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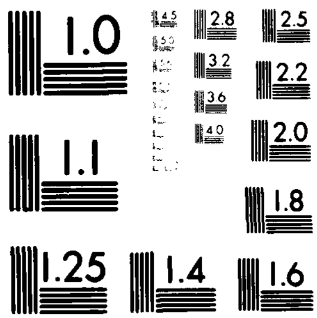

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ON THE ESTIMATION OF MENTAL WORKLOAD

JOHN W. SENDERS
Department of Industrial Engineering
University of Toronto
Toronto M5S 1A4 Canada

ROBERT M. GOTTSDANKER
Department of Psychology
University of California
Santa Barbara, California 93106

Prepared for
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The only practical way to attack the problems of mission delimitation, machine improvement, and operator specification in respect to mental workload appears to be computer simulations of both man and system performing a well-specified mission. As real systems afford the operator relative freedom of choice, the simulation of the human operator must possess intelligence. Unfortunately the data gathered in the laboratory on human performance are highly synthetic and concern the lowest elements of behaviour. Uncritical

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use of these data to solve problems of mental workload cannot be justified. The utilization of methods of artificial intelligence to bear upon the intelligent restructuring of tasks appears feasible at the present time. It will probably suffice to include rational decision making and a capacity to solve certain classes of games.

TABLE OF CONTENTS

ABSTRACT

We have explored the literature on mental workload and have found serious lack of consideration given to the intelligent restructuring of tasks which is a common characteristic of skilled operators of complex man-machine systems. Virtually all existing methods for measuring or estimating the workload imposed on human operators by simulated systems involve either real-time system simulation and the use of real human operators, or the use of data banks of human performance data. Since such data gathered in the laboratory are highly synthetic and obtained under conditions quite unlike the relative freedom of choice of human operators using real systems, we have also come to the conclusion after much analysis, that computer simulations of both man and system performing a well-specified mission are the only practical way to attack the problems of mission delimitation, machine improvement, and operator specification.

These almost contradictory statements are brought into consonance by requiring that the simulation of the human operator possess intelligence and be able both to play with alternative ways of doing things and (to quote Sheridan) to report on "[its] private subjective experience of [the] cognitive effort."

The work on mental workload that has been done to date by all of those in the field is largely concerned with the reductionist approach.

All have, in fact, used the lowest elements of behaviour, for which data exist, and have tacitly assumed that the linear hypothesis holds: the whole is no more than the sum of its parts. Proof that this is true for intelligent behaviour is not likely to be found in the near future.

We thus arrive at a more difficult and demanding problem, that of artificial intelligence. Fortunately, the kind of intelligence which must be simulated is not completely beyond our capabilities. It will probably suffice to include rational decision making and a capacity to solve certain classes of games.

LIST OF TABLES AND FIGURES

INTRODUCTION

With the continually increasing application of digital hardware to cockpit instrumentation, there have arisen problems relating to the methods of displaying information to the pilot and accepting inputs from him.

As the pilot's functions become more and more those of a systems supervisor the task of integrating him into the systems design becomes more difficult. In particular, the continuous control loops tend to be subsumed by the computers and the pilot becomes an observer whose principal function is more to choose amongst various alternatives than to execute them.

One of the major design difficulties stems from the fact that human beings appear to operate best, as controllers, from spatially organized information. Such information is inherently difficult to present and is more costly in terms of hardware and less realizable, than digital, discrete, symbolic displays. How successful the pilot can be when presented with digital information on which to make spatial decisions is a matter of conjecture, and can be best approached through workload estimation procedures.

One direction of possible solutions lies in the use of models of human behaviour which can predict satisfactorily the performance of the pilot. Many such models exist. Among these are the quasilinear control models of McRuer et al., the visual sampling models of Senders, and the taxonomic structure of Teichner. This latter is based on the notion of the single channel model of the human operator and is compatible with a multi-dimensional model of human operator workload. We first consider these models and their application to the solution of the problems of complex digital cockpit design and man-machine integration.

MENTAL WORKLOAD

General

Mental workload is a concept as well as a group of models. The concept is created by analogy with the concept of physiological work. In general, it seems reasonable to assume a less-than-infinite capability to do "mental acts." Given that assumption, it follows that some mental acts or different numbers of them will approach closer to or further from the finite capability than will others. The closer a "mental act" comes to the limit, the greater the "mental workload."

Some models are useful as guides to conceptual thinking about mental workload; some are strictly utilitarian; most fall somewhere in between. The models have been constructed both for their theoretical utility and the applicability to real world problems. When one attempts to apply a model to a real system, there is immediately generated a demand for data about the system, its mission, and the role to be played by the human operator(s) in it. Unfortunately it is difficult to obtain the data in a form which will permit direct calculation of workload as a function of time throughout the mission. There are a number of reasons for this difficulty and each difficulty can be dealt with only at some cost, since they stem from fundamental characteristics of systems, missions and human operators.

Obviously a system with no mission has no definable workload since there is no demand on the human operator that any particular act be performed at any particular time with any particular precision or accuracy. The human operator can do things when he wishes, so that he can adjust his load at will. It is clear, also, that if the system itself is not suitably characterized, there can be no definable workload since there can be no definition of what is to be done. Lastly, the capacities of the human operators must be specified since it is clear that the load imposed on two human operators of different capacities or training will be different even though the demands of the system and the mission are the same for the two.

Thus for good calculation we must specify what is to be done at each moment of time, with what accuracy and precision (the demands), and by whom (the capacities to perform).

Models

Although there are many models of workload, they can be broadly classified as being either statistical or causal in nature. A statistical model is usually concerned with ratios of system demand to operator capacity aggregated over some significant period of time. A causal model is concerned with demands at every instant of time.

An example of a statistical model (and calculation stemming from it) is the scanning model of Senders (2). In this model the signal characteristics of the various stimulus displays are used directly in the calculation of the frequency and duration of eye fixations which must be made in order to perform the monitoring task of the defined mission. The output of such a calculation is an estimate of the load imposed (the percentage of available time which must be spent looking) and of those mission phases wherein transient overload may occur either as a result of calculated loads greater than unity, per se, or as a consequence of the queueing nature of the process modelled. However, the model does not say when an event will occur; it deals only with probabilities in time.

A causal model would examine every transaction between operator and machine and, for example, compare the time required for its accomplishment with the time available before the next transaction occurred. Any of the single channel models (Broadbent (3) for example) is of this sort.

The demands made upon the systems analyst are quite different from the two kinds of model. The statistical model is based on the "transfer" of input statistics to output statistics. The causal model is based on the "transfer" of input stimulus to output action. Since in any mission there are apparent great differences in load at various times within the duration of the mission, the calculations must be separately made for these times. The principal difference is that for the statistical models, the data cover an entire period of (approximate) uniformity of demand whereas for the causal model the data must be acquired for intervals of time short compared to the duration of mission phases.

The Fine Structure of Work

How finely must time be divided for the calculation of workload? There are two controlling factors: the time used by a human operator to perceive, interpret, and respond to stimuli, and the intervals at which signals are presented and responses required. We will call the former "human time" and the latter "systemic time." Human time for some elementary actions can be determined from the scientific literature and lead one to the notion that a mission description at intervals of 0.5 second would be sufficiently fine to permit the use of a causal or moment-to-moment model. However, the descriptive task of the analyst is enormous if the mission is long—7200 elements per hour. Further it may, for reasons to be presented, be impossible to define the mission and the demands on the operator to this degree of temporal precision.

Let us consider element *i* of a sequence of actions required of the operator during a mission. Input *i* appears as a signal at some time $T_i = t_i \pm dt_s$, where t_i is the nominal instant when input *i* should occur, and dt_s the standard deviation of its actual time of occurrence, since there is always some uncertainty as to when an input will occur. This uncertainty arises both from the fact that some inputs are externally developed and from the fact that variation in machines and operators will induce cumulating uncertainty in the timing of events. Output i is the action of the operator in response to input i. There will, for any time of input i, be uncertainty of time of output i and, in general, output i will occur at $T_i \pm (dt_s^2 + dt_a^2)^{1/2}$, where dt_a is the standard error of output timing.

It will further be the case that the output i does not have a required precise time of performance. That is to say, there is some flexibility allowed the operator to perform when it is convenient. Of course this flexibility is limited else there would be no demand at all from input i for any action at all. There will be either a range of acceptable delays between input i and output i, or a range of acceptable times when output i must be performed. These are quite different in effect. The former allows the timetable of the mission to slip, the latter imposes an overall timetable but with less than complete internal constraint. Thus, if a transmitter frequency is to be changed, there is usually a broad interval within which mission accomplishment is indifferent as to the time of change, with respect to probability of success. Thus systemic time may be very coarse indeed. In general we would expect it to be coarser than human time. Also, in general, the coarser the systemic time the less short-term workload is generated since the operator has freedom to move actions around to fit into slots of available time subject to the memory load which may be imposed by the transient nature of the input events.

As a consequence of the logic of the foregoing it is necessary for us to modify our earlier simplistic notions about the workload imposed on a human operator by the demands of the system and its mission. It remains true, of course, that the load will increase with the number of demands, and with an increase in the intensity of demand, cet. par., but it is also true that number and intensity (or complexity) are conditional upon systemic time constraints.

The Pacing of Tasks

The notion of time constraint forces us to examine the concepts of self-paced and machine-paced tasks.

Traditionally there have been two dichotomous categories of task: the self-paced and the machine-paced. The self-paced task is one in which the next action to be performed cannot be demanded until the previous action is complete. It does not preclude the appearance of the next or even of a large number of stimuli in succession or simultaneously; it is only the output which is at the discretion of the human operator (HO). The HO therefore may choose how fast he is to work, how much time he may take on each action and so on.

The machine-paced task is one in which actions are demanded by the task irrespective of whether the human operator has performed an antecedent task component. Thus it is possible for the operator to fall behind if the demands are beyond his capacity, or that portion of capacity which he has allocated to the task.

If one examines these two classes carefully, it becomes clear that real tasks have components of both in almost every case. Self-paced tasks in a real situation may in fact have ultimate bounds of freedom as to time of performance even though there is no short term boundary. An act may not need to be done "right now" or at any particular time, but it may have to be done some time. Such a task is by no means a pure self-paced form. Machine-paced tasks in real life may permit neglect if circumstances demand it so that the operator may decide not to perform or may miss the opportunity to perform without complete failure of the mission. Such a task is by no means machine-paced, and its position on the dimension from self- to machine-paced depends on the constraint on time of performance specified by the mission and the system involved. Acts (or task components) nearer the zero constraint end may be done ad libitum or neglected altogether. Tasks nearer the other end must be done when the system demands them or neglected only at great cost to the success of the mission.

The load placed on an operator by a task is clearly a function not only of what is to be done in response to what stimulus but also of when and with what time-constraint it must be done. Furthermore, the calculation of the workload of a task with a low degree of time constraint may be a prohibitively expensive chore due to the basic uncertainty as to what is to be done when.

Another dimension of description of task components is that of serial ordering. Some task components must be performed in strict order; others may be performed in any order. Here again, if the degree of "order freedom" of a set of task components is high, then the calculation of the workload associated with them may be difficult due again to uncertainty as to what is next done and when.

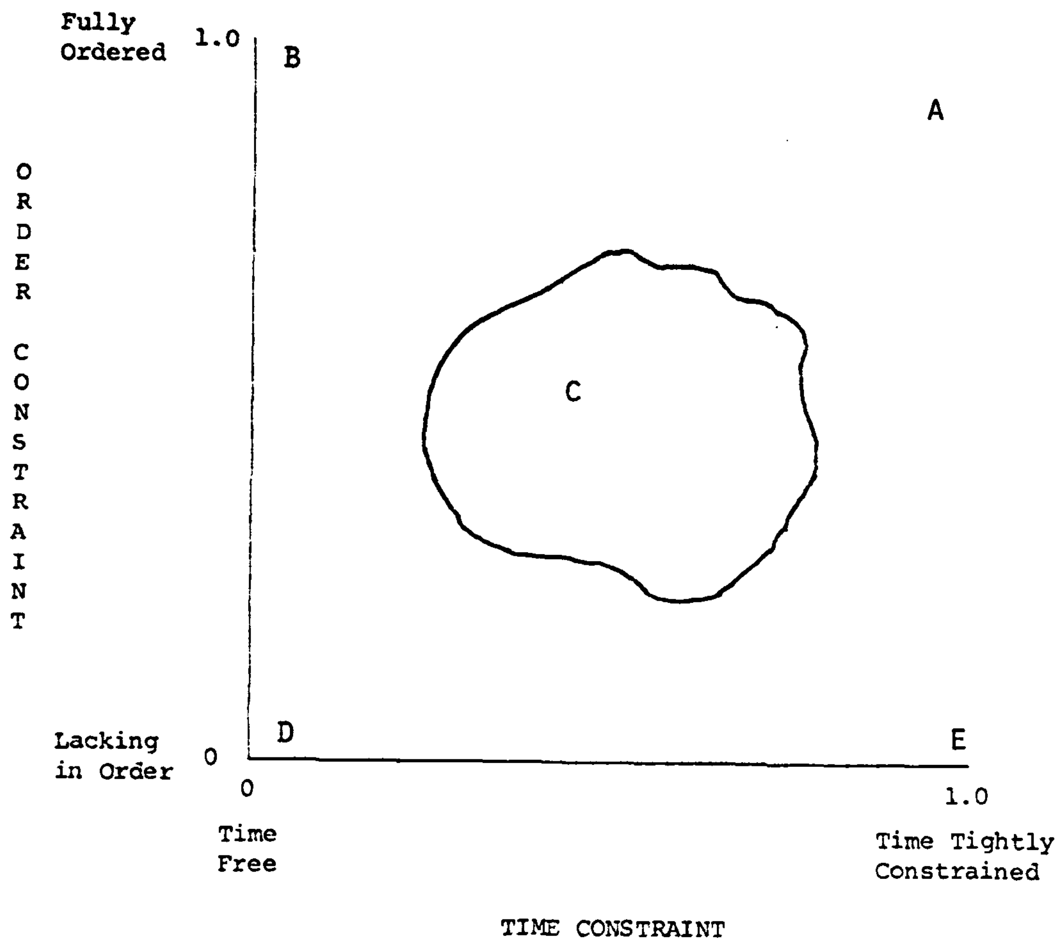
Thus self-paced and machine-paced as categories are inadequate and the degrees of time-constraint and of order-constraint must be substituted. A task component may be represented as a point in two dimensional space as suggested in Figure 1.

The Analysis Problems

The problem exposed by these theoretical notions is as follows. Since time pressure is one of the most common forms of load on a human operator, the degree of time and order constraint markedly influences the load imposed by a task component or a group of such components. The operator is free, to varying degrees, to move acts from moments of high demand to moments of low demand. To the extent he is able to do this efficiently, he can avoid overload subject to the limitations of his memory for those acts which must be serially ordered either in whole or in part.

Thus it can be seen (as we see it) that there can be no solution to the workload analysis based on molecular examination of human performance. The difficulty stems directly from the (literal) immensity of the calculation required to arrive at the actual sequence of acts which minimizes the load placed on the human operator and which a skilled HO will tend to asymptotically.

A way out can be found by expanding the time unit of analysis and the problem is that of determining how large that unit is to be. There are many alternative approaches.



A: Common Machine-paced Task

B: Common Self-paced Task

C: Real World Tasks

D: Do-What-You-Want-When-You-Want Task. SIRO, in Queueing Terminology

E: Do-What-You-Want-But-Don't-Let-Anything-Slip Task. A stressful possible real task.

Figure 1. The Two-dimensional Space of Time- and Order-Constraints

One could use an arbitrary size of time slot and require that all acts will be performed within that time. Then within the time slot all acts would be aggregated and the load computed as an average over the duration of the time slot. This has the advantage of greatly simplifying the calculation. However, it may inflate the estimate of load and be unduly conservative since it restricts the freedom of time of performance.

Another alternative would use a time-varying time slot which is large in periods of relatively low demand and small in periods of relatively high demand. A useful method might be one which had time slots in which equal numbers of acts were demanded. The advantage would be a relatively uniform calculational effort per time slot.

In either case, there might be acts which had such lack of time constraint that they could be performed at any moment over a relatively long span. These acts would have to be treated in a separate way and used as fillers for those time slots which were singularly low in load and fell within the larger time span of these unconstrained acts. Arbitrarily, any act with a constraint so low that it could be performed during a span of time greater than two time slots, would be designated a "time-free act" and assigned to the slot within its reach with the lowest load.

Since for any of these schemes there would be variation of calculated load with variation of length of time slot it would be desirable to have a program which would calculate load as a function of slot length (up to the limits determined by calculational demands). In all cases, the determination of the length of the time slots, and the character of the time-free acts would depend on the detailing of the mission on a fine time basis and the specifying for each act of its serial time dependency and time constraints.

The Task Description Problem

Workload cannot be calculated without a detailed description of events in the mission as a function of time. This has been evident from the very first attempts. Lindquist and Gross (4) used a "Second-by-Second Operational Analysis" to estimate the workload placed on the astronaut by the first orbital mission in the Mercury spacecraft. Most of the workload calculations were made on the basis of Information Theory (5) or on the basis of Sampling Theory of Visual Attention (6). There could not in the ordinary course of events be any validation of the numbers generated other than the success or failure of the mission and this was a rather unsatisfactory validation at best.

Siegel et al used a simulation technique for the human operator (HO) performing mission elements and introduced stochastic variation into the performance of the simulated HO. Then, by the use of Monte Carlo methods, they were able to generate distributions of probability of success of the mission as a function of variation in the task. This method had the distinct advantage over the Lindquist and Gross approach of using the full range of human performance instead of mean data taken from the literature. Again, however, validation was difficult.

Both of the foregoing attempts did not consider the time lability of events—signals and required actions on the part of HO. As a result both probably overestimated the load to be imposed.

The queueing models of Senders and Posner (6), Carbonelle (7), Rouse (8), and others, generally are based on the assumption of machine-paced task structure. The demands come along and, if two or more occur at once, there is a transient overload, or the sytem has to wait for the action demanded while the one chosen is dealt with. If the system is tolerant or absorbent of delay, then there is no inherent problem with that state of affairs. It is only when the action may not be delayed, or has a definite period of acceptance with non-absorption after that, that true overload can occur from the simultaneous demand. The systems/mission analyst has responsibility, therefore, for specifying which demanded actions have time lability and to what extent, if the results are to be reasonable.

There are other problems in description. These stem from the fact that much of what HO does is not in response to a definable stimulus (if indeed to any stimulus at all). Thus HO may think, daydream, plan ahead, consider alternatives and so on. The Table 1 taken from Johannsen and Rouse (9) is an example of a description at a level which prohibits the assignment of load based on performance data. Here the elements of behaviour are not those which psychologists, for obvious reasons, have spent their time in the laboratory studying. They are intrinsically difficult to deal with, to define, to measure. Yet at one level of discouse they most precisely describe what is being done however inconvenient for the missions analyst it may be.

Table 1. Protocol for Typical City Trip

INSERT KEY IN IGNITION

PUT ON SEAT BELT

PRESS GAS PEDAL TO FLOOR AND ALMOST TOTALLY RELEASE

TURN KEY

LISTEN FOR ENGINE SOUND

  IF SO, THEN GIVE GAS

  ELSE, STOP AND GO BACK TO TURN KEY

WAIT FOR CAR TO WARM UP--DAYDREAM

LOOK AROUND--SEE IF I CAN BACK UP OKAY--INCLUDES USING MIRRORS

  IF SO, THEN PUT CAR IN REVERSE

  ELSE, WAIT FOR ALL CLEAR

PUT RIGHT ARM ON REAR BACK SO AS TO SEE BETTER

STEER WITH LEFT ARM, ACCELERATE AND BACK ONTO STREET

DETERMINE WHEN CLEAR TO GO FORWARD--STOP BACKING UP--PRESS BRAKE

PUT CAR IN DRIVE

LOOK AROUND--SEE IF I CAN PROCEED

  IF SO, ACCELERATE

  ELSE, WAIT FOR ALL CLEAR

LIMIT SPEED SINCE STOP SIGN COMING UP--CONTINUE LOOKING AROUND

STEER SO AS TO STAY "SORT OF" IN LANE

ESTIMATE DISTANCE TO STOP SIGN--CHECK FOR TIME TO DECELERATE

  IF SO, REMOVE FOOT FROM GAS AND OVER TO BRAKE

  ELSE, UPDATE ESTIMATE OF DISTANCE--CONTINUE LOOKING AROUND/STEERING

Table 1 (continued)

TURN ON LEFT DIRECTIONAL

WHEN FAIRLY CLOSE TO STOP SIGN, PUSH BRAKE HARDER AND STOP

LOOK LEFT AND RIGHT FOR TRAFFIC

    IF ALL CLEAR, TURN LEFT AND ACCELERATE

    ELSE, WAIT FOR ALL CLEAR AND CONTINUE UPDATING ESTIMATES

STRAIGHTEN OUT SO AS TO KEEP "SORT OF" IN LANE

ACCELERATE, BUT NOT TOO MUCH BECAUSE STOP SIGN COMING UP

LOOK AROUND AT TRAFFIC--ALSO AT HOUSES AND YARDS--DAYDREAM

EXECUTE STOP SIGN ROUTINE--ONE FOR STOPPING--ONE FOR STARTING

--USE FOUR-WAY STOP SIGN ROUTINE

EXECUTE ENROUTE ROUTINE--INCLUDING TALKING, SIGHTSEEING, ETC.

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PLAN ROUTE--WHAT STREETS TO TAKE

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EXECUTE STOP SIGN/STOP LIGHT/TURNING/PASSING/LANE CHANGING ROUTINES

.

.

LOOK AROUND FOR APPROPRIATE PARKING SPACE

    IF ONE FOUND, DETERMINE PLAN FOR GETTING INTO IT

    ELSE, CONTINUE LOOKING AROUND AND STEERING

Table 1 (continued)

EXECUTE PLAN OPEN-LOOP, WITH FINAL UPDATES AS ERRORS CAN BE ESTIMATED

PUT CAR IN PARK

TURN OFF RADIO, HEATER, ETC. IF APPROPRIATE

TURN OFF KEY

REMOVE KEY

Can these high level global acts be broken down in a reasonable way into more elemental acts? We might do the following:

Insert Key in Ignition

Identify from memory the location of key; control hand (of choice) toward location of key, (using closed loop as well as open loop control), grasp key, tactually examine orientation of key, correct orientation (closed loop either tactual or visual or both), direct key toward lock (using closed loop control), insert key into lock (using closed loop control tactual this time), test whether key is "home" (tactual feedback).

We have now reduced the act of inserting key to a series of more elemental acts some of which, at least, have been studied in the laboratory and for which data exist or can be inferred. One can go further. Consider the elemental act: direct key toward lock. This can be further broken down into a time sequence of error detections of disparity between plan and actuality, and the emission of correcting impulses to the appropriate muscles to reduce the error. The mathematics of transfer function analysis can be applied to predict time and error.

The demand that "key be inserted in ignition" is not quantifiable without a part task simulator involving keys and locks and subjects. But it is precisely these that we wish to eliminate from the workload analysis process. To overcome this we have broken down the insertion of the key into smaller parts. Now, if we had a sufficiently detailed description of the actual location of the key, its shape, the size of the keyhole, the presence or absence of guiding marks around the keyhole, the illumination around the keyhole, the force involved in inserting the key, and so on, we could begin to derive man-machine data from our knowledge of man and our description of the machine.

The following steps are required for application of the model:

1) A description of the task as a series of elemental acts in units of time smaller than the least significant unit of time of human performance.

2) A statement of the time-lability and order-constraint of each of the ordered task elements.

3) A classification of each task element in terms of an acceptable taxonomy of human performance.

4) A statement of the expected capacity of the human operator to perform that taxonomic element.

5) A statement of the expected level of demand for that element.

6) The calculation, for each unit of time, of the load imposed with that time unit.

7) A calculation of the probability of interference between task elements, derived from the queueing model previously described.

8) A calculation of the resultant human failure and error rates, derived from the queueing model.

In order to obtain the information needed for step 1, it would be necessary to construct a mission description which stated, for each unit of time, what had to be done, with what precision, and with what time constraints. Obviously, if the human operator may perform a task element any time in a period of ten minutes, that element is less contributing to load and interference than if the same element had to be performed within a period only ten seconds in duration. When time constraints are great, the probability of queueing problems and consequent interference and error is increased. It is clear that load and performance are strongly specified by the specification of the mission; if the latter is not properly done, then the former cannot be properly done.

In general, it is this kind of process that is undertaken for a reductionist analysis. There must be a MISSION DESCRIPTION which can be mapped into a MAN-MACHINE PERFORMANCE encyclopedia which derives from a SYSTEM DESCRIPTION which interacts with a HUMAN OPERATOR PERFORMANCE encyclopedia. HO performance data combined with the physical description of the system (the work environment) yields man-machine performance data. The mission description, when "forced" through the man-machine system, yields a sequence of transactions and processes required throughout the course of the mission.

All of these elements are necessary for analytical solution of workload by any model for any real system doing a mission. The critical question is whether such a solution is achievable and meaningful.

SOME EARLY EXAMPLES OF ANALYSIS

Lindquist and Gross (4)

Some missions, with some systems, are by their nature easy to analyze. Where the mission designer has precisely stipulated the sequence of events; where there are no free periods of time left unaccounted for; where there are no "unexpected" events: a precise sequence of elemental acts and the loads associated with them can be constructed. The first Mercury capsule flights were of this nature. An analysis was made of this mission by Lindquist and Gross (4) using a technique newly developed for the purpose. The underlying assumptions were: every demand made by the system had to be satisfied as rapidly as possible by the HO (astronaut in this case); loads imposed by overlapping elements of demand were strictly additive; no loads were generated by sequences of activities per se other than the loads associated with those activities. The entire mission was described by a simple tabulation of every event that occurred (or was supposed to occur) during each second from prelaunch to landing. Then for each of these events a load figure was assigned based on whatever laboratory data were available from the literature. In some cases ad hoc experiments were run to determine loads. In some cases the measure of load would simply be the proportion of the time available for the activity actually required for performance.

The sum of the loads in each second was found and the result plotted as a function of mission time. Where (if at all) the load exceeded 1.0, adjustments of events would have to be made. Where the load was close to the 1.0 level, adjustment would also be made but the urgency of the adjustments was a function of the level, of course. Certain high load intervals were found and, where possible, relieved by judicious moving of events to other time. No provision was made in the analysis for flexibility of the mission and the system in allowing events to be done on an ad lib basis within certain temporal boundaries. No variability data were entered into the solution and none came out. There was no way to estimate the probability that an overload would occur, nor whether a load of 0.9 was acceptable (other than that it was less than 1.0).

Siegel and Wolf (5)

The method of Siegel and Wolf involves a simulation model realized on a digital computer. The model works its way through a mission in a succession of discrete time intervals and calculates, using Monte Carlo techniques, the time taken for the performance of a microelement of the mission. The time remaining for the accomplishment of all waiting events is recalculated, "stress" levels calculated, distributions altered on the basis of the "stress" and the next time interval entered. Then the process is repeated for the next event needing to be done. The program is capable of generating distributions of the outcomes of the successive runs and assigning a success or failure to each. For some runs, of course, the time will have run out, and the run termed a failure, because of the random nature of the selection of operating times from specified distributions. The models have been extended to include more than one operator and machine systems of varying complexity.

Wherry (10)

Even more sophisticated, more complex, and more detailed is the Human Operator Simulator (HOS) described by Wherry (10). HOS is an active encyclopedia of human performance data against which the requirements of a task can be played. What come out are "time to perform" and "error probabilities." Here such simple acts as reaching for a knob, grasping it, and then turning it are separately analyzed and quantified. Naturally the system demands a very low level of description, highly detailed and matched to the data base. This system is a first approximation to the generalization made on page 19.

A practical analysis technique must have aspects of all three predecessors: the fine time structure of Lindquist and Gross, the Monte Carlo method of Siegel, and the store of human performance data of HOS along with the means to attach the data to the task. This last is of the greatest significance.

Comment

Because of the non-analytic nature of the description which is required, it is almost surely the case that the solution to practical problems will come from algorithmic rather than from formal methods. In general, models must be built of the machine and the HO. These two must have a set of rules of interaction, the man-machine interaction. Finally, there must be a way of introducing information about the mission into the model in order to derive estimates relevant to particular practical problems.

Earlier we indicated that one of the chief features of the time-based description of a mission is that events are not serially ordered in time. For each class of events, and for each event within a class, there will be some degree of flexibility of timing which will vary as well with the point in a mission that the event occurs, the skill of the operator, the presence or absence of other events and, in all probability, many other factors as well. Therefore for any event a large number of descriptors is required. Among these are: the degree of serial constraint, the degree of time constraint, its classification as transaction or process, its classification as being a response-dependent, a stimulus-dependent, or an independent stimulus; its being a response-dependent, a stimulus-dependent, or an independent response.

The following analysis is a restructuring of the analysis task which includes all of these factors.

The Analysis of Speeded Operation

Workload is of consequence when the HO is involved in a more or less prolonged mission of which some aspects must be performed within a limited period of time. This circumstance may be called speeded operation. The units—some of which may overlap—into which speeded operation may be analyzed for the purpose of assigning demands or deadlines, on the one hand, and capacities or performance times, on the other, may be called events. An event is the coupling of a response by HO with its eliciting circumstance. Some functional events may easily be described as transactions between a specified environmental stimulus and a response that is completely determined by that stimulus. For other events there is either no determinate stimulus or a response that will vary for the same stimulus as a consequence of states of other stimuli or the effects of recent or remote experiences of the HO. Such an event, then, must be regarded as an internal process of the HO, including the culminating response.

Definitions, Examples, and Characteristics of the Classes of Events

1. A Stimulus-Response (SR) Transaction is defined as one in which the stimulus occurs independently in time of preceding responses. Some familiar tasks made up of such transactions are tracking and typing from dictation. Tasks of this kind are often called forced pace. There may be more or less sequential dependency in the sequence of stimuli,

with successive letters in words to be typed illustrative of high sequential dependency and a sequence of stimuli for various emergency responses illustrative of low sequential dependency. Typically, there is a buit-in time constraint in making responses, as a stimulus may be forgotten as new stimuli occur. However, time constraint may range from excessively tight as in tracking to very flexible as in turning down the volume of a headset. In addition, there is more or less serial constraint, the degree to which the sequence of responses must match the sequence of stimuli.

2. A Response-Stimulus-Response (RSR) Transaction is defined as one for which the stimulus occurs or becomes appropriate only after a preceding response. One example is typing from text. Another is performing on the Senders bit-box where a new signal for response occurs on the making of the previous response. Tasks made up of such transactions are often called self paced as--in contrast with forced-pace behaviour--the time pressure is indirect, depending on instructions, over-all deadlines, etc. Responses are serially constrained as there is no stimulus for response until the preceding response has been made. Although it is typical for signals to be permanent (as on a printed page) or to persist until a response is made (as in the bit-box) this is not necessarily the case. For example, the bit-box could be modified to produce a transient signal.

3. A Process is defined as an event for which there is no single identifiable signal that elicits the response but rather some internal activity of the HO. Examples include all cases where the response is made on the basis of a plan, a remembered instruction, or a combination of preceding stimuli or responses. Such responses often occur at an upper level of the response hierarchy, where they take the form of decisions. It is typical for there to be flexible time and serial constraint for these responses.

Properties

For the modeling of workload, transactions and processes need to be more fully described as they are profoundly affected by the functional properties of the stimuli, of the responses themselves, and of the relation between stimuli and responses. Some of these properties were alluded to in the preceding treatment of the elicitation classes: e.g., time constraint, serial constraint, and sequential dependency. Following are definitions and examples of properties:

1. Stimulus Properties

a. Sequential dependency is defined as the degree of necessity for a particular stimulus to appear at a particular time in the series of stimuli. At one extreme there could be an entire mission that is described in advance. At the other extreme there is a random series of stimuli. In the middle ground is a series of stimuli having a probabilistic relation to one another.

b. Group size is defined as the number of stimuli not yet responded to that are available to the operator in making a response to one of them. For the bit box group size is 1 as the only stimulus present is that for the imminent response. In typing from text there is a large group of stimuli present when making a response, with perhaps eight or ten useful for the HO's performance.

c. Duration is defined as the length of time the stimulus is presented. In typing from dictation each stimulus is presented momentarily. In the bit box each stimulus persists until a response is made. In typing from text stimuli usually remain present even after their responses have been made.

2. Response Properties

a. Serial constraint. A serially constrained response is defined as one that will not be accepted by the system or is inappropriate unless it is made after certain responses and before others. In typing from text each response is serially constrained within the series of responses. In recording the settings of a group of meters there is often no necessary serial constraint.

b. Time constraint. A time constrained response is defined as one that must be made within some specified time window after the appearance of the signal or within a specified phase of the mission. A sudden move of a target must be responded to immediately in tracking. Answering a question from mission control can be put off for a little while until a tracking error has been corrected. For both of these SR transactions there is direct time constraint. In typing from text the time constant is indirect. The operator may be trying to type as quickly as possible, as quickly as possible with no more than five percent errors, to complete a passage within six minutes, etc.

c. Hierarchical level is defined by the events subsumed under a given event. In the bit box each transaction is at the lowest hierarchical level. A decision to adjust altitude subsumes the transactions of checking the altimeter and altitude indicator and operating each of a number of controls. A decision to abort a mission subsumes, in turn, such transactions as the decision to adjust altitude. It is characteristic as hierarchical level increases for the events to be processes rather than transactions as a good deal of information may be integrated with no single eliciting stimulus being identifiable.

3. Stimulus-Response Property: Directness of Implementation

Directness of implementation is defined by the probability that the stimulus will instigate a particular response. In typing there is a defined particular response to each letter. However, a signal may be given to the operator with a more general message: e.g., perform a certain manoeuvre if possible. Even less directly, the operator may be advised of possible weather conditions to "keep in mind." In the first case the stimulus is part of a transaction. In the latter cases it is possible that it will form part of a process.

Thus the task of typing textual material at sight is a serially constrained (because the letters must be typed in the same order as they are in the text), time-unconstrained (because there is no stipulated time pressure), sequence of transactions. Typing from oral dictation is a serially constrained, time constrained (since the speech goes on independent of the typing responses) sequence of transactions. In both cases the events are response dependent (since no response can be made until the preceding one has been completed). A common laboratory task is one in which the new stimulus appears only after the preceding response has been completed, as in an information processing task. Independent events appear at random and the responses may be made in any order as convenient to the performed. In all cases these are transactions. A process is exemplified by the event of going through an intersection when the light is yellow. Here the response is a function of a large number of factors including memory information brought to the decision process by the performer.

Some of the possible types of events are inherently contradictory, others are common in real world situations. Still others occur almost without exception only in the laboratory. It is unfortunate that many of the available data derive from this last class of event. Both the classical machine-paced and self-paced tasks are rare outside the laboratory situation.

DATA REQUIREMENT FOR ANALYSIS

In order to clarify and make graphic the nature of the defining statements Figure 2 is presented to show a time-line analysis which could serve as the basis for a computer program for the estimation of the demand of a task.

Let the capacities of the operator be C_1, C_2, and so on. Let the demands of the system on these capacities be D_1, D_2, and so on. The loads, then, according to the Senders model (1) are defined as

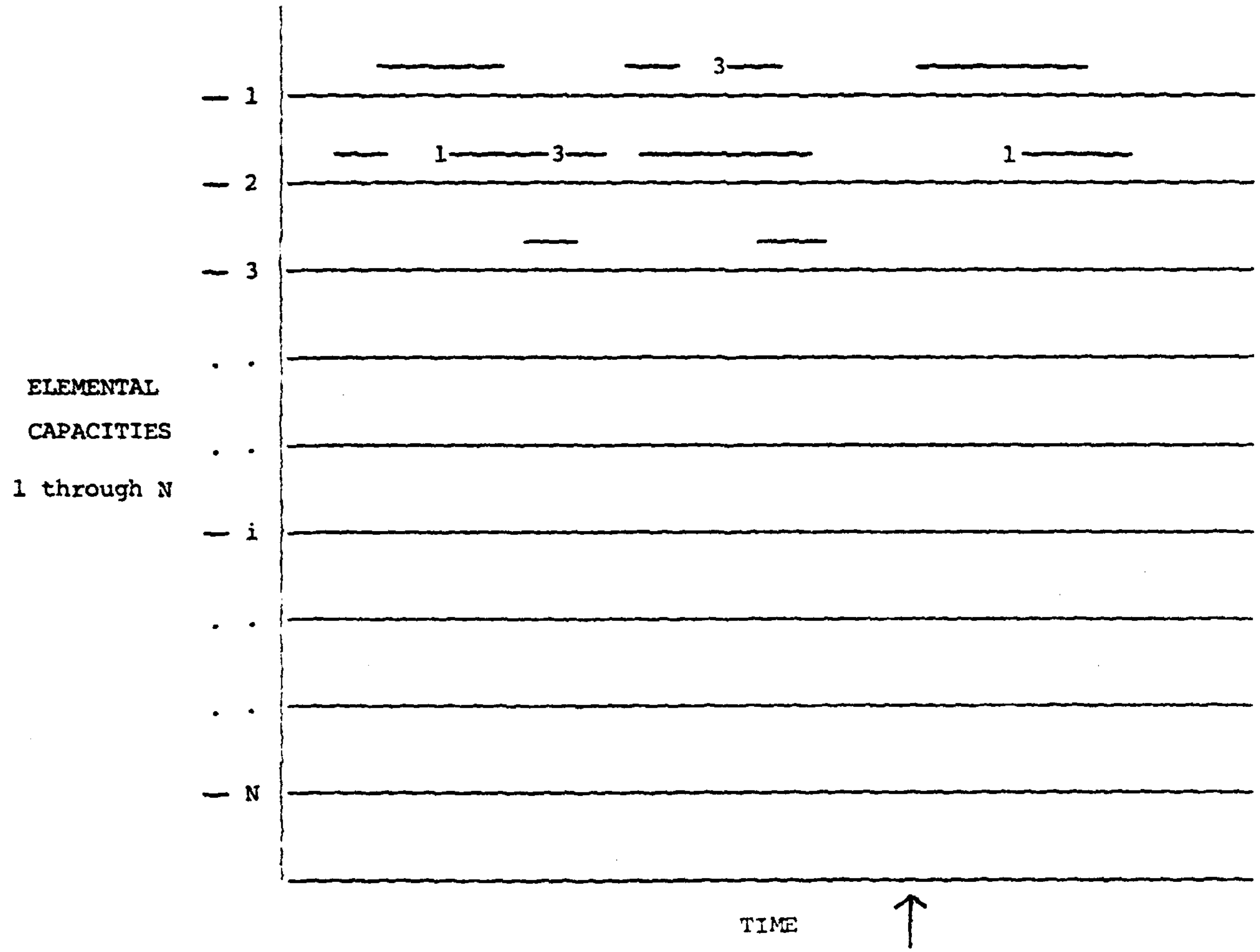

Figure 2. Diagram showing how Time and Order Constraints arise

the ratios of demand to capacity. For each load applied to an elemental capacity we can generate a time line as shown in Figure 2. When a mark is made on the line 1, it indicates that a demand has arisen and an act is required. The act may be as simple as monitoring an indicator, or as complex as choosing to abort a mission. The duration of each mark shows the time constraint associated with that event. When the mark is long, the event can be completed, i.e., the act performed, at any time over the length of the mark. When the mark is short, as in the first mark on line 3, the response must be completed within a short time. We can also specify the serial constraint of each of the events. For example the third event in line 2 has a 3 before it indicating that the overlapping event in line 3 must be completed before the act called for in line 2 can be completed. In general, for any event which is serially constrained at all there will be some linking symbols with other lines. The first event in line 1 has no symbol indicating that it may be performed at any time within its time band. This set of lines and links is the first step toward the estimation of the load imposed by a mission. The next step must take into account the interval over which the events are to be combined and treated statistically. In the figure there are natural boundaries which are apparent to the eye without analysis. The arrow along the abcissa indicates natural break or chunk of events. The sequence of events shown by the figure is then: 2, 1, 2, 3, 2; or 1, 2, 2, 3, 2, and so on. With a large number of possible paths through the temporal maze the analysis problem becomes formidable.

Still further information can be usefully added to the figure. For each line there will be a distribution of performance times. The mean for each line is shown as a length of bar to the left of the line. (Here they are all the same.) The relationship between these times to perform and the permissible times within which performance must be completed provides insight into the pressure or time-stress which is placed on the human operator by each event. Thus the third event in line 2 must be performed immediately upon its arrival since the time to perform is virtually as long as the acceptable window of performance. The same is true of the second and third events of line 1.

Since the event in line 3 must be completed before the third event in line 2, and since the event in line 3 takes a significant part of the time available for it, there is a transferred requirement to the event in line 3 that it be done immediately upon the stimulus to the transaction. Otherwise there would not be time for the event in line 2 to be completed within its allotted time.

If one now increases this diagram to include everything which might occur during a mission, the difficulties both of description and action by HO can be appreciated. Yet such a description is necessary if we are to have a complete analysis. How to escape this dilemma is a major problem.

Most models have been concerned with transactions even though it is probably the case that a highly skilled HO uses processes far more than transactions in operating complex systems. Process analysis is a more difficult task. A process may be determined by events in the future as well as those in the past. Thus a skilled operator may "play a game" with the system and the mission in such a way as to minimize the future load that will be imposed on him. We would in fact expect and hope that skilled operators would behave in an optimum forecasting way to achieve this goal. How can it be done? The operator may use the techniques of a chess player in analyzing the possibilities of the system's "next moves" and choose the behaviour that improves, according to some criterion, the situation for him in the near or distant future. The operator, when confronted with a choice, may analyze the effects of future demands on the present choices and choose the act which leads to a series of diminishing loads or demands. Thus the first choice may not necessarily be the apparently "best" if the future implications are taken into account. Then on each succeeding choice, one more step into the future is added and the process repeated. Although this seems like a complicated process, it is no more than what a skilled game player does in "rapid transit chess" without conscious thought, and in a second of decision time. How can such a program be implemented? The chess playing programs offer a solution. Examine all choices, evaluate each according to a set of criteria, examine the consequences of those what exceed a threshold level, repeat with all choices available at this level and so on until some horizon is reached. That sequence which led to the best state at the horizon is followed for one step. Then the process is repeated. This latter involves only the addition of whatever new choices may have arisen subsequent to the first choice act, plus those possible events which "rose above the horizon" because of the passage of time in the mission. Then the process is repeated throughout the mission. The distance of the horizon is one variable which corresponds to the ability of the operator to "look ahead"; the criteria by which various choices are evaluated correspond to the "wisdom" or experience of the operator.

The data resulting from such a game of operator against mission would provide a most useful base against which to evaluate the performance of actual operators, by means of which to alter training processes and materials, and so on. In other words, if we can use such a gaming system to establish the best procedure, we have obtained an absolute standard, with all its attendant advantages and applications, for that system engaged in that mission.

A CONCEPTUAL SYSTEM

There must be ways to get the mission, the machine, the operator, the man-machine interaction into the system.

All four parts must be capable of change. A new machine configuration, new data about the operator, new constraints on the mission, new models of man-machien interaction, all must be put into the system easily without interfering with what is not changed and with the basic logic of the system.

This means that there must be a superordinate operating system which manages the various parts and uses information from the various parts to accomplish its calculations.

The superordinate system must have the following characteristics:

It can call upon the mission description to find out what events have been initiated over a time period of length τ and what events will be initiated up to some time T, in the future.

It can call on the machine system data to determine whether the machine can follow the trajectory (in multi-dimensional space) required by the mission events in time τ+T.

It can call on the man-machine interaction data to determine what the operator will be required to do to drive the machine along the trajectory demanded by the mission.

It can call on the operator data to determine whether the HO can do what is needed, and how much of HO's capacity is required to do it.

It will then, if all the foregoing do not lead to a negative conclusion, play the game to establish the optimum path in the space of time and behaviours for the HO to follow. The process will be repeated at each time instant, τ, throughout the mission.

Since there are three components involved in the calculation of the load imposed on the HO by the mission, and assuming that the descriptive process has been done for the mission and the system, then, even without a thorough knowledge of HO's capacities and of the man-machine interactions, it would be possible to compute, conceptually, the minimum characteristics that HO would have to have to meet the demands of that mission with that system. Similarly, if one knew HO and the system, one could establish the boundary conditions within which the mission would have to fall to be feasible. And, of course, given a necessary mission and the capabilities of the HO, one could, conceptually at least, calculate the boundary conditions within which the system would have to fall to be useable. Given any two, one can determine the limits for the third which would still permit successful accomplishment.

Since missions are what is wanted, it is unlikely that in the first instance one would attempt to calculate the limiting missions unless there were severe limitations on the kind of hardware and human beings one could imagine applying to the mission. Therefore we would assume that mission descriptions would be a given input to the estimation process. Then, given HO capabilities, one could gain some insight into the directions of new equipment development which would be needed to do the missions; or for a given system, one could determine either whether it could do the mission with the available personnel or what additional information about HO one would need to get to answer the question of feasibility.

CONCLUSION AND RECOMMENDATIONS

There appears to be no simple reductionist solution to the problem of estimating the workload imposed on a human operator by a system engaged in a mission under human control and supervision. This is the direct consequence of the fact that the elements of a complex task are not immutably fixed in time and sequence. Thus most, if not all, elements may be moved about in time and reversed or otherwise changed in sequence without altering the success or efficiency of the system. From the point of view of the Human Operator (HO), there is much more flexibility in scheduling the allocation of resources and this is particularly helpful when HO's resources are strained by the demands.

As we have indicated earlier, one of the major problems is that of mission description. Historically, missions have been analyzed into successive units. By using sufficiently small elements as units, reference could be made to an HO data file. In many cases simple experiments had already been performed, often by laboratory psychologists—so that information was available on mean required times, variabilities in populations, and error rates. In other cases recourse could be taken to simple ad hoc experiments. This is the method of mission analysis. What is being proposed here is its eventual replacement by mission characterization. First we shall list some shortcomings of mission analysis. Second we shall describe the steps that are required for the development of mission characterization.

It may be doubted that it is reasonable to expect a good fit between the elemental data provided thus far by the laboratory and skilled behaviour in the real world. Following are some of the concerns:

1. Laboratory conditions favor fast responses at the cost of a fairly high error rate. However, it is typical that the sub-tasks of missions must be performed with practically no errors. While a 5% error rate is considered low in a reaction-time experiment it is intolerable in the control of a high-speed vehicle.

2. Laboratory experiments are performed on tasks on which the subject usually has had very little practice. We now have two reasons for suspecting the generalities provided by laboratory research. We do not know, for example, whether Hick's Law of the logarithmic relation between uncertainty and latency is applicable to skilled performance. First, reaction-time performance has usually been characterized by high error rates. Second, data have been obtained from unskilled persons.

3. With the exception of tracking, single-episode tasks have prevailed in the laboratory. One cannot infer from the time of a single stimulus-response the amount of time that will be required if that response is embedded in serial activity. The speed of a pianist's finger movements

is far faster than would be provided by estimates from reaction time.

4. Where control may be described as supervisory, it is already understood that hierarchical organization exists, which in turn implies intelligent behaviour. HO is allowed to move time windows, within limits, to select among operations, adding some, deleting others, etc. Stimulus-response elements, which are the units of analysis, cease to dominate behaviour.

5. However, it is likely under time stress that behaviour will revert to being less intelligent parallelling Bartlett's findings on the effects of fatigue. Thus, even a more sophisticated analysis may not be successful since there is no way of dealing with the essential factor of concern: how performance changes as time stress increases.

What is being suggested is that complex tasks be characterized rather than analyzed into sequential units and then attempt to learn how values of the characterization variables influence the effect of time stress on performance. Characterization variables might include the amount and difficulty of inspecting, stabilizing, estimating, etc. Also, a mission might be characterized by the stochastic distribution of the transactions. Finally, the frequency of possible intelligent actions would be described. We hardly have a vocabulary for such characterization, but we can expect one to emerge from a program of research that may have the following stepwise structure.

1. Observe performance in real tasks, using skilled operators, and devise a table of characteristics for each. Subject the operators to varying degrees of time pressure in performing a mission. Obtain performance measures of errors (graded amount, incidence of commission and omission errors, etc.), of indications of intelligent behaviour, of workload ratings.

With various tasks studied in this way, task characteristics could be related to time stress. For example, more mechanical tasks might show a gradual decline, but tasks where intelligence operations is possible might show more sudden breakdowns. It is also possible that quite different slopes will be obtained with the different degrees of stochastic dependence, other variables being constant. For example, it has been shown that the requirement to change set more frequently results in poorer performance.

2. Devise synthetic tasks, including clear indicators (usually lacking in real tasks) of when intelligent behaviour is being engaged in. Train operators in these synthetic skills and test them with varying degrees of time stress. This would be a way of verifying or falsifying hypotheses derived from the real tasks in (1) above.

3. Establish the validity of the derived characteristics by devising new tasks with the same formal characteristics but with considerably different concrete transactions.

4. Using characteristics that have proved to be rugged, develop a method of computer simulation of HO interacting with a device on a mission. If it is found that behaviour changes in type with time stress this must be included in the simulation.

5. Characterize the human operations on a device and mission of interest. Subject the synthetic operator to variations in time stress by computer simulation to establish boundary conditions for satisfactory performance.

SUMMARY

Any workload estimation technique as opposed to virtually all workload measurement techniques requires a comprehensive description of the human operator, the system HO is to use and the mission the man-machine system is to accomplish. In the absence of any one of these three parts, it is manifestly impossible to make a rational estimate of the load imposed by that system doing that mission on an HO. Simple linear description of the sequence of events that will take place during the mission is not enough. Events are not rigidly fixed in time so that the HO has significant freedom to move component tasks around when things pile up. In a complex task, the number of events which may be moved can be large with resulting great difficulties for the analyst.

Task pacing, self- versus machine-paced-, is discussed and redefined as measures on continuous scales of the degree to which events during a mission are time and sequence bound. Problems with some of the existing techniques are discussed and some possible paths toward solutions are suggested. It has become clear that the present reductionist methods are not able to provide satisfactory models of intelligent human operator behaviour which allow estimates of mental workload to be obtained from computer-based analysis methods. This leads the analyst inevitably toward artificial intelligence as the ultimate solution of the workload estimation problem. Virtually

all workers in the field agree that a highly trained and properly motivated human operator can provide excellent reliable and valid reports on the subjectively assessed effort required to perform. The Cooper rating scale is an example.

Since the principal validation of any workload estimation method is either long term statistical data on system effectiveness and performance or the report of the human operators of the system; and since the former is usually very difficult to obtain, one is left with the notion that the simulation of an intelligent and introspective participant-observer coupled with an adequate system characterization is the best way to obtain reliable and valid workload estimates.

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APPENDIX

Intelligent Behaviour and Time Stress

It may be hypothesized that as time stress (Siegel & Wolf, 1969) increases, there will come a point at which the employment of intelligent behaviour begins to diminish. If this hypothesis is true, any computer simulation that includes intelligent behaviour by HO must also include an interaction between the employment of intelligent behaviour and time stress. As HO becomes skilled on a task, he learns many ways of making the task easier in addition to the acquisition of rote habits. These include the learning of permissible temporal limits for responses and the making of optimal placements of responses within these windows. It also includes the recognition of familiar stimulus patterns so that a standard series of responses may be used. Without these accomplishments HO is in danger of encountering overloads from time to time. An operator who employs intelligent behaviour may perform at a higher rate of pacing than one who does not. However, it should be evident that the employment of intelligent behaviour itself demands a portion of HO's limited capacity. It is here suggested that as rate of pacing increases so that HO is unable to both respond and plan, the planning will drop out as urgent responses are made. Since intelligent behaviour is necessary to maintain a high pace there is necessarily a sharp drop in the quality of performance.

A parallel may be found in the effect of fatigue, which increases time stress by reducing capacity rather than by increasing rate of objective pacing. In the historical study by Bartlett, "Fatigue following highly skilled work" (1943) it was, in fact, found that intelligent behaviour was reduced, as is evident from the following statement: "When an operator was fresh a glance at the dominant signals meant an interpretation of the whole panel, and a movement of a controlling lever meant something that the machine was doing, or would very soon begin to do. As the task continued the panel split up, so that it became twenty or so separate recording instruments. And the controlling movements split up also, so that when any one was made it was not pictured in a pattern of machine control, but only as the correction of a particular instrument reading." Thus, there was a regression from the intelligent control of an integrated system to mechanical reaction to the separate elements.

An initial attempt was made to devise a test that would illustrate the reduction of intelligent behaviour as time stress was increased. This is the Pointers Test that is attached. The subject moves from left to right in judging the relation between the pointer positions on a three-dial frame with the frame to its left. Basically the operator has to decide which of the three pointers moved differently than the other two, or if that was the case. The instructions also allow the subject to examine earlier parts of the test which may be transferred directly to the new problems. Six college students were tested (one of whom, unfortunately, did not understand the instructions) with time allowance in voiced pacing ranging from 0.59 to 1.82 of each subject's personal required time (without the option of intelligent behaviour). Only the subject given the slowest pacing made consistent use of the opportunities to use earlier parts of the test. The two subjects who were paced considerably behond their personal level made no use of that option. Interestingly, the subject who was given the slowest pacing tied for second in terminal rate of performance (relative to personal rate). These results are very preliminary and only suggestive. The method of voiced pacing is inadequate for putting sufficient speed stress on the subject so that performance will suffer. Still it was seen that removal of time stress may paradoxically result in fast performance if the opportunity exists for intelligent behaviour.

The test, of course, is severely limited in the kinds of intelligent behaviour that are possible. Especially neglected is HO's ability to use flexible timing to prevent responses from piling up. To study this aspect of intelligent behaviour would require testing with a more direct kind of pacing, which is not possible with a paper-and-pencil test. Also, the test contains very few items so skilled performance was not actually obtained. With the use of more direct pacing, opportunity for a variety of intelligent behaviours, and highly practiced subjects data could be obtained that would be instructive on the reduction of intelligent behaviour and the breakdown of performance that occurs with increase of time stress. Following Sanders' suggestion of assessing workload by "testing the task to its limit" (1979) a simulated mission might be evaluated by simply plotting performance against rate of pacing. A task near the margin could be identified as such because very little increase in speed of pacing would bring about a breakdown of performance. It should follow that if a task depends very strongly on intelligent behaviour, the breakdown in performance will occur rather suddenly as some critical rate of pacing is reached.

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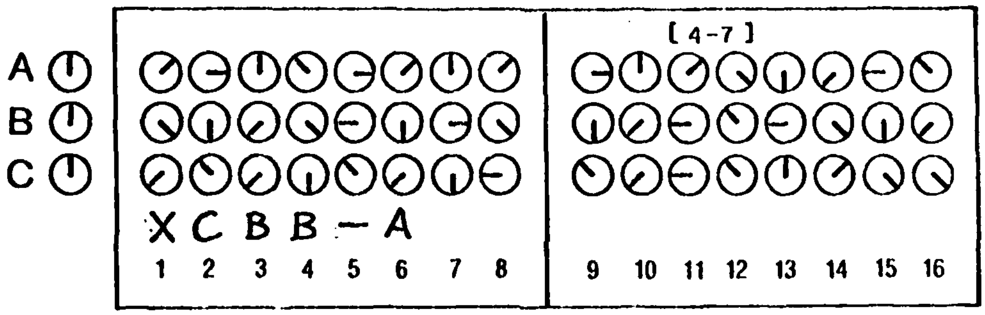
THE POINTERS TEST

The small circles, such as you see on this page represent dials. The short line on each circle represents a pointer on the dial. A pointer can have one of eight positions, thus:

In going from left to right in the series above, the pointer has rotated *clockwise*, one step at a time. However, in the test, a pointer may rotate in the opposite direction, *counterclockwise*. It may also move more than one step from one frame to the next, or not move at all.

Each frame of the test consists of a vertical column of the three dials, A, B, and C. In the example below there are 16 frames. The task is to indicate for each frame whether the three pointers have rotated in the same way from their positions on the frame to the left.

Here is a series for which the first six frames have already been marked.



You are to continue the series using the following rules:

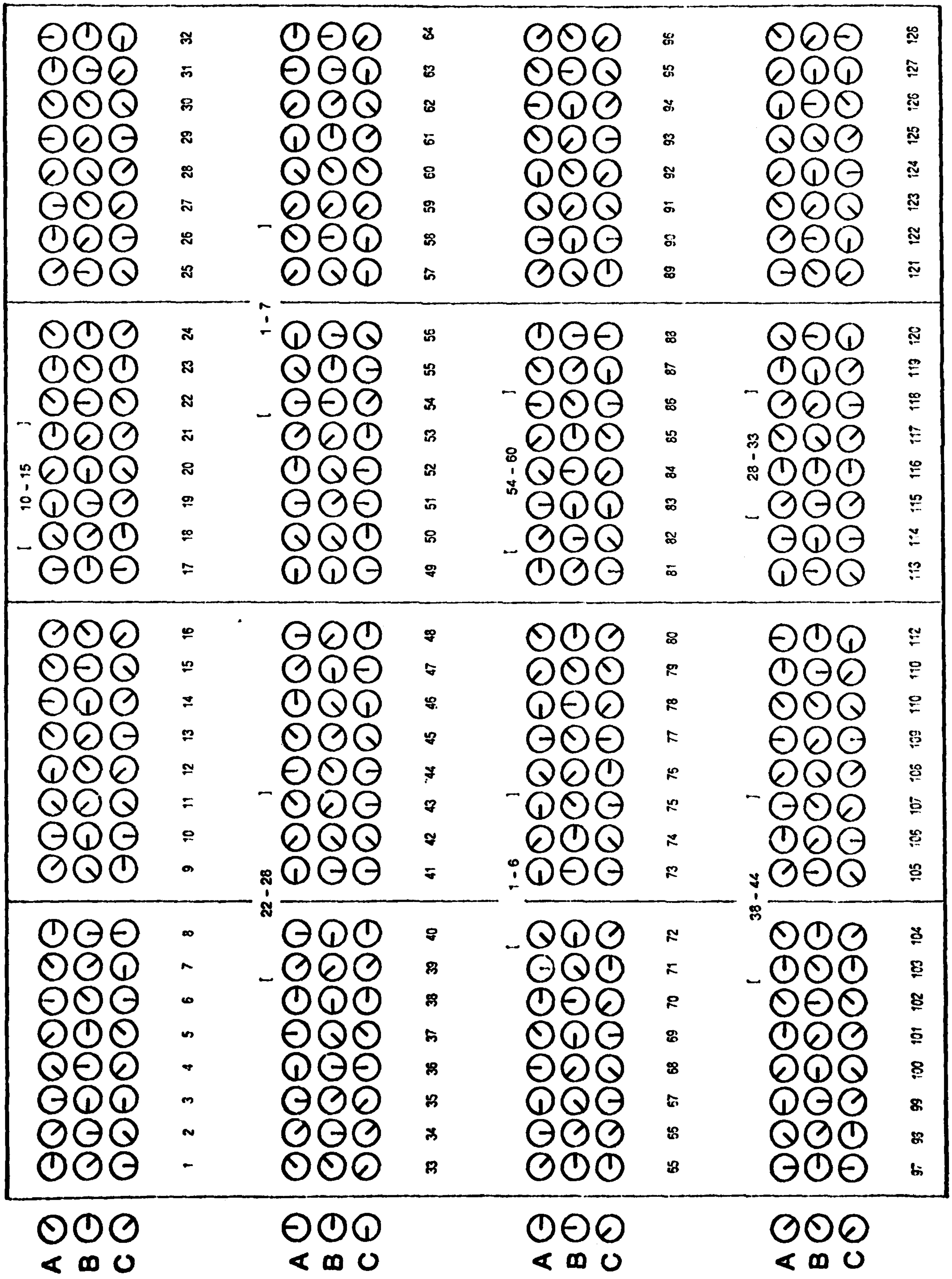
1. If all three pointers rotated in the same direction (clockwise or counterclockwise) and the same number of steps, draw a bar (—) above the frame number.

2. If two pointers rotated in the same direction and the same number of steps, but one pointer differed either in direction or number of steps, write down the letter for that dial (A, B, or C).

3. If all three pointers rotated differently as to direction or number of steps, write down an X.

As you move through the series you can simplify your task by writing in the trial numbers of previous frames instead of the —, A, B C, X marks. This can be done when the previous marks are correct on the new frames. The brackets above frames 11-12 tell you that the correct marks occurred in the range 4-7. Thus, you could have written in 5 and 6 instead of — and A. Frames 8-10 are identical with frames 1-3. Thus, you could have written in 1, 2, and 3 instead of C, —, and X. You may finally note that the correct entries for frames 13-16 are exactly the reverse of those for frames 1-4. Thus, you could have written 4, 3, 2, and 1 instead of B, B, C, and X.

incorrect
revise


10 - 15
1 - 7
54 - 60
28 - 33
22 - 28
1 - 6
38 - 44
A
B
C

THE POINTERS TEST

SCORING KEY, PAGE 1

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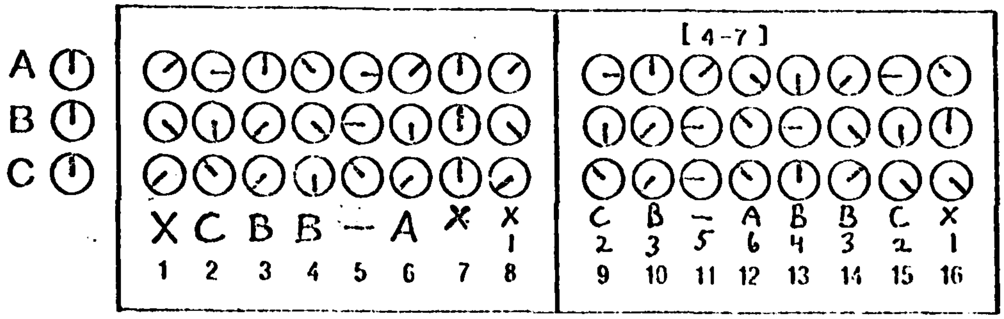

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As you move through the series you can simplify your task by writing in the trial numbers of previous frames instead of the —, A, B C, X marks. This can be done when the previous marks are correct on the new frames. The brackets above frames 11-12 tell you that the correct marks occurred in the range 4-7. Thus, you could have written in 5 and 6 instead of — and A. Frames 8-10 are identical with frames 1-3. Thus, you could have written in 1, 2, and 3 instead of C, —, and X. incorrect
You may finally note that the correct entries for frames 13-16 are exactly the reverse of those for frames 1-4. Thus, you could have written 4, 3, 2, and 1 instead of B, B, C, and X. revise

SCORING KEY, PAGE 2 (including alternative trial-number responses)