Performance Criteria—Direct or Indirect

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•HUMAN FACTORS studies often involve the use of simulation. Simulation permits the economical and easy manipulation of what seem to be the primary variables in a given experimental situation. The general success of simulation studies has led to a growing investment of thought, time and capital in the further development of simulation techniques. However, this investment is producing less than maximal returns due to the increasingly apparent lack of a satisfactory measure of human fatigue. There has certainly been no dearth of attempts to develop such a measure and the very number of these attempts attests to their general lack of success. The implications of a satisfactory measure of fatigue are many. Aside from facilitating evaluation of control systems, information displays, road conditions, etc., a satisfactory measure will act as a common denominator by means of which the separate effects of time on task, task difficulty, loss of sleep, environmental distractions, motivation, etc., on performance potential can be determined. In this paper, from a theoretical consideration of the nature of fatigue, a measure is developed which, hopefully, will fulfill the requirements for a satisfactory measure of fatigue.

PRIMARY CONSIDERATIONS

Driving a car is fatiguing. At least, after driving for many hours, especially in heavy traffic, people will say that they feel tired. One might expect to find these subjective feelings of fatigue reflected in driving performance. That is, one might expect a steady decrement in driving performance corresponding to increasing subjective feelings of fatigue. However, this is not the case. For example, Shaw (35) found that the driver who was fatigued by long periods of continuous driving but was concentrating hard at his task, cannot be distinguished from being fully rested on the basis of what he is doing with his controls or in terms of the actual path traveled by the vehicle, its speed changes, accelerations, etc. (Fig. 1). One explanation of this constancy of performance, first advanced by Krendel and Bloom (27), is that a man adapts to the fatigue or to other stressing conditions by altering his mode of responding; for example, by increasing the amount of effort he puts forth to maintain a constant level of performance. The observation by Shaw that driving performance remains constant during extended periods is not surprising. On the contrary, the observation that performance is unaffected over wide ranges of fatiguing or stressing conditions is very general (1, 18, 28, 38, 39, 40).

If one disregards performance decrements produced by very effortful muscular work such as heavy labor or sprinting, and those decrements produced through extreme environmental conditions such as mechanical vibration of high intensity or extremes of temperature and humidity, the typical form of the performance curve as a function of fatigue is shown in Figure 2. In this figure a generalized form of the curve is shown by the heavy line. Vigilance and tracking tasks show similar curves. It can be seen that, presuming knowledge of results, performance remains essentially constant or decreases only slightly for an extended period of time; subsequently, the performance shows an abrupt decline. It is often expensive or impractical to test a subject for the time interval required in order to show this sharp decrement in performance. It would be desirable to have some measure which would show a steady change related in some simple manner to the amount of work performed, the magnitude of stressing situation, or other relevant variables. Perhaps the sharp decrement in performance which occurs

Paper sponsored by Special Committee on Driving Simulation.

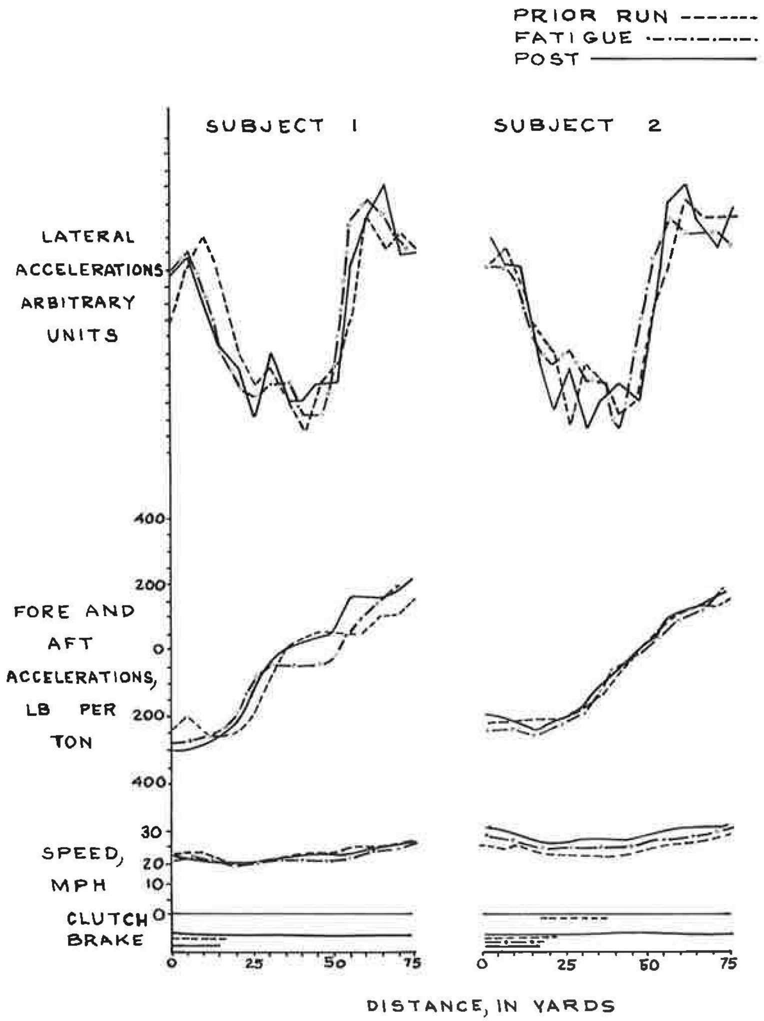

Figure 1.

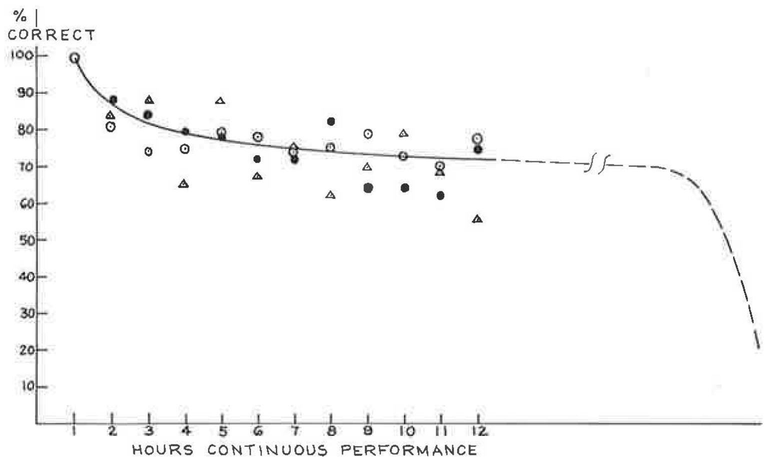

Figure 2. Idealized performance curve. Each point represents averaged hourly performance of four 12-hr sessions by one individual (24).

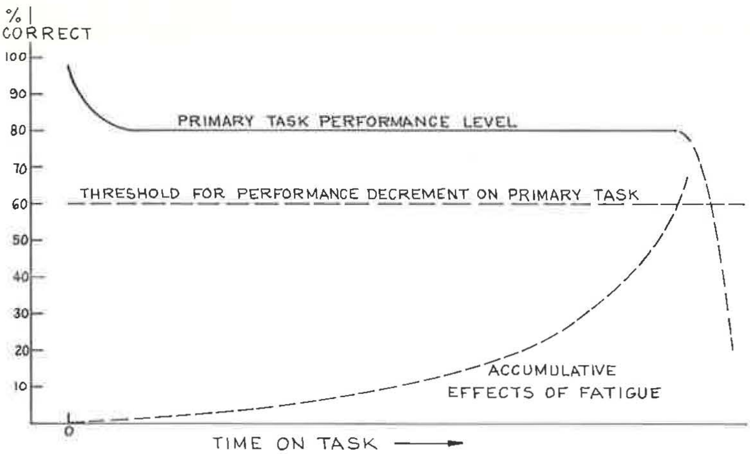

Figure 3. Hypothesized model.

after an extended period of stress or fatigue is not the result of some discrete event occurring at that time but rather is the result of some continuous process which has accumulated to a superthreshold level. Figure 3 shows a theoretical conception of what may be occurring. As before, the heavy line indicates the level of performance, whereas the dotted line shows presumed accumulation of the effects of fatigue, stress, etc. When the accumulated level reaches the indicated threshold, the sudden decrement in performance is observed. A desirable measure of fatigue should show a continuous change and thus allow prediction of when the breakdown will occur as well as comparison of rates of decrement. As previously stated, performance on the criterion task does not show the kind of decrement that is expected.

INDIRECT MEASURES OF FATIGUE

Everyone feels, however, that although objective measures of performance may indicate no significant decrement, the task becomes ever more taxing or arduous with the passage of time. This subjective feeling has led to the search for indirect objective measures of an individual's performance potential; for measures not of the criterion performance but of other behavioral or physiological processes which might be correlated in some way with this performance. One approach is to measure part-processes, i.e., physiological activity, biochemical indicators, and portions of behavioral sequences. Table 1 gives some of these

TABLE 1

INDIRECT MEASURES OF PERFORMANCE

I. Physiological Indicators
- A. Physical
  - 1. Respiratory rate
  - 2. Pulse rate
  - 3. Blood pressure
  - 4. Body temperature
- B. Chemical
  - 1. Contents of blood
    - (a) Glucose
    - (b) Lactic acid
    - (c) Creatine
    - (d) Glutathione
    - (e) Cholinesterase
    - (f) Asorbic acid
  - 2. Contents of urine
    - (a) 17-ketosteroids
    - (b) Potassium ions
    - (c) Calcium ions
    - (d) pH
  - 3. Contents of saliva
  - 4. Metabolic rate
- C. Electrical
  - 1. EEG
  - 2. EKG
  - 3. EMG
  - 4. GSR

II. Psychological-Functional Measures
- A. Sensory
  - 1. Visual
    - (a) CFF
    - (b) Color perception
    - (c) Rate of eye blink
    - (d) Visual acuity
    - (e) Accommodation time
    - (f) Persistence of after images
  - 2. Auditory
    - (a) Absolute thresholds at different frequencies
  - 3. Tactile
    - (a) Absolute pain threshold
    - (b) Absolute vibration threshold
  - 4. Olfactory
    - (a) Absolute thresholds
  - 5. Gustatory
    - (a) Absolute thresholds
- B. Motor
  - 1. Rate of movement
  - 2. Accuracy of movement
  - 3. Steadiness of movement
  - 4. Muscular strength
  - 5. Muscular endurance
  - 6. Reflex sensitivity

. . . . .and many many more . . . .

TABLE 2

SOME PERFORMANCE MEASURES USED IN RECENT STUDIES

Invest. and Ref.	Measures Used	
Adams et al. (1)	Breathing rate	Skin temperature
	Heart rate	Skin resistance
Frederick (18)	Visual acuity	Kraepelin test
	Dark adaptation	Bourdon-Wiersma test
	Ocular muscular balance	Grunhorn test
	Color perception	Pulse rate
	Absolute auditory threshold	Rate of breathing
	Sense of equilibrium	Blood pressure
	Choice reaction time	17-ketosteroids in the urine
Hussman (23)	Arm steadiness	Critical flicker frequency
	"Blind" arm steadiness	tapping rate
Takakuwa (37)	Critical flicker frequency	Donnagio reaction
	Tapping rate	Ogawa's colloid reaction
	Aesthesiometry	Takano's agglutination test
	Knee reflex	

indirect measures. Most studies of performance decrement or fatigue have sought to establish some correlation between one or more of these measures and performance on the primary criterion task. A review of some typical studies provides an idea of the effectiveness of this approach.

Adams, et al. (1) performed a study in which the results of seven tests of pilot performance and four physiological measurements showed no significant correlation. Frederick (18) made an extensive study of the effects of fatigue resulting from three consecutive days without sleep on the results of the tests given in Table 2. He states, "to our astonishment, the majority of these tests never showed a significant deviation from normal values even during this test of three days." Hussman (23) found that out of four measures only steadiness changes significantly as a function of fatigue. The intercorrelations between the measures were low, however, and the highest correlation, that between steadiness and blind steadiness, which one might expect to approach 1.0, was only 0.55. Takakuwa (37) performed a study on the effect of fatigue resulting from a day's work on each of four functional tests and three biochemical reaction tests. Each of the measures was taken prior and subsequent to the working period. During four years, 333 samples were obtained and the correlations between these tests determined. Statistically significant correlations were obtained between aesthesiometry and critical flicker frequency (-0.524), Takano's agglutination reaction, and critical flicker frequency (-0.287), and aesthesiometry and the knee reflex (0.284). Here, as in Hussman's study, even the highest correlations were relatively low. The correlations between these tests and the criterion performance were not stated, but were evidently low, inasmuch as the authors were trying to validate still another measure.

The results of the preceding four studies are typical in that often no significant effect of fatigue or environmental stress on the various measures was noted, and where there were significant changes in some measures, their intercorrelations and/or their correlations with the criterion performance were low. In light of these results, the random selection and evaluation of measures which will hopefully be sensitive to changes in the subject's level of fatigue are inefficient and unproductive. Perhaps fuller theoretical consideration of the nature of the processes underlying performance decrement will provide the necessary rationale by means of which successful measures of performance decrement may be developed.

SUBSIDIARY TASKS

To provide a groundwork for such a theory, another approach to prediction of performance decrement is examined. Thus far concern has been with measures arising from functions of only a part of the organism. Except for measures of the criterion task itself, there has been concern with discrete physiological or behavioral processes. Another interesting approach to the prediction of performance decrement is to measure how well a man performs a second task simultaneously with the criterion activity. This is often known as the "subsidiary workload" method. This technique resulted from earlier work on the division of attention and has been used by Bornemann (6, 7), to study the interactions between a subsidiary task of mental addition and a wide range of primary tasks. It has since been used to study automatization of performance resulting from practice; Bahrick et al. (4), Bahrick and Shelley (3), Broadbent (8), to measure the relative difficulty of listening tasks, Broadbent (9), to measure the order of difficulty of motor tasks, Poulton (31), and to compare man-machine tracking systems, Garvey and Taylor (22). Poulton, following Broadbent, stated the basis of this technique as "the assumption that there is a limit to the rate at which an operator can deal with information—in other words he has a limited 'channel capacity.' When the demands of the primary and subsidiary task together exceed this limit, errors must occur."

The subsidiary workload method is of value in measuring task difficulty, at least in the sense of the magnitude of information transduction required. This method has also been applied to the measurement of the effects of fatigue, but with less than ideal success. Although it is undoubtedly felt that a task is more "difficult" when a man is fatigued, this is probably not true in terms of the amount of information that is processed.

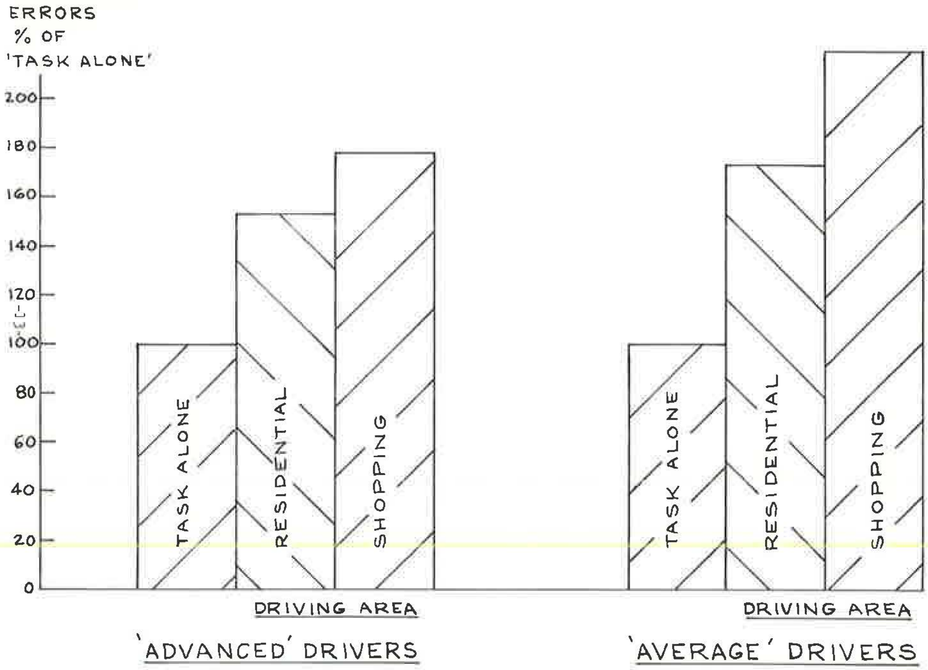

Figure 4. Mean errors on subsidiary task as a function of primary task difficulty (10).

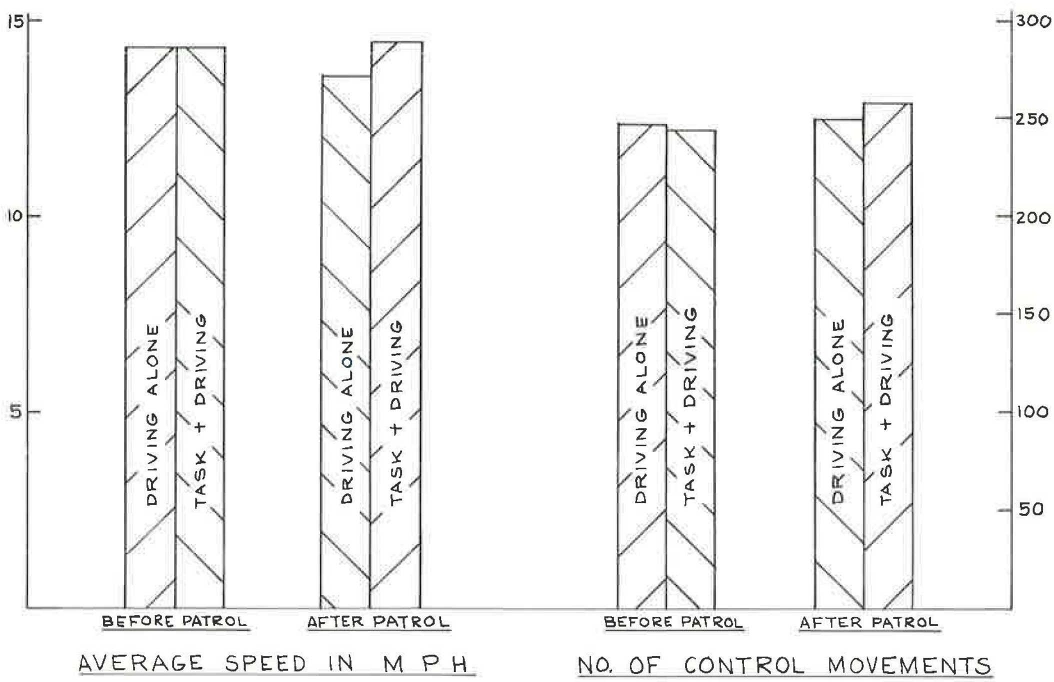

Figure 5. Driving performance as a function of fatigue and subsidiary task (11).

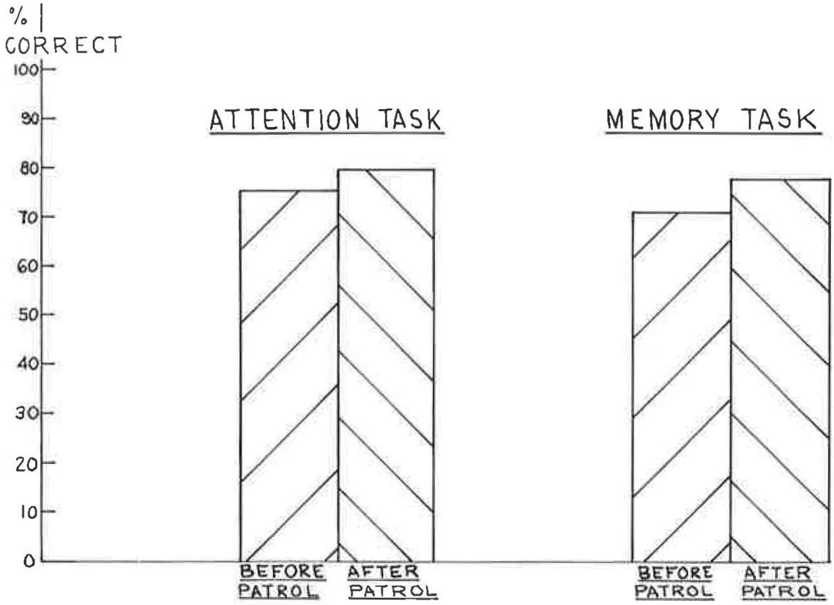

Figure 6. Subsidiary task performance as a function of fatigue (11).

SOME UNEXPECTED DATA

Figure 4 shows that subsidiary task performance nicely reflects the difficulty of the primary task for both "advanced" (N=8) and "average" (N=7) drivers. Performance on the subsidiary task is poorest while driving in a shopping area, better while driving in a residential area, and best while performing the subsidiary task alone. Having seen that task difficulty affects subsidiary task performance, the question arises as to whether the addition of a subsidiary task affects primary task performance. Brown (11) has provided an answer. Figure 5 shows that there is no significant effect of a similar subsidiary task on driving performance as measured by average speed and number of control movements either before or after an 8-hr driving patrol. Thus, subsidiary tasks are sensitive to the difficulty of the primary task, but the primary task performance is relatively insensitive to the addition of a subsidiary task. Can the subsidiary task also be used to measure fatigue? Brown (11) asked this question and received the answer shown in Figure 6. There is a definite effect of fatigue on subsidiary task performance but in the opposite direction to what one would expect. This figure shows that the number of correct responses increased as a result of 8 hours driving on patrol. Brown gave three possible, circumstantial explanations for this finding. Perhaps there is another, more basic, explanation for this initially disturbing result.

AN EXPLANATION

Here is an apparently typical picture. The primary task performance has remained constant over a relatively extended period and the subsidiary task not only does not show a decrement, but actually shows an increment. Probably there is a relatively simple explanation of what has occurred that gives an important clue as to how a really useful measure of performance decrement can be achieved. First, the reasonable notion should be accepted that the drivers did indeed become fatigued as a result of 8 hr driving in a patrol car. Second, the increase in performance of the subsidiary task should be accepted as genuine. It is noted that, as has been repeatedly demonstrated, the onset of fatigue is characterized by an increase in muscular tension (Freeman, 19). An increase in tenseness (Jacobson, 26) is a facilitator for many responses ranging from simple reaction time to mental arithmetic. The classic example of this effect is the facilitation of mental arithmetic and other responses resulting from squeezing a hand dynamometer while performing these tasks. Therefore, assuming that the drivers did become fatigued as a result of their 8-hr patrol and therefore were somewhat more tense at the end of the 8-hr period than they were at the beginning, it might be predicted that their performance on this auditory task would be increased.

If this explanation is correct, then the use of subsidiary workload as a measure of fatigue is not theoretically justified. A distinction must be made between the effects of increasing task difficulty and the changes which result from fatigue. In the case of task difficulty the concept of channel capacity is not unreasonable. Bahrick et al. (4) found, for example, that errors in subsidiary task decreased as subject acquired skill on a primary task. It is reasonable to suppose that at least part of the skill involved in learning the primary task was that of not attending to irrelevant cues. Thus, as the subject became more skilled, he processed less irrelevant information, using less "channel capacity," and thus making more available for the subsidiary task, the result being a decrease in the number of errors in the subsidiary task as the subject learned the primary task. The concept of channel capacity is essentially a "central" concept. That is, it refers to a process which affects all tasks in about the same way. This is not true with regard to tension as has been conceived. Tension is a peripheral phenomenon.

The fatigue of responses is relatively specific to the particular response elements involved. The interaction of tasks or responses as one fatigues, is a function of distance from the response element which is being fatigued to the point of measurement. Therefore, the degree to which a subsidiary response will be affected by the fatiguing of a primary response is a function of the spatial relations between the respective response elements involved. The evidence for such facilitative interaction is clear (Freeman, 20), (Jacobson, 25). Apparently the locus of the responses, which are called "mental activity," is rather diffuse. At least it seems that practically any increase in body tension can have a facilitative effect on "mental" tasks. If "mental" or perceptual responses are relatively diffuse it is easy to appreciate how the fatigue of driving, resulting in increased tension distributed widely over the body, could interact to facilitate mental and perceptual tasks, thus accounting for Brown's data. However, the effect of increasing tension is not always facilitory. Stauffacher (36) and Courts (12) have shown that there is first an increase and then a decrease in performance as tension increases. The reason for the interference is apparently somewhat as follows: When only a moderate amount of tension is induced there is facilitation of other simultaneously occurring responses. These responses, however, can only be facilitated up to some physiological limit. Beyond this limit there is no further facilitation; but responses, often competing responses, of lower habit strength are likewise facilitated. The result is that the differential in response strength between the "correct" response and competing response is decreased. Thus there is an increased response variability coupled with a decrease in the probability of a correct response. When tension is increased, ultimately a point is reached where more inappropriate facilitation occurs than appropriate, and from that point on increasing tension appears to be inhibitory rather than facilitory in terms of the correctness of the responses being made. Thus, early in learning, increased tension may be facilitory because the correct responses are not near their physiological limit, whereas late in learning, increasing tension tends to be inhibitory because the competing "incorrect" responses are facilitated to a greater extent than the "correct" responses. In this way, it is found that "mental blocking" is associated with fatigue (Ash, 2), (Bills, 5). When competing responses are facilitated to the point where they are approximately equal in strength to the correct response tendencies, there is an internal "dilemma." Response time may be then greatly increased.

In a sense, then, fatigue is the opposite of learning. During learning, extraneous facilitative responses are eliminated. Because interaction is a function of proximity, the sequence of elimination is important. Renshaw and Schwarzbek (32) took movies of a subject practicing a tracking task. They found that the trunk muscles relaxed first, then the shoulders, upper arm, and lower arm, in that order. More distant muscle groups are also involved in the changes. Freeman (19) found a progressive reduction in leg muscle-tension as the subject learned either a manual tracking task or mental arithmetic. During learning the direction of change is from distribution to focalization of muscular activity. During fatigue, however, the reverse of this process occurs even though performance measures remain constant. Muscular tension is generalized under most of the conditions that are associated with effortful performance. This was first pointed out by Duffy (15) and has been studied by Ryan, Cottrell, and Bitterman (34). Factors thus far shown to increase the spread of muscular tenseness are lack of practice; prolonged work periods (Ash, 2), (Robinson and Bills, 33); distraction (Morgan, 30), (Davis, 13); increased difficulty of task (Davis, 14), (Eason and White, 16); and increased incentives (Freeman, 21). This formulation of the effects of muscular tension is adapted from Meyer (29) and from earlier unpublished work by the same author. The responsibility for errors in interpretation or application of this formulation, however, must lie with the present author.

A POSSIBLE MEASURE

On the basis of the foregoing discussion, an indirect measure for predicting response decrement is examined. This measure is the distribution of muscular activity during a behavioral "instant" (a time interval short enough so that sequential responses will not occur); all muscular activity measured during that instant may be taken as being simultaneous. One method of measurement is as follows: a suitably large number (e.g., 20) of electrodes are placed upon a subject and are distributed widely over the body surface. The resting level of muscular activity at each electrode is noted. Then, as the subject performs the fatiguing task (e.g., driving a car or a simulator) the number of electrodes exhibiting activity above the initial level are determined during a behavioral instant. Successive measurements during the course of fatiguing activity should exhibit an increase in the number of electrodes showing increased activity, thus indicating an increase in the distribution of tension over the body. As recruitment proceeds and the distribution of response rises, there will come a point at which the recruiting of additional response elements occurs at so great a distance from the fatiguing response site that the contribution of the newly recruited units is not sufficient to maintain the required performance level. At this point, as shown in Figure 1, a sharp decrement in performance will be observed.

Theoretical justification alone, however, indicates nothing about the feasibility of the measure. A measure should be (a) within the technological state of the art; (b) immediately available (not requiring processing, developing, etc.); (c) not damaging to the subject; and (d) relatively economical. Within the past decade, technological progress in bioelectronics has been such that development of equipment for the amplification, integration and recording of muscle potentials entails merely the selection of parameters to optimize the equipment for use in any specific application. An excellent survey of bioelectronics is provided by Ford (17).

Inasmuch as the integrations will be performed within a "behavioral instant" (approximately $\frac{1}{10}$ of a sec), the values of all 20 points will be available for recording 10 times per sec, thus satisfying the criterion of "immediate" availability. Although surface electrodes will be used, which will restrict the subjects range of movement, they will cause no damage, and little discomfort to the subject. Finally, the development of high-performance transistors and circuitry permit the design of relatively economical circuits using a minimum number of components to achieve maximum effectiveness of operation. It is hoped that this new approach will provide a reliable, indirect measure of the rate of recruitment by means of which the point of sharp performance decrement can be predicted.

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