ARMY RESEARCH LABORATORY

Mental Workload and ARL Workload Modeling Tools

Diane Kuhl Mitchell

ARL-TN-161 APRIL 2000

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5425

ARL-TN-161 April 2000

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Diane Kuhl Mitchell
Human Research & Engineering Directorate

Abstract

The author of this report provides an overview of mental workload theory and mental workload measurement. She also describes the development, application, and validation of the mental workload modeling tools developed by the Human Research and Engineering Directorate of the U.S. Army Research Laboratory (ARL). These ARL tools, VACP (visual, auditory, cognitive, psychomotor) option in the improved performance research integration tool (IMPRINT) and WinCrew, can help the designers of military systems to assess the mental workload associated with different configurations of soldiers and equipment involved in the performance of a mission. System designers can conduct this assessment in the concept development phase of system design and reduce the need to build costly system mock-ups.

ACKNOWLEDGMENTS

The author wishes to express thanks to Mr. John Lockett for providing technical assistance during the preparation of this report.

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MENTAL WORKLOAD AND ARL WORKLOAD MODELING TOOLS

1. Introduction

The purpose of this report is to provide an overview of mental workload theory and mental workload measurement and to describe the development, application, and validation of the mental workload modeling tools developed by the Human Research and Engineering Directorate of the U.S. Army Research Laboratory (ARL). ARL has developed several workload modeling tools that can help the designer of military systems to assess the mental workload associated with different configurations of soldiers and equipment involved in the performance of a mission. Mental workload assessment is necessary because military systems are becoming extremely complex, requiring the system's operator to process a large amount of information. The system designer's task is therefore a threefold task. The designer must (a) strive to reduce system complexity and enhance operator performance, (b) ensure that automation, if implemented in system design, is used where it is most beneficial to the operator, and (c) ensure that the proposed system does not overwhelm the operator with too much information in too short a time. The system designer can accomplish these tasks by assessing the mental workload of the operator with the ARL workload modeling tools. Using these tools, the system designer can estimate and improve performance through the study and prediction of workload. To use these workload-modeling tools effectively, however, the system designer should understand the concept of mental workload and its importance to system design.

2. Mental Workload Definitions and Concepts

Mental workload is usually associated with information processing tasks, but any human activity includes mental processing and thus, mental workload (Nachreiner, 1995). Driving a car, for example, creates a certain level of mental workload for the driver. The driver must scan the highway, maintain control of the vehicle, maintain pressure on the gas or brake, and be aware of surrounding vehicles. All these tasks require mental processing and increase the mental workload of the driver. The driver of the car, as well as the operator of a military system, will perform most effectively if his or her mental workload is optimized as he or she performs tasks. Because the optimization of workload is so critical, it has been acknowledged as a goal for good system design in Part 2 of International Organization for Standardization 10075, an international standard for ergonomic principles (Nachreiner, 1995). Therefore, if a system designer wants a good system design, he or she must understand not only the concept of workload but also "optimal" workload.

Hart (1991) defines "optimal" workload as "a situation in which the operator feels comfortable, can manage task demands intelligently, and maintain good performance" (p.3). She uses an operational definition of workload, rather than a definition of the concept itself, because researchers do not agree on one definition of the workload concept (Huey & Wickens, 1993; Moray, 1988; Williges & Wierwille, 1979). Traditionally, workload has been defined as (a) imposed task demands, (b) level of performance, (c) mental and physical effort exerted by an operator, or (d) the operator's perception (Huey & Wickens, 1993). Most contemporary psychologists use definitions similar to the one given by Hart (1991), which assumes that workload results from some combination of a specific operator and the task assigned (Huey & Wickens, 1993).

Whichever workload definition he or she prefers, the system designer's goal is to optimize performance by optimizing workload. The designer optimizes workload by reducing it to just below the level where it has an adverse effect on performance (Nachreiner, 1995). This goal can be difficult to achieve, however, because there is sometimes a disassociation between workload and performance. The disassociation means that an individual's mental workload may increase while having no effect on the individual's performance. A number of workload theories have attempted to account for this disassociation and to define the nature of the workload and performance relationship. Understanding this workload literature can help the system designer to optimize workload in his or her system designs because it helps the designer interpret the relationship between workload and performance in his or her designs.

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3. Mental Workload Theory

Although more than 400 reports about the topic of workload have been published since 1979, there is no one accepted theory of workload, just as there is no one accepted definition (Huey & Wickens, 1993; Moray, 1988; Williges & Wierwille, 1979). Many of the workload theories are based on the information-processing model, which views the human as analogous to a computer. The cognitive energetic (CE) theory (Gaillard & Wientjes, 1994) is one example of this type of theory. CE theory assumes that each human activity has its own optimal energetic state at which performance is most efficient. Performance suffers when the individual's actual state deviates from the optimal state.

Wickens' (1991) multiple resource theory (MRT) of attention is another information-processing theory of workload. Whereas CE theory explains a performance decrement as a deviation from the optimal state, Wickens' theory views performance decrement as a shortage of resources. Wickens' theory proposes that the human has a limited capacity for processing information. Thus, if an operator is asked to perform two tasks at the same time, the performance of one or both of the tasks may suffer. Performance may suffer because each task has fewer available resources than when each task was performed separately.

Inherent in both the CE and MRT theories is the assumption that the human is a limited capacity processor who can perform tasks at a finite rate. Because of this assumption, Moray, Dessouky, Adapathya, and Kijowski (1991) propose that the appropriate model for studying workload is scheduling theory. This theory is widely used in industrial engineering. This model views the human as a machine with cognitive tasks or "jobs" to perform. A criterion is identified which the operator must meet. The rules of scheduling theory are then used to decide in what order tasks will be done, how long each job will take, and whether the criterion can be met.

The scheduling theory models, as well as the CE and MRT models, assume that people are performing tasks. Tasks are usually defined as behaviors with an identifiable beginning and end. Vallacher and Wegner (1987) have proposed a workload theory that is based on the hierarchical nature of tasks. For example, the same act could be described as pressing keys, typing a paper, proposing a new research concept, and so forth. Their action-identification theory attempts to explain how people identify tasks and when they switch from one level of task processing to the next. The theories just presented are four of the prominent theories or models used to describe the relationship between workload and performance. Note that there is a lot of overlap among these theories. Scheduling models, for example, are sometimes used to represent MRT and CE theory. This overlap between workload theories is a common problem in workload research. Because subtle differences in workload theories can be important, it is important for system designers to review as many theories as possible. Further descriptions of workload theories and models are given in Huey and Wickens (1993), Damos (1991), Kramer (1991), and Moray (1988).

The theory selected by ARL researchers for their workload modeling tools was Wickens' (1991) MRT. This theory was selected for several reasons. It allows the system designers to predict when tasks can be performed concurrently, when tasks will interfere with one another, and when increases in the difficulty of one task will cause losses in performance of another task (Little et al., 1993). For these reasons, MRT is the underlying foundation for the prediction of workload in the ARL modeling tools. The tools themselves, however, are not a theory but one of several methods for measuring and predicting workload.

3.1 Mental Workload Measurement

Just as there are many theories of workload, there are many standard methods for measuring workload. Typically, workload is measured with either an empirical or analytical approach. Empirical techniques are used when the system designer has an idea for improving an existing military system or piece of equipment. The system designer can measure the effects of the new design on the system operator by using mock-ups or simulators of the existing system. The analytical techniques can be used in these same conditions. However, the analytical techniques can also be used to predict workload when the system is still just a concept and no mock-ups or simulators exist.

All the workload measurement techniques, whether analytical or empirical, vary in sensitivity, diagnosticity, and intrusiveness (Damos, 1991). Sensitivity is the ability of a technique to discriminate between the workload imposed by one system or task versus that imposed by another system or task. Diagnosticity, on the other hand, refers to the ability of the technique to discriminate between different types of workload (e.g., visual versus cognitive workload). Intrusiveness refers to the effect, if any, that the workload measurement technique has on the main task being performed by the system operator. Because the workload techniques vary in sensitivity, diagnosticity, and intrusiveness, a system designer should use a combination of analytical and empirical techniques when measuring workload. The analytical technique used most often by researchers is workload modeling, whereas the major empirical techniques are physiological measures, behavioral measures, and subjective measures.

Physiological measures of workload are reviewed extensively by Kramer (1991). These measures of workload can include measures of electroencephalograph activity (EEG), event-related potentials (ERPs), measures of the magnetic field activity of the brain (MEG), measures of brain metabolism such as positron emissions tomography (PET), electro-oculograph (EOG) activity, eye movement, and heart rate. Researchers propose that each of these physiological measures is sensitive to some part of workload. Heart rate, for example, is expected to increase as workload increases. Therefore, if the system designer gives the system operator a new target detection system, the operator's workload would be expected to increase as the number of targets he or she is required to detect increases. Furthermore, if heart rate is a physiological indicator of workload, then the operator's heart rate should increase as his or her workload increases. Unfortunately, physiological measures are not very useful in early system design because at this phase, it is highly unlikely that physical mock-ups of the system exist. Therefore, the system designer cannot take physiological measures of the operator's workload in a mock-up. Once a prototype has been built, the physiological measures are useful to identify any areas where the system user might be experiencing excessively high levels of workload. The system designer relying on physiological indices of high workload needs to recognize that individuals can sometimes manage the high workload they are experiencing without its affecting their performance. In other words, physiological indices of high workload sometimes do not correlate with individuals' performance (Kramer, 1991). However, the physiological measures can help identify potential areas of high workload that may affect performance. The system designer can then use other workload measurement techniques to identify any performance decrements, and the system can be modified, if necessary, before it is actually fielded.

Another empirical workload technique system designers can use with physiological techniques or to replace them are behavioral workload measures. When system designers use behavioral measures as an indicator of workload level, they usually look at two types of measures: a primary task measure and a secondary task measure. Using the primary task measure, the designer assesses workload by examining some part of the system operator's ability to perform a required task such as speed and accuracy of detecting targets. For example, the system operator could be asked to perform a primary task such as detecting a target, and the system designer could measure the operator's performance in terms of speed and accuracy in that task. The system designer then assumes that when the operator's workload increases, his or her performance usually decreases. This performance decrement should be reflected in the operator's performance by an increase in errors or longer target detection times. However, a performance decrement does not always occur because individuals can devise strategies that allow them to maintain current performance levels as workload increases. Despite this limitation, the primary task methodology is often employed in field test settings.

The secondary task methodology augments the primary task methodology. This technique introduces a second task, which is performed concurrently with the primary task. For example, the operator's ability to perform mental arithmetic (secondary task) while detecting targets (primary task) might be assessed. The concept here is that the individual can use reserve processing capability to perform the second task (Eggemeier, Wilson, Kramer, & Damos, 1991). The secondary task methodology is good for laboratory settings. It can be used to collect a database of tasks that interfere with each other. It is difficult to use in real-world settings, however, because introduction of the secondary task is so invasive. In addition, the secondary task may be viewed as annoying or boring, and the individual being assessed may stop performing it (Hart & Wickens, 1990). To prevent these problems, system designers try to have the subject perform a secondary task, which is a natural part of the real-world setting (Hart & Wickens, 1990). For example, the military system operator might be asked to remember critical radio call signs while he or she detects targets.

The empirical technique that has achieved the greatest success is subjective measurement of workload (Moray, 1988). Subjective measurement usually consists of asking the operator to assess his or her own workload level. In this case, the system designer assumes that when the system operator expends more mental energy to perform a task(s), the operator then experiences a corresponding feeling of effort or exertion that can be judged accurately by him or her. Most researchers of mental workload agree that individuals find it easy to provide estimates of their workload and that these estimates have good face validity (Cohen, Wherry, & Glenn, 1996). However, the system designer needs to recognize that the subjects can report that they are experiencing high workload before this high workload actually affects their performance. Therefore, the designer should incorporate performance measures along with subjective workload ratings when he or she is evaluating a system to ensure that the workload reported by the system operators is actually affecting their performance. In addition to this limitation, researchers do not agree about what information should be obtained from individuals or how the information should be used to predict performance (Tsang & Velazquez, 1996). This disagreement probably results from the lack of a workload theory that adequately predicts the relationship between workload and performance.

Despite the disagreement among researchers, there are a number of different methods such as rating scales, questionnaires, or interviews, that system designers can use to collect subjective opinions of workload. The scales typically used to obtain subjective ratings of workload are the subjective workload assessment technique (SWAT) (Reid, Potter, & Bressler, 1989); the National Aeronautics and Space Administration (NASA) task load index (TLX) (Hart & Staveland, 1988); and the visual, auditory, cognitive and psychomotor (VACP) model (McCracken & Aldrich, 1984). Researchers have demonstrated that these scales do reflect variations in workload demand for different types of tasks (Eggemeier et al., 1991; McCracken & Aldrich, 1984). They are the most sensitive, most transferable, and the least intrusive techniques for workload estimation. Furthermore, several scales have demonstrated global sensitivity, which is the ability to identify a number of different factors that affect workload. These scales, which include SWAT and NASA TLX, would provide appropriate workload indications if a mock-up of the proposed system exists (Wierwille & Eggemeier, 1993). Unfortunately, the requirement for a physical mock-up of the existing system is a critical limitation of the subjective measurement techniques. The analytical techniques, on the other hand, can be used to predict mental workload when no mock-up exists and the system is just a concept.

4. ARL Analysis Tools

A primary analytical technique that researchers use to measure and predict mental workload is workload modeling. Researchers have designed a number of software-based tools that allow system designers to model and predict mental workload and its effect on system performance. ARL researchers developed two of these tools: the improved performance research integration tool (IMPRINT) and WinCrew. These tools have their origin in two tools developed by the Army in the 1980s: the manpower-system evaluation aid (MAN-SEVAL) tool (Allender, Kelley, Archer, & Adkins, 1997) and Crewcut (Little et al., 1993).

MAN-SEVAL was one of the modules in a suite of tools known as Hardware Versus Manpower III (HARDMAN III). System designers used MAN-SEVAL to identify the operator(s) of a proposed system, their tasks, and the operator(s) predicted workload. Workload in MAN-SEVAL was based on the mental aspects of the VACP components of tasks. Although MAN-SEVAL allowed designers to predict mental workload, the software did not allow them to model the dynamic interactions between the operators' performance and their mental workload. The software simply provided the system designer with two separate profiles, one for workload and one for system performance. Another tool, Crewcut (Little et al., 1993), took workload modeling a step further and allowed system designers to model the dynamic relationship between mental workload and performance.

System designers could use Crewcut to compare the operator workload imposed by various crew station designs. More importantly, Crewcut also allowed system designers to develop models of how crew members manage workload. The designers modeled the crew members' workload management using a default set of basic workload management strategies available in the software or workload management strategies they defined from their own research. These strategies helped the designers to obtain an accurate picture of the relationship between workload and performance. For example, in a real-world situation, a crew member may have three tasks that need to be performed at the same time. Realizing that he or she cannot maintain effective performance, the crew member gives one of the tasks to another, less busy crew member. Because reallocating a task to another qualified crew member is one of the default strategies in Crewcut, the system designer could model this situation and obtain an accurate estimate of performance. At the time Crewcut was developed, this unique feature was not available in any other workload modeling tool.

In 1992, the organizations that developed Crewcut and MAN-SEVAL merged into one organization, the U.S. Army Research Laboratory. Because system designers needed both the fast turn-around analysis offered by MAN-SEVAL and the higher fidelity analysis offered by Crewcut, a decision was made to maintain both modeling capabilities as Microsoft Windows™-based software tools. MAN-SEVAL was incorporated into a larger software package called IMPRINT (Allender et al., 1997) as the "VACP" option. Because IMPRINT is the principal human performance modeling tool for ARL and the U.S. Army, WinCrew workload modeling capabilities were incorporated into IMPRINT as the advanced workload analysis. WinCrew is also maintained as a stand-alone commercially available tool.

The system designer uses IMPRINT to estimate the likely performance of a new military system by building models of each operational or maintenance mission that the system will be required to accomplish (MicroAnalysis and Design, 1998). Because one of the critical components of operator and system performance is operator workload, IMPRINT has two options for generating workload profiles. The simpler workload option is the VACP option. The system designer would use this option early in the design process when many of the details of the crew stations may not yet be identified. The other option, advanced workload analysis, is the same as WinCrew. This option gives the system designer the capability to perform a more detailed and dynamic workload analysis than the VACP option. However, because the advanced workload option associates operator workload with the equipment interfaces the crew member uses, the system design must be at a more advanced stage than with the VACP option. Therefore, the system designer would usually begin a system design analysis using the VACP method and, if necessary, would apply the advanced workload method as the analysis matures (Archer, 1998). The underlying structure for both the VACP option and the advanced workload analysis option, as well as IMPRINT itself, is task-network modeling and discrete event simulation.

Task network models are computer-based simulation models that the system designer can use to predict task and procedure execution and mental workload. The model consists of the tasks needed to accomplish a particular job or mission, the amount of time it takes each task to execute, the sequence by which the tasks are performed, and the individual or operator who performs each task.

To build a task-network model, the system designer begins with a mission or job that an operator(s) will be performing. Next, the system designer reduces the mission to the specific tasks and subtasks that the operator(s) need to accomplish to perform the mission. He or she then enters the sequence by which the operator(s) perform the tasks. This process is relatively easy for the designer to perform and can be done early in the design process. It has the added benefit of forcing the designer to think in great detail about the entire proposed system. In addition to the tasks to be performed and their sequence, the system designer building a task-network model must also estimate the time required for the operator to complete each task. These task times are then entered into the computer model and are used to calculate overall system performance time. If the task network model is a deterministic model with non-parallel tasks, then the times entered for each task will equal the estimated mission time. With a stochastic task-network model, however, the times for each task can be drawn from a distribution of times. The resulting system performance times for the stochastic model are an average of the randomly selected times. Because human behavior varies, the stochastic task-network model is a more realistic representation of system operators than the deterministic model. Therefore, the IMPRINT software is based on a stochastic rather than on a deterministic task network modeling technique.

In addition to being a stochastic task-network modeling tool, IMPRINT uses discrete event simulation to model human performance. Discrete simulation and continuous simulation are two broad classes of simulation models. The type of simulation an analyst uses depends upon the types of problems to be solved. "For example, a model of traffic flow on a freeway would be discrete if the characteristics of and movement of individual cars are important. Alternatively, if the cars can be treated 'in the aggregate,' the flow of traffic can be described by differential equations in a continuous model" (Law & Kelton, 1991). Because the system designer is interested in the operator's tasks individually, not as an aggregate, discrete simulation was selected as the basis for IMPRINT. More specifically, IMPRINT is based on a discrete <u>event</u> simulation. A discrete <u>event</u> simulation is appropriate when the elements of the process modeled have a distinct beginning and ending as do all the missions and tasks modeled with IMPRINT. The specific task network tool and discrete event simulation model used in the IMPRINT software is the commercially available MicroSaint™.

MicroSaint™ is a task network simulation language developed by MicroAnalysis and Design, Inc., for the U.S. Army Medical Research and Development Command. MicroSaint™ makes it simple for system designers to build task network models by providing a graphical interface and flow chart approach to modeling. Using MicroSaint™, the system designer builds a graphical representation of the task network that is also a graphical representation of the job or mission the system operator will be performing. Figure 1 depicts an example of a graphical representation of a task network. As Figure 1 depicts, the system designer uses rounded rectangles to represent modeled tasks and arrows to connect the tasks to represent the order of task execution within the mission. Once the designer has completed the task network, the MicroSaint™ software links the tasks, task times, and individual performance together in the model and simulates the system operator performing a mission. The system designer uses a modified version of the MicroSaint™ graphical interface to model the operator's tasks with IMPRINT. In addition to modeling the tasks and task times, however, the system designer can also use IMPRINT to model operator mental workload with either of its two options, VACP or advanced workload analysis.

5. VACP Method

VACP is based on a tailored version of the task analysis/workload (TAWL) methodology (Hamilton, Bierbaum, & Fulford, 1991) which evolved from the Army light helicopter experimental (LHX) program. The first step in a TAWL is to identify the tasks that are necessary to operate a proposed system. Similarly, the system designer building a VACP IMPRINT model must first identify the tasks required for operating the proposed system. However, with IMPRINT, the designers do not have to put all the tasks for the proposed system into one model. If necessary, each mission performed by the system and its tasks can be a separate model. The tasks incorporated into each model generally should be tasks that are performed in seconds, minutes, or hours rather than tasks that take days or weeks. For example, system designers modeled a howitzer crew, which included emplacing the howitzer, conducting a fire mission, and displacing the howitzer as three separate missions rather than as one large mission.

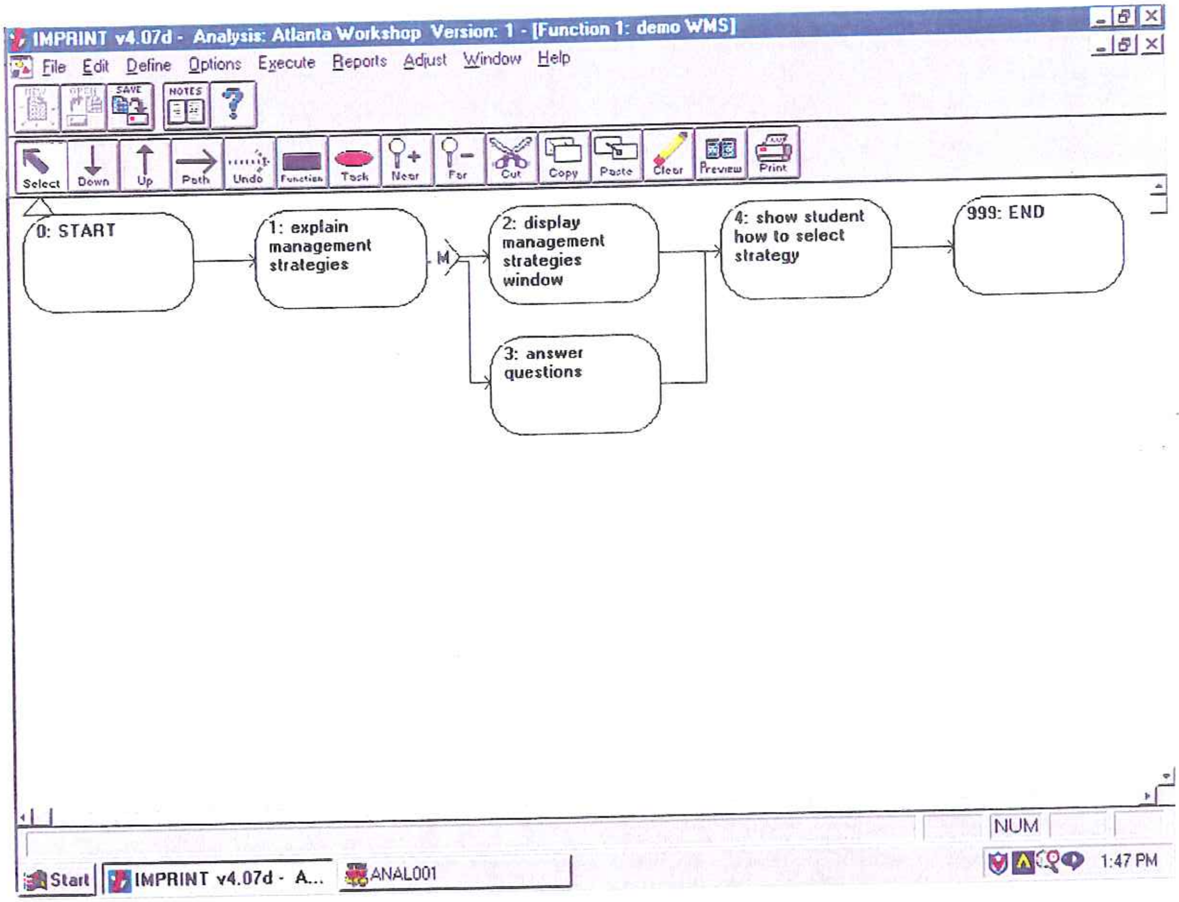

Figure 1. MicroSaint™ graphical interface.

After the system designers have identified the tasks necessary to complete the mission, they must identify the operators of the system. Furthermore, because IMPRINT models are models of individuals moving from task to task, the designer must also designate which operator is performing which tasks. Once the tasks and operators have been identified, the system designer must specify the order in which the tasks will be performed and the times to perform the tasks. The system designer usually gets this information from a subject matter expert (SME). The SME for an existing system would be the system operator. If the system is still in the concept phase, then the SME could be someone who is operating an existing system that is similar to the proposed system. The SME would also help the system designer to estimate the workload values for each task, which is the next step in the VACP analysis. The system designer estimates workload for each task, based upon the mental resources the operator needs to perform each task. With the VACP method, the resources the operator is expected to use for any task may be visual, auditory, cognitive, psychomotor, or a combination of any of these four resources. After the system designer selects the resources the operators use for each task, he or she then enters numerical values for the selected resources using scales developed by McCracken and Aldrich (1984) and enhanced by Bierbaum, Szabo, and Aldrich (1989).

The scale for each resource is based on a 7-point interval and contains verbal anchors that describe the behaviors expected for each interval. As an example of the scales that the system designer is using to rate workload, the scale and verbal anchors for the visual resource are presented in Table 1. The system designer selects values from the scales for each resource being used for each task and enters the values into the IMPRINT software.

Table 1

Visual Workload Scale for the VACP Option

Scale value	Visual scale descriptor
0.0	No visual activity
1.0	Visually register or detect (detect occurrence of image)
3.7	Visually discriminate (detect visual differences)
4.0	Visually inspect or check (discrete inspection or static condition)
5.0	Visually locate or align (selective orientation)
5.4	Visually track or follow (maintain orientation)
5.9	Visually read (symbol)
7.0	Visually scan, search, or monitor (continuous or serial inspection, multiple conditions)

After the system designer enters the workload ratings for each resource required by each task performed by each operator, the IMPRINT software sums the workload ratings within each resource across concurrent tasks. Although the values for each resource are limited to a 7-point scale, an operator's workload is often higher than seven. An operator's workload can exceed seven because the software is adding the workload for all tasks that are occurring simultaneously. For example, the same operator could perform two tasks at once. The first task has a visual rating of 4.1 and the second one has a visual workload rating of 3.2. For the amount of time these two tasks overlap, the operator's total visual rating would be 7.3 (MicroAnalysis and Design, 1998). The software computes the workload rating while the simulation is running. The simulation run provides the system designer with graphs and tables of the workload values over time for each operator of the system. The system designer can examine the workload graph and determine where the workload peaks are and which tasks were being performed at that time and contributed to the peaks. If the workload graph shows that all operators had peak workload at the same time, then the system designer should consider automating some of the tasks the operators are performing during that time period. If the tasks cannot be automated, then the system designer might reduce the operators' workload by redesigning some of these tasks and making them less resource intensive. If, on the other hand, the workload graph indicates that one operator has a high workload peak and another operator has a low workload, then the system designer might decide to reallocate some of the tasks to the less busy operator. Thus, the workload graph allows the system designer to decide when tasks should be redesigned, automated, or allocated to another operator in order to reduce the workload of the operator.

Although the VACP method provides the system designer with workload estimates, the workload for an operator does not affect the operator's performance during a simulation run. On the other hand, the advanced workload analysis option allows the system designer to model the dynamic relationship between workload and performance.

6. Advanced Workload Analysis

The relationship between workload and performance is complicated. It is not simply that as workload increases performance decreases. Instead, the relationship between workload and performance is traditionally described as an inverted "U" because decrements in performance may occur if workload is either too low or too high. Furthermore, there can be a disassociation between workload and performance at certain levels. This means that as workload increases, the operator's performance may not decrease because the operator has a strategy for handling task demands to compensate for the increased workload. Hart (1989) proposed that operator workload strategies play an important role "in determining the relationship between objective task demands, experienced workload, and system performance" (p.4). The advanced workload analysis feature of IMPRINT allows the system designer to incorporate operator workload management strategies into the workload model. Thus, the advanced workload analysis feature provides the system designer with a more detailed representation of the relationship between workload and system performance than the VACP method does.

The procedure for building a model with the advanced workload analysis feature is very similar to the procedure used with the VACP method. To obtain a workload estimate using the advanced workload analysis option, the system designer first selects a job or mission that the operator(s) of the proposed system will perform. Next, the system designer decomposes the selected mission into the tasks the operator(s) will be performing in order to accomplish this mission. The task sequence and the operator(s) who will perform these tasks are then identified. The procedure at this point has been identical to VACP. However, unlike the VACP method, the advanced workload analysis option links workload to the specific equipment used by the operator. It does this because it contains an embedded workload calculation algorithm. This algorithm, which is depicted in Figure 2, is based on a variation of the workload index model (North & Riley, 1989). It calculates workload, based on the resources being used by the operator, and incorporates the fact that multiple tasks are being performed simultaneously. In addition, the algorithm relates the resources used to crew station displays and control surfaces (Little et al., 1993). Because the advanced workload analysis option contains this algorithm, the system designers must specify the equipment interfaces (e.g., keyboard, helmet-mounted display) that operators will be using to accomplish each of their assigned tasks. Furthermore, the designer must also specify the mental resources a crew member uses with each equipment interface as he or she performs each task.

$$W_T = \left[\sum_{i=1}^{l}\sum_{t=1}^{m} a_{t,i}\right] + \left[\sum_{i=1}^{l} c_{i,i}\sum_{t=1}^{m} a_{t,i} + \sum_{i=1}^{l-1}\sum_{j=i+1}^{l} c_{i,j}\sum_{t=1}^{m-1}\sum_{s=t+1}^{m}\left(\left(a_{t,i}+a_{s,j}\right)+\left(a_{t,j}+a_{s,i}\right)\right)\right]$$

W_T = instantaneous workload at time T
i, j = 1…l are the interface channels
$n_{T,I}$ = number of tasks occurring at time T with nonzero attention to channel i
t = 1…m are the operator's tasks or activities
$a_{t,i}$ = attention to channel i required to perform task t
$c_{i,j}$ = conflict between channels i and j
$c_{i,i}$= conflict within channel I

1. if at $a_{t,i}$ or $a_{s,j}$ = 0, then ($a_{t,i}$ + $a_{s,j}$ =0),
2. if $a_{t,j}$ or $a_{s,i}$= 0, then ($a_{t,j}$ + $a_{s,i}$ = 0),
3. if $n_{T,I}$ is < or = 1, c_{ii} =0.

Figure 2. Workload algorithm.

The VACP method limits the system designer to four mental resources: visual, auditory, cognitive, and psychomotor. With the advanced workload method, these resources are expanded to a set of five resources: visual, auditory, cognitive, psychomotor, and speech. In addition, the system designers can create their own resources. For example, the system designers' research may indicate that the tactile resource is important for their design. They can then add this to the resource list in the advanced workload analysis option. However, no default scales are available to help the designers estimate workload for this resource. They must substantiate values for this resource, based on current research. If the system designers choose to use the default resources, they can rate the amount of each of these resources required to do a task using 7-point rating scales very similar to the McCracken and Aldrich (1984) scales used with the VACP method. However, the McCracken and Aldrich scales have been revised in the advanced workload analysis option. The original scales were developed for estimating workload for the Army's light helicopter. When the (former) Human Engineering Laboratory was developing the Crewcut tool, SMEs with armored vehicle and psychology expertise studied the helicopter scales. Based on the SMEs' recommendations, some of the scale values were revised. In addition, the psychomotor resource was divided into two separate resources: motor and speech. Because the advanced workload analysis option is identical to WinCrew and WinCrew is the Windows™ version of Crewcut, the revised scales are used in the advanced workload option to estimate workload for each resource. The revised scales are provided in Table 2. Just as with the VACP method, the system designers must use these scales to estimate the resources required for each task an operator performs. Although the system designers are using similar scales to rate workload with both the VACP and advanced workload analysis options, the method the software uses to calculate the workload, based on the ratings, is very different. Both of the calculation methods are based on MRT, but the implementation of this theory in the advanced workload analysis option is much more sophisticated.

According to MRT, when an individual performs a task, he or she requires different mental operations and to some extent, each operation uses the mental processing resources necessary to accomplish the task. These mental resources are limited, and a supply-and-demand problem occurs when the individual performs two or more tasks that require a single resource. As a result of the time sharing of resources, some task performance times may increase, the probability of successfully completing a task may change, or performance times may decrease (Little et al., 1993). These MRT concepts are the underlying assumptions for both workload options in IMPRINT. MRT, however, also explains how two tasks can conflict with each other.

According to the multiple resource model, two concurrent tasks will suffer greater interference to the extent that the component tasks are more difficult (demand more resources) and that the components compete for overlapping resources. Furthermore, the effects of difficulty and resource overlap interact. The greater the degree of resource overlap, the more pronounced will be the effect of the level of difficulty of one task on the level of performance of another task (Little et al., 1993, p 9).

In the VACP option, conflict between tasks is not considered in the calculation of workload. The workload calculation is simply the sum of the workload ratings within each resource across concurrent tasks. The workload algorithm in the advanced workload analysis option, however, does incorporate the MRT findings. It sums the resource demands and includes penalties for situations when two tasks require the same resources and for situations when the use of different resources causes interference. The workload algorithm itself is presented in Figure 2.

The first part of the workload algorithm computes the resource demands for all active tasks. Therefore, each time a new task is started, the algorithm adds the workload ratings for each resource for the new task and all other tasks being performed at that time. The next two terms within the second bracket of the equation compute the penalties for two tasks using the same resource at the same time and two tasks requiring different resources at the same time. For example, if one task requires a system operator to look at a computer screen on the right side, while a second task simultaneously requires the operator to look at a computer screen on the left side, then the equation assigns a penalty to the task. In this case,

Table 2

Revised UH-60 Helicopter Workload Component Scales

Scale value	Descriptors	New values
	Visually unaided (naked eye)	
1.0	Visually register or detect (detect occurrence of image)	3.0
3.7	Visually discriminate (detect visual differences)	5.0
4.0	Visually inspect or check (discrete inspection or static condition)	3.0
5.0	Visually locate or align (selective orientation)	4.0
5.4	Visually track or follow (maintain orientation)	4.4
5.9	Visually read (symbol)	5.0
7.0	Visually scan or search monitor (continuous or serial inspection, multiple conditions)	6.0
	Visually aided (with NVGs)	
4.0	Visually register or detect (detect occurrence of image) with NVGs	5.0
4.8	Visually inspect or check (discrete inspection or static condition (with NVGs)	5.0
5.0	Visually discriminate (detect visual differences) with NVGs	7.0
5.6	Visually locate or align (selective orientation) with NVGs	5.0
6.4	Visually track or follow (maintain orientation) with NVGs	5.4
7.0	Visually scan, search, or monitor (continuous or serial multiple conditions) with NVGs	7.0
	Auditory	
1.0	Detect or register sound (detect occurrence of sound)	1.0
2.0	Orient to sound (general orientation or attention)	2.0
4.2	Orient to sound (selective orientation or attention)	4.2
4.3	Verify auditory feedback (detect occurrence of anticipated sound)	4.3
4.9	Interpret semantic content (speech) simple	3.0
	(1 to 2 words) complex sentences	6.0
6.6	Discriminate sound characteristics (detect auditory difference)	6.6
7.0	Interpret sound patterns (pulse rates, etc.)	7.0
	Cognitive	
1.0	Automatic (simple association)	1.0
1.2	Alternative selection	1.2
3.7	Sign or Signal recognition	3.7
4.6	Evaluation or judgment (consider single aspect)	4.6
5.3	Encoding or decoding, recall	5.3
6.8	Evaluation or judgment	6.8
7.0	Estimation, calculation, conversion	6.8
	Rehearsal	5.0
Psychomotor (this scale was divided into speech and motor in revised scale		
	Speech	
1.0	Speech simple (1 to 2 words)	2.0
	Complex (sentence)	4.0
	Motor	
2.2	Discrete actuation (button, toggle, trigger)	2.2
2.6	Continuous adjustive (flight control, sensor control)	2.6
4.6	Manipulative	4.6
5.8	Discrete adjustment (rotary, vertical thumb wheel, lever position)	5.5
6.5	Symbolic production (writing)	6.5
7.0	Serial discrete manipulation (keyboard entries)	7.0

the penalty would be that one task could not be performed. In other cases, the penalty might be that a task's time is increased. The penalty is assigned because the two tasks are using the same resource at the same time. The system designer determines the amount of interference between resources being used by concurrent tasks by entering values into a conflict matrix provided in the software. This conflict matrix displays each resource paired with the equipment interface that uses the resource. For each resource and interface pair, the designers enter conflict values, based on guidance from their own research, or the software can provide default values, based on the MRT literature. The conflict values, which can range from 0 (represents no conflict) to 1.0 (represents total conflict), will be unique to each system design because the values are linked to both equipment interfaces and resources. Each design will have a different set of equipment interfaces that use specific resources and therefore its own set of conflict values.

After the system designers have provided conflict values and workload ratings for each operator for each task, the algorithm calculates the workload for each operator before a new task begins, at the start of a new task, and after a task is completed. In addition to calculating this overall workload, the advanced workload analysis option allows system designers to specify how the system operator will manage the workload. They do this with the workload management strategies.

7. Workload Management Strategies

Workload management strategies allow the system designer to account for the fact that individuals employ different strategies for performing tasks during conditions of work overload. The need to model workload management strategies was initially suggested by Hart (1989) who argued that individuals learn and adapt and therefore respond dynamically to changes in their mental workload. She explained that individuals learn strategies for adapting to increasing workload demands. When workload becomes too high, the individual's strategy may deteriorate and an observer could then see a change in the individual's performance as a result in this deterioration in strategies. It is important to have these strategies in the advanced workload analysis option because they allow the system designer to more accurately estimate the effects of workload on performance.

To use the workload management strategies, the system designer must first enter a workload threshold. It must be a number ≥ 0. This threshold represents the point where the proposed system's operator will be considered overloaded and a workload management strategy will need to be applied. For example, if the system designer selects 40 as the threshold number for a particular operator, then any time that operator's workload exceeds 40, he or she will be considered overloaded. At this time, the overloaded operator will employ the workload management strategy selected by the system designer to handle the overload. An operator is also considered to be overloaded any time multiple tasks require a resource interface pair that has been assigned a conflict value of 1.0. When this situation occurs, the operator will use the workload management selected by the system designer to handle the overload.

The advanced workload analysis option includes six workload management strategies for overload conditions:

1. No effect. All tasks are performed, regardless of the workload value. This is the default strategy.

2. Do not begin the next task. The next task is not started by any other operator. This is sometimes referred to ask "task shedding."

3. Perform tasks sequentially, beginning with ongoing tasks and then performing the next task.

4. Interrupt ongoing tasks in favor of starting the next task. Restart ongoing tasks in "windows of opportunity" (i.e., when the operator's workload drops below the threshold value).

5. Reallocate the next task to the contingency operator if a contingency operator has been designated. (The contingency operator can be an automated system.)

6. Reallocate ongoing tasks to the contingency operator or automation.

In addition to these default strategies, system designers can create their own strategies for the operators to use. They create these strategies by combining pre-defined system variables and arithmetic and logical operators into "if-then-else" statements. Variables the designers can use in the expressions are

P - Priority of the next task (each task can be assigned a priority from 1 to 5)

H - Highest priority of any ongoing task

T - Total workload for the operator after beginning the next task.

S - Operator's workload threshold value.

An example of a strategy a designer might create using these variables is "if P > H, then D, else C." In this example, D and C are the pre-defined strategies C and D that are embedded in the software. This system designer-created strategy translates to "if the priority of the new task is higher than that of any other ongoing task, then perform the new task and suspend the ongoing tasks until workload goes below the threshold." The critical aspect of the workload management strategies created by the system designer, as well as the pre-defined workload management strategies, is that they represent dynamic task scheduling, based on operator workload. In other words, the system designer does not specify exactly which task the operator will do next in performing the mission. The next task(s) will be determined in part, based on the momentary workload of the operator (Archer & Lockett, 1997). The designers can view the effect of the workload management strategies and the interaction of the workload and performance for the mission by viewing the advanced workload analysis output reports.

The advanced workload analysis reports include a mission summary, critical path report, workload graphs, and reports describing the operator activity, overload, and channel conflicts. From these reports, system designers can view the total workload value over time for each operator of the system. Because this value is on an ordinal scale, it allows the system designer to make only relative comparisons of workload at different times during the mission. This means that the system designer should not compare specific overall workload numbers. Instead, the designer examines the workload graphs and determines where the workload peaks are and which tasks were operating at that time and contributed to the peaks. The designer can then select these tasks as candidates for redesign, automation, or reallocation to another crew member (Archer, 1998). Furthermore, the process of building and inputting data into the models helps the system designers to think about those interfaces and tasks that are contributing factors to workload and performance.

8. Validation

The IMPRINT workload analysis options help the system designer to make accurate predictions about operator workload and its effect on performance of a proposed system. In order for the analyst to make the correct design decisions using the IMPRINT workload options, however, the predicted mental workload and performance estimates obtained from the IMPRINT model must be accurate representations of actual mental workload and performance in the real world. Therefore, to evaluate the validity of the IMPRINT workload predictions, researchers at ARL participated in an international effort to determine which workload models make the best predictions of workload and performance and during what conditions these capabilities exist. Workload models from the United Kingdom (POP), Canada (IP/PCT), and the United States (IMPRINT advanced workload option) were evaluated with the same set of data collected during two experiments at Wright-Patterson Air Force Base. In fulfillment of its part of this effort, ARL built IMPRINT advanced workload models to represent the two experiments. Preliminary data analyses comparing the experimental workload ratings with the IMPRINT predicted workload ratings indicate that IMPRINT advanced workload method has good predictive validity. Specifically, the workload ratings from the IMPRINT models correlated with the subjective workload ratings given by the participants in the Wright-Patterson experiment. Furthermore, the differences between experimental conditions predicted by the IMPRINT models were the same as the differences between experimental conditions provided by the performance measures gathered during the experiment (Mitchell, 1999). This validation effort proved that the IMPRINT advanced workload analysis option can be used to provide valid predictions of the mental workload of individual operators. Indeed, the IMPRINT workload options have been used to make valid predictions about the mental workload of the operators of military systems.

9. Applications

System designers have used the VACP workload option for a number of military applications. They used MAN-SEVAL, which is synonymous with the VACP workload option in IMPRINT, to model the U.S. Army's Land Warrior system. The designers built baseline models of a squad leader and a squad member equipped with current equipment. They then built models of the squad member and squad leader wearing Land Warrior equipment. The designers compared the two model sets to determine the effect of the Land Warrior equipment on mission performance (Adkins, Murphy, Hemenway, Archer, & Bayless, 1996).

Designers have also used the IMPRINT VACP option to model joint base station variant (JBS V1) missions. IMPRINT analyses were conducted to assess skill and requirements, workload, and mission performance to assist in determining the appropriate quantity and military occupational specialty of JBS (V1) operators (Malkin, Allender, Kelley, O'Brien, & Graybill, 1997). Most recently, system designers have used IMPRINT to build models of the Crusader 155-mm howitzer system to evaluate the effects of crew size, continuous operations, and number of vehicle work stations on mission performance (Beideman, Munro, & Allender, in press).

WinCrew, the stand-alone version of the advanced workload analysis, has been used to model the workload and functional allocations of the bridge activities aboard a U.S. Navy destroyer (Archer, Lewis, & Lockett, 1996). During this study, system designers built a baseline model of the existing nine-person bridge crew. Then they built three more models to represent different configurations of automation and function and task allocations for a reduced crew of three (Archer & Lockett, 1997). The U.S. Federal Aviation Association also used WinCrew to evaluate alternate crew and function allocations for oceanic air traffic controllers (Archer & Lockett, 1997).

10. Future Needs

In combat situations, military system operators usually work in crews or as teams rather than in isolation. Therefore, ARL researchers plan to incorporate the prediction of team mental workload and performance into the IMPRINT workload options. Recent research has demonstrated that team performance is more than just the sum of the performances of individuals (Bowers, Braun, & Morgan, in press). Therefore, system designers need guidelines for team performance in the models of the proposed system. Currently, the IMPRINT software provides the designer with some capabilities for modeling the operator as part of a crew. For example, one of the workload management strategies employed by a crew member is to have a contingency operator perform the new task in an overload situation. Therefore, the designer can assign one crew member as the primary person or operator who will perform a task and another individual as a "contingency operator." The contingency operator is someone who would not normally perform that task but has access to the controls and displays to do it. If the primary operator becomes overloaded, then the contingency operator may be able to perform the task for him or her. If performing this additional task will overload the contingency operator, then the task goes back to the primary operator.

Although IMPRINT features provide some preliminary capability for the analyst to handle team performance, they do not provide the analyst with any theoretical basis for how teams handle multiple tasks. Therefore, the goal of the present ARL advanced workload IMPRINT research effort is to review the literature about team performance, especially as it relates to mental workload, and to identify data sources and data that can be used to further develop the IMPRINT advanced workload team performance modeling capabilities.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 2000

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Mental Workload and ARL Workload Modeling Tools

5. FUNDING NUMBERS
AMS: 622716.H700011
PR: 1L161102B74A
PE: 6.11.02

6. AUTHOR(S)
Mitchell, D.K. (ARL)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Human Research & Engineering Directorate
Aberdeen Proving Ground, MD 21005-5425

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Human Research & Engineering Directorate
Aberdeen Proving Ground, MD 21005-5425

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-TN-161

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The author of this report provides an overview of mental workload theory and mental workload measurement. She also describes the development, application, and validation of the mental workload modeling tools developed by the Human Research and Engineering Directorate of the U.S. Army Research Laboratory (ARL). These ARL tools, VACP (visual, auditory, cognitive, psychomotor) option in the improved performance research integration tool (IMPRINT) and WinCrew, can help the designers of military systems to assess the mental workload associated with different configurations of soldiers and equipment involved in the performance of a mission. System designers can conduct this assessment in the concept development phase of system design and reduce the need to build costly system mock-ups.

14. SUBJECT TERMS
IMPRINT
modeling tool
WINCREW
mental workload
task network model

15. NUMBER OF PAGES
35

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102