THE USE OF MONTE CARLO SIMULATION TO REFLECT THE IMPACT HUMAN FACTORS CAN HAVE ON SYSTEMS PERFORMANCE

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Summary

Man-machine simulation is one approach to determining system effectiveness as a function of subsystem performance, but often man has not been treated as a viable element in system effectiveness studies. The model discussed here is an example of how human factors can be explicitly dealt with in mission simulation. The application discussed also demonstrates the feasibility of a new, systematic method for integrating multidisciplinary biological research data into a composite description of performance degradation in a nuclear attack environment. The approach, however, appears to be generalizable to other threat environments and mission conditions. Besides being a potentially useful design evaluation method, the model has served to focus attention on critical problem areas for future laboratory investigations.

Introduction

Human factors engineering has become an integral part of weapons systems development, but methods for reflecting the impact of human factors in the earlier conceptual phases of the design process are not readily available. As a first step in this direction, the Navy funded the development of Monte Carlo simulation models of operator and crew performance.[7] These models provide at least a design assessment or evaluation capability. It is recognized that the tradeoffs made during conceptual design may require more than an assessment of proposed alternatives. Specifically, methods must eventually be developed which suggest promising new alternatives or ways in which to optimize man-machine relationships. It is believed that feasible and pragmatic approaches to this design issue can best be discovered and explored as by-products of the current efforts to simulate operator and crew performance in existing man-machine systems.

A specific case is the assessment of vulnerability/survivability in a nuclear attack environment. While ultimately one would like to arrive at design criteria and methods for performing design tradeoffs, it appears desirable to first be able to estimate the vulnerability/survivability of existing systems, with the implicit assumption that this experience, if not necessary, will at least be sufficient for suggesting how to approach such questions during the design of new systems.

The Air Force Special Weapons Center (AFSWC) has the primary responsibility for assessing the nuclear survivability/vulnerability of existing Air Force systems. Much of the Center's effort has focused on hardware and system response to weapons effects and until recently, little detailed treatment had been given to the crew response to these weapons effects. Where biological considerations were incorporated in such studies, they borrowed heavily from the research literature in radiobiology and flashblindness and were oriented toward an overall assessment of whether the crew might be expected to complete a mission of a prescribed duration following a defined level of exposure to the weapons effect of interest. The typical symptoms associated with radiation illness were mentioned, but the implications of these effects were not explored in any depth.

It was suggested that the Aerospace Medical Division (AMD) could support AFSWC study efforts by organizing a joint effort between the School of Aerospace Medicine (USAFSAM) and the Aerospace Medical Research Laboratory (AMRL). This would provide a multidisciplinary team of radiobiologists and engineering psychologists, and it was hoped that a more detailed, systematic methodology could be developed for determining how crew vulnerabilities might affect system performance. AMRL proposed that the so-called Siegel-Wolf two-man model was a suitable means for determining how operator performance affects mission success and could be used to estimate system survivability in a more quantitative fashion than had been done previously. Human vulnerability to ionizing radiation and flash effects of nuclear weapons were presumably derivable from USAFSAM data. The principal technical gap was in developing a technique for using the USAFSAM data to adjust the human performance input data to the Siegel-Wolf model in a manner appropriately reflecting the expected performance decrements. Comparison of the model's predictions of mission success "pre"- versus "post"-exposure (using these modified input data) would then provide estimates of the impact weapons induced performance degradation could have on the probability of mission completion.

Approach

The nature of the Siegel-Wolf model, its development, application and validation are all well documented[7,8] and will only be superficially treated here. Basically, the model is time oriented and views operator performance in a mission as a series of discrete tasks. Intraoperator variability in task performance is represented as a normally distributed random variable with a separate mean and standard deviation of performance time for each task. This distribution depicts operator performance under nominal conditions. Interoperator variability is reflected in various run parameters of the model representing such considerations as proficiency (F_j - for speed; A_j - for accuracy; j being the operator identifier) and a time stress threshold (M_j). Performance reliability estimates are also assigned in terms of probability of success for each task, along with: (1) an indication of task criticality, (2) which tasks are performed next if this task is a success or failure, and (3) various contingency events (such as waiting until a partner performs a prescribed task, waiting until a prescribed period of time has passed, waiting for an equipment function to be completed, jumping to a special task sequence if a partner's performance dictates an alternate procedure, etc.). The primary mission related model parameter is the time available for completing the prescribed sequence (T_j). If the last essential task of the sequence is successfully completed before T_j, that iteration of the run conditions is considered to be a success; and if T_j occurs prior to successful completion of the last task of the sequence, the simulated mission is considered to have failed.

To capture the dynamic nature of operator performance, a number of psychological constructs have been defined and incorporated into the model, the most important of which is time stress. Operationally, as an operator perceives that the time remaining for completing tasks yet to be done is less than that required to complete the sequence before T_j if he continues at his current pace, he has two options: (1) he can increase his attentiveness to the tasks (performing them faster, with less variability and more reliably), or (2) he can decide to skip less essential tasks. It has been observed that the latter course of action is resorted to when the former is inadequate to compensate for the discrepancy between time required and time remaining. Further, there appears to be a limit beyond which adaptive, compensatory efforts are effective, and one begins to see more disorganized behavior--lower probabilities of success, greater variability in performance and larger mean performance times.

Table I shows the task input data format and figures 1 and 2 provide a schematic representation of how these features might be used in a hypothetical task sequence. Each operator starts on his respective task, and the Monte Carlo generator is entered with the values of $\bar{t}$ and σ to determine the actual time used (T^U) by the operator in performing this task. The Monte Carlo generator is then entered again to determine whether the task succeeded or failed. Processing continues then at NXTS (I,J) or NXTF (I,J) respectively, depending on the success or failure of the current task.

The second task for operator 2 illustrates the case where failure on that task dictates the performance of tasks 4 and 5. Note also the provision for repetitive looping, where failure on task 4 leads to a repetition of task 2 where success requires performance of task 5 before proceeding to task 3.

An alternate form of looping is illustrated as a consequence of operator 1 failing his own first task, independent of operator 2 performance. In this case, one can have a hierarchical set of corrective measures, where failure of one task leads to yet another branch. In another version, task 3 may actually be a repetition of task 1, where in this case failure leads to trying this same task over again instead of performing task 2.

Task 5 for operator 1 illustrates a case where failure on a given task requires repetition of a previous task, and in this case the loop which is inadvertently created can present problems. Repeated failure of tasks in this loop (of tasks 2-5) could readily utilize considerable time, which in some cases realistically mimics the phenomenon to be represented, but applications have been made where this sort of loop was the source of trouble; and the task analysis had to be modified to provide a mechanism for terminating an unreasonable situation. Other kinds of branching, for example the two kinds of special jump tasks, can also lead to difficulties. So while the model itself has a great deal of capability in realistically capturing and simulating task contingencies, as always there is a considerable burden placed on the user in not only performing a task analysis but in appropriately translating the results of the task sequence into a suitable set of input cards. This sometimes requires partitioning a single task in one's a priori analysis into several tasks for simulation purposes. For simple task sequences, one may remain fairly naive about the model's logic, but for more complex situations, it is often necessary to understand the program logic in greater detail. The flow chart for the model can be found in reference 8.

Task 6 for operator 1 illustrates the case where failure dictates that both operators jump to a different task sequence, identified here as exit A. There are two alternate ways in which such a jump might occur. Operator 1 may have decision responsibility for determining whether he and his partner proceed as usual or branch to the other sequence. Instead, the jump may be dictated by the time stress on operator 1, such that if task 6 is nonessential and will be ignored, both operators perform a sequence of tasks which would not be executed if task 6 was performed.

In figure 2, the triangular decision block following task 6 for operator 2 illustrates the use of the time precedence feature of the model, where it is possible to forestall the execution of task 7 until some specified amount of time has passed relative to the beginning of the simulation. Delays can be injected in three other ways. First, an equipment task can be inserted into the sequence, where task 9 for operator 1 cannot be executed until the equipment function of task 8 is successfully executed. Note also that manual recycling can be represented where failure of the equipment task or failure of task 7 itself leads to re-executing again through task 7. Second, a delay can be caused by having to wait for one's partner to finish some specified task. This is shown by the IPREC decision triangle preventing operator 1 from going on to task 9 until operator 2 completes task 7 successfully. Third, a delay may be injected because a task cannot be executed or repeated until the beginning of the next cycle in some periodic process, for example looking at images on a PPI radar display. This is depicted by the decision block preceding operator 2's task 8.

Finally, task 9 for operator 1 shows the simplistic treatment of decisions by a single operator. This type of task is used simply to select one of two sequences when either may be performed in some specified portion of the cases run. No time is associated with the task and the associated p value simply forces the selection of the task sequence alternatives in the proportion desired. Time to make such decisions, if in fact the operator makes the selection, can be simulated as an ordinary task. More sophisticated representations of decision making have been proposed for inclusion in the model, including the logic required, but to date these revisions have not been made (though they will be in the near future).

Figure 3 illustrates the manner in which time stress influences selected parameters of task performance ($\bar{t}$, σ, and p). Up to the operator's stress threshold (M_j), which is a run parameter, increasing time stress acts as an organizing influence on behavior, augmenting the probability of task success and attenuating both the mean and standard deviation of performance time. Beyond this threshold, the reverse prevails; both the variability and average time for performance increase and the probability of task success decreases. The general form of this relationship agrees with intuition, but empirical data[3,6] have been used to determine the nature of the expressions used in the model and to determine what values of M_j reasonably represent interoperator variability in the time stress threshold. A value of 2.3 for M_j has been found to be representative of the expected threshold, and past simulations have used values ranging from 1.9 to 2.8 representing the more hyper and hyposensitive extremes, respectively. Table II shows how the task time (t_{ij}) and its probability of success (p_{ij}) are calculated from the input parameters ($\bar{t}_{ij}$, σ_{ij}, and p_{ij}) considering the current value for time stress (S_{ij}) and the run parameters for the stress threshold and operator proficiency (M_j and F_j, respectively). The stress value is based on the average time required for all remaining essential tasks (T^E) relative to the difference between time used (T^U) up to the current task and the total time available (T_j), also a run parameter. Thus,

$$S_{ij} = \frac{T_{ij}^{E}}{T_j - T^U} \qquad (1)$$

and is limited as follows:

$$1.0 \leq S_{ij} \leq 5.0$$

This is the simplest case. Stress is also affected by one's partner's performance.[7] Consideration of branches, loops, graded task essentiality, etc. affect the calculation of T^E and correspondingly influence S_{ij}, but detailed discussion of such concerns will be beyond the scope of this paper.

The model itself has been validated in several applications, as depicted in figure 4. Measurements of an outside criterion (the horizontal bars) provide point estimates for comparison with the output distribution of the model. In all but one case, the outside criterion of mission success fell within 5% of the expected value predicted by the model. Other validation[5,4] have similarly shown the model output is representative of actual operations.

Since the predicted impact radiation has on crew and system performance cannot be empirically validated, prior success of the Siegel-Wolf model and its demonstrated construct validity made it a prime candidate for the proposed survivability/vulnerability application. Written in FORTRAN IV, the model had already been run on a wide variety of machines (IBM 7094, GE 635, and CDC 3800 and 6600) and had been successfully converted to run on AMRL's HESS (Human Engineering Systems Simulation) facility, an IBM 360/40H.[8]

Following a review of the literature on the performance decrements and incapacitation produced by exposure to supralethal doses of ionizing radiation, it became apparent that a conceptual framework was needed to permit a systematic adjustment of the model's input so that the revised parameters would appropriately reflect the impact of the absorbed dose. A "strawman" approach was taken; the contractor (Applied Psychological Services, Inc.) formulated the conceptual scheme, reviewed it with USAFSAM and AMRL, implemented the scheme, and submitted the model output for critique. The nature of this development is extensively documented in Siegel et al.(in preparation)[9] and summarized by the author in a recent presentation.[1] Basically, the conceptual scheme assumes that task performance is a function of intellective and psychomotor abilities. Knowing how radiation degrades these capabilities, one can attempt to infer (estimate) the corresponding change in performance time and probability of success. In application, the Guilford SI (Structure of the Intellect) model[2] was used to represent intellective capabilities, and psychomotor abilities were represented by the factor structure proposed by Ulich[10], although in both cases only selected parts of the respective models were used. For each factor, the radiation data were interpreted to provide estimates of the percentage decline from baseline (pre-exposure) capability as a joint function of dose and time since exposure (see reference 1 for details of these curves).

Since the model had been previously validated, it was decided that adjustments of the task data would be made external to the model in a preprocessor subroutine rather than internal to the model. This slight loss of realism in capturing the simulated "time since exposure" versus a priori calculations was justified on the grounds that the task sequence simulated was short enough (600 sec $\leq T_j \leq$ 900 sec) that errors created were probably less than the experimental error in the radiobiology data. Further, by keeping these preprocessing algorithms separate from the model, adjustments could be made to the radiobiology decrement curves without affecting the model per se. This proved particularly beneficial when it was subsequently discovered that recent unpublished radiobiology data did not exactly agree with prior results. It was therefore desireable to be able to modify the representation of degraded intellective and psychomotor abilities to reflect this uncertainty in the underlying nature of radiation induced performance decrement. Interactive graphics routines are now being developed by AMRL to facilitate making such adjustments and correspondingly altering the way the described degradation is reflected in the input data to the model.

Results

Since the numeric results of model runs involve the simulation of an air intercept mission of an existing aircraft, they are classified and will not be presented here. The results were reviewed both by USAFSAM and by operations analysts for the Air Defense Command. Initial critique of the model output led to the discovery that the nature of the statistical analysis of the radiobiology research data had not been understood. This led USAFSAM to replace the "strawman" representation of radiation induced degradation (which had previously been reviewed and accepted) with an updated version which better depicted the results of their research. In revising the model to reflect the updated radiobiology decrement curves, a decision was made to vary T_j to determine the extent to which time stress might interact with radiation. It was postulated that allowing less time (than normally required) for mission completion would lead to added time stress and would therefore accentuate any problems resulting from radiation decrement. This was confirmed by model output, as expected. It was further postulated that more time allowed would act as a compensating mechanism. With increased radiation, task times increase and probabilities of success decrease, which normally leads to the repetition of "failed" tasks and the accumulation of stress as more time is used to reach a given point in the task sequence. By allowing more time for mission completion, time stress should build more slowly and permit correction of task errors without necessarily jeopardizing mission completion. While the output data reflect the viability of this rationale, it also led to a critical empirical question: to what extent would radiation degrade the efficacy of time as a compensating mechanism? It was argued that the higher the dose, the greater the incapacitation, and at some point, additional time to perform is of no consequence. Since the model suggests that time allowed could have a dramatic effect on mission success for high exposure levels, it appears necessary to confirm or refute the postulated relationship between radiation and time stress on an empirical rather than deductive basis if at all possible. In this light, the model has provided the impetus for laboratory research which is immediately relatable to a problem of operational significance. Independent of the validity of predicted mission success, this result of model application has a high utility with declining research budgets and the normally large time lag between research and application.

During the initial effort, the treatment of human vulnerability was being addressed in parallel with an AFWL study of hardware vulnerabilities. In effect, it was necessary to tacitly assume that the equipment was unaffected by exposure to the radiation environment. While admittedly unrealistic, this presumption is no worse than the typical engineering assumptions about human performance and in any case the combined treatment of man-machine vulnerabilities necessarily requires data on how the equipment degradation manifests itself at the man-machine interface. The model has recently been revised to consider the impact such hardware malfunction has on performance.

The logic is simple and straightforward. The engineering studies provide data on the probability of equipment outage as a function of radiation exposure. Conceptually, two results ensue: (1) operator(s) must modify their task sequence, and/or (2) the tasks in the sequence are made more difficult by the degradation in controls and/or displays. In practice, the latter case proved to be virtually (though not completely) irrelevant for the system being studied, so greatest emphasis was placed on demonstrating a workable method for handling the case where hardware becomes wholly inoperative, thus forcing an alternate mode for accomplishing mission objectives. Obviously, situations where inoperability of an equipment item forces a mission abort need not be simulated since they can be separately treated.

Given the nature of single and multiple outages of equipment, experienced operations personnel were interviewed to determine how the pilot (in this case) would respond to such contingencies (the pros and cons of this and alternate approaches to this data collection problem are discussed in reference 1). Thus, in the input preprocessing subroutine, this so-called "family" of tasks is substituted in lieu of the task which would have been performed had the equipment been operational.

In redesigning the preprocessing subroutine, consideration of hardware vulnerability and human vulnerability are first treated separately and then jointly. This allows one to determine the nature of the changes made to the input; but more than that, this separability allows for the potential expansion to a treatment of non-nuclear survivability/vulnerability, where equipment outages have a different cause but a similar effect. From a pilot's point of view, it makes little difference whether an equipment operating deficiency is due to equipment reliability, battle damage, or radiation induced degradation. Consequently, so far as the model is concerned, one need only determine and specify the probability of the operating deficiency. Given pilot response to this contingency, one may simulate the event and its impact on mission success. One may further consider the case where the pilot sustains injury. This would require a new effort to define and quantify the ways in which performance might change as a function of the number, type, and location of wounds and the time since injury. Although no attempt has been made to explore this matter in detail, it does appear to be feasible. Thus, the potential exists for looking at degraded man, degraded equipment, or both for either conventional or nuclear weapons.

In the combined treatment, it is necessary to first consider how the weapon's ionizing radiation affects the task sequence because this will affect the time lapse between exposure and performance of selected tasks in the "final" sequence generated for the prescribed mission conditions. Since performance degradation and recovery are both dose and time dependent, human performance parameters cannot be appropriately adjusted until this task sequence has been constructed.

The complete man-machine survivability/vulnerability model has been implemented and successfully run. Preliminary examination indicates the results are in the expected direction and appear reasonable. Further validation will be attempted for the following limited cases. Given data collected by the operating command (ADC) on mission success for those intercepts where equipment malfunctioned after takeoff, one could potentially compare these data with those model predictions where it was assumed that equipment degradation occurred with no degradation in the pilot's performance.

Discussion

Based upon the limited success of this initial feasibility demonstration effort, AMRL has initiated two additional contractual studies and has prepared extensive plans for both an in-house modelling effort and a joint experimental program with USAFSAM.

First, the basic two-man operator simulation model used to assess the survivability/vulnerability of fighter-interceptor aircraft will be expanded to treat the larger crew sizes and team performance of bomber and cargo type aircraft. Second, a multi-man model of team performance in information processing and decision making tasks associated with air surveillance and command/control systems is being conceptually designed in a separate contractual effort.

Third, in-house modelling will expand and refine the existing two-man model. Expansions include examining the impact of the prodromal radiation syndrome for lower exposure levels and treating the effects of flashblindness. Refinements will consider alternate ways of capturing the radiobiology data and the development of post-processing routines to facilitate the analysis and interpretation of run results (e.g., orthogonal polynomial trend tests for generating a least squares response surface and graphics routines to plot such results).

Fourth, several sorts of research are in the planning stage. The radiobiology decrement data for supralethal doses are based primarily on primate studies. It has been suggested that drug emulation of radiation illness might provide a means of determining how human performance might be impaired by the effects of ionizing radiation. USAFSAM is in the process of developing a suitable drug protocol. AMRL is in the process of developing suitable simulations of selected systems as the laboratory test vehicle for measuring performance decrements as a function of drug induced degradation emulating the prodromal syndrome of radiation illness. Obviously, considerable research will be necessary before initiating human studies; but potentially, the data would further validate the estimated human performance vulnerabilities which are necessarily a prerequisite to any comprehensive analysis of the survivability of manned aerospace systems.

Conclusions

The Siegel-Wolf two-man operator simulation model provides a basic capability to examine the extent to which mission success can be affected by certain human factors considerations. A workable methodology has been developed for examining the consequences of human and hardware degradation following exposure to nuclear weapons effects. Generalization to non-nuclear threats appears feasible. The model is being expanded and refined in-house, and a contractual effort now underway will build on past experience to develop a model of crew performance in larger systems.

In addition to being a viable tool for assessing current systems and evaluating design alternatives for proposed systems, the modelling effort has been remarkably useful in focusing attention on specific basic and applied research issues not previously apparent. This may ultimately prove to be the most useful result of the whole effort.

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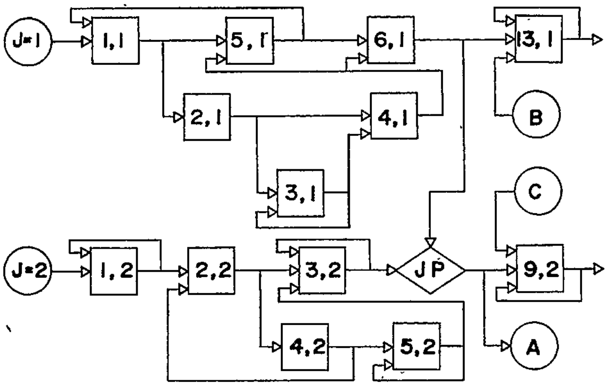

Figure 1. Overall Task Sequence Schematic

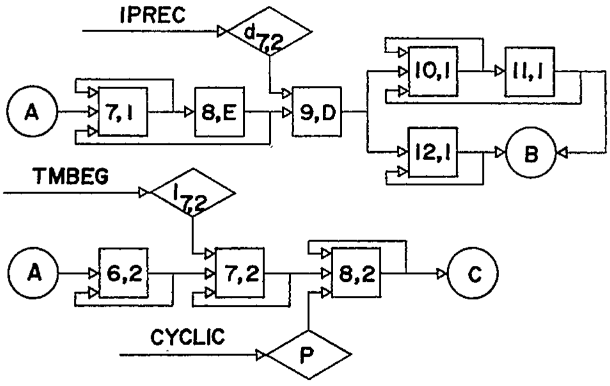

Figure 2. Additional Details of Task Sequence

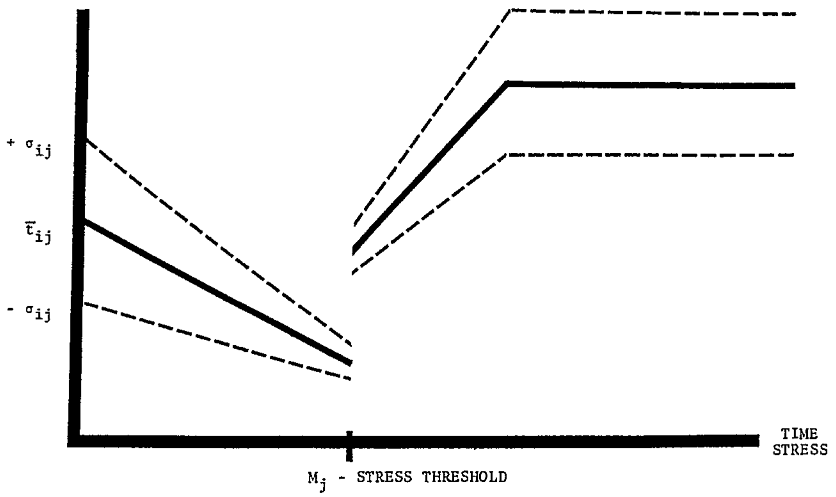

Figure 3. Time Stress as a Moderator of Task Parameters ($\bar{t}$ and σ)

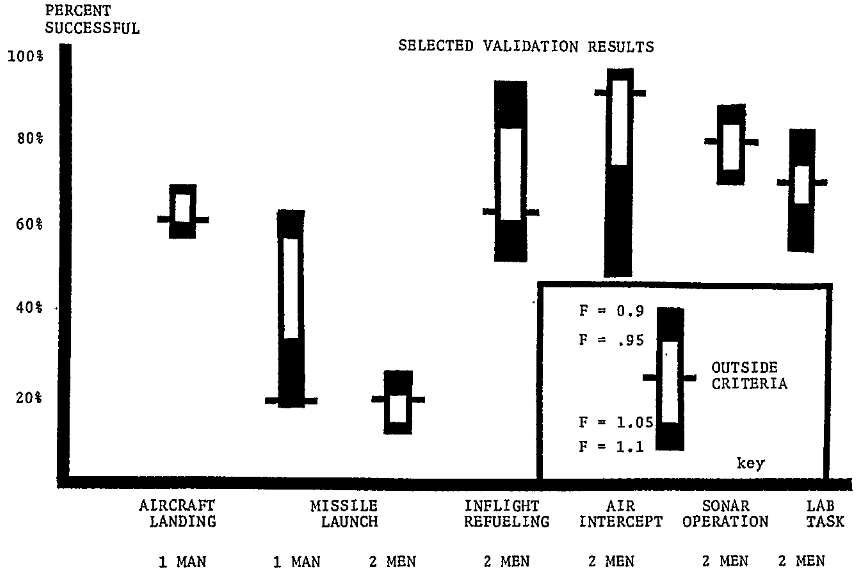

Figure 4. Comparison of Model Predictions with Measurements of an Outside Criterion for Several Applications

Table I. Format of Task Parameter Data

Contents	Symbol	Symbolic FORTRAN Name	Card Columns	Format
operator number	j	J	1	I 1
task number	i	I	3-5	I 3
type of task (J = Joint; E = Equipment; D = Decision; C = Cyclic)	-	J, E, D, C	7	A 1
essentially indicator	E_{ij}	N; Blank	9	A 1
task precedence	d_{ij}	IPREC(I,J)	10-12	I 3
time precedence	I_{ij}	TMBEG(I,J)	13-20	F8.2
next task, success	$(i,j)_s$	NXTS(I,J)	21-24	I 4
next task, failure	$(i,j)_f$	NXTF(I,J)	25-28	I 4
average time	$\bar{t}_{ij}$	AVGTM(I,J)	29-37	F9.2
time deviation	$\bar{\sigma}_{ij}$	AVGTMD(I,J)	38-45	F8.2
probability of success	$\bar{p}_{ij}$	PRBSUC(I,J)	46-50	F5.2
time remaining, essential	$T^E{}_{ij}$	TMLE(I,J)	51-59	F9.2
time remaining, nonessential	$T^N{}_{ij}$	TMLN(I,J)	60-67	F8.2
special jump task type blank = none 1 = special type 1 2 = special type 2 (Team Decision)	-	ISJT(I,J)	69	I 1
next task for j, if special jump required	-	NXTJ(I,J)	70-72	I 3
next task for j', (i.e. j's partner) if special jump required	-	NXTJP(I,J)	73-75	I 3

Table II. Calculation of (t_{ij}) as a Function of Stress (S_{ij}), Stress Threshold (M_j) and Operator Proficiency

$$
t_{ij}\begin{cases}
\left.\begin{cases}
\text{1.a} & \dfrac{V_{ij}F_j}{S_{ij}} \quad \text{(originally)} \\
\text{1.b} & F_jV_{ij}Z_{ij} \quad \text{(revised)}
\end{cases}\right\} S_{ij} < M_j \\
\underline{\underline{\text{where}}}\text{:} \quad Z_{ij} = -1.829\left[\dfrac{S_{ij}-1}{M_j-1}\right]^3 + 3.472\left[\dfrac{S_{ij}-1}{M_j-1}\right]^2 - 2.350\left[\dfrac{S_{ij}-1}{M_j-1}\right] + 1.0 \\
\text{2.} \quad \left[(2S_{ij} + 1 - 2M_j)\, V_{ij} - (S_{ij} - M_j)\, \bar{t}\,\right]\cdot F_j, \; M_j \leq S_{ij} \leq (M_j + 1) \\
\text{3.} \quad \left[3V_{ij} - \bar{t}_{ij}\right]\cdot F_j, \; S_{ij} > (M_j + 1) \\
\underline{\underline{\text{where}}} \text{ (in all cases):} \quad V_{ij} = \bar{t}_{ij} + K_{ij}\,\sigma_{ij}, \; K_{ij} \text{ being } N(0,1)
\end{cases}
$$

$$
p_{ij}\begin{cases}
\text{1.} \quad p_{ij} + \dfrac{(1 + p_{ij})\,(S_{ij} - 1)}{M_j}, \; S_{ij} < M_j \\
\text{2.} \quad p_{ij}\,(S_{ij} + 1 - M_j) + (M_j - S_{ij}), \; M_j \leq S_{ij} \leq (M_j + 1) \\
\text{3.} \quad 2p_{ij} - 1, \; S_j > (M_j + 1)
\end{cases}
$$