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Figure 1. Emergency room workers are among those most susceptible to the effects of fatigue, including diminished task performance.

A Conceptual Framework for the Estimation of Worker Fatigue

James C. Miller

any emergency service providers, (see Figure 1) and the military services, faced with the requirement for 24-hour operations in an environment of declining revenues, must determine how to redesign their operations. They must take into consideration the strengths and weaknesses of workers, such that operations will be accomplished safely and effectively. Reductions in the number of personnel used to accomplish a given operation will be successful only if great care is exercised in the designs of jobs, tasks, and human-system interfaces. Pitfalls associated with such design projects include the risks of creating jobs and tasks that are not matched to human cognitive strengths and that do not protect the human-machine system from human cognitive weaknesses. Also, they include the risk of causing personnel to exert efforts that tax them beyond their limits of cognitive and physical endurance.

This article describes a conceptual framework that may help determine whether operations con-

tribute to excessive fatigue, thus exposing workers to unnecessarily high risks of incidents, accidents, injury, and mission failure. The framework includes the concepts of circadian rhythms, workload (stress), effort (strain), performance, and fatigue. It allows one to consider interactions among a number of contributors to fatigue, including:

- Both physical and mental stressors
- Work-sleep schedules
- The effort with which an individual responds to stressors, including the individual's general level of motivation
- The physiological and mental costs of the effort
- The quality of performance displayed overtly by the individual, and
- The degree of fatigue experienced covertly.

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Circadian Rhythms. The operational impact of a human circadian rhythm that is not aligned with the day-night cycle is familiar to anyone who has suffered jet lag. Consider the inability of an individual from the West Coast to awaken refreshed on the first morning of a sojourn on the East Coast. At 0600 on the East Coast, the brain's circadian

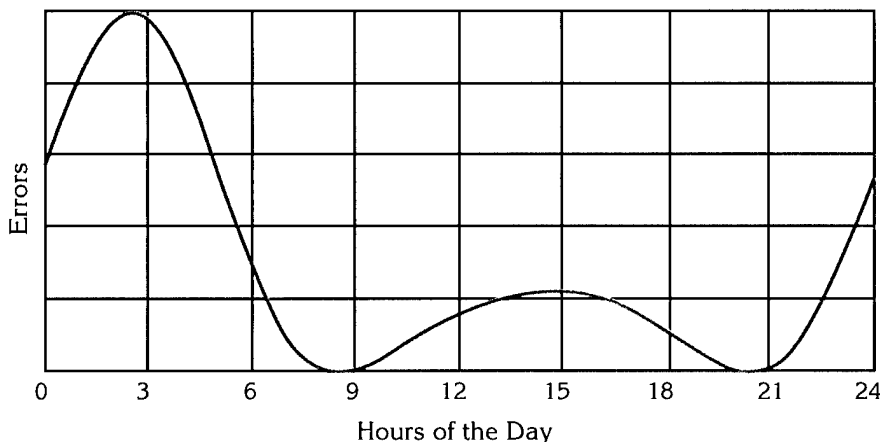
include loss of motivation, feelings of anxiety, sleepiness, boredom, and loss of vigilance capability.

Performance. Performance is often the "bottom line" of the measures of interest in fatigue studies. Performance measures may include aerobic and anaerobic work accomplished per unit time, numbers of messages created and their accuracy, and numbers of navigation fixes taken and their accuracy. Worker performance may also be measured

indirectly by presenting and collecting data from computer tasks that are not associated with operations.

Unfortunately, performance measures are not always sensitive to the effects of fatigue. This problem is due to the "two-edged sword" of human adaptability. The "good" edge is the ability of workers to motivate them-

Figure 2. Circasemidian pattern of error occurrence (Adapted from Mitler & Miller, 1996).



rhythm is operating as if it were 0300; it is generating sleep activity, reaction times are slowed, aerobic physical capacity is slightly impaired, and the expected frequency of job errors is increased.

Workload (Stress) and Effort (Strain). Work demand is viewed as a stress, to which one responds with some evidence of strain. We differentiate physical (muscular) stress from mental stress. An example of a physical stress would be the requirement to remain standing in a ship tossed by high seas. An example of a mental stress would be the requirement to navigate the ship safely within a fishing fleet, avoiding collisions. An example of strain in the physical domain would be the metabolic effort of maintaining an upright position in a ship tossed by high seas. An example of strain in the cognitive domain would be the mental effort required to navigate a Coast Guard cutter within a fishing fleet and avoid collisions. The degree of effort brought to bear on a specific work demand is assumed to be modulated by motivation. Specifically, greater motivation is expected to lead to greater efforts.

There are physiological costs, metabolic in nature, associated with physical effort. Similarly, there are psychological costs associated with effort. These

selves to face challenges and accomplish difficult tasks in acceptable manners in the presence of high levels of strain and resulting fatigue. Typically, the fatigued but motivated human can mobilize resources quite well for brief periods. However, the "bad" edge of the sword is the eventual effect of physiological and mental costs: there may be a catastrophic drop in performance or an involuntary onset of sleep. Thus the measured performance of the fatigued but motivated worker may show no impairment at all until performance ceases abruptly.

Fatigue. Besides measuring performance, we wish to determine the degree of fatigue that physiological and mental costs may cause. Fatigue is viewed as a covert result of the costs generated by effort and performance as found in the perceptions of the workers, diminished task performance, and behaviors associated with sleepiness. Fatigue may also lead to injury. An acute physical stress that exceeds connective-tissue limits may lead to a sprain or strain of a joint. We watch for data pertaining to personnel injuries, real property damage, and close calls associated with operations.

We divide fatigue into three categories: circadian effects, acute fatigue, and cumulative fatigue. Circadian and circasemidian effects usually lower mental and physical performance and cause extreme sleepiness during the pre-dawn hours, with a similar but milder impairment during the mid-afternoon hours. This results in a predictable daily pattern of errors of commission and omission as shown in Figure 2.

Acute fatigue is assumed to develop within one work period. The word "acute" is used here in its medical connotation, suggesting a brief occurrence of a condition (for example, one work period). Cumulative fatigue is assumed to develop across work periods when inadequate rest is obtained between work periods. We expect circadian effects to be larger than cumulative and acute effects, and cumulative effects to be greater than acute effects.

Workload and Allotted Sleep Time. Worker sleep time and workload are often two sides of the same coin. If one were to design a work-rest schedule based solely upon the adequate daily recovery (i.e., through sleep) of human resources, then the amount of sleep acquired by workers would be somewhat independent of the amount of time spent working. The single, major allotted sleep period for each worker might be set, for example, at the 99th percentile of the average sleep requirement for 20-29 year old males (i.e., about 8 hours). However, operational demands, job and task designs, and the amount of available human resources determine many work-rest schedules. Thus the amount of sleep acquired by a worker depends upon the amount of work to be done. Because of that interdependence, several of our sleep measures and our workload measures are viewed as determinants of the work demand placed upon the worker.

Work-rest Schedules. Work-rest schedules and their impact on human circadian and circasemidian rhythms have very large effects on individual workload, effort, performance, and fatigue measures. One aspect is that the level of worker alertness and performance is governed strongly by the amount and quality of rest acquired before and between periods of work. There are three major determinants of sleep tendency during a period of intended wakefulness: (1) circadian effects, (2) the amount of preceding sleep, and (3) the length of time since the last sleep period. In addition to the well-known circadian effect of high sleep tendency during the typical sleep period for humans from midnight until dawn, the amount of sleep a person has obtained in the preceding 24 to 48 hours is an extremely important determinant of sleep tendency. Thus it is necessary that we document both the time of day that work takes place, and the time and amount of sleep obtained preceding each work period.

This conceptual framework may be useful to investigators who wish to determine whether operations contribute to excessive fatigue. To study the impact of work-rest schedules on circadian and circasemidian rhythms and individual workload, effort, performance, and fatigue measures, we design Daily Logs for workers. The Daily Log provides information about the workers' daily cycles of work, rest, and sleep, as well as body temperature and subjective ratings. It documents varying work-rest cycles

and helps pinpoint obvious circadian disruptions of sleep patterns. The date- and time-stamped data in the Log are presently entered manually into spreadsheets for data selection, display, and reduction.

Our data reduction process uses a custom spreadsheet template which, in turn, we created using methods published by Paul Naitoh et al. (1985) and others in the research literature. It apportions total variance into variance (1) attributable to linear trend (cumulative fatigue), (2) attributable to a cosine function (circadian effect; circasemidian to be added), and (3) attributable to other factors, including random error and acute fatigue.

One of the measures we use is body temperature (T_{body}). Body temperature is acquired using a small, hand-held infrared probe shaped like the otoscope a physician uses routinely to check the ear canal during a physical exam. Workers are given detailed instruction, issued thermometers, and take their own temperatures approximately once every two hours, except when asleep.

In a recent Coast Guard study, the 24-hour cosine curve was fitted to body temperature, surrogate performance task scores, and subjective ratings. We acquired good quality temperature data from 38 watchstanders and 9 non-watchstanders across five cutters. The use of the spreadsheet template for T_{body} allowed us to make the following statements, "The strength of the [circadian] cycle differed significantly between watchstanders and non-watchstanders, at $14.4 \pm 9.8\%$ and $22.8 \pm 21.5\%$ of total variance, respectively" ($p = 0.03$). Similar statements were also possible for other measures, revealing interesting circadian effects and linear trends that suggested the accumulation of fatigue across days. ■

References:

- Mitler, M. M., & Miller, J. C. (1996). Methods of testing for sleepiness. *Behavioral Medicine*, 21, 171-183.
- Naitoh, P., Englund, C. E., & Ryman, D. H. (1985). Circadian rhythms determined by cosine curve fitting: Analysis of continuous work and sleep-loss data. *Behavioral Research Methods, Instruments, & Computers*, 17 (6), 630-641.

The Fatigue Component Analysis Spreadsheet is available through CSERIAC at no charge. Please contact CSERIAC to order a copy.

For more information about the Spreadsheet, please contact:

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Human Factors in Urban Operations

Editor's note: Benjamin A. Knott, an Associate at Booz-Allen & Hamilton who recently completed a Ph.D. at Catholic University of America, has written a guest column at the request of Dr. Fineberg for this issue of Gateway. Dr. Fineberg's regular column will return in the next issue.

Benjamin Knott Today's military is facing an increasing number of operations that take place within urban centers. American forces have conducted major operations in Panama City, Port-Au-Prince, and Mogadishu, and non-combatant opera-

tions in Tirana, Kinshasa, Monrovia, and Freetown (see Figure 1). These Urban Operations (UO), often called Military Operations in Urban Terrain (MOUT), place unique psychological and physical demands on the troops involved. This article identifies some of these demands within the context of the urban environment, and identifies areas where there is a need for the application of human factors methods and expertise. Urban operations pose a significant challenge to the human factors community over a broad range of problems. Human factors professionals must be prepared to solve critical problems in equipping, manning, protecting, and motivating operational personnel.



Figure 1. A Haitian man 'blows a kiss' to an MP from the 555th MP CO while she tries to keep a crowd of cheering Haitians from interfering with a weapon seizure operation.

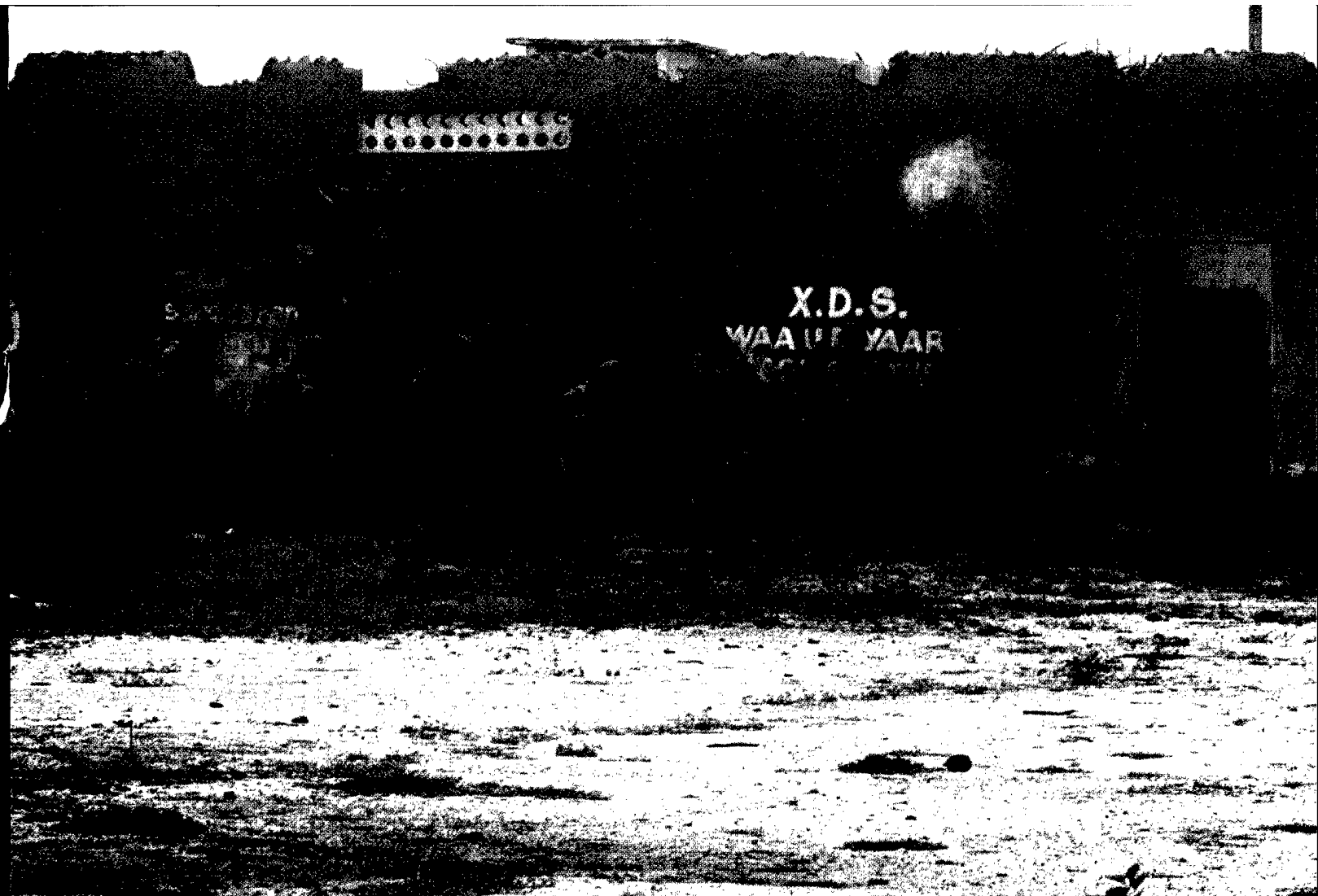


Photo courtesy of the Defense Visual Information Center.

Warfare in urban terrain presents the soldier with a uniquely complicated and dynamic environment in which man-made structures impede mobility and maneuverability. The action can take place in close quarters, within and between buildings, expanding horizontally and vertically, and absorbing manpower and munitions. The individual combatant must think about the battlespace in three dimensions instead of two. Every building or structure can serve as a fortification, and tall buildings can be used to create deadly fire zones. Buildings, roadways, and subterranean infrastructure channel troop movements and provide ample opportunity for the enemy to hide or to fortify himself (see Figure 2). In addition, the terrain can change rapidly and dramatically as buildings collapse, prominent landmarks are reduced to rubble, and throughways become blocked by debris.

Confusion results when buildings interfere with communications or navigation aids, such as global positioning systems (GPS), or when they cannot be used quickly to keep up with a fast-paced battle. Mission rehearsal and training help reduce this confusion, but training and personnel selection technology has not been optimized for urban operations.

The urban warrior needs a great deal of specialized expertise in new tactics and procedures. Novel skills include room-clearing operations, employing security forces in hallways and alleys, building demolition, and crowd control. Soldiers will be more effective if they have knowledge of structures, materials, and the effects of various munitions on these to minimize collateral damage.

When the urban terrain and fast pace isolates small units, junior officers are faced with making very tough decisions that would normally be made by much higher ranks. Fighting in close quarters and the presence of a large number of non-combatants impose unique demands on the warfighter's ability to identify enemy and friendly forces. While technology solutions may ameliorate the problem of combat identification, new training techniques are needed to prepare soldiers for the

Figure 2. In the urban terrain, every building is a potential enemy fortification. New tactics, weapons, and sensor technology can aid the warfighter in this challenging environment.

continued on next page

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specter of high military and civilian casualties and human suffering.

Urban operations require a soldier to change from a warrior to a peacekeeper in very short order. One day he may

be engaging the enemy in intense building-clearing operations, and the next he may be involved in humanitarian efforts. The urban soldier needs to be trained in distributing aid, policing, restoring utilities, and all the other functions necessary to run an occupied city.

High-tech weaponry, such as air power, mechanized armor, and cruise missiles, that surprised and overwhelmed the enemy in Desert Storm and Kosovo are often inappropriate for urban operations. Facing ground troops, an enemy with relatively unsophisticated weaponry can fortify himself quite readily using the urban terrain and the civilian population as cover.

Urban operations require high-tech weapons that are mobile enough not to impede agility and that are effective in the high-stress urban environment, as well as in other environments. A new family of technologies needed to equip the land warrior includes sensors, Command, Control, Communication, and Computers (C4), Intelligence, Surveillance, Reconnaissance (ISR), and both lethal and non-lethal weaponry.

The Marine Corps is leading the effort to identify new technologies that will support the demands of urban combat. The Urban Warrior, Advanced Warfighting Experiment (AWE), The MOUT Advanced Concept Technology Demonstration (ACTD), and the Non-Lethal Weapons Program, are examining tools that will provide technological dominance in urban operations. Unmanned ground and air vehicles, and remote weapon systems show promise for intelligence, reconnaissance, target acquisition, and force-protection applications. This type of technology requires soldiers to interact with

systems from a remote site. Various implementations of this technology were demonstrated in support of urban operations, including the Mobile Counter Fire System with counter-sniper sensors and a remote-control unit; the Boom Gun, consisting of a camera and .50 Cal machine-gun mounted on a crane; and the SARGE (Surveillance and Reconnaissance Ground Equipment) remote-control 4-wheel vehicle. Information technologies have impacted all areas of the armed forces, and urban operations is no exception. The information technology (IT) examined in the Urban Warrior AWE includes the palmtop-based GOSSIP (Ground Observation Special Support Intelligence Program), and the Multi-lingual Interview System (see Figure 3). These systems must have an easy-to-learn, usable interface to maximize their effectiveness in urban operations.

Current testing and demonstration thrusts in sensor technology include combat identification sensors, through-wall sensors, sniper and intrusion detection systems, and hand-held target designators. Hands-free, non-line-of-sight communication systems are also needed. Navigation aids, including digital maps of urban centers and devices that will indicate a soldier's position and location in buildings, are being considered.

In the future many of these technologies will be integrated into a system designed to support the warfighter under a variety of conditions. For example, the Marine 2010 concept provides the individual with an integrated helmet assembly with a head-up display, a communications suite including imagery, video and voice, and a situation awareness (SA) control panel (see Figure 4 on page 10).

The urban environment presents new challenges for employing fire power and for force protection. Appropriate weaponry will employ precision munitions that minimize collateral damage. Breaching devices are needed that will allow units to maneuver through walls, floors, and other obstacles. In addition, non-lethal weapons are necessary when an operation involves hostile civilian populations. Non-lethal weapons under review including acoustic systems that disorient or incapacitate individuals, soft rounds and grenades that deliver non-lethal trauma, and riot control agents.

These technologies will be used in a very unforgiving environment, under the stress and pressures of close, high-intensity engagements where communications and line-of-sight are often obscured, and subterranean and superterranean mobility is essential to success. We must consider human perceptual and cognitive capabilities and limitations,

continued on page 10

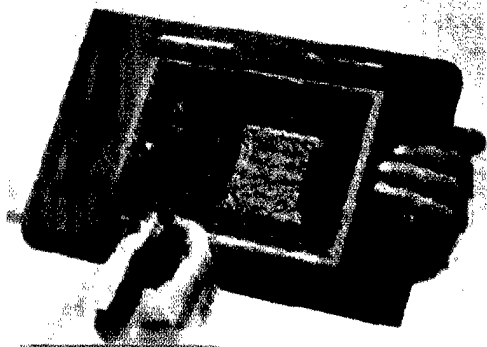


Figure 3. The Multi-lingual Interview System with voice recognition.

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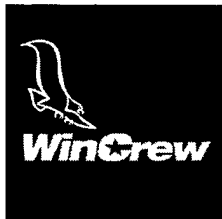
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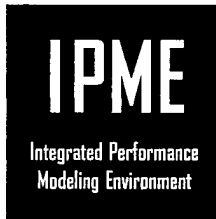
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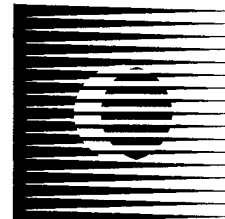
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Calendar

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Toulouse, France. September 27-29, 2000

International Conference on Human-Computer Interaction in Aeronautics, HCI-Aero 2000

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Edinburgh, Scotland. October 25-27, 2000

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Contact Dr. Don Harris, Human Factors Group, College of Aeronautics, Cranfield University Cranfield, Bedford MK43 0AL, UK. Tel: +44-1234-750111 ext. 5196, Fax: +44-1234-750192, E-mail: icep@cranfield.ac.uk, URL: http://www.cranfield.ac.uk/coa/coa_conf.htm

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Figure 4. The Marine 2010 with head-up display, integrated combat utility uniform, communications suite, SA control panel, and integrated individual combat weapon.

and how they interact with environmental variables likely faced in urban operations. Principles of human-computer interaction and human-system integration should be applied, and cognitive task analysis can guide new training approaches. Further, sensor-based navigation and imaging technologies should depict information in a way the soldier can readily comprehend. Weapons should be mobile, easy to operate, and easy to maintain. All these issues should be taken into account within the context of the emotionally and cognitively demanding scenarios of urban warfare. Human factors opportunities exist in the application of known principles, as well as offering new areas of research. Urban operations give the human factors professional new opportunities to make a significant contribution to our national security. ■

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Note: Images and details of urban warfare technologies are borrowed from:

1. Urban Warrior AWE (<http://www.mcwl.quantico.usmc.mil/mcwl/uw/index.html>)
2. MOUT ACTD (<http://yorktown.dc.isx.com/mout/>)
3. Non-Lethal Weapons Program (http://iis.marcorsyscom.usmc.mil/jnlwd/JNLW_Program.htm)

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Dear CSERIAC

To show the diversity of support that CSERIAC provides, the column below contains a sampling of some of the more interesting questions asked of CSERIAC. In response to these questions, CSERIAC conducts literature and reference searches, and, in some cases, consults with subject-area experts.

These questions were compiled by Aaron Gannon, Human Factors Analyst. If you would like to comment on any of these questions or issues related to them, please write to "Dear CSERIAC" at the address found on the back cover of **GATEWAY**.

- A college student in California requested information regarding on-board aircraft turbulence detection and display.
- A U.S. government contractor requested information on cognitive workload and situation awareness for dismounted soldiers.
- A pharmaceutical company representative contacted CSERIAC for information on 95th percentile male thumb-force data.
- An engineer from a military aircraft contractor requested references on vertical-lift force using an ejection-seat shoulder harness, and information on male and female population percentile data for static two-handed lift at 38 cm.
- A medical doctor from Israel requested information on Army helicopter-helmet design recommendations and crash studies of crashworthy seats.
- A university professor in Ohio requested information on child anthropometry, strength, and endurance relevant to interior trunk lid release design.
- A science advisor in the U.S. Army contacted CSERIAC to identify gloves for Petroleum, Oils, and Lubricants (POL) capable of -65 degree F protection, with a three-finger design to facilitate dexterity and warmth.
- A U.S. Air Force engineer requested information on the minimum ceiling height of a passageway for a transport aircraft application.
- A researcher from a U.S. DoD Service safety center requested information on the effects of aging on a pilot's cognitive performance.
- An engineer from a commercial aircraft manufacturer requested data on studies that compared foveal versus peripheral vision and reaction time.

<http://iac.dtic.mil/CSERIAC>

Modeling Human Performance

on the Road to Manpower Optimization

Gwendolyn Campbell &
Ron Laughery

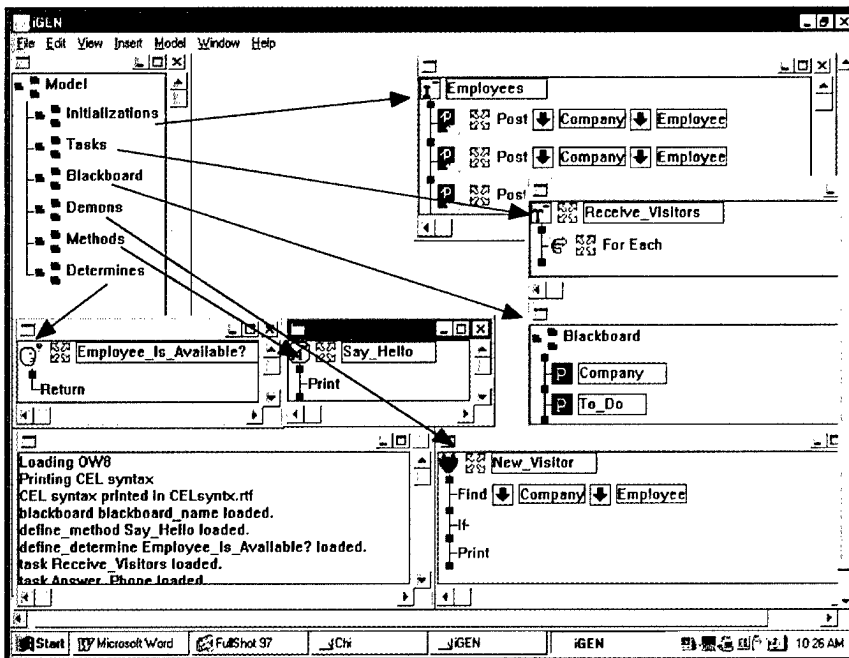


Figure 1: Cognitive process model in iGEN.

One of the largest lifecycle costs in the Navy is associated with the people onboard ships. Given the shrinking defense budget, future ships must be operated with dramatically reduced crew sizes. For example, the official goal for the next destroyer is 95 sailors—about a 75% reduction in crew size from the 400+ sailors on current destroyers. Of course, fewer people must not lead to a drop in readiness or performance. In fact, future Navy ships will be expected to handle an even wider variety of missions than today.

How can tomorrow's Navy handle increasingly complex missions with a dramatically reduced crew? Obviously, there is no one answer. This level of manning reduction will require advances in everything from the durability of the paint used onboard ships to the automated capabilities of fire-fighting systems, as well as changes in the recruitment, training, and career pipelines of future sailors. However, it is also going to

take a revolutionary change in the way that we design ships, a change that incorporates the knowledge and skills of human factors and cognitive engineers from the beginning of the design process.

Towards this end, in 1997 the Navy launched a five-year Manning Affordability Initiative to investigate the impact of advanced user-interface technologies and a human-centered design process on manning. One of the major thrusts of this effort, led by Dr. Cannon-Bowers at the Naval Air Warfare Center Training Systems Division, involves investigating the application of human performance modeling technologies to the design and operation of complex systems such as a Naval Command Environment.

A "human performance model" can be defined as a software representation that is capable of predicting human behavior. Like other types of models (e.g., model airplanes), any human performance model will reflect only limited characteristics of human behavior. Also, like other classes of models, there are a variety of different human performance modeling frameworks, each with its own requirements, underlying assumptions and outputs, and, thus, each best applicable to solving different problems. Dr. Cannon-Bowers' team is pursuing several different modeling approaches to support the design and the operation of a future Naval Command Environment.

In particular, our team is investigating three different human performance modeling techniques. The first application will facilitate the incorporation of human factors knowledge during the design process through an intelligent design agent. We are using a cognitive process modeling technique called "iGen" to build this agent (see Figure 1). Factual knowledge about system design and human factors will be stored in a relational database. Procedural knowledge, for reasoning and making decisions with factual knowledge, will be stored in goal hierarchies which represent "chunked" human factors expertise. The agent will work with the designer to obtain relevant information about the system being designed. Then, it will use its knowledge and reasoning capability opportunistically to find information about specific human factors issues that need

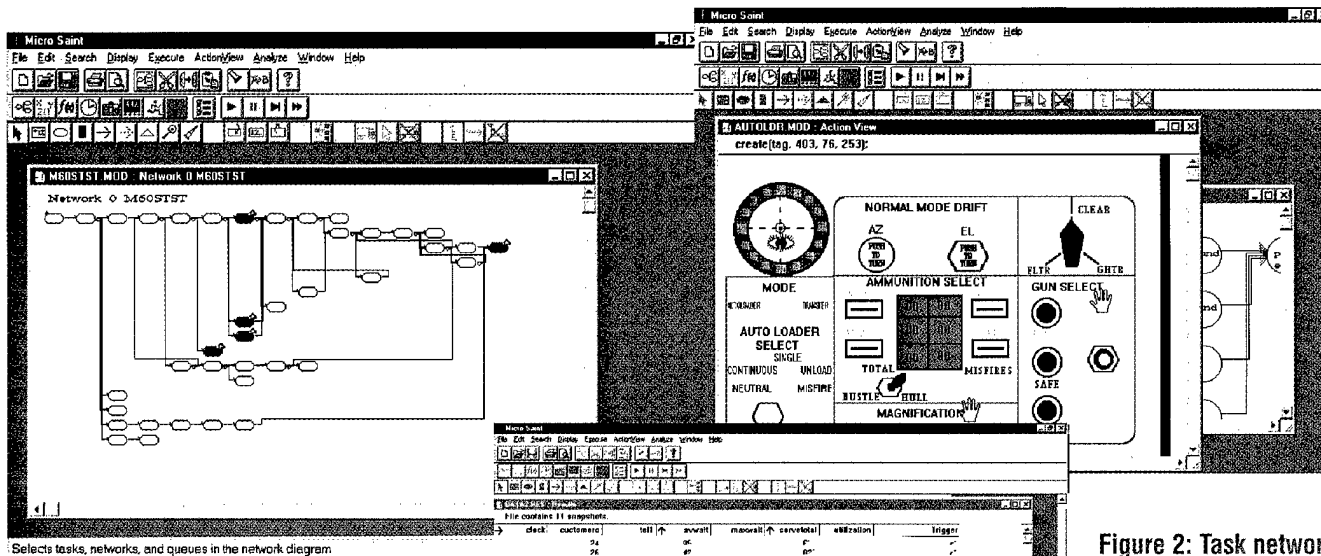


Figure 2: Task network model in Micro Saint.

to be addressed and provide recommendations as appropriate.

Human performance modeling can also support team design. We are pursuing a new approach to team design that uses multi-objective optimization algorithms to generate a team structure. These algorithms are applied to a set of mission functions, and information and weapons resources available to accomplish the mission. The user can set optimization criteria (e.g., to minimize the number of team members) and the algorithms systematically allocate mission tasks, resources, and people until an optimized team structure is found. While the resulting team structure will still require independent evaluation, this tool will allow users to design a team by taking a top-down, mission-driven approach, as opposed to the ad hoc system-centered method that has often been used in the past.

Finally, all design processes are iterative in nature and cycle between evaluating design concepts and refining them. Hardware and software engineers have been using simulation to evaluate design concepts for years, but evaluating the human's contribution to system performance has typically been put off until the end of the design process. However, the same basic modeling approach that systems engineers use, network modeling, can be applied to model human performance within a complex system. Task network models represent human behavior in a flow-chart-like representation, with characteristics such as statistical distributions of time and accuracy assigned to each of the tasks (see Figure 2). Then a simulation engine runs the model and predicts measures of human and system performance. We are integrating an existing task network modeling tool called Integrated Performance Modeling Environment (IPME) with other engineering tools. This will allow engineers to simulate the complete

system, humans included, early and often throughout the design process, supplementing human-in-the-loop studies to help eliminate designs that do not support optimal human and system performance.

The potential applicability of human performance modeling does not end once a design is complete. Human performance models of experienced operators may also support the operation of complex systems. For example, human performance models can be used as intelligent software agents to play the role of surrogate team members. The models can perform their tasks, coordinate with human activities, and respond to human queries. We are investigating the application of human performance models as software agents, providing functionality ranging from decision aids to supervised automation components.

In this paper, we have presented an overview of our ideas as to how human performance models and modeling technologies can contribute to optimized manning. By enhancing the engineering process as well as directly supporting human performance, human performance models will provide a path to do more with fewer people. ■

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Virtual Analysis of Aircraft Cockpits

Steve Harper &
Janet Gerace

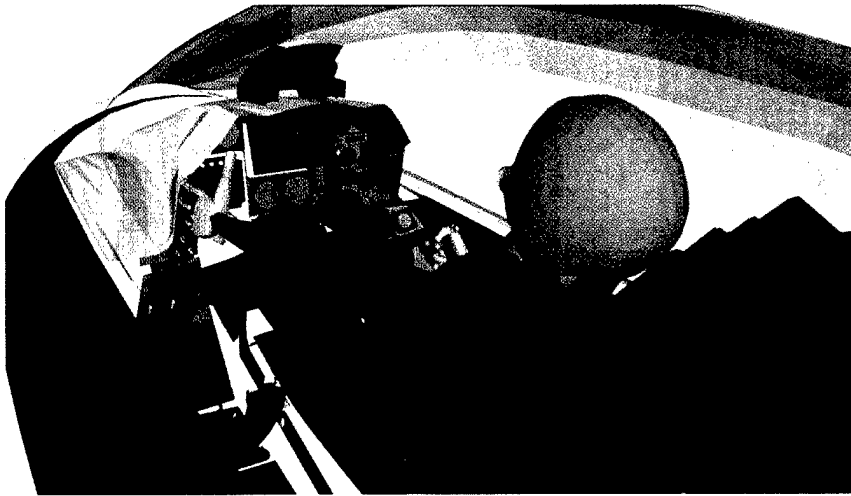


Figure 1. 3-D model of a pilot in an F-16 cockpit.

The ability of pilots to operate in cockpits is a prime interest of the U.S. Air Force and the aerospace industry. Pilot-machine interfaces have been traditionally studied with subjective data and opinions or with expensive mockups and human subjects. With the advent of more powerful computers and three-dimensional (3-D) analysis software, cockpits can be analyzed in a virtual environment with dimensionally accurate 3-D humans. A method has been developed by XonTech, a Dayton-area contractor, that takes advantage of the virtual environment technology. It is a two-part procedure involving creation of accurate, 3-D cockpit models and use of virtual humans in a 3-D environment to analyze the cockpits.

Creation of a 3-D Cockpit Model

Early 3-D Model Generation. Initial attempts to create 3-D cockpit models of fighter aircraft were ineffective. They involved working from equipment installation drawings, procuring models from major airframe manufacturers, and building a model from scratch using hand-collected measurements.

The use of installation drawings did not provide adequate detail to create a model of sufficient fidelity. Procurement of 3-D cockpit models from the manufacturer involved additional costs, and the models lacked sufficient consistency to facilitate comparisons from different manufacturers. Creating models from hand measurements proved to be labor intensive, prone to wide variance in the data, and resulted in reams of raw data to transform. It was estimated that it would take more than 500 hours to complete a 3-D model using these methods.

In the Fall of 1995, Dr. Joe McDaniel of the Air Force Research Laboratory Crew System Interface Division procured a Coordinate Measurement Machine (CMM) which was capable of reverse engineering existing hardware to create accurate 3-D models. CSERIAC engineers utilized this equipment to address the dilemma of generating standardized models to support cockpit analysis.

Current 3-D Model Generation. The initial successes gained from CSERIAC's application of CMM technology have been refined and updated by industry through process improvement and advances in software and computer processing capabilities. Continual process improvements have resulted from experience on numerous projects. For example, the 3-D model generation process was used to reduce errors from 80% to 2% on an Air Force Center of Gravity Inertia Meter (CGIM). Also, radar signatures were accurately predicted using 3-D models of threat representative targets. In addition, 3-D model generation was used to create models for finite element analysis on objects undergoing live-fire testing by the Survivability and Vulnerability Information Analysis Center (SURVIAC). The state-of-the-art method resulting from these projects yields highly accurate 3-D models of aircraft cockpits (such as an F-16 fighter shown in Figure 1 and a commercial 767 shown in Figure 2) in as little as 80 hours.

The modeling procedure entails use of a portable CMM connected to a notebook computer to collect coordinate data of the equipment being modeled. Features such as arcs, circles, planes, and splines (figures created by connecting a series

of dots) are collected to within 1/16th of an inch. Later, these raw geometric data are post-processed on a more powerful computer to create either 3-D surface or solid models.

Human Factors Analysis in Virtual Environments

The resulting 3-D models are imported into the ergonomic/human factors analysis software (examples include Boeing Human Modeling Software, Combiman, Crewchief, Deneb, Jack, RAMSES, Safework, and others) where dimensionally accurate pilots can be sent on virtual missions to assess the human-machine interface. Using the virtual environment, many "what if" scenarios can be explored. For example, analysts can vary the pilot's torso height and assess the performance impacts of a pilot with a very short-seated eye height to determine if his outside view is limited. Task sequence can be studied and inferences on difficulty for an adversary to operate critical instruments can be provided. Various cockpit designs can be compared and assessments of mission effectiveness can be made. Exploring these scenarios gives the military important information that can be exploited for a tactical advantage.

NAIC Uses Virtual Analysis Process

One of the agencies interested in the ability of pilots to operate in cockpits is the Aerospace Vehicle Technologies Branch of the National Air Intelligence Center (NAIC). Pilots still find themselves in real dogfights and other visual combat situations. Pilots want to know if there is something an enemy can exploit. They also want to know if there is something in an enemy's aircraft that U.S. pilots can exploit. Typically, NAIC relied on subjective data and opinions to analyze a cockpit's human-machine interface. Although subjective data yielded valuable information, NAIC wanted to update its analysis process to include more objective data. To improve their analysis capability, NAIC wanted to use this cockpit and pilot modeling technology to develop a quantitative method to assess the pilot-vehicle interface.

One feature of interest to NAIC was the ability to present high-quality images illustrating which cockpit items were within the pilot's reach. Reach envelopes provided by some analysis utilities illustrated the overall volume of space accessible to the pilot. However, they did not allow the ana-

lyst to quickly see which items were reachable. To overcome this difficulty, XonTech developed a process to map the reach envelopes directly onto the aircraft cockpit. Using this technique, valuable reach information could be generated for different-sized pilots during a multitude of task sequences.

Another feature of importance to NAIC was visibility. Not only was internal cockpit visibility important, but also the ability of the pilot to see outside the aircraft. Pilots are extremely interested in external vision, even today with radar and beyond-visual-range attacks. The virtual human modeling environment allowed NAIC to answer pilots' visibility questions by allowing them to illustrate the vision envelope and to see the cockpit from the pilots' eyes. For example, NAIC

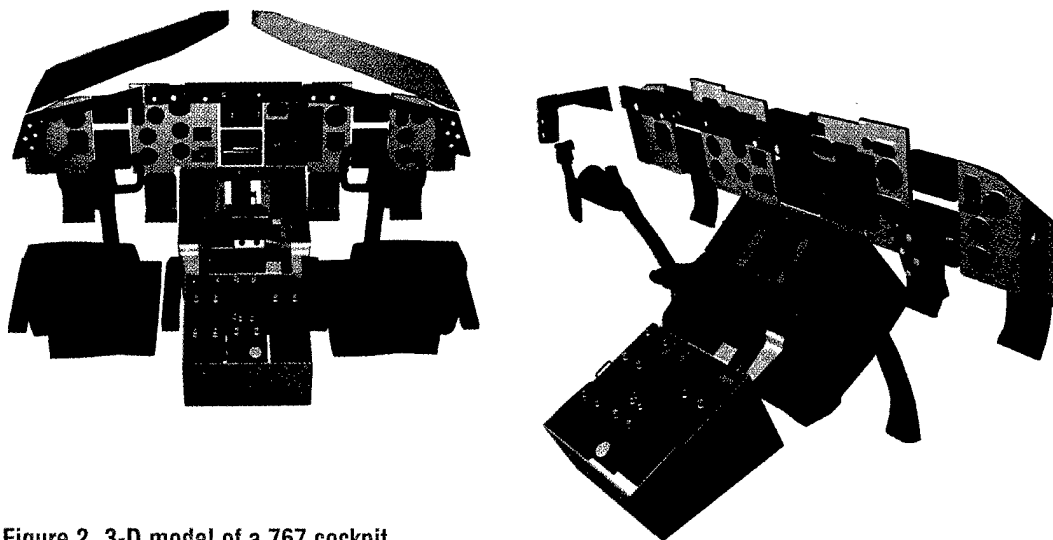


Figure 2. 3-D model of a 767 cockpit.

could not only tell a pilot exactly how an adversary's performance may be impaired when wearing chemical gear, but also to show him, through his adversary's eyes.

3-D modeling techniques and human modeling software tools continue to improve. As this article illustrates, the human factors community is nearing the point where comparisons between aircraft cockpits will no longer be based primarily on subjective data and opinions, but on objective data. In the future, use of these techniques will permit more rapid assessments, more cost-effective designs, enhanced safety, and improved usability. ■

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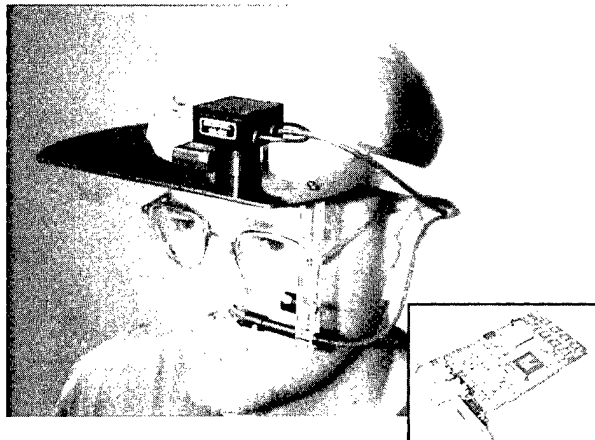
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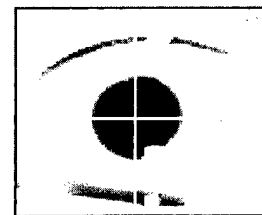
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