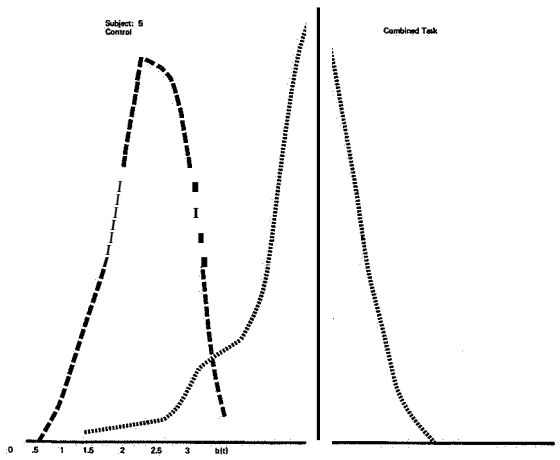


FIGURE 7.—Representative empirical probability density functions of vertical axis closed loop error $e(t)$ and horizontal axis $b(t)$ function at ground level.

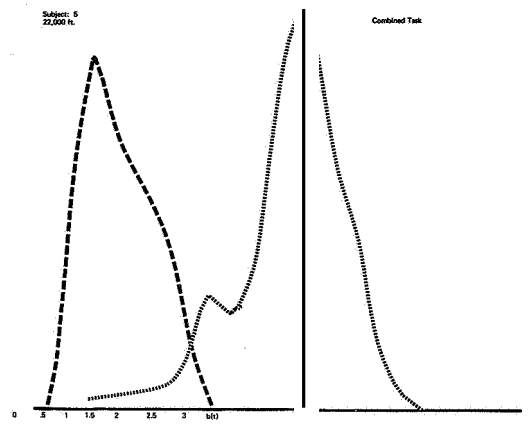


FIGURE 8.—Representative empirical probability density functions of vertical axis closed loop error $e(t)$ and horizontal axis $b(t)$ function at 22 000 feet.

error curve for the unstable task has a broader variance at altitudes. The b curves however shift their mean to a lower value at higher altitudes. The variance due to interaction was too large to demonstrate significance in the change of the mean b at altitude. If the mean b scores are normalized however a student's T test shows significance at the **0.01** level.

Figures **3** and **4** are the empirical probability density functions for the displayed error in the stable tracking task. There is relatively little difference between the curves at the control altitude, sea level, and at the **22** 000 ft altitude. Figures 5 and **6** are the probability density functions for both b and e in the unstable tracking task. Not only does the shape of the error curve e change but also the mean of the b curve is lower at **22** 000 ft and has a broader variance at **22** 000 ft. Figures **7** and 8 are the probability density functions for the combined task at control and at sea level and at **22** 000 ft. Again, there is relatively little change in the error curves for the vertical axis whereas the mean value for the b curve shifts to a lower point at **22** 000 ft.

The purpose of these experiments is not to evaluate a unique way of identifying a performance measure. Rather, the purpose of these experiments is to demonstrate that control theory principles can be used to identify changes in human operator performance as a result of environmental factors. The data clearly demonstrates that standard measurements of error are insensitive to changes in human operator performance at **22000** ft. That changes in the human operator occur at **22** 000 ft is evidenced by the changes in the unstable tracking task parameters. One of the exciting aspects of the experiments was that the same changes and effects were suggested at **12000** ft. The effects at **12** 000 ft, however, were severely masked by the large amount of subject variance and interaction variance.

SUMMARY

Although the performance of a man-machine control system is best represented as a function of the closed loop system error, the compensatory actions of the human operator will obscure the effects of stress on the man until the point is reached where his compensation is not effective. In order to predict this point instead of merely observing it, the parameters of the human operator, the effect of stress on these parameters, and the range of control of these parameters must be described.

REFERENCE

1. JEX, H. R.; MCDONNELL, J. D.; AND PHATAK, A. V.: **A Critical Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time. Part I: Theory and Experiments with a First-Order Divergent Controlled Element. NASA CR-616, Nov. 1966.**