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Toward a Mathematical Formalism of Performance, Task Difficulty, and Activation

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INTRODUCTION

Both people and their environments are **reciprocal** *determinants of each other.*
A. Bandura (Social Learning Theory, 1977)

The continually evolving sophistication and complexity of military and civilian technology is increasing the burden on human operators in man-machine systems. Whether a weapons platform or space vehicle, a power plant or factory control station, or even an aid for the handicapped, the informational and operational demands will ultimately exceed human capabilities, unless the man can be relieved by the machine. Dynamic task partitioning, shifting and sharing tasks between human and machine in real time is theoretically feasible. However, it is currently impossible to implement, since the man-machine interface lacks **reciprocal** status assessment capability. This lack of reciprocity is a key indicator of the low level of man-machine integration and results in the realization that the interface is a weak link, which can directly degrade mission success and jeopardize system survival.

In order to achieve reciprocal status assessment, it is necessary to provide means for the machine to monitor the human, while continuing to improve the means by which the human monitors the machine. Assessment of human functional status should include both physical and mental-state estimation, which may be approached by physiological and behavioral monitoring. While this is presumed necessary, is it sufficient? Functional status, of human or machine, is only operationally relevant in the context of predicting performance - for our ultimate end point is to maximize system performance, while conserving valuable resources (men, machines, and information). Therefore, functional status is an input for predicting performance, survival and mission success.

Workload is frequently offered as a means of evaluating system design and predicting system performance, survival, and mission success. But the term "workload" has numerous connotations (ref. 1) and, rather than referring to a well-defined, unique, and generally agreed upon phenomenon, it serves as a convenient label for a number of events, ideas, states, dimensions and other constructs that are ill-defined and difficult to measure (ref. 2). Sheridan and Stassen (ref. 1) have illustrated six alternative definitions (D1 - D6) and four corresponding measurements (M1 - M4) of "workload" in a control paradigm (see Figure 1). Clearly, only one (or none) of these definitions is scientifically permissible. Part of this dilemma may be circumvented by operationally segmenting "workload" into physical (D4) and mental components, reducing the candidate set of definitions for "mental workload" to five possibilities. Performance (D6) is not "workload", further reducing the candidate set to four. An attempt could be made to further segment "mental workload" into objective, operator-independent (D1 & D2) and subjective, operator-dependent (D3 & D5) components. However, D1 and D2 are not independent of the person performing the task; even the most well-intentioned individuals covertly corrupt (interpret) their assigned tasks and performance criteria, based on their perception of their organization's "reward structure" - which is, unfortunately, temporally unstable, because organizations are usually diachronically and synchronically inconsistent.

Given the definitional problems of "workload", it is theoretically and practically not useful if the objective is to realize an *engineering* solution for the problem of predicting man-machine system performance, survival and mission success. There may be numerous alternative approaches for solving this problem. One potentially useful path is to invoke the relatively old Yerkes-Dodson postulate (which purports to relate performance as a function of task difficulty and activation (**refs.** 3 and 4)) (see Figure 2) and the relatively new psycho-technology of cognitive behaviorism (Organizational Behavior Management, which purports to be a systematic, structured approach to human performance problem-solving (e.g. **ref.** 5)). Let us assert that performance is what is important, in the practical world of military and civilian operations, and that if performance is maximized, while minimizing the loss of valuable resources, the same endpoint is obtained as if it were practical to define, measure and control "workload". This "end run" around "workload" requires definition of performance, task difficulty, and activation in a manner useful to the system designer - an engineer normally lacking extensive training in physiology and psychology.

PERFORMANCE, TASK DIFFICULTY AND ACTIVATION

The rudiments of a mathematical formalism for integrating system performance, task difficulty, and physiological activation are offered here with the explicit understanding that it is unnecessary for this formalism to be correct or true - but that it is essential for the formalism to be useful! The implication here is that a *technology* is under development, which is to be evaluated by its effectiveness, as opposed to a *science*, which must be evaluated by the correctness of its theories. The purpose of this mathematical formalism, which employs existing mathematical tools that are well known to engineers, is to provide a framework for developing a structured, systematic approach **for:**

a) communicating physiological and psychological requirements, in a qualitative and quantitative manner, to the system design engineer, and
b) simplifying the problem of instructing a machine in the measurement and utilization of performance.

Basic Definitions

Define a mission ($\underline{M}$) as an ordered set of m explicit goals (G_i), such that:

$$\underline{M} = \{\underline{G}_1, \underline{G}_2, \underline{G}_3, \ldots, \underline{G}_i, \ldots \underline{G}_m\} \qquad \text{[Eqn. 1.01]}$$

A mission segment, a commonly used term, can then be viewed as a subset of these goals. In this formalism, a mission cannot exist unless one or more explicitly defined goals exist and it follows that mission performance cannot exist without goal performance. The term *explicit* is used in the same fashion as Farina & Wheaton (ref. 6); explicit means a goal was presented to, at least, the operator and one independent observer (not necessarily human) and that some objective procedure exists, allowing the observer to verify whether or not a goal has been achieved. A specific goal ($\underline{G}_i$) is then defined to be a function of a specific task ($\underline{T}_i$) and a task-specific criterion (C_i).

A task will be viewed as a position vector in some N-dimensional, time independent, state space ($Ð^N$), such that the task describes the difference ($\Delta\underline{S}^g$) in **position** between the goal state ($\underline{S}^g$) and the origin state ($\underline{S}^o$) in the, usually local, environment.

$$\underline{T} = \Delta\underline{S}^g = \underline{S}^g - \underline{S}^o \qquad \text{[Eqn. 1.02]}$$

A task is thus defined as a criterion-independent **vector** variable that is solely a function of the component dimensions of $Ð^N$. In order to simplify this exposition, it is explicitly assumed that $\underline{S}^g$ is an idealized point, rather than a volume, in task space. This allows consideration of performance only relative to a criterion of time. Considerations of performance relative to variations in the task (the goal state as a volume, instead of a point) are also appropriate, but only **make** this exposition more complex - without contributing additional conceptual information.

A criterion (C_i) is defined as a time-dependent scalar variable that is independent of $\mathrm{Đ}^N$ and will be viewed as the time lapse (Δt^g) that is required for translation from the origin state ($\underline{\mathbf{S}}^o$) to the goal state ($\underline{\mathbf{S}}^g$), in order to complete the task and attain the goal.

$$C = \Delta t^g = t^g - t^o \qquad \text{[Eqn. 1.03]}$$

A goal is then defined as the algebraic ratio of a task and a task-specific criterion.

$$\underline{\mathbf{G}}_i = \underline{\mathbf{T}}_i/C_i = (\Delta\underline{\mathbf{S}}^g)_i/(\Delta t^g)_i \qquad \text{[Eqn. 1.04]}$$

The analogous construct in classical physics is velocity, which is the time rate of change of position in space; it is the ratio of a position vector and time. In this formalism, goals will be conceptualized analogous to mean velocities, tasks analogous to displacements and criteria as time lapses (until the goal state is generalized from a point to a volume).

Conceptualizing a task as a displacement in the environmental state - from origin state to goal state, it is further recognized that:

a) a task is a change in state which is the consequence of time-dependent behaviors (overt or covert and voluntary or involuntary), just as a "physical" displacement is a consequence of (time-dependent) velocities;

b) a task may be characterized according to its difficulty, just as a "physical" displacement may be characterized according path-dependent dissipative effects; and

c) a task requires physical and/or mental energy release, just as a "physical" displacement requires work.

Equation 1.04 describes a goal as a mean velocity across a geometrically minimum (presumed optimal) path from origin state to goal state. Given that the integral state change is the consequence of time-dependent behavior(s), the instantaneous temporal rate of change in state, at any instant, is construed as the vector variable behavior ($\underline{\mathbf{B}}$). Thus,

$$\underline{\mathbf{B}} = d\underline{\mathbf{S}}/dt \qquad \text{but} \qquad \underline{\mathbf{G}}_i = (\Delta\underline{\mathbf{S}}^g)_i/(\Delta t^g)_i$$

Decomposing the resultant vector into orthogonal components, with one component ($\underline{\mathbf{r}}^g$) having the same direction as the goal vector ($\underline{\mathbf{G}}_i$), yields a goal-directed vector component ($\underline{\mathbf{B}}^g$) that will be termed *purposive* behavior.

$$\underline{\mathbf{B}}^g = d\underline{\mathbf{r}}^g/dt \qquad \text{[Eqn. 1.05]}$$

A benefit of this approach is that, while an "instantaneous goal" can have no meaning, progress (both direction and magnitude) toward or away from a goal may be determined at any point in time. This lays the foundation for predicting whether or not the goal state will be achieved within the time criterion. Furthermore, it begins to permit determination of whether the operator is "leading" or "lagging", so that "leveling" via dynamic task partitioning can be implemented:

a) if the operator is "lagging" the goal trajectory, then assistance in various forms can be provided to "lighten the load"; or

b) if the operator is "leading" the goal trajectory, then slack time will result which may be used for lower priority goals, including preventing boredom or decrements in vigilance.

At this juncture, a few clarifications are required. First, what are the dimensions of the task space and is it necessary to identify all of the task dimensions for any given task?

Let us assert that only those dimensions containing critical features of the task need to be identified; other dimensions, where variation on these dimensions does not lead to significant redefinition of the task, can (in the first approximation) be ignored. This is not an example of logical positivism, but merely a standard engineering ploy to capture the important aspects of a process/problem without unnecessarily expending resources on higher order effects. Thus, the definition of the task determines the dimensions of the task space. Second, doesn't this formalism fail in the case of a "tracking" task (e.g. just maintain a constant altitude), where the goal state and the origin state are the same? Doesn't this imply that the goal does not exist, since the task is zero ($\Delta\underline{S}^g = \underline{S}^g - \underline{S}^o$)? No, quite the contrary. The goal does **exist**, and the goal is to have a zero change in altitude (tasks have direction and magnitude) in the specified time period.

Performance

Performance is defined as a scalar variable whose functional form will depend on assessment of the values assigned to various alternative outcomes. This is a classical problem of operations research and can be approached by standard decision theory and utility theory techniques, with the aid of probabilistic risk assessment. While the details are beyond the limited scope of this exposition, let us assume that the decision-maker's "utility" function (performance versus outcome) has been determined, either by direct measurement or by any one of a number of standard indirect methods, and has the following form:

$$P = f\,[\underline{\mathbf{G}},\underline{\mathbf{B}}(t)] = e^{-[x/\lambda]^2}$$

where:

$$x = \left\{(^1/_{\Delta t}) \int_{t^o}^{t} \underline{\mathbf{B}}(t)dt\right\} - \underline{\mathbf{G}}$$

and λ is some shape factor, $\underline{\mathbf{B}}$ is the measured behavior, and $\underline{\mathbf{G}}$ is the goal. This functional form is no more than that of a normal distribution and was selected somewhat arbitrarily. It is by no means the *only* form nor is it the *correct* form of the performance function; the correct form can only be that form chosen (directly or indirectly) by the decision-maker responsible for setting the goal and defining performance. It does, however, have some interesting properties:

a) it is a continuous function with range $0 \rightarrow 1$ and infinite domain (all possible outcomes);
b) it is symmetrical about $x = 0$, the implication being that reaching the goal state too early (*wasting fuel*) is just as bad as arriving too late (*missing the rendezvous*); and
c) when the value of $x = 0$, performance is 1.0 and as $|x|$ increases in magnitude, performance decreases towards zero.

The specific functional form of performance has not been defined, since it may vary with each goal and each decision-maker. However, a mathematical basis for completely determining its functional form, independent of the operator and using standard tools **has been defined**. While, at first, this appears to place an unreasonable burden on the organization defining the mission, this is not true. Both military and civilian organizations are constantly striving to structure operations and define objectives. For any specific man-machine system (SC/AT* **heli**copter, sonar/radar system, nuclear power plant, etc.) the number and diversity of tasks and goals are finite and considerably constrained. Therefore, not only is the problem tractable, but clear definitions of tasks, time criteria and performance measures are an integral and necessary part of effective and efficient communication of the mission objectives to the human operator.

* Scout/Attack (SC/AT)

Difficulty

Let us view task or goal difficulty as a construct that impedes goal attainment. A number of investigators have proposed "dimensions" for characterizing human operator tasks. One example is that of Farina & Wheaton as described by Fleishman & Quaintance (ref. 7) and contains 21 "dimensions" and associated measuring scales, with range $1 \rightarrow 7$. In this formalism, some of these dimensions will be used to develop a scalar coefficient termed task or goal *difficulty*, in keeping with the Yerkes-Dodson principle requiring performance to be a function of task difficulty and activation. Fleishman & Quaintance (ref. 7) cite examples in which polynomial constructs using various of these dimensions have been correlated with performance - a result expected based on the Yerkes-Dodson principle. Table 1 enumerates the original 21 candidate dimensions and identifies four which do not appear independent (items [4], [5], [13], and [20]). Since orthogonality is essential, only the remaining 17 appear acceptable. Furthermore, consistent with this formalism, candidate dimension [2] is recognized as time-dependent and thus permissible for constructing goal difficulty, but not task difficulty. Task difficulty is then defined using a weighted combination of the 16 remaining dimensions; goal difficulty (ξ) is defined when the 17^{th} criterion-based dimension, [2], is included in the combination. There are two classical forms for constructing such a combination, a weighted sum or a weighted product:

$$\xi = \sum \beta_k X_k \qquad \text{or} \qquad \xi = \prod \beta_k X_k \qquad \text{[Eqn. 1.06]}$$

where k = dimensional identifier ($1 \rightarrow 17$), β_k = regression coefficients from a population of operators, and X_k = an individual operator's rating ($1 \rightarrow 7$ using the existing rating scales or 0, if the dimension is not relevant), so that individual differences can be accommodated. Discriminating between these two functional forms, or some intermediate form, is a classical problem; consider, for example, the well-known Valency-Instrumentality-Expectancy (VIE) theory (refs. 8 and 9), where both forms often correlate well with the intervening variable. Selection of the preferred functional form of ξ must await empirical investigation.

Once again, as in the case of performance, this formalism does not provide a simple answer for determining task or goal difficulty. Difficulty is expected to vary with the individual operator and the specific goal. However, the formalism does provide a structured, systematic means of determining difficulty that may allow psychologists to communicate to engineers **quantitative** information that can be employed in the system design, development, and implementation process.

Activation

Every *living* organism exists in a state of dynamic quasi-equilibrium and may be viewed as an energy transducer - obtaining, storing, and releasing energy in different forms. This release of stored energy results in the production of work and heat which may (directly or indirectly) be detected in the form of behaviors (overt or covert) having magnitude (intensity) and direction (goal-directed or otherwise). The concepts of arousal (phasic) and activation (tonic) have their origins at least as early as the beginning of this century, when attempts were made to relate variations in behavioral intensity and performance to variations in psychophysiological activity (ref. 10). This work suggested that behavior could be regarded as varying along a continuum of intensity, from deep sleep to extreme excitement, and attempts were made to specify the physiological changes taking place at crucial points on this continuum - which became known as the level of activation or arousal (refs. 11, 12, and 13).

If the premise that behavior, as defined, requires the release of energy, the existence of a continuum can be logically deduced. At one extreme, a *living* organism must expend some minimal energy to sustain fundamental life processes. At the other extreme, there must be some maximum release rate beyond which the organism will be destroyed due, if nothing else, to its inability to shed heat rapidly enough to prevent thermal denaturation of its constituent macromolecules. Between these limits, a variety of release rates are expected as the organism attempts to cope, as best it can, with the vagaries of its environment.

Merely employing the total energy release rate as an index of activation, while attractive in its simplicity, ignores an intrinsic property of the organism - the homeostatic tendency that operates over a reasonably wide dynamic range, that tends to maintain the organism in a state of dynamic quasi-equilibrium, and that arises because the organism is, as Sherrington* indicated, integrated. In the absence of changing external (environmental) and internal (needs, drives) forces, the organism will generally waver about the same release rate. Conversely, in the presence of changing external or internal forces, the level of energy release changes until the forces acting on the organism abate.

This wavering, in the "relaxed" state, is probably due to the looseness (wide deadband) of the organism's internal feedback control systems; candidate physiological measures of arousal or activation - taken while subjects were simply doing nothing in a relaxed state - were found to have fairly low positive correlations. However, when the system is driven (a standard engineering ploy in systems analysis) so that arousal is presumably induced, the candidate measures change in the expected direction. An example is Berlyne's meta-analysis (ref. 14) of several studies on mental effort; average EEG frequency, muscle tension, heart rate and skin conductance increased with purported increases in mental effort. Furthermore, Eason & Dudley (ref. 15) measured EEG evoked potentials, heart rate, skin resistance and muscle tension and reported that, with increasing task difficulty (they presumed this to be more arousing), the greater the change and all measures acted together.

The activation phenomenon, however, is not simple. Physiological indices that *hypothetically* measure arousal or activation actually move in different directions for different tasks. During tasks that require intake of information, Lacey (ref. 16) has shown that heart rate decreases while skin conductance increases. Alternatively, with tasks requiring internal processing or thinking, the reverse has been reported. What appears implicit from these findings is that careful consideration of the underlying energetics, from the organism's point of view, is imperative. Simply monitoring a physiological or behavioral parameter, without consideration of the specific operational circumstances, should not be expected to yield useful information.

In this formalism, activation energy (A) level is defined as a scalar variable, the resultant level of energy release derived from a weighted set of physiological (Φ) and behavioral (Ψ) measures. One possible form is:

$$A = \sum \gamma_j Y_j \qquad \text{[Eqn. 1.07]}$$

where j = the Φ or Ψ measure specifier, γ_j = bipolar weighting factors, and Y_j = the preprocessed Φ or Ψ data. It must be obtained while the human is being driven, not by operationally irrelevant secondary tasks, but during the normal control cycle of a dynamic task partitioner that is shifting and sharing mission relevant tasks between man and machine. Furthermore, the sign of the bipolar weighting factors must be determined based on rules that integrate the specific physiological and behavioral measures with the specific task(s) or, more realistically, task categories. Such rules, except for very simple cases, are currently undetermined. However, it is not unreasonable to expect that, in the presence of well-defined tasks and an appropriate set of physiological/behavioral measures, such rules can be developed from physiological principles and energetic considerations. Whether or not activation and difficulty, as defined here, will provide a robust estimate of performance can only be determined empirically.

*Sherrington, C.S.: Integrative action of the nervous system. New Haven: Yale University Press, 1906.

Derivative Quantities

We have defined quantities analogous (in physics) to time interval (criterion), displacement (task), mean velocity (goal), and instantaneous velocity (behavior or behavioral component). Much of classical physics deals with a large number of physical quantities that can be expressed in terms of a very small number of arbitrarily defined "articles of faith"; the fundament of physics is the existence of mass (m), length (l), and time (t). Each of these is arbitrarily defined and a standard quantity of each, agreed upon by most scientists, is maintained for reference in Paris and Gaithersburg. With these standards and the *principle of concatenation* we are able to determine other masses, lengths, and times, as well as derivative quantities. Examples of some derivative quantities, in terms of m,l,t are: area (l^2), volume (l^3), velocity (lt^{-1}), acceleration (lt^{-2}), density (ml^{-3}), momentum (mlt^{-1}), force (mlt^{-2}), energy (ml^2t^{-2}), frequency (t^{-1}), angular momentum (ml^2t^{-1}), and pressure ($ml^{-1}t^{-2}$). Even electric charge (q) was measured in terms of these basic and arbitrary quantities - through the ingenious Millikan oil drop experiment.

What this implies is that, no matter how complex the physical phenomenon, measurements can only be made in the very small number of arbitrarily defined dimensions that underlie the nomological network of classical physics. Analogously, this mathematical formalism requires a similar set of fundamental dimensions. Time and length have already been proposed as the underlying dimensions for criterion, task, goal, and behavior. However, without a hypothetical construct analogous to physical mass, more complex derivative quantities are prevented.

In this formalism, motivation ($\underline{\mathbf{M}}$) will is defined as a vector variable and an acceleration analogue, in that changes in behavior can be construed to be the consequence of motivation. In physics, the existence of acceleration requires the existence of force(s) - actually a net force. Invoking the principle of continuity of cognitive behaviorism, external (environmental) forces will be recognized as creating internal (need or drive) forces ($\underline{\mathbf{N}}$) which result in motivation. Can motivation or needs be directly measured? No, but then forces and acceleration cannot be directly measured; only mass, length and time can be measured!

Theorists in motivational psychology have postulated that performance is a function of the product of ability and motivation (ref. 8). This is consistent with the proposed formalism, if ability is considered as a mass analogue, since a need or drive would create motivation which would create a change in behavior leading to a displacement in task space. It would then become possible to conclude that, for a given ability, the greater the need, the greater the resultant motivation. Conversely, for an **observed** motivation, the less the ability, the greater the need. This latter statement initially appears counter-intuitive. However, in this formalism ability (α) is defined as a scalar variable that includes not only genetically determined (physical and mental) aptitude as well as experience and training, but also self-concept (a variable traditionally included in motivation). Therefore, if one's expectancy is that one cannot execute a task, then (in order to obtain the same level of motivation) it will require a greater need/drive than if one's expectancy was that one was quite proficient (and that the requisite behavior would lead to accomplishing the task, that one wanted to emit the requisite behavior, and that one wanted the reward - in other words, VIE theory).

In this formalism, it is postulated that the vector variables $\underline{\mathbf{N}}_\ell$ and $\underline{\mathbf{M}}_\ell$ are functionally related by the scalar variable α, such that:

$$\underline{\mathbf{M}}_\ell = \alpha \, \underline{\mathbf{N}}_\ell \qquad \text{[Eqn. 1.08]}$$

It is presumed that over reasonable time intervals, the magnitude of α should remain relatively stable (time independent). However, in the presence of fatigue, boredom, stress, or injury, apparent ability decreases. Therefore, it may be useful to define α - over reasonable time intervals - as the product of two variables, α_i and α_e, such that:

$$\alpha = \alpha_i \, \alpha_e \qquad \text{[Eqn. 1.09]}$$

where α_i has a relatively stable (*intrinsic*) value for a given individual and α_e is unstable (*extrinsic*) depending on fatigue, etc.

How can α_i be measured? In classical physics, the mass of an unknown object is found by comparison of its behavior to the behavior of an arbitrarily defined reference mass (the principle of concatenation). By analogy, it is therefore possible to define α_i in terms of some *arbitrary* reference ability. Of course, this raises the problem of how to apply a standard "force" in order to permit the determination; but this is no greater a problem than that found in classical physics. It can be solved by ingenuity, just like Millikan and his oil drop experiment! One potentially useful approach may be the Ability Rating Scale approach cited by Fleishman & Quaintance (ref. 7). Furthermore, one approach for determining α_e, in real time, may be a variant of Schmidtke's theory of destabilization classification in which fatigue is staged based on changes in the mean and variance of performance (ref. 17).

As originally stated, only the **rudiments** of a formalism are offered here. This mathematical structure (and associated measurement procedures) is far from complete. But there may be considerable power in this approach as indicated in the following simple example. Work is a path dependent function. Transition from an origin state to a goal state can be characterized by a minimum energy trajectory - this "optimum" path having been defined by the goal. Based on this, the goal-directed work requirement ($\underline{W}^g$) can be computed as:

$$\underline{W}^g = \xi \int_{S^o}^{S^g} \underline{N}^g d\underline{S} \equiv \xi \int_{S^o}^{S^g} \alpha^{-1} \underline{M}^g \, d\underline{S} \equiv \xi \int_{S^o}^{S^g} \alpha^{-1} (d^2 \underline{r}^g / dt^2) d\underline{S} \qquad \text{[Eqn. 1.10]}$$

which is expressed solely in terms of task, time, ability, and the subjective difficulty scale factor (ξ). This is not the actual work expended to attain the goal, as work will vary depending on the specific path taken; instead it may be viewed as the minimum increment (decrement) in work resulting from including (deleting) this particular goal in (from) the mission. $\underline{W}^g$ is an important quantity for any decision algorithm attempting to dynamically partition predetermined tasks between man and machine or to modify tasks in "mid-flight".

CONCLUSIONS

The rudiments of a mathematical formalism for handling operational, physiological, and psychological concepts have been developed for use by the man-machine system design engineer. The mathematical formalism provides a framework for developing a structured, systematic approach to the interface design problem, using existing mathematical tools, and simplifying the problem of "telling" a machine how to measure and use performance. If this formalism proves useful, the wealth of human knowledge in mathematics and physics can be transported, at very little cost, to solving problems in this area.

Figure 3 presents a diagrammatic means of envisioning how an "expert" metacontrol unit might be implemented within a man-machine system (ref. 17). Physical data from the machine (via its data bus) are acquired and preprocessed; physiological and behavioral data from the operator (via appropriate sensors) are acquired and preprocessed. These dynamic data are periodically introduced into the knowledge base, which also contains **machine** attributes (from the machine developer), **human** attributes (from biomedical/training personnel), **mission** attributes (from the mission planners), **operator** attributes (from simulator training), the rules of a complete "mathematical formalism", the rules of the OBM interventions, and other relevant deterministic and stochastic information. An inference engine utilizes this knowledge base to decide how to partition tasks between man and machine to maintain maximum *system* performance with the minimum cost in valuable resources.

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Table 1: Task Characteristics
(adapted from Fleishman & Quaintance, (ref. 7), pgs 474-494)

[1] **number of output units** - an output unit is what is produced by the task

[2] **duration for which an output must be maintained** - in our terminology this is a criterion which, together with a task, defines a goal

[3] **number of elements per output unit** - elements are the parts or components which comprise the output unit

[4] **workload** - defined as a function of the number of output units **[1]** to be produced relative to the time **[2]** allowed for their production or the length of time for which an output must be maintained

[5] **difficulty of goal attainment** - defined as a function of **[3]** and **[4]** and thus not an independent dimension

[6] **precision of responses** - the degree to which fine or exacting responses are required

[7] **response rate** - the frequency with which responses must be made

[8] **simultaneity of responses** - the number of effectors (e.g. hand, foot, arm, voice) used for responding in order to produce an output unit (mental activities are not included here, but **are** in item **[21]**)

[9] **degree of muscular effort involved**

[10] **number of procedural steps** - the number of responses needed to produce one output unit

[11] **dependency of procedural steps** - the degree of sequencing or linkage of procedural steps required

[12] **adherence to procedures** - the degree of criticality of following a prescribed sequence and stated procedures

[13] **procedural complexity** - defined as a function of **[10]** and **[11]**

[14] **variability of stimulus location** - the predictability of the physical location of the stimulus or stimulus complex

[15] **stimulus or stimulus-complex duration** - the fraction of time that the stimulus or stimulus-complex is available

[16] **regularity of stimulus occurrence** - the duration of inter-stimulus intervals (constant presence is considered equivalent to regular interval) and is a measure of the randomness of stimulus presentation

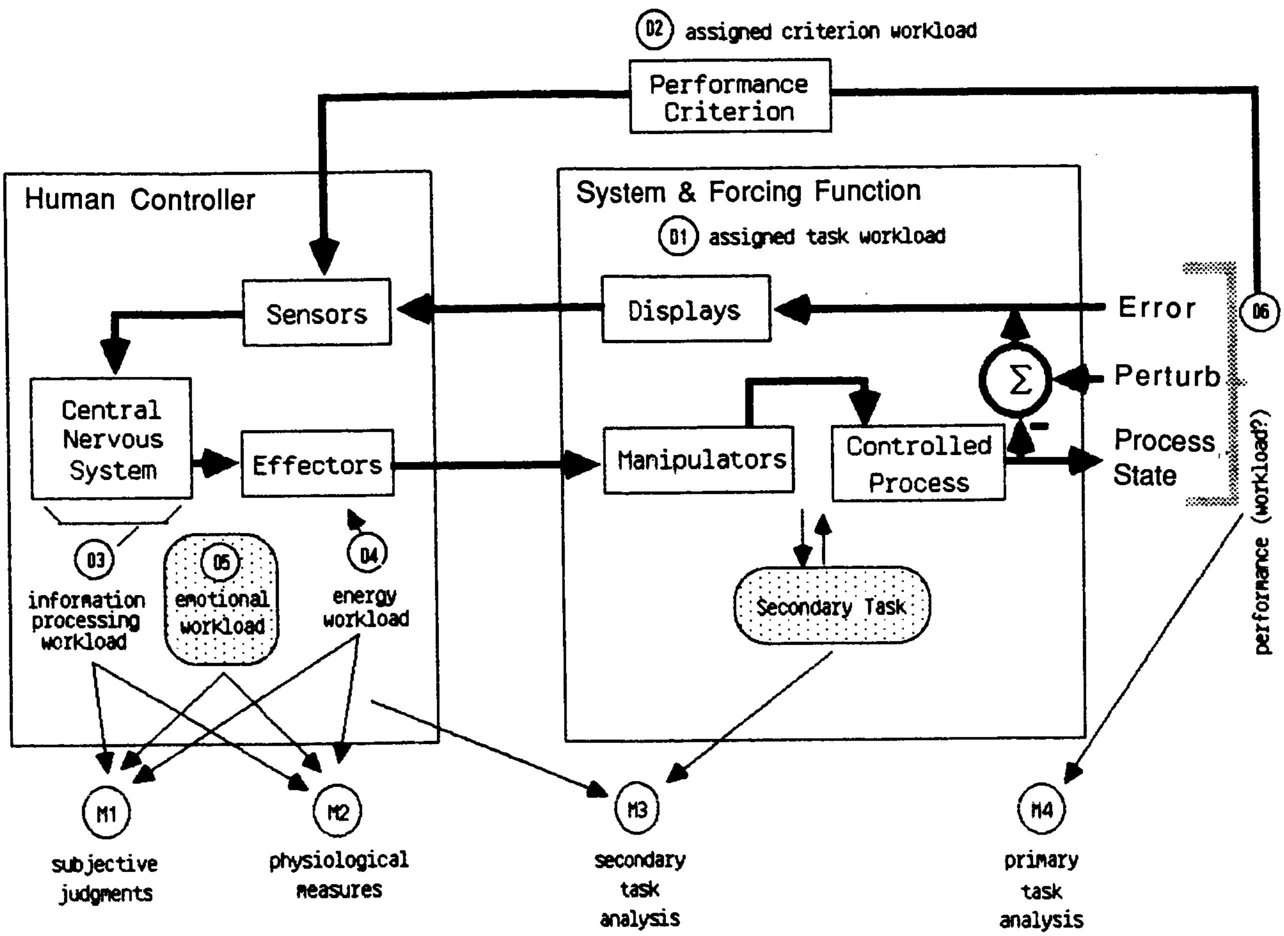
[17] **operator control of stimulus**

[18] **operator control of response**

[19] **reaction-time/feedback-lag relationship** - the ratio of the intervals defined by the (reaction) time from stimulus initiation to response initiation and the (feedback-lag) time from response initiation to feedback initiation

[20] **feedback** - how quickly feedback occurs once the response is made and is, thus, defined as a function of **[19]**

[21] **decision-making** - the multiplicity of choice-nodes, where the operator must decide which of several potential steps should be done next



(adapted from Sheridan & Stassen, Ref. 1, pg 242)

Figure 1. Alternative Workload Definitions.

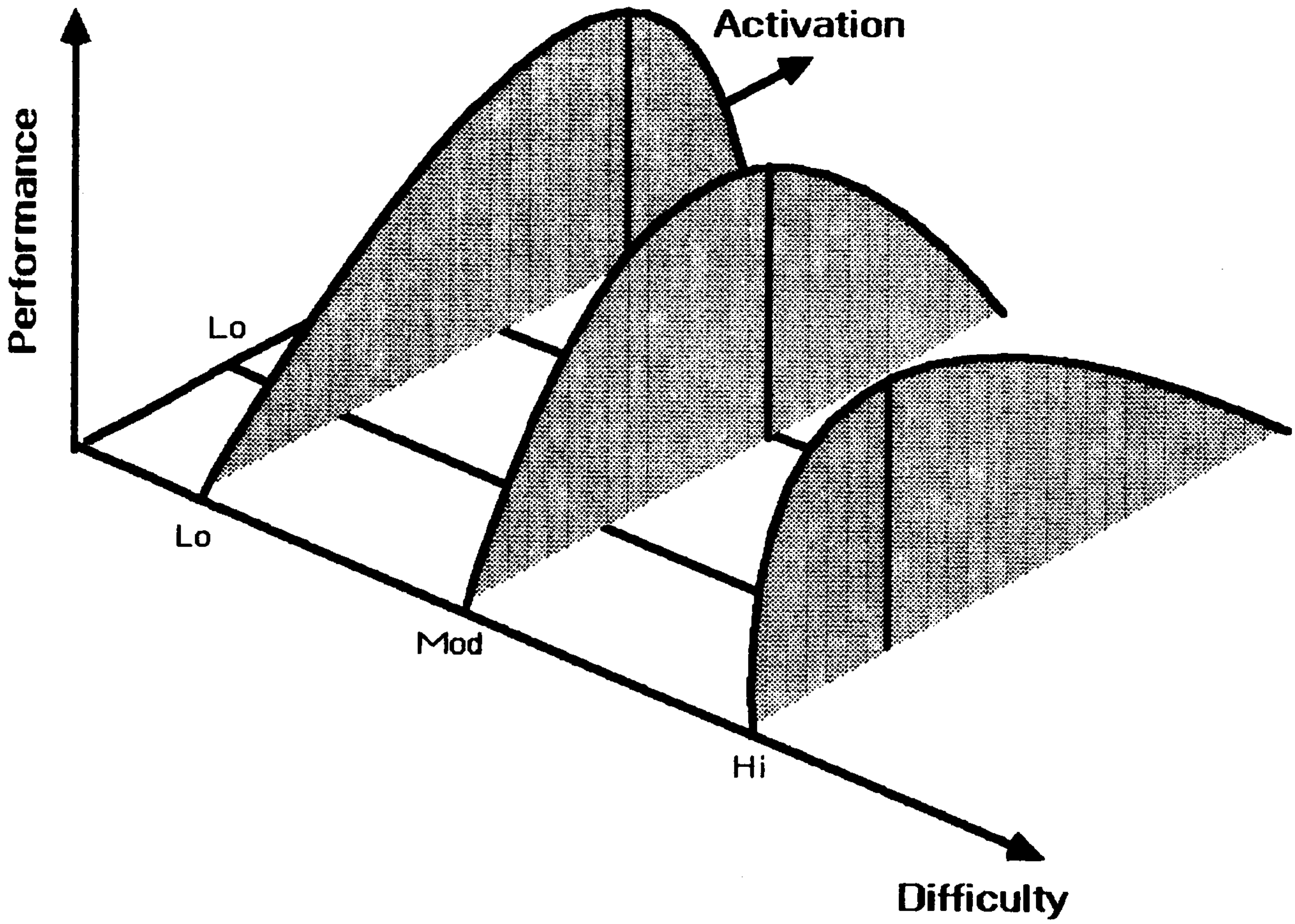


Figure 2. The Yerkes - Dodson Principle.

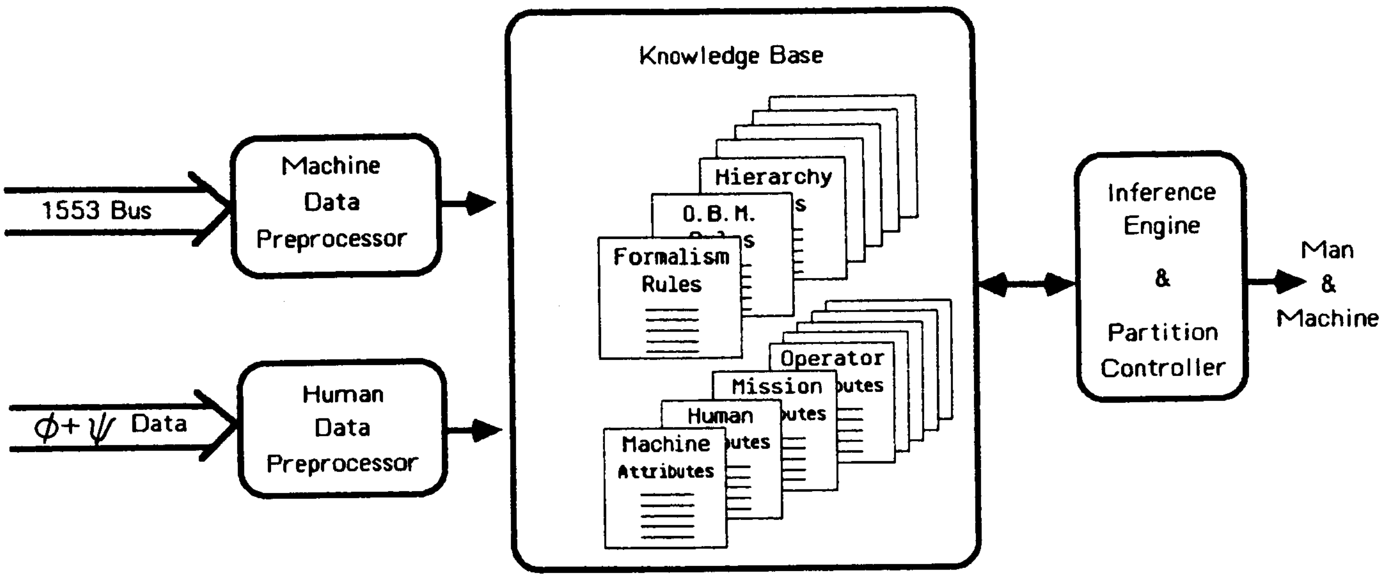


Figure 3. Metacontrol Unit Diagram.