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PREDICTING OPERATOR WORKLOAD DURING SYSTEM DESIGN

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INTRODUCTION

Current Army policy requires that human capabilities and limitations be addressed during the conceptual phase of new weapon systems development. In furtherance of this policy, Anacapa Sciences, Inc. researchers, under contract to the U.S. Army Research Institute Aviation Research and Development Activity (ARIARDA), developed a methodology to predict aviator workload in advance of aircraft system design. The methodology features models that predict workload under varying automation configurations for both single- and multi-crew system designs. This paper (a) describes the methodology for developing and exercising the workload prediction models and (b) presents flight simulator-based research plans for validating the workload predictions yielded by the models.

THE WORKLOAD PREDICTION METHODOLOGY

Background

The Army's Air/Land Battle 2000 scenario represents a high-threat environment that will place heavy workload demands on Army aviators. Accordingly, future aircraft systems are being developed with advanced technology designed to automate many of the functions traditionally performed by crew members. Examples of the advanced technology include:

- an increased number of sensors and target acquisition aids
- improved navigation and communication systems
- advanced crew station design features
- improved flight controls
- extraordinary avionics reliability
- subsystems that are automatically reconfigured if components fail

Although advanced technology is typically designed to reduce aviator workload, the tasks required to use the

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technology may actually increase workload in some instances. For example, technology designed to reduce an aviator's need to maintain physical control of system functions often increases the aviator's role as a systems monitor or problem solver. Consequently, while psychomotor workload demands are decreased, sensory and cognitive attentional demands are increased.

The development of new and improved aircraft systems also presents problems in the prediction and assessment of operator workload. Metrics that are appropriate for analyzing physical workload are inadequate for assessing sensory and cognitive workload. Accordingly, workload research has shifted from a focus on physical effort required to perform a task to an emphasis on the attentional demand associated with the sensory, cognitive, and psychomotor workload components of the tasks. The workload prediction methodology developed by ARIARDA and Anacapa researchers operationally defines workload in terms of attentional demand. Consequently, the methodology is designed to measure "mental state" associated with task performance.

The workload prediction methodology was developed in response to a request for research support from the Army's Aviation Systems Command (AVSCOM) Program Office charged with the development of a new multipurpose, lightweight helicopter, designated the LHX. A detailed description of the manner in which the methodology was developed and applied to the LHX is presented in reference 1.

The original LHX workload prediction methodology currently is being refined during analyses of three additional Army helicopter systems and one advanced-technology crew station for an experimental research flight simulator. The four additional analyses are:

- a baseline analysis for the AH-64A, Apache, prior to predicting crew workload in a proposed AH-64B configuration (ref. 2)

- a baseline analysis for the UH-60A, Blackhawk, prior to predicting crew workload in a redesigned MH-60X configuration (ref. 3)

- a baseline analysis for the CH-47, Chinook, prior to predicting crew workload in a redesigned MH-47E configuration

- a baseline analysis for an advanced technology LHX-type crew station for the Crew Station Research and Development Office (CSRDO) at NASA Ames, prior to predicting crew workload in high-fidelity flight simulation experiments

In applying the methodology to the aircraft and flight simulator systems, three major phases of research must be performed:

- conduct mission/task analyses of critical mission segments and assign estimates of workload for the sensory, cognitive, and psychomotor workload components of each task identified
- develop computer-based workload prediction models using the data produced by the task analyses
- exercise the computer models to produce predictions of crew workload under varying automation and/or crew configurations

Each of the three phases in the refined methodology is described below:

Phase 1: Conduct Mission/Task Analysis

The first phase of the methodology is to conduct a comprehensive mission and task analysis for the proposed aircraft or simulator system. The mission/task analysis uses a top-down approach in which mission profiles for the system are subdivided into mission phases, and subsequently into mission segments. A segment is defined as a major sequence of events that has a definite start and end point. The events in a segment may occur concurrently or sequentially.

Each segment is then divided into functions. A function is defined as a set of activities that must be performed either by an operator or by equipment to complete a portion of the mission segment. Functions are categorized as continuous, discrete fixed, or discrete random and are placed on a rough time line using a Segment Summary Worksheet, such as the example selected from the AH-64A mission/task analysis (ref.2) and depicted in Figure 1.

The functions for each segment are subsequently divided into tasks. Each task is a specific crew activity that is essential to the successful performance of the function. The task consists of a verb and an object and is analyzed to

- identify the crewmember(s) performing the task
- identify the subsystem representing the primary man-machine interface
- estimate the workload imposed on the crew member(s)
- estimate the time required to complete the task

The crew member(s) performing each task and the subsystems associated with each task are identified by examining the manner in which similar tasks are performed in existing Army helicopters. Predictions of the visual, auditory, kinesthetic, cognitive, and psychomotor workload for each task are derived by writing short verbal descriptors of the requirements for each task component. The descriptors are then compared with the verbal anchors contained in the rating scales shown in the table (ref. 2). The rating (i.e., 1 - 7) associated with the anchor that best matches the verbal descriptor is assigned as the numerical estimate of workload. Two or more analysts perform the ratings independently and then reach consensus on the final ratings for each task. Task time estimates are assigned after interviews with subject matter experts (SMEs), or in some cases, after actual measurements of performance times on similar tasks.

Information derived from the mission/task and workload analyses is recorded on Function Analysis Worksheets, such as the one shown in Figure 2 for the AH-64A function "Fire Weapon, Missile" (ref. 2). The tasks are listed in the first two columns. The crew member performing each task is indicated by the letter (P for pilot; G for gunner; and B for both) that is presented in the third column along with a numerical identifier for the task. The subsystems associated with each task are presented in the fourth column. Verbal descriptors of the sensory, cognitive, and psychomotor components of workload and the ratings associated with each component are entered in the next three columns. The eighth column describes the type of switch for each task for which a specific switch is involved. The estimated length of time for discrete and continuous tasks is presented in the final two columns of the worksheet. The total time to perform all the tasks in the function appears in the upper right corner of the Function Analysis Worksheet.

Phase 2: Develop Computer-Based Workload Prediction Models

Phase 2 of the methodology consists of developing computer models to predict total workload experienced in the performance of both individual and concurrent tasks. The procedure used to develop the computer models represents a bottom-up approach in which the tasks identified in the Phase 1 mission/task analysis serve as the basic elements of analysis. Specifically, the information derived for each task is entered into computer data files from which estimates of total workload at the segment level are produced. Computer programs developed from time-based decision rules are then written to build functions from the tasks, and subsequently, to build segments from the functions. The decision rules define the temporal relationships among tasks and functions as determined in the mission/task analysis. By implementing the decision rules, the computer models produce estimates of total workload, at half-second intervals, for each workload component (i.e., visual, auditory, kinesthetic, cognitive, and psychomotor). The estimates are derived by summing the ratings assigned to each workload component across concurrent tasks. A total value of "8" on any single half-second time line constitutes the threshold for an overload within a given workload component. A more detailed description of the Phase 2 methodology is provided in references 1, 2, and 3.

Phase 3: Exercise the Computer Models

During Phase 3, the computer models are exercised to predict workload associated with individual automation options and/or combinations of options. Three steps are performed to produce the workload predictions:

- select the automation options to be exercised by the model
- revise the estimates of workload for each task
- exercise the model to produce new workload predictions

The automation options are selected in consultation with engineers from the system program office responsible for acquiring the new aircraft or flight simulator. The tasks identified in the mission/task analysis are then reviewed to determine how each of the proposed automation options is likely to change the workload estimates in the baseline analysis. For each task affected by the automation options, new verbal descriptors of workload are written. These descriptors, in turn, provide the basis for assigning new workload ratings to the components of the tasks. New computer files containing the revised workload estimates are then established. Finally, the model is exercised with the new files to predict workload for any single automation option or any combination of automation options. Use of the model to predict crew workload for the LHX weapon system is described in detail in reference 1.

Application of the Workload Prediction Methodology

The methodology described above represents a systematic approach for predicting operator workload in advance of system design. As various automation options and alternative crew configurations are considered during the design of a weapon system, the methodology can be repeated so that the workload predictions keep pace with the system design process. Additionally, the methodology produces a number of

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products that can be applied to the development of **any** complex weapon system. The products include:

- a mission/task/workload analysis that provides estimates of (a) sensory, cognitive, and psychomotor components of workload, and (b) performance times at the task level of specificity
- scales for rating sensory, cognitive, and psychomotor components of workload
- a timeline analysis that depicts concurrent crew tasks
- a procedure for evaluating total workload for concurrent crew tasks
- a numerical index for identifying crew overloads
- computer models that produce comparisons of workload for proposed alternatives in system design and crew composition
- a procedure for identifying an optimum design configuration for reducing crew workload

Workload predictions produced by the models have already been used by the Army in system trade-off analyses directed toward determining whether one or two aviators will be required to perform the LHX mission on the future battlefield and to assist in making decisions regarding the optimum configuration of LHX automation options.

VALIDATION OF THE WORKLOAD PREDICTION MODEL

The workload predictions yielded by the models have not been validated. Consequently, the next phase of the research will consist of (a) validation of the parameters used to develop the models, and (b) the validation of the workload predictions yielded by the models.

Parameters of the model that require validation include:

- workload ratings assigned to each task
- total workload estimates for concurrent tasks
- estimated times assigned to each task
- threshold for excessive workload
- temporal relationships among tasks
- procedural relationships among tasks

In designing the validation research a number of critical issues were considered. In this section, two of the critical issues most relevant to the workshop topic, *Mental-State Estimation,* are discussed and major provisions of the validation research plan are presented. A more complete discussion of the critical issues and a full description of current research plans are presented in reference 4.

Critical Issues

The problems and issues that have a critical bearing on the research required to validate the parameters in the workload prediction methodology include the following:

- reliability and validity of workload predictors
- selection of appropriate criterion measures.

Reliability and Validity of the Workload Predictors

The methodology used to derive the workload predictions requires that the reliability of both the rating scales and the predictors of workload be established. Specifically, it must be demonstrated (a) that the workload rating scales discriminate accurately between levels of attentional demand, and (b) that different raters will derive consistent estimates of workload for the sensory, cognitive, and psychomotor components of individual tasks. The reliability of the ratings assigned to the individual task components is important because these ratings are the basis for producing the predictors of total workload for concurrent tasks. If the individual workload ratings are found to have high reliability, the predictors of total workload produced by summming the ratings also will have high reliability.

The procedures used to develop the workload predictors are designed to ensure that the predictors have high face and content validity. The research for validating the workload model will attempt to establish that the predictors also have predictive validity. The predictive validity will be established by comparing the workload component ratings for each task, as well as the predictions of total workload associated with concurrent tasks, with (a) objective measures of primary task performance and (b) other subjective measures of workload. The primary task measures will be compared with the predictors at half-second intervals for each task on the mission segment timeline, while the subjective measures will be compared with the predictors for selected portions of the mission segments. Predictive validity will be demonstrated to the extent that the workload component ratings and/or the total workload predictors correlate with the criterion measures.

Selection of Appropriate Criterion Measures

A number of performance measures will be selected as criteria for validating the workload predictors. Although evidence suggests that, in some instances, task performance may be relatively independent of workload (ref. 5), a critical assumption of the workload prediction model is that, when total attentional demand is driven close to or above the threshold of overload, performance on one or more of the concurrent tasks will be degraded. Consequently, the primary basis for selecting the performance measures to be used in the validation study will be their sensitivity to degradations in task performance due to increased workload. Additionally, the measures will be selected on the basis of their relevance to specific operator tasks. For example, deviations from a specified airspeed will be the criterion for workload encountered in the task "control airspeed." Such measures have high face, content, and construct validity.

Subjective measures of workload also will be collected during the validation research. The subjective measurements will be selected from among presently recognized and partially validated techniques, including (a) the NASA bipolar rating technique (ref. 6), (b) a modified Cooper-Harper rating technique (ref. 7), and (c) the subjective workload asessment technique (SWAT) (ref. 8).

Subjective measurements offer the system designer information that is not provided by the more objective techniques; furthermore, subjective methods of measurement are generally well received by operators and require little instrumentation. The greatest disadvantage of subjective workload measurements from the standpoint of the validation research is that the measurements do not provide information regarding the composition of the primary task. That is, it is just not feasible to collect subjective ratings at the task level of specificity. A second disadvantage is that subjective methods rely on the ability of operators to retrieve information from short-term and long-term memory regarding their experiences during task execution; yet, the behavioral literature is replete with examples demonstrating the fallibility of the memory retrieval processes (refs. 9 and 10). Even if the retrieval processes were reliable, it is not clear whether the recollections reflect task input modality (ref. 11), number of concurrent tasks (ref. 12), working memory load (ref. 13), or some other aspect of the task situation. Finally, empirical findings (ref. 14) suggest that retrospective subjective measures reflect the average workload experienced during task execution, thus precluding the analysis of workload at different points in time.

For several reasons there presently are no plans to employ physiological workload measurement techniques during the validation research. No single physiological measurement technique exists that is sensitive to task loading, diagnostic of task demand, **and** unobtrusive. A more serious problem with physiological measures is that they do not directly address the relationship between system design and workload, an important consideration on which system engineers base their design decisions. There are simply not enough data to establish whether the fluctuations of physiological measures actually reflect mental effort, some other operator "state" condition such as stress or fatigue, or a combination of several workload-related states.

The Validation Research Plan

The proposed research for validating the workload prediction methodology will be accomplished in three phases. During Phase 1, the reliability of the workload rating scales and the workload predictors will be evaluated. During Phase 2, validation data will be collected through a series of studies employing part-mission and full-mission simulation. During Phase 3, the results from Phases 1 and 2 will be used to refine the workload prediction model. Each of the three phases are described briefly below. More complete details are provided in reference 4.

Phase 1: Establish the Reliability of the Workload Rating Scales and the Workload Predictors

Phase 1 of the validation research will evaluate how closely the researchers' judgments in assigning numbers to the verbal anchors correspond with the judgments of other human factors scientists engaged in workload research. First, a psychophysical experiment using the method of paired comparisons (ref. 15) will be conducted by survey to (a) verify the ordinal ranks of the verbal anchors for each of the five workload component scales, and (b) produce equal interval scale values for each verbal anchor. Second, the empirically derived interval scale values will be applied to the workload component descriptors for all tasks. Finally, predictors of total workload will be produced by summing the interval scale values across concurrent tasks.

The human factors scientists also will be requested to rate the short descriptors of visual, auditory, kinesthetic, cognitive, and psychomotor components of workload for each task in the model. These same judges subsequently will be teamed in pairs. Each pair of judges will be instructed to assign a consensus rating for each of the verbal descriptors. Correlational techniques will be used to evaluate the inter-rater reliability of the ratings produced by (a) each independent rater and (b) each pair of raters.

Phase 2: Conduct Part-Mission and Full-Mission Simulation

During Phase 2 of the validation research, both part-mission and full-mission simulation experiments are planned. The simulator configuration for both the part-mission and the full-mission simulation will be identical. For the part-mission simulation, mini-scenarios will be generated by selecting concurrent and sequential tasks from the mission/task analysis. An equal number of the mini-scenarios containing high- and low-workload sets of tasks will be selected. For the full-mission simulation, a composite mission scenario will be developed by selecting segments from the mission/task analysis.

The part-mission simulation will be conducted using a repeated measures experimental design in which each subject will fly the mini-scenarios multiple times. The order of presentation of the mini-scenarios will be counterbalanced to control for order effects and other extraneous variables. Analyses will then be performed to assess the correlation between the workload predictors and the performance measures recorded throughout the mini-scenarios. The correlation coefficients resulting from the analyses will serve as the primary measure of how accurately the workload predictors forecast excessive workload at the task level of specificity. Analyses also will be performed to assess the correlation between predictions of workload and subjective estimates of workload. These correlations will indicate the degree to which the workload prediction model predicts workload at the mini-scenario level of specificity.

To assess the validity of the time estimates used in the model, the actual amount of time required to perform the various tasks in the mini-scenarios will be compared with the estimated times produced during the task analysis. Differences will be resolved by adopting the recorded times. The time analysis will be used to validate the temporal relationships among the tasks as they exist in the workload prediction model. The procedural relationships among the tasks will be evaluated by noting the subjects' ability to progress through the mini-scenarios following the sequence of tasks specified by the model. Any new sequences adopted by the subjects to complete the mini-scenarios will be used to refine the workload prediction model.

During the full-mission simulation experiments, each trial will start at the beginning of the composite scenario and continue without interruption to the end. The analysis of results from the full-mission simulation will include all of the analyses performed during the part-mission simulation data analysis.

Phase 3: Refine the Workload Prediction Model

The final phase of the validation research will be to refine the workload prediction model. The first refinements will be made when the research results from Phase 1 are available. Additional refinements will be made when the part-mission simulation results are available; final refinements will be made when the full-mission simulation results are available.

CONCLUSIONS

Successful completion of the validation research will result in several useful products. The products will include (a) reliable and valid scales for predicting visual, auditory, kinesthetic, cognitive, and psychomotor workload at the task level of specificity, and (b) a validated workload prediction methodology that can be applied early in the system design process. Even without validation, the workload prediction methodogy proved useful during the trade-off analyses and other system studies conducted for the LHX. The baseline analyses currently being performed for the AH-64A, UH-60A, and CH-47 aircraft will benefit proposed modification programs for additional systems. After the validation research has been completed, the human factors community will have a tool with proven value for predicting operator workload early in the design of **any** proposed system.

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WORKLOAD COMPONENT SCALES

SCALE VALUE	DESCRIPTORS
	Cognitive
1	Automatic (Simple Association)
2	Sign/Signal Recognition
3	Alternative Selection
4	Encoding/Decoding, Recall
5	Evaluation/Judgment (Consider Single Aspect)
6	Evaluation/Judgment (Consider Several Aspects)
7	Estimation, Calculation, Conversion
	Visual
1	Visually Register/Detect (Detect Occurrence of Image)
2	Visually Inspect/Check (Discrete Inspection/Static Condition)
3	Visually Scan/Search/Monitor (Continuous/Serial Inspection, Multiple Conditions)
4	Visually Locate/Align (selective Orientation)
5	Visually Track/Follow (Maintain Orientation)
6	Visually Discriminate (Detect Visual Differences)
7	Visually Read (Symbol)
	Auditory
1	Orient to Sound (General Orientation/Attention)
2	Orient to Sound (Selective Orientation/Attention)
3	Detect/Register Sound (Detect Occurrence of Sound)
4	Verify Auditory Feedback (Detect Occurrence of Anticipated Sound)
5	Discriminate Sound Characteristics (Detect Auditory Differences)
6	Interpret Semantic Content (Speech)
7	Interpret Sound Patterns (Pulse Rates, etc.)
	Kinesthetic
1	Detect Preset Position/Status
2	Detect Movement (Discrete Actuation--Toggle, Trigger, Button)
3	Detect Movement (Discrete Adjustive--Rotary Switch)
4	Detect Movement (Continuous Adjustive/Flight Controls--Cyclic, Collective)
5	Detect Movement (Continuous Adjustive/Switches--Rotary Rheostat, Thumbwheel)
6	Detect Serial Movement (Keyboard Entries)
7	Detect Conflicting Cues
	Psychomotor
1	Discrete Actuation (Button, Toggle, Trigger)
2	Discrete Adjustive (Rotary, Vertical Thumbwheel, Lever Position
3	Speech
4	Continuous Adjustive (Flight Control, Sensor Control)
5	Manipulative
6	Symbolic Production (Writing)
7	Serial Discrete Manipulation (Keyboard Entries)

SEGMENT SUMMARY WORKSHEET

PHASE 3 Enroute SEGMENT 08 Takeoff

PILOT			GUNNER		
DISCRETE (FIXED)	DISCRETE (RANDOM)	CONTINUOUS	DISCRETE (FIXED)	DISCRETE (RANDOM)	CONTINUOUS
Perform Hover (100) Perform Before Takeoff Check (091) Perform External Communication (099) Establish Climb (059) Establish Level of Flight (060)	Receive Communication (Internal) (116) Transmit Communication (Internal) (148)	Monitor Audio (078)	Perform Before Takeoff Check (090)	Receive Communication (Internal) (116) Transmit Communication (Internal) (148)	Monitor Audio (078)

Figure 1. Example of a Segment Summary Worksheet developed during the mission/task analysis (ref. 2).

FUNCTION ANALYSIS WORKSHEET

FUNCTION 065 Fire Weapon, Missile TOTAL TIME (Approximate) **5.5 Seconds**

TASKS		ID #	SUBSYSTEM(S)	WORKLOAD COMPONENTS			SWITCH DESCRIPTION	DURATION (SECONDS) DISCRETE/ CONTINUOUS	
VERB	OBJECT			SENSORY	COGNITIVE	PSYCHOMOTOR			
Verify	Firing Constraints	G239	Sensor Display (VSD)	Visually Discriminate Alignment Differences V-6	Evaluate Sensory Feedback and Verify Constraints Met C-2			1	
Pull	Weapons Trigger	B643	Weapons (AW)	Feel Trigger Movement K-2	Verify Correct Position (Trigger Activated) C-2	Lift Cover and Pull Trigger P-1	Springloaded Trigger (SPTR)	1	
Verify	Missile Launch	G417	Fire Control Computer/ Sensor Display (AFC/VSD)	Visually Detect Image V-1	Verify Correct Status (Missile Launched) C-2			1	
Release	Weapons Trigger	B644	Weapons (AW)	Feel Trigger Movement K-2	Verify Correct Position (Trigger Deactivated) C-2	Release Trigger P-1	Springloaded Trigger (SPTR)	.5	

Figure 2. Example of a Function Analysis Worksheet developed during the mission/task analysis (ref. 2).