Understanding and Enhancing Crew Endurance

Megan L. Moundalexis, Jennifer A. B. McKneely, William B. Fitzpatrick, and Cory C. Sheffer

Warfighters possess steadfast dedication while conducting operations to maintain national security. Regardless of their motivation, however, working long hours in extreme conditions can compromise alertness and performance. Certain factors, such as schedules, sleep needs, lighting, nutrition, diet, and exercise, can be managed to support crew endurance. Several U.S. service branches have adopted crew endurance management (CEM) programs to decrease operational risk and increase mission readiness by educating and training personnel on endurance risks and management strategies. APL is currently investigating how performance stressors impact operations and how these stressors can be managed. A holistic approach involving management strategies, education, and training is recommended to enhance crew endurance. Continued research is needed to develop appropriate monitoring and management tools and strategies. This article describes the state of research on CEM as well as work APL is currently undertaking in this arena.

INTRODUCTION

Warfighters are essential to the security of our nation. High standards are in place, requiring crews to perform consistently at high levels in extreme conditions over extended periods of time. Such performance often comes at a cost to the crew members' stamina, which may lead to operational risks. Sustained and continuous operations often have adverse effects on human performance. For example, if their alertness is degraded, warfighters can have difficulty maintaining enough situation awareness (SA) to make good risk-based decisions.[1,2] Understanding how crews can safely maintain performance while undergoing physical, environmental, physiological, and psychological challenges on the job is critical to the support of our nation's most valuable asset.[3] This ability has been termed crew endurance. Many factors can be managed to support crew endurance, including workload, schedules, sleep needs, lighting, nutrition, diet, exercise, and stress. While several branches of the

U.S. military and the Department of Homeland Security have already implemented programs to manage crew endurance, there is still a need to enhance crew stamina across the board. APL has already contributed efforts in this critical area, and current projects continue to improve our understanding of performance stressors and other factors that affect operations.

CREW ENDURANCE

What Is Crew Endurance?

Crew endurance is "the ability to maintain performance within safety limits while enduring job-related physical, psychological, and environmental challenges."[3] The two terms crew endurance and stamina can be used interchangeably. Crew endurance is not simply ensuring the crew has enough rest, although rest is one of the major factors. Other stress factors that can affect a crew's endurance are described in the following section.

Endurance Factors

Many factors impact crew endurance and affect warfighter performance and safety.[3] These factors are generally categorized into operational, environmental, policy-related, and behavioral factors, as shown in Fig. 1. Operational risk factors include psychological state, physical health and condition, propensity for motion sickness, quality and duration of sleep, diet, and biological clock stability. Environmental risk factors, such as temperature, humidity, light, noise, and vibration, can degrade stamina and alertness, affecting both productivity and the safety of operations. Company policies and operational/shipboard practices can affect endurance when these policies lead to work-related stress, irregular sleep periods, and adverse working conditions. Additionally, behavioral risk factors such as heavy workload, sleep deficiency, and caffeine addiction can threaten operational safety and crew member efficiency. Each single factor on its own can affect crew members and their ability to maintain performance, but the interdependencies among the factors can magnify the effects. Most research to date has focused on individual factors. Examples of sleep, temperature, and stress research are included below.

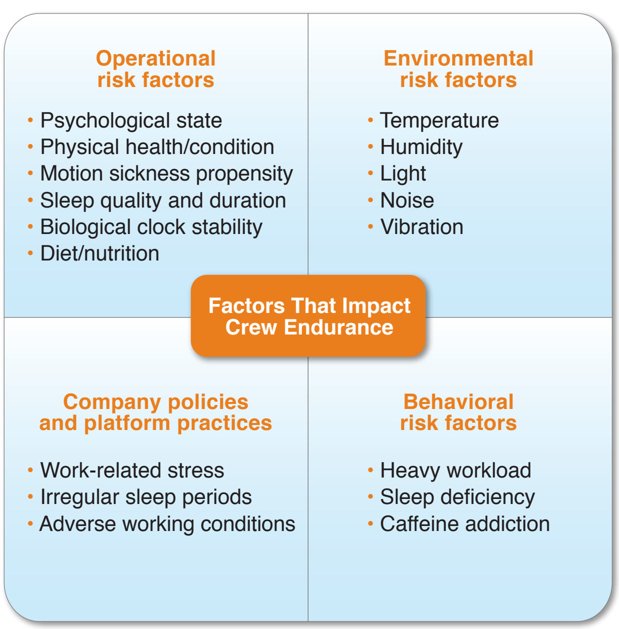

Figure 1. Four categories can be used to describe factors that impact crew endurance.[3]

Sleep

Much research has been conducted on the effects of sleep loss on performance, and it is clear that losing sleep negatively affects performance. Research on sleep deprivation of pilots and others shows decrements in performance in a wide array of tasks, including vigilance and monitoring.[4,5]

Human beings operate on a ~24-h cycle of sleep and wakefulness because the body's clock or circadian rhythm couples with synchronizing mechanisms. While light is considered the most influential *zeitgeber* (or synchronizing influence), exposure to meals, exercise, and social cues also help regulate the 24-h circadian clock.[6] Circadian rhythms continue to persist even in the absence of night/day information because our brain regulates the cycle.[7] Humans may adopt non-24-h sleep/wake behaviors in the absence of synchronizing mechanisms such as light and other temporal cues.[6,8] Circadian rhythms influence endocrine functions such as hormone release (melatonin, human growth hormone, etc.), physiological functions such as body temperature, and psychological functions including memory and processing speed.[6,9]

It is well known that individual work/rest schedules affect performance if this natural rhythm is disrupted. The Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model shown in Fig. 2 illustrates how sleep factors (e.g., sleep intensity, sleep quality, and sleep accumulation) impact cognitive effectiveness.[10,11] Complex cognitive performance such as understanding, adapting, and planning in rapidly changing circumstances is degraded by sleep deprivation.[12] Accident reports continue to cite fatigue and lack of sleep as contributing factors, particularly where monitoring and decision making are involved. Killgore et al.[13] examined how sleep deprivation affects judgment. In their study, they found that individuals who are sleep deprived make riskier decisions on the Iowa Gambling Task. Wilson[14] also discusses how fatigue can negatively affect decision making. In fact, the effects of sleep deprivation are similar to those of alcohol intoxication, in that 18–20 h of sleep deprivation yields performance similar to that of a person who is legally intoxicated (shown in Fig. 3).[15–17]

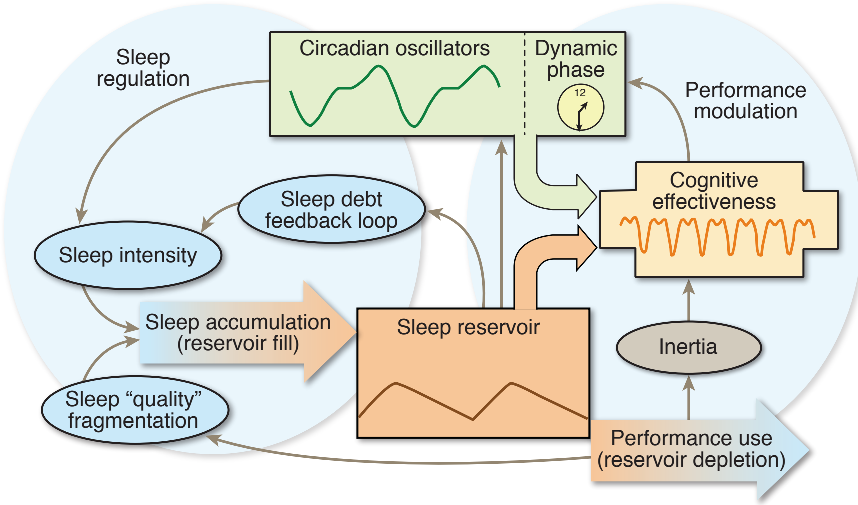

Figure 2. This schematic of the SAFTE model depicts the impact of sleep factors (e.g., circadian rhythms, sleep/wakefulness, and sleep quality) on cognitive effectiveness.[10, 11]

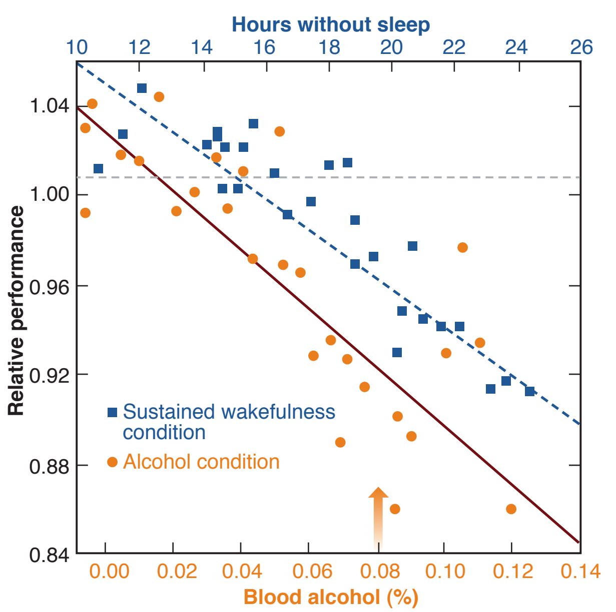

Figure 3. Research shows that after 18–20 h of sustained wakefulness (hours without sleep), participants performed a variety of cognitive psychomotor tasks at a level equivalent to legal intoxication in most states (blood alcohol content of 0.08%).[17]

These findings suggest that people making decisions under conditions of uncertainty (such as those warfighters face) may be particularly vulnerable to sleep loss. The following findings are general themes in the research on fatigue:

- Disruption of circadian rhythms leads to a decrease in performance.
- Repeated disruption of sleep schedules (inability to get regular sleep) can lead to decreased performance. Sleep quality or uninterrupted sleep is an important factor.[18]
- Human beings are not very good at estimating their current level of alertness. There can be a discrepancy between how people are feeling and how sleepy they are physiologically.
- Short naps have been found to restore an individual's capacity for performance under certain conditions.
- Time off alone may not guarantee a rested workforce. Education, planning, and predictability are needed to maximize utilization of work/rest schedules.

Additionally, the DoD has documented mission failures and "Class A" mishaps (which result in loss of trained personnel and valuable aerospace platforms) that have occurred as a result of human fatigue.[19] A Class A mishap is defined as a fatality, permanent total disability, destroyed aircraft, or $1 million or more in damages.[20]

Many years of research have shown that individuals who work during the hours they would naturally be sleeping experience fatigue and are not as productive.[21] Alertness and performance are negatively impacted by night work. The following are general themes from the research on shift work:

- Shift work negatively affects sleep duration and sleep quality.[21]
- An altered shift schedule (e.g., night work) does not directly lead to an altered internal circadian pattern; intervention to shift circadian rhythm may be needed.
- Chronic sleep restriction changes brain activity to provide stable (but reduced) performance levels that take longer to return to baseline when restricted sleep is alleviated.
- Shift workers that go back and forth between shifts experience more difficulties synchronizing circadian rhythms and sleep times.
- Moving a shift schedule forward involves easier physiological adaptations than moving the schedule backward.

Nevertheless, it is often imperative that work continue around the clock. To support the need for night work, improve work effectiveness, and minimize shift work's deleterious effects, researchers have investigated numerous principles and interventions for shift work scheduling. There are generally two strategies that can be used to cope with fatigue: (*i*) enhancing wakefulness and (*ii*) improving sleep and aiding fatigue recovery. Both of these strategies can be addressed through pharmacological interventions, behavioral modifications, or a combination of both. There are pros and cons for each.

Pharmacological interventions include the use of caffeine, modafinil, and dextroamphetamine to enhance alertness or the use of drugs such as temazepam, zolpidem, and zaleplon to promote sleep.[22] A pharmacological compound needs to be selected carefully to address the appropriate aspect of fatigue management and should be carefully administered and managed. The potential side effects (e.g., irregular heartbeat, dizziness, nausea, and constipation) and risk of dependency can outweigh the benefits of the chosen compound's purpose as a fatigue countermeasure.[22] While the U.S. military approves the use of these fatigue countermeasures, drugs should not be used as substitutes for good work/rest schedules. It is recommended that sleep deprivation be avoided if possible and that the pharmacological compounds be resorted to as an aid to help sustain alertness.[22]

Examples of behavioral interventions include scheduling work/rest to avoid sleep deprivation and implementing techniques to shift circadian rhythms. Shift work scheduling principles include adopting a fixed shift, allowing a period of long uninterrupted sleep, maximizing time off between shifts, and limiting work shifts to 8 h for every 24-h period.[23] These principles support restorative sleep in off-duty hours. If individuals involved in shift work have to work the night shift for an extended period of time, it may be beneficial to invoke a circadian rhythm shift. This can be done using light therapy, where light–dark cycles are used to align circadian rhythms to night work and day sleep schedules. The timing and intensity of light exposure is managed at work, and then external light/dark exposure is minimized by such techniques as wearing dark goggles during the transit to or from work.[24,25] It may also be necessary to administer melatonin to aid phase shifting of the circadian rhythm.[26]

Although both pharmacological and behavioral modifications are effective, shifting the circadian rhythm is preferred because this method can be maintained for long durations and it does not have the side effects of drug interventions. It does, however, require managerial effort to maintain.

It is clear that sufficient rest is necessary for optimal performance, but rest may not be the only contributor. Additional factors affect the performance aptitude of the crew. Challenging environments that subject warfighters to extreme temperatures, altitudes, sustained wakefulness, and varying workloads can also pose risks to overall endurance.

Temperature

Extreme temperatures impact human performance in multiple ways. A meta-analysis review showed that hot temperatures of 90°F and above as well as cold temperatures of 50°F and below result in significant performance decrements when compared with neutral temperature conditions.[27] It was specifically reported that exposure to temperatures above 80°F affected attentional, perceptual, and mathematical processing tasks more negatively, whereas exposure to temperatures below 65°F had the most negative effect on learning, memory, and reasoning tasks.[27] The same study found worse performance in these tasks when both the exposure to extreme temperature conditions and the duration of the task were short than when exposure to extreme temperatures and task duration were longer.[27]

A significant performance decrement was also found when subjects were exposed to extreme temperatures for more than 1 h before commencing a task.[27] Extreme temperature conditions (hot or cold) can negatively affect performance.

Stress

The effect of stress on human performance has been studied often in the past and continues to be important in today's high-demand settings. Environmental stimuli such as noise, time pressure, threat, task load, and group pressure can cause stress.[28] Upon evaluation of the stimuli, individuals determine whether they have resources available to cope with the perceived demand. If the demand cannot be met, then negative performance expectations are formed, whereas positive performance expectations are formed when available resources do exceed the perceived demand. The outcome can be different types of stress.[28] Stress can cause physiological changes, emotional reactions, cognitive effects, and social behavior effects, as described in Table 1.[28]

Sometimes stress can be seen as a positive factor because it can enhance performance in certain conditions. For example, stress can keep an individual engaged and alert in an environment lacking stimulation.[28] The focus for crew endurance is that stress can

Table 1. Types of effects caused by stress and examples of negative reactions induced by stress for each type of effect[28]

Type of Effect	Negative Reactions Induced by Stress
Physiological	Increased heartbeats, trembling, labored breathing
Emotional	Fear, frustration, anxiety, annoyance
Cognitive	Narrowed attention, distraction, tunnel vision, degraded problem solving, decreased search behavior, memory deficits, longer reaction time to peripheral cues, decreased vigilance, performance rigidity
Social	Loss of team perspective, decrease in prosocial behaviors (e.g., helping and cooperation)

also negatively impact performance. Stress needs to be considered as a risk factor for crew endurance because of its potential for degrading performance.

Warfighters' performance on mental and physical tasks may become degraded should these crew endurance risk factors go unmanaged. As a result, their capacity to make good decisions, communicate with others, think clearly, and maintain their immune systems could suffer. Warfighters could exhibit signs of irritability and unwillingness to resolve problems, in addition to decreased endurance during work and leisure time.[3] Management strategies can be developed once these crew endurance risk factors are identified.

Gaps in Knowledge of Crew Endurance

While individual contributing factors of crew endurance have been studied (e.g., sleep deprivation, temperature, and stress), there is limited scientific research on comprehensive crew endurance. Thus, a gap remains in defining crew endurance in a measurable way.

Current research is generally based on simple tasks in tightly controlled settings and measures results such as reaction time, task speed, and accuracy. On the basis of such studies, sleep models and cognitive performance prediction tools have been developed to assist with estimating particular impacts on crew members. However, metrics need to be developed for complex cognitive tasks so that operational tasks can be investigated in real-world environments. More team performance research can also aid in the knowledge of crew endurance. Crew endurance management (CEM) can become more effective with scientific research that is directly applicable.

Currently no theoretical model of crew endurance exists. A basic framework is being developed as part of the Littoral Combat Ship (LCS): Ship Motion Study, in which the direct and indirect influences on performance will be identified and mapped. This framework will be a first step, and future research should be conducted to quantify the influences and better understand the interdependencies. This will help the research community to formulate better ground principles of endurance and integrate them into a macro-model that reflects a better representation of the operational environment.

ENDURANCE MANAGEMENT

CEM is a "system for managing the risk factors that can lead to human error and performance degradation in [maritime] work environments."[3] CEM includes practices and procedures beyond those of solely sleep management. "Crew endurance management encompasses the full range of environmental, physiological, operational, and psychological risk factors affecting performance and safety in normal operations."[3]

The military has investigated fatigue for many years, as noted in a recent annotated bibliography by Miller et al.,[29] in which 165 articles were identified as studying the effects of fatigue on performance in military operations. However, they found few reports that studied healthy populations during military operations. The value of CEM activities within the studied populations may still reflect approaches that are warranted in other circumstances. Research into the effectiveness of a holistic CEM program in healthy populations is recommended. Whereas the U.S. Coast Guard has embraced CEM, the U.S. Navy has been slower to adopt it, even though it appears just as necessary for the Navy.

Crew endurance issues will be a factor as the Navy looks to optimize the manning of its of ships, including its newest ship, the LCS. Based on insights gained from the LCS Total Crew Model (TCM), various innovative work schedules and work assignments, combined with opportunities for additional sleep as crew members' fatigue limits are reached, appear to offer the LCS crew the best opportunity to minimize fatigue across multiple LCS missions.[30]

Like the LCS, the submarine force places high demands on its sailors. Currently fast attack submarines (SSNs) operate on an 18-h schedule during which all watchstanders stand watch for 6 h and then are off for 12 h. On this type of schedule, it is rare for crew members to get 6 h of continuous sleep because of the responsibilities beyond those of their watch (drills, training, etc.),[31] but the recommendation for healthy adults is between 7 and 9 h of continuous sleep.[29,32,33] Miller et al.[29] point out that many in the junior enlisted and junior officer ranks serving in the military are young adults who typically require 8.5–9.25 h of sleep each night. The SSN 18-h schedule is inherently inconsistent with the 24-h circadian rhythm and has been shown to have some subjective negative results. A survey of 538 experienced sonar operators reported concern about their own fatigue and ability to stay alert often due to work cycle factors.[34] Research has looked at alternate watchstanding schedules in a simulated submarine environment and found that a 24-h work/rest schedule produced better shifting of the circadian rhythms but did not show distinct performance differences, which could be attributed to the short duration of the study.[35] A follow-up at-sea study aboard a ballistic missile submarine (SSBN) showed that the 24-h schedule did not have any significant differences from the existing 18-h schedule.[35] This was not studied on board an SSN, which has different missions and different operational tempos and which may have provided different results.

What these studies also suggest is that resolving fatigue and the effects of working against one's circadian rhythms cannot be mitigated by schedule alone. A holistic approach to sailor readiness and endurance is needed;

this approach needs to include leadership, education, tools, and continued support.

A CEM program cannot be implemented solely at the level of the personal warfighter. The entire organizational culture needs to adopt the practice in order for its implementation to be effective. The U.S. Coast Guard assesses measures at four specific levels.[36] The first is the environmental level, which accounts for work environments, sleeping quarters, and exercise facilities, as well as light, noise, vibration, temperature, and humidity. The second is the organizational level, which is responsible for watch and duty schedules, crew rest policies, food services, and the operational tempo. At the personal level (level three), measures surround one's circadian rhythm, sleep management, stress management, physical fitness, and diet. Mission objectives make up the fourth and final level, which includes around-the-clock response (24/7), night operations, and the operational tempo.

The U.S. Coast Guard outlines five steps for implementing a CEM program: (*i*) forming a working group, (*ii*) completing an assessment of crew endurance risk factors, (*iii*) developing a CEM plan to control the identified risk factors, (*iv*) deploying the CEM plan, and (*v*) assessing the plan's effectiveness.[36] The success of the program depends on these five steps.

Elements of Good Endurance Management Programs

A review of endurance and fatigue management programs reveals key elements that should be included in a CEM program to ensure its effectiveness. As shown in Fig. 4, these elements include:

- Workload balancing
- Appropriate scheduling
- Training (for staff and supervisors)
- Tools to plan and monitor crew endurance
- Consideration of environmental conditions
- Promotion of physical fitness
- Diet/nutrition considerations

Each element is described in more detail below.

Workload Balancing

Crew workload demands stem from the allocation of tasking. Often the projected level of workload is exceeded by actual work demand. This can be the result of relying on legacy manning levels and not accounting for new and emerging missions or operational requirements. Additionally, failing to fully analyze the required tasks to complete a function or mission may result in more work being required than was planned. The unexpected increase in workload is sometimes met with existing crew members who go the extra mile to complete the tasks at the expense of rest, diet, and exercise. Understanding workload requirements and building manning concepts around analyzed task demands can help mitigate this impact.

Figure 4. Several key elements must be included for an endurance management program to be effective.

Scheduling

Endurance can be improved by modifying work, watch, and rest schedules. Circadian rhythms dictate the body's natural ebb and flow of energy and alertness over a 24-h period.[3] Incorporating knowledge of physiological factors into the development of schedules can support crew endurance.

Sleep loss affects mental or cognitive performance earlier than it affects physical performance.[37] Monotonous and repetitive tasks are generally the first to be impacted by performance degradation. However, those who are responsible for complex decision making and other cognitive tasks are also vulnerable to the effects of sleep loss, including attention lapses, extreme sleepiness, and susceptibility to accidents. Some researchers posit that there is a 25% decline in effectiveness for every 24 h without sleep.[37] The physiological state of the warfighters will influence the overall safety and performance of operations. Hence, the management of sleep and wakefulness during operations cannot be ignored.

The Crew Endurance Training Tool developed by the U.S. Coast Guard suggests that watch schedules should follow fundamental criteria such as allowing crew members to obtain 7–8 h of uninterrupted sleep per 24-h period; maintaining the same work/rest schedule for a minimum of two continuous weeks; minimizing the change from day to night work or from night to day work (which creates a condition similar to jet lag); refraining from work periods lasting longer than 8 h, especially in extreme environments; and employing light-management techniques if crew members need to be adapted to night watch.[38] Results from a study of a submarine watchstanding schedule support the advantages of a fixed work/rest schedule on the basis of data collected on body temperature, simple response time performance, and perceived sleepiness.[39]

Training

An endurance management program can be effective only if it is administered and implemented correctly. The comprehensive program is more influential than the sum of its parts. Individuals responsible for overseeing the program, such as staff and supervisors, need to be trained so that they are familiar with the various components and how they work together for maximum benefit. Strategies to enforce the program within the crew should be included. Because the crew will wonder how the endurance management program impacts their daily routine, enforcers should be knowledgeable about the long-term goals in addition to the day-to-day crew activities. Instructional advice on how to relay information to the crew is advised. Training staff and supervisors will help to optimize the implementation and results of the endurance management program.

Tools to Plan and Monitor Crew Endurance

To support a comprehensive program, a component is needed to monitor all aspects of crew endurance. One aspect of planning and monitoring is including a capability to identify emerging problems; a second is providing resources to address the emerging problems. Having a full range of strategies and methods for managing risk factors will help to bolster crew endurance.

In particular, scheduling tools are needed to help manage and rapidly replan schedules due to the ever-changing environment that warfighters face. Modifications are often needed when emergencies occur, operators become ill, or training opportunities arise. A dynamic scheduling tool could help ensure that warfighters can meet mission objectives while still supporting the crew's fatigue and alertness levels.

Makeig and Neri[7] proposed an integrated shipboard alertness management system with the vision of developing a hardware and software suite to support the Navy. Their proposed tool consists of actigraphs (wristbands that monitor activity levels) to collect data on the crew's sleep, dynamic software to optimize work/rest schedules on the basis of changing circumstances, and electroencephalographic and eye motion data to achieve real-time monitoring of crew alertness at workstations. The electroencephalogram could be fitted to the standard audio headsets or into tight-fitting hats.

The authors explain that this type of integrated system could allow the scheduling software to detect estimated crew fatigue levels and provide the commanding officer with advice for meeting the ship's tasking in a safe manner by either reviewing the allocated tasking or introducing fatigue countermeasures. Additionally, the system could make suggestions for scheduling extra rest if the software detects that an individual's sleep record conflicts with sustained alertness. Furthermore, the real-time monitoring system could provide operators with immediate feedback to enable self-management of alertness. Another desirable feature would be the system's capability to adjust the information or information rate presented to the operators depending on their brain and eye patterns. A searchable sleep history database could even provide recommendations for replacement operators who are more alert.

Research is still needed to validate the effectiveness and practicality of real-time monitors today, but the technology has progressed to a point at which this type of integrated system could become a reality. Implementing an alertness management system is especially important to support reduced manning.

Other aspects of crew endurance still need to be monitored, such as the environment, physical fitness, and diet/nutrition, which are described in the following sections.[7]

Environmental Conditions

The environment to which warfighters are exposed during both operations and rest needs to be considered in an endurance management program. The conditions of the warfighters' rest environments are often overlooked but are just as important to their endurance. Environmental conditions such as light, noise, vibration, temperature, and humidity have effects on performance and alertness.

Environmental conditions of both work and rest areas need to be improved. Auditory stimulation, bright light, and ambient temperature can be optimized to support work and rest areas. For example, natural light from windows as well as white light are the best for supporting our body's physiological cycles.[37] Bright lights best support nighttime shifts to synchronize the circadian rhythm.[40] Sleep areas should remain dark and, if desired by the crew member, something that generates white noise such as a fan can be used to aid sleep.

Physical Fitness

Physical fitness also needs to be factored in because it impacts crew endurance. Those who are physically fit may have better tolerance for working during unusual hours. Studies have shown that in general, people who exercise report lower levels of fatigue, sleep for longer periods of time, and have better quality of sleep.[37]

Improved sleep can decrease sleepiness and improve alertness. Adrenaline is released into the bloodstream during exercise, which results in increased brain activity.[41] Note that the studies cited in this section were not conducted on warfighters, who must meet specific physical fitness guidelines.

Not only does exercise improve health, but research also reports that individuals working night shifts can benefit particularly from the effect of exercise on the body's circadian rhythm. Because exercise generally increases the body's temperature, the circadian rhythm can become slightly shifted. Also, exercise can slightly change the time when the sleep-inducing hormone melatonin is released. One company reports that people on the night-shift schedule can time their exercise to effectively benefit from these physiological changes and consequently shift their circadian rhythms.[41]

Diet/Nutrition

Food and drink are additional factors that should not be overlooked when managing crew endurance. Research has shown that high-carbohydrate foods may produce sleepiness, whereas low to moderate amounts of foods that are high in protein may help sustain arousal.[37] These two claims are refuted by certain management programs that state that no particular diet prevents fatigue or improves performance. Rather, regular meals, a balanced diet, and adequate hydration are encouraged, while large meals are discouraged.[42] Warfighters commonly use the stimulant caffeine in its various forms (coffee, tea, chocolate, etc.) to improve alertness and vigilance. Although many come to rely on it, many also attest that a tolerance is soon developed to caffeine's effect. Fine motor coordination and control may be impaired by high doses. Those not used to caffeine may experience negative sleep effects. Caffeine is not an equivalent substitute for sleep.[42]

Each of the aforementioned factors can individually degrade warfighter performance. The combination of poor sleep, stressful environmental conditions, poor physical fitness levels, and poor diet can contribute to operational risks.

EXISTING ENDURANCE MANAGEMENT PROGRAMS

Solutions to address the management of crew endurance depend on many factors, including the type of platform, the type of mission, available resources (both financial resources as well as people), and time. Hence, the ability to tailor a specific program to a unique environment is critical. Several of the U.S. service branches and departments, including the Army, Navy, Coast Guard, Air Force, and Department of Transportation, have developed their own CEM programs for targeted personnel. These management programs can serve as references for future CEM programs. Each community has its own characteristics that may require these guides to be altered to meet the specific needs of the crew, environment, and mission areas.

Army

The U.S. Army Aeromedical Research Laboratory and the U.S. Army Safety Center[40] published a *Leader's Guide to Crew Endurance* in 1997. Chapters are dedicated to stress and fatigue, sleep deprivation, work schedules and the body clock, and the systems approach to crew rest. Each chapter contains general descriptions, signs and symptoms, resulting hazards, and how hazards can be managed. Domain-specific scenarios and supervision examples are provided for the leaders to understand how the information can be applied while executing their tasking. The guide has separate appendices with additional information on fatigue, sleep management, pharmacological sleep aids, napping, pharmacological stimulants, and circadian rhythms. Much of the research that went into the guide has been leveraged by other service branches.

Navy

In 2000, the Navy distributed *Performance Maintenance during Continuous Flight Operations: A Guide for Flight Surgeons*.[43] This guide contains information on continuous and sustained operations, sleep, circadian rhythms, fatigue, performance, antifatigue medications, U.S. Air Force experience in Desert Storm, strategies and ideas (for the air wing, squadron, individual, and flight surgeon), and medication protocols. Also included are briefing materials that help to teach individual aviators the criticality of performance maintenance. The scope is limited to the naval aviation community rather than to the entire Navy. The guide is also geared more toward fatigue management than toward CEM. A Navy-wide resource is currently lacking.

Coast Guard

The U.S. Coast Guard developed a more extensive program called the Crew Endurance Management System (CEMS), which is composed of tools and practices for maritime operators to use to manage operations in terms of productivity and safety. "This guide provides proven practices for managing endurance risk factors (sleep loss, stress, heat, cold, etc.) that affect operational safety and crew member efficiency in the maritime industry."[3] The document describing the Coast Guard's program, *Crew Endurance Management Practices: A Guide for Maritime Operations*, has sections explaining CEM and provides a real-world example of an implemented CEM program on a maritime vessel. It discusses how to manage periods of least energy and alertness to optimize endurance and how operational risk factors can be controlled, and it provides recommendations for implementing CEM practices. The appendix is composed of four sections that contain additional information on sleep management, napping, and circadian rhythms as well as shift work, sleep, and biological clock management.

The CEM practices are comprehensive and reach into work schedules, policy modifications, and improvements to the environment. CEMS is a cyclical process in which improvements can be made as problems arise or conditions change.

Air Force

The Air Force has its own guide entitled *Warfighter Endurance Management During Continuous Flight and Ground Operations: An Air Force Counter-Fatigue Guide*.[42] It is intended to inform the Air Force community about fatigue, its effects, and how to address those effects in operational settings. The guide mostly contains information on fatigue, sleep, and circadian rhythms. However, it also has some content on nutrition and performance, an introduction to the Fatigue Avoidance Scheduling Tool (FAST), and strategy suggestions for the wing, squadron, individual, and flight surgeon.

U.S. Department of Transportation

The *Commercial Transportation Operator Fatigue Management Reference* was developed for the Department of Transportation in 2003 by McCallum et al.[44] This reference contains operational fatigue risk factors, fatigue management program components, a review of fatigue countermeasures, and basic information on sleep. As its name suggests, this document covers fatigue management rather than crew endurance, and thus it does not include other key aspects of endurance.

Crew endurance is affected by many factors. Even so, several of the services do not include in their programs key aspects of crew endurance such as environmental, physiological, operational, or psychological risk factors. All of these factors need to be considered to ensure a comprehensive program that supports performance and safety during operations. Except for the Coast Guard's comprehensive CEMS, which is currently in practice, we do not know how well the other services use or implement their published guidance documents.

APL RESEARCH EFFORTS AND SPONSORED WORK

Realizing the criticality of this topic, APL has participated in efforts to understand and enhance crew endurance. Starting in 2005, APL was tasked to create an LCS version of the TCM, which was originally built for the DD(X) program to help garner insight into that ship's crew performance. This has led to models of both LCS-1 and LCS-2 in mine warfare (MIW), anti-submarine warfare, and surface warfare scenarios. In addition, APL is currently tasked to study the effects of ship motion on crew fatigue and implement findings into the TCM. These studies have led to the development of a concept for a fatigue management tool that would support supervisory knowledge of sailor state and real-time proactive management of the watch schedule. APL has also undertaken multiple Independent Research and Development (IRAD) projects looking at fatigue and its impact on SA and on submarine crews. Outside of the Navy, APL was tasked to develop a methodology to assess the physical loading of American soldiers deploying to Afghanistan on the basis of the gear they carry. Each of these efforts is described in more detail below.

The LCS TCM Effort

On the LCS platform, the fatigue component of sailor performance is of particular concern because of the small crew size. APL was involved in an LCS TCM effort. The purpose of the project was to model the baseline LCS crew-manning concept in a realistic and stressing scenario to evaluate crew design by using the TCM. The model takes into account routine schedule, planned events, and unplanned events. Potential crew workload can be examined by modeling all the tasks and assigning them to specific crew members based on a given watch, quarter, and station bill (WQSB). Excursions from the baseline can then be run to investigate the effects of changes in factors such as schedule and work assignments.

The model's results suggest that management of crew fatigue is critical to meeting LCS mission requirements and maintaining human performance. Three factors in particular are suggested as contributing to LCS crew fatigue during a MIW scenario:

1. The cyclic nature of certain MIW evolutions, including vehicle launch and recovery
2. The use of watchstanders to support regularly occurring evolutions
3. Misalignment between crew sleep and work schedules, leading to fragmented sleep and circadian rhythm disruptions

SA and Fatigue

In a FY2006 undersea warfare IRAD experiment, APL found that SA is affected by fatigue and also that this effect varies from person to person.[45] Data analysis revealed a positive relationship among fatigue level, subjective reports of effort and frustration, and frequency of eye movements. Also, these findings demonstrated the feasibility of fatigue assessment by using physiological-dependent variables and SA measures in a near-real-world scenario.

Because fatigue was seen to affect SA, research also was conducted to develop objective, nonintrusive measures of SA. The current state of the art in measuring SA is to ask participants directed questions about the tactical situation and their expectations as to what will happen. This is then compared to subject-matter expert judgments of what the participant should know. This measure of SA is problematic, in that SA can be changed by the simple act of querying someone. The FY2008 and FY2009 Precision Engagement IRAD and Command and Control Cross Enterprise Initiative (C2CEI) sponsored research sought to develop SA metrics that are based on neuropsychophysiological response. Although these metrics are still in the basic research stage, the knowledge gained from conducting this research will help the researcher team in the Sailor Endurance Management System (SEMS) concept, which is explained in the following section.

The SEMS Concept

One element of a holistic approach that APL has considered is the SEMS concept, which is a proposed scheduling tool to avoid fatigue by supporting supervisory knowledge of sailor state and real-time proactive management of the watch schedule. General principles behind the design of the SEMS concept tool emerged from the sponsor-directed and internally resourced work that APL has engaged in. The following are the principles that would be leveraged and developed into system requirements:

- There should be a general-purpose CEM tool.
- This tool should maintain and use the actual crew watch bill.
- It should use the actual ship's schedule.
- Multiple baseline schedules should be built into the tool as should the capability to create new schedules and modify these baseline schedules.
- An underlying fatigue model should provide an indication of the crew's ability to perform.
- The tool should have high-level overview of the crew's capacity and sailor readiness and endurance.
- Finally, the tool should provide a graphical ship schedule that is simple to create and modify.

The underlying fatigue model used to develop the scheduling tool would be based on the SAFTE model used in the Air Force's FAST.[11] FAST was developed to compare the impact of mission schedules on crew performance and make recommendations to mitigate the problems. Its applications go beyond the cockpit. The Department of Transportation's Volpe Center used it to assist Amtrak in their scheduling needs. The fatigue model and physiological sensors would form the baseline prototype for the SEMS tool; future research would incorporate cognitive models and mitigation recommendations.

SEMS is a concept that APL would like to develop into a fully operational system because it has the potential to improve crew endurance across the Navy.

Submarine Schedule IRAD

The submarine community has implemented the same watchstanding schedule for the past 44 years.[31] Although the "6 h on, 12 h off" schedule sounds like it could meet the recommended 7–8 h of sleep for every 24 h, this is hardly the case for submariners. Rather, it is rare for crew members to get 6 h of continuous sleep because of the responsibilities beyond that of their watch (drills, training, etc.).

Relevant studies dating back to the 1950s have explored the circadian rhythms and fatigue levels of the men on submarines. Some studies have used FAST in conjunction with an actigraph to collect data and study fatigue levels at the conclusion of the experiments. No studies have proposed creating crew schedules by using scenarios and the watch, quarter, and station bill (WQSB) and inputting the information into FAST to predict the effectiveness of several different crew schedules.

APL continued this line of research with an undersea warfare IRAD study conducted in FY2007 to compile research findings from a previous submarine crew schedule analysis, to provide input to FAST, and to model submarine watch schedules in a predeployment scenario. Specifically, APL modeled three different crew watch schedules (the Straight 6, a special drill set schedule, and Close 4). The Straight 6 refers to the rotating schedule of 6 h on and 12 h off. The special drill set schedule is a modified Straight 6 that allows all three sections to be on watch during drills in a given day. These two schedules are currently used on submarines. The Close 4 is a proposed fixed schedule based on work by Kleitman[46] and Utterback and Ludwig[47]; this schedule consists of 2- and 4-h watches in a nonrotating schedule in which each watch section has a continuous 12-h off-watch period. The results for the three watchstanding schedules showed that the Close 4 fixed schedule held some promise over the currently used schedules for improving submarine crew performance.

Soldier's Load

APL developed a soldier's load analysis plan. The basic problem is as old as warfare itself, in that transporting heavy materials over long distances creates fatigue and slows troop movement; hence, an investigation was undertaken to look at what could be done to lighten the soldier's load. This historic challenge has resurfaced today in the war in Afghanistan. The remote and desolate environment of Afghanistan compels soldiers to carry as much ammunition and as many provisions as possible. Therefore the soldier's load often far exceeds the U.S. Army Infantry Board's suggested load carrying standards of 48 lb for fighting and 72 lb for approach marching. Exacerbating the issue is the trade-off between weight and protection; protective armor plating adds significant weight to the soldier's overall load. APL has taken one of the first essential steps to meeting this challenge by creating a method of testing and evaluation that defines the metrics and criteria in order to determine the impact on soldier performance.

In addition to the excessive loads carried by the soldiers, Afghanistan's environment is especially harsh, with high altitude, low temperatures, high winds, and extremely rugged terrain. Of particular concern, the high-altitude, low-oxygen environment exposes soldiers to the risk of high-altitude pulmonary or cerebral edema, which certainly reduces physical and mental performance but can also lead to death. Soldiers go through training to identify and properly address the onset of altitude-related illnesses, but tactical situations may not afford the proper and timely remedies.

APL developed a test plan and ran a pilot study within the continental United States that laid the foundation for the actual experiment that would be later carried out outside the continental United States. The pilot test examined soldier performance (e.g., by measuring performance when using treadmills, distance running, navigating obstacle courses, and shooting) using various metrics (e.g., heart rate, time, and accuracy) under two types of loads (backpacks). In an attempt to emulate the high-altitude environment, participants also performed various tasks in the mountains of Western Maryland (not quite the extreme elevations found in Afghanistan). After the pilot study was successfully conducted, all testing materials, required equipment, and detailed instructions were packaged for delivery to Afghanistan.

Improvements in materials and load-carrying equipment are constantly being developed to help solve the excessive soldier's load problem. This pilot study helped to define a methodology for testing and evaluating current and future designs. Although this effort was targeted toward Afghanistan's extreme environment, the basic methodology developed by APL could be applied to other environments (the jungle, the Arctic, the desert, etc.) that soldiers may face in the future.

LCS: Ship Motion Study

The Navy is aggressively pursuing optimal manning for new ships. To achieve this goal, each individual sailor is critical to the mission effectiveness. Therefore, it is essential to ensure that the right number of crew members are on board. Over the last 5–10 years, significant progress has been made in developing tools and analysis techniques that provide insight into manpower, workload, and human performance implications of ship and crew design concepts. The TCM, developed by Micro Analysis and Design, Inc. (currently known as Alion MA&D Operation), is one such tool and has been applied to both the Zumwalt-class (DDG 1000) guided missile destroyer and the LCS ship designs. Although TCM is accredited by the Naval Sea Systems Command for use in evaluating crew performance and manpower requirements, shortcomings in accurately predicting fatigue levels of deployed personnel remain. In particular, the effect of ship motion is not directly considered by TCM. It is common knowledge among those who work on ships that motion leads to drowsiness and fatigue.[48,49] The literature characterizes this fatigue in two ways: motion-induced fatigue,[50] which is related to physical fatigue, and sopite syndrome,[51] a manifestation of motion sickness. These effects can have a considerable impact on sailors, possibly doubling the level of fatigue that a person experiences while doing the same work on shore.[49] Not considering these effects in the TCM, which currently considers only the effects of wake and sleep time on fatigue, may lead to underestimating the true effect fatigue is having on sailors' performance.

To overcome these limitations, the LCS Mission Module Program Office (PMS420) has tasked APL to extend the TCM to consider the effects of ship motion on crew performance and fatigue in a shipboard environment. The fatigue model will be enhanced with knowledge gained from shore-based and at-sea experiments. At-sea data collections were conducted in January, February, and March 2011. At the successful conclusion of the project in February 2012, both the acquisition and operational Navy will be provided with a modeling and simulation tool that can be uniformly applied to reliably evaluate the effectiveness of whole-ship designs in the context of workload and fatigue metrics, within particular operating scenarios and crew concepts.

FUTURE RESEARCH AND ENDURANCE MANAGEMENT SYSTEM NEEDS

Although efforts have been made to support crew endurance, and various U.S. military branches have implemented management programs, further improvements can be made to aid warfighters. Specifically, more research should be dedicated to the environmental conditions, physical loading, and physical fitness risk factors. There is currently research on each factor, but there is a lack of information on the relation of these factors to operational mission areas. We need to adequately understand how these factors can be controlled in the real world. Developing, refining, and validating metrics to support these relations is also important. Once this research has progressed, scheduling and management tools can be developed and enhanced to monitor and manage crew endurance so that performance can safely be supported in the operational environment.

Science/Basic Research Needs

Environmental Conditions

Because noise and lighting affect sleep quality and performance, a holistic endurance program should enlist the findings of the literature to ensure that the operational environment is conducive to work. This includes creating an environment that promotes alertness in working areas and sleep in sleeping quarters.

Physical Loading

Tools, technology, and materials are now available to better quantify and directly address the problem of physical loading. A fundamental trade-off is protection versus weight. As better materials and new packs are developed, the methods defined in this article can be used to determine the impact of these new materials on human performance. The use of biometric sensors (such as taking blood to measure oxygenation levels and perhaps stress hormones as well as 24-h monitoring with wearable biometric sensors) may also be investigated to assess how well such sensors can measure performance impacts. Additionally, it is feasible to build biometric sensors into the body armor itself or to use wearable, net-enabled biometric sensors for real-time command and control monitoring of vital signs, stress, and fatigue.

Physical Fitness

Physical fitness also is an important aspect of crew endurance. Although research involving physical exercise has been conducted with the general public, certain military branches have demanding physical requirements that may exceed the average person's fitness level. Current research does not address the relationship between warfighters' physical fitness and crew endurance. Also, most of the research linking exercise and circadian rhythm is based on 24-h days.[41] Warfighters often follow schedules that do not align to regular days. For example, the submarine community implements 18-h days. It should be investigated whether and how exercise influences circadian rhythms in varying schedules.

Metrics

Common metrics currently include the time it takes to perform a task (speed), the number of errors during a task (accuracy), and the variability in speed or accuracy. In-depth metrics that go beyond speed, accuracy, and variability need to be developed and validated. Relevant ties to the operational environment are important. More research needs to be conducted to provide metrics for complex cognitive tasks. Additional team performance metrics and validation would also be helpful in determining which aspects of teamwork are helpful in supporting crew endurance. Studying the interdependencies of multiple factors rather than just the single factors will also help improve understanding and enhancement of crew endurance.

Endurance Management System Needs

A holistic approach to enhancing crew endurance depends on education, training, and successful adoption of management strategies. The tools used by the crew need to support these endeavors.

Schedule Management Tools and Development

Although current modeling tools are available to coordinate schedules, most of them are time consuming and not conducive to use in operational settings. Tools are needed that are simple to use and have algorithms to support an optimal balance between operational needs and the management of crew endurance. The scheduling tool also should support rapid replanning in case modifications need to be made suddenly (e.g., training opportunities, sickness, or other emergencies). The operator should be allowed to easily change schedule inputs. A manual entry could also be featured to allow crew members to experiment with different schedules (that is, a "what-if" tool function).

Metrics for Monitoring Tools

Tools for monitoring the environment as well as the physical fitness and diet/nutrition of the crew would also be beneficial for CEM. Sensors can be researched for use in collecting and adjusting environmental factors such as temperature, humidity, and light settings. It is recommended that behaviors of individual crew members, such as their exercise and diet, be monitored, but any type of individual measure should be nonintrusive. Data monitoring should require little, if any, effort from the crew member. The goal is to improve crew endurance, not to negatively impact their operational performance by burdening them with monitoring efforts.

SUMMARY

The security of our nation relies on individual warfighters working together to perform critical missions. Their performance and alertness can be compromised when they are required to work long hours in extreme environments with limited and poor sleep, improper nutrition, and under other conditions that cause stress, whether physical, mental, or emotional. Although some U.S. military branches have implemented CEM programs to support the warfighters and to address these issues, there is room for improvement. More comprehensive programs across all services and within the Department of Homeland Security would make a positive impact. Education, training, and successful adoption of CEM strategies can minimize operational risks and improve mission readiness. APL is striving to contribute to the understanding and enhancement of crew endurance by conducting research and participating in development efforts.

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The Authors


Megan L. Moundalexis


Jennifer A. B. McKneely


William B. Fitzpatrick


Cory C. Sheffer

Megan L. Moundalexis is a member of the APL Associate Staff in the System Performance and Measurement Group of the National Security Technology Department (NSTD). She helped conduct studies investigating the effects of fatigue on SA and performance and is a member of the Ship Motion Study for the LCS. **Jennifer A. B. McKneely** is a member of the APL Principal Professional Staff in the System Performance and Measurement Group of NSTD. She provides human systems integration (HSI) support to the Military GPS User Equipment program Hand Held and the LCS TCM Ship Motion Study and serves as a Defense Threat Reduction Agency HSI subject-matter expert. She is responsible for coordinating human systems engineering efforts and activities within APL. **William B. Fitzpatrick** is a member of the APL Senior Professional Staff in the Command and Control Group of the Global Engagement Department. He worked on the soldier's load project in addition to the augmented cognition studies. **Cory C. Sheffer** is a member of the APL Senior Professional Staff and a Section Supervisor in the System Performance and Measurement Group of NSTD. He has led the LCS Total Crew Modeling effort at APL for the past 5 years and is currently supporting the LCS Ship Motion Study. For further information on the work reported here, contact Megan Moundalexis. Her e-mail address is megan.moundalexis@jhuapl.edu.

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