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14. ABSTRACT
The Sleep and Performance Research Center (SPRC) at Washington State University will conduct laboratory and field studies of sleep loss and performance in normal humans. These studies will provide the scientific basis for the effective management of sleep to sustain performance in the operational environment, including all 24x7 operations, extended work hours, and shiftwork. They will improve effectiveness, productivity, safety, health and well-being in military and civilian operations, reducing the likelihood of fatigue-related error, incident, accident or catastrophe.

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Introduction:

Acute total sleep deprivation and chronic sleep restriction degrade human performance. Even modest sleep restriction leads to loss of productivity and effectiveness, and can result in error, incident, accident, and catastrophic failure. Operational environments are those in which if the human fails to perform effectively the system fails; it is any setting in which performance of the human in the decision loop is critical to a successful outcome. Examples of operational settings include military operations, commercial aviation, medicine, shipping and transportation, police work, fire fighting, manufacturing, and most other 24-hour a day, 7-day a week operations. Sleep related factors that affect operational performance are: 1) sleep/wake history (time slept and time since last sleep); 2) circadian rhythm (time of day); 3) task duration (time on task and task intensity); 4) adaptation and recovery from restricted sleep; 5) individual differences in response to time awake, time of day, time on task and adaptation and recovery.

We are building, staffing, and equipping a Sleep and Performance Research Center (SPRC) at Washington State University (WSU). The SPRC is for the purpose of studying the relationship of sleep and sleep loss to operational performance in normal sleepers through multi-day studies conducted in both in-residence in the laboratory and in the field. This work will be of relevance to managing sleep to sustain performance in all operational settings involving 24x7 operations, extended work hours and working the backside of the clock (shift-work). Thus our findings will be important for the Army, the Navy, the Marine Corps, and the Air Force, for all modes of transportation (truck, rail, air, and sea), for hospital and emergency room personnel, as well as for manufacturing, power generation, and finance (now a 24-hour operation). The capacity to do this scientific work in the United States is limited. There were only three laboratories (Harvard, University of Pennsylvania, and the Walter Reed Army Institute of Research) capable of conducting multi-day in-residence laboratory studies and multi-week field studies of sleep and performance in normal humans. With the SPRC here at WSU there are four. The SPRC is an important national resource. It is worth noting that Dr. Belenky comes from the Walter Reed Army Institute of Research and Dr. Van Dongen from the University of Pennsylvania, two of the three labs mentioned above. Our work at the SPRC will improve productivity, health, and well-being of operational personnel and reduce the human and economic costs by preventing fatigue-related error, incident, accident, and catastrophe. Our immediate goal is to begin laboratory and field studies. Over the longer term we will make the SPRC self-sustaining through grants and contracts. We will leverage funds from a variety of sources to conduct studies relevant to sustaining sleep and performance in military operations.

Body:

Summary of Approved Statement of Work –

Task 1. Conduct field studies of work shift timing and duration and their impact on sleep and performance

Task 2. Build, equip, and staff sleep and performance research laboratory at Washington State University Spokane; the building of research space will be funded by $650,000 from WSU; funds for staffing and equipping the laboratory will come from the congressional earmark.

Task 3. Plan and conduct laboratory studies of chronic sleep restriction and performance.

Program – Beginning in September 2006, we will conduct long-duration field and laboratory studies of sleep and performance. Objectives of the field studies are: 1) determine the impact of shift duration and timing on sleep and subsequent performance; 2) assess the utility of currently field-able objective measures of sleep and performance in managing shift duration and timing; and, 3) provide objectively measured sleep/wake histories and performance metrics for the purpose of developing and validating mathematical models predicting individual performance from sleep/wake history. Objectives of the laboratory studies are: 1) determine the time course of performance degradation during multiple days chronic sleep restriction; 2) determine the time course of subsequent recovery; 3) determine the nature and predictive correlates of individual differences in response to sleep restriction and recovery.

The field studies are planned in four operational venues - resident physicians in the University of Washington internal medicine residency program; police patrol officers in the Spokane Police Department; air-refueling crews at Fairchild Air Force Base; and production personnel in Hollister-Stier, LLC, a biotechnology company. They will involve 4-10 weeks of objective measurement of sleep (using actigraphy), objective measurement of performance using the psychomotor vigilance task (PVT) and the relation of these variables to shift timing and duration. We are planning field studies in trucking and in aviation to support the development of a sleep science-based plan for fatigue risk management.

The laboratory studies will be conducted in the in-residence in the SPRC. The first experiment, already funded by the NIH, will be a 12-day in-residence study of the effects of repeated (three bouts of 36 hours of total sleep deprivation) sleep deprivation and varying workload. Further experimental designs remain to be specified but the overall plan is multiple days of chronic sleep restriction followed by recovery with continuous objective measurements of sleep and performance. The data from the laboratory and field studies will enable the development of mathematical models to predict individual performance from sleep/wake history.

We will provide objective information to the U.S. Army in support of its effort to build a system to manage sleep to sustain operational performance. This work will enable the development of mathematical models to measure sleep and predict individual performance in operational settings. These models will be incorporated into the U.S. Army War Fighter Physiological Status Monitor (WPSM) and other similar soldier-centric computer and communications systems. Together they will provide Commanders with the tools to manage sleep as an item of logistic re-supply. Through the WPSM and related systems, Commanders will know how much sleep their men have been getting, how long this will sustain them, and how to plan for timely replenishment. Effective management of sleep to sustain performance will reduce errors, incidents, accidents, friendly fire incidents, and catastrophic failure. The work is relevant to managing sleep to sustain performance in civilian operational settings.

We will continue the development (building, equipping, and staffing) of the Sleep and Performance Research Center at Washington State University Spokane and seek grant support for further work in the area of sleep and performance relevant to the U.S. Army, other military settings, and civilian operations.

We will begin laboratory and field studies in September 2006.

Personnel – Dr. Hans Van Dongen joined the SPRC from the University of Pennsylvania in October 2005. Dr. Van Dongen is an accomplished researcher in the field of sleep loss and human performance. Along, with Dr. Belenky, he has pioneered the contemporary study of the effects of sleep restriction on performance. He is the world leader in the study of how individual differences modulate the response to sleep loss. He brought with him grants from the NIH and from the U.S. Air Force. In addition, to Dr. Van Dongen, in the past year we have brought on board two graduate students (Adrienne Tucker and Will Clegern), one undergraduate research assistant, two master's level mathematicians to assist with modeling work, a study manager, a polysomnographic technician, and an administrative assistant. We will be recruiting more undergraduate research assistants to staff our multi-day in-residence laboratory studies and to assist in data reduction and analysis.

Facilities – In September 2005, WSU began the build out of the SPRC in the university's Spokane campus South Campus Facility, a former BNSF Railroad warehouse. The university provided $650,000 for this work. This work was completed in February of 2006. Up to this point the SPRC was operating out of two offices in the Health Sciences with two people per office and zero lab space. We moved into the SPRC facility in May of 2006. The completed SPRC contains 5,000 sq feet of which ~2,500 sq ft is the actual in-residence sleep and performance research laboratory or "sleep suite". The sleep suite contains 4 bedrooms, a lounge area for study participants complete with a kitchenette, two full bath rooms, a monitoring room, a medical procedures (e.g., physical exam, blood drawing, and electrode placement) room, and a room with a washer and dryer. It is equipped for long-term (days and weeks) in-residence studies of sleep and performance. See "Supporting Data" for the floor plan of the SPRC and some photos. The remaining 2500 sq feet is offices and office bay space for faculty, study and administrative personnel, and undergraduate and graduate students, and post-doctoral fellows to support study design, data reduction and analysis, and writing grants and papers, as well as routine administrative functions.

Equipment – For laboratory studies, we are acquiring state-of-the-art 1) polysomnographic sleep recording equipment, including electroencephalogram (EEG), electrooculogram (EOG), electromyogram (EMG), electrocardiogram (EKG) systems to physiologically measure sleep and wakefulness and the stages of sleep, 2) near-infrared optical topography equipment to do continuous, ambulatory brain imaging during waking, waking task performance, sleep onset, sleep offset, and sleep itself, 3) EEG equipment to do evoked potential work and measure electrical impedance changes during task performance as a complement to the infrared optical topography, and 4) a server-based data acquisition and archiving system to integrate and store these data streams. We estimate completing these acquisitions in 6 weeks. For field studies, we have acquired 25 sleep watch actigraphs to unobtrusively measure sleep in normal people working extended work hours and doing shift work. In addition, we are acquiring 25 Palm Pilots PDAs with psychomotor vigilance task (PVT) testing software. As we move into the field studies, we will acquire more sleep watch actigraphs and Palm PVTs (to a total of 50 each).

Further Funding – In addition to the funding from the U.S. Army we have grant/contract support from the NIH and the U.S. Air Force. We also have obtained from the U.S. Air Force a Defense University Research Improvement Program (DURIP) grant to further equip the laboratory with electrical impedance and optical brain imaging systems. We have applied for a grant from the W. M. Keck Foundation to support electrical impedance and optical brain imaging studies of sleep and performance. In addition, we have an application to the NIH for funds to support validating the Firearms Training System (FATS) as a measure of police officer fatigue. We are preparing two grant submissions to the NIH, one to investigate the effects of sleep deprivation on executive function (the most complex mental operations) and the other to study the interaction sleep loss with time on task and task intensity. We have a grant application being reviewed by the U.S. Navy. We are exploring the possibility of funding from the US DOT Federal Motor Carrier Safety Administration and from commercial motor carrier companies to evaluate the safety, productivity, and health consequence of the new hours of service regulations for long and short haul truckers.

Key Research Accomplishments:

- Built, staffed, and are equipping the SPRC

- Developed laboratory and field research protocols
- Published a paradigm shifting paper in the Army War College journal *Parameters* describing the nature of network centric warfare, the importance of human performance at all levels in the network centric environment, and the role that sleep plays in sustaining that performance [See References (for citation) and Appendices (for full text of paper]
- Interfaced with researchers and stakeholders in all modes of transportation (aviation, trucking, rail and maritime) regarding systems for fatigue risk management

Reportable Outcomes:

- Published multiple papers and abstracts in the area of sleep loss and human performance, including a paradigm shifting paper on network centric warfare (Dr. Belenky) (see References and Appendix)
- Obtained an equipment grant (DURIP) from the U.S. Air Force (Dr. Belenky & Dr. Van Dongen)
- Associate editor of the journal *Sleep* (Dr. Van Dongen)
- Member Editorial Board of the journal *Aviation, Space, and Environmental Medicine* (Dr. Belenky)
- Served on the organizing committee of the USDOT-sponsored International Conference on Fatigue in Transportation (Dr. Belenky)
- Participated in the UN's International Civil Aviation Organization (ICAO) advisory group on fatigue risk management and consulted to Boeing, Qantas, Union Pacific, and the Airline Pilot's Association (ALPA) on the same issue (Dr. Belenky)
- Served on the Board of Directors of the National Sleep Foundation (Dr. Belenky)
- Conducted multiple outreach activities (talks, seminars, etc.) on the importance of sleep for health, well-being, and productivity in Washington State and around the U.S. (Dr. Belenky & Dr. Van Dongen)

Conclusion:

With the completion of the SPRC which will serve as a venue for the laboratory studies and as a staging area for the field studies, we will be ready to begin both. This summer we will complete equipment acquisition, complete our staffing, train staff, trouble-shoot new equipment, and complete the process of IRB approval with the aim to begin both laboratory and field studies in September. With a superb facility and state-of-the-art equipment we are confident of seeing the SPRC through to sustainability through grants and contracts.

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Cognitive Readiness in Network-Centric Operations

NANCY J. WESENSTEN, GREGORY BELENKY, and THOMAS J. BALKIN

From *Parameters*, Spring 2005, pp. 94-105.

"Battle remains the freest of all free enterprises."
— S. L. A. Marshall[1]

"Machines don't fight wars. People do, and they use their minds."
— John R. Boyd[2]

In a 1998 article in *Proceedings*, Arthur Cebrowski and John Garstka described network-centric warfare as the "next revolution in military affairs,"[3] comparable in magnitude to the revolution triggered by mass conscription during the Napoleonic era. The term network-centric operations refers to military operations enabled by networking the military force.[4] Networking has multiple meanings, but in the network-centric context it means computer network-based provision of an integrated picture of the battlefield, available in detail to all levels of command and control down to the individual soldier. The latter is achieved through command post, vehicle, and helmet- or head-mounted displays, and individual soldier computers, all linked by radio-frequency networks. As stated in a 2001 Defense Department report to Congress, "Network-Centric Warfare is to warfare what e-business is to business."[5] E-business applications may have come first, but as indicated in the introductory quote from S. L. A. Marshall, "battle is the freest of all free enterprises," making battle and network-centric organization a natural fit.

Network-centric operations (whether of a military or commercial nature) are characterized by information-sharing across multiple levels of traditional echelons of command and control. This information-sharing is made possible by networking the entire force down to the individual level. Therefore, network-centric operations depend upon the availability of information on the status and disposition of friendly forces, enemy forces, and all other relevant aspects of the operational environment—typically rendered as icons on a map displayed on a computer screen.[6] An underlying assumption of information-sharing is that the latter translates into a shared situational awareness and self-synchronization through shared mental models of the current situation and of the desired end-state (synonymous with commander's intent, i.e., the object of the operation), leading to a warfighting advantage. As outlined in *Joint Vision 2020*, information superiority is advantageous only if it ultimately translates into decision superiority.[7] In network-centric warfare, the basis for Army Future Force Warrior doctrine and operations, the capacity to convert information superiority into decision superiority is optimized.

Self-Synchronization

Fundamental to network-centric operations in general—and network-centric warfare in particular—is the notion that, with accurate, detailed information available at all levels, highly complex groups organize naturally (and optimally) from the bottom up.[8] Such bottom-up organization ("self-synchronization") in its most basic form (coordination without verbal or written communication) stands in stark contrast to what has historically and traditionally been a highly centralized, top-down command and control approach (to include commander's intent communicated linearly from the top down). By enabling more extended self-synchronization, network-centric operations are likely to change the balance between bottom-up initiative and top-down directive in favor of bottom-up initiative—an initial shift in balance that is already evidenced by the Army's decision to eliminate divisions in favor of a brigade-based organization.

Top-down directive command and control was implemented as a necessary response to the limitations imposed on self-synchronization by the need for unaided line-of-sight contact. Thus, to the extent that network-centric military operations reflect a "revolution in military affairs," they do so in a straightforward manner: by expanding unaided line-of-sight through the use of technology (in effect, "enabled" line-of-sight). Consequently, opportunities to self-synchronize (a behavior that appears to have been and continues to be an inherent characteristic of military operations at the small-unit level throughout history) also are expanded.

The Battle of the 73d Easting during the 1990-91 Gulf War exemplifies such self-synchronization based primarily upon line-of-sight enabled by thermal sights. In this battle, the US Army's 2d Armored Cavalry Regiment was ordered to find the enemy, defeat any forward covering forces, determine the position and extent of the main defenses, and fix them in position for assault by the heavier forces advancing behind them.[9] They were to execute this while advancing through a heavy sand and rain storm. When the regiment's lead troop made contact with the main Iraqi position, they determined that the risk incurred to their own force by waiting for follow-on forces exceeded that of attacking at once, and they immediately launched an assault. The troop of nine M1 Abrams tanks and 12 M3 Bradley fighting vehicles subsequently destroyed the entire defensive belt in front of them, including 37 Iraqi T-72 tanks and 32 other armored vehicles, in about 40 minutes. The lead troop appears to have done this (and won their lopsided victory) by maneuvering on-the-fly (using technologically enabled line-of-sight) to exploit Iraqi errors. They did this without sustaining any casualties themselves. Counter-factual analyses indicated that the troop had found a singularly casualty-free path through the battlespace—i.e., almost any change would have led to a less-decisive victory and to American casualties.[10]

Self-synchronization of individuals within groups prosecuting aggressive actions is an ancient practice, likely drawing on cognitive modules shaped by our evolutionary history of hunting and fighting in small groups. At its most basic level, self-synchronization is modeled by "flocking algorithms."[11] The simple algorithm describing this flocking behavior, as in a flock of birds in flight, is based on autonomous units programmed to (a) steer to avoid crowding local flock mates, (b) steer toward the average heading of local flock mates, and (c) steer to move toward the average position of local flock mates. Thus one's movement makes use of information regarding the location, speed, and direction of the three or four closest flock mates. Flocking behavior emerges from these simple rules, and effectively constitutes coordination of actions without overt communication of intentions. This is pure self-synchronization, without a hint of top-down command and control, based on discernible information provided to the individual. What emerges is a fluid flow of the virtual flock over terrain, including dividing around obstacles and reforming once the obstacles are passed. Flocking algorithms have been used by the Marine Corps and others to model the maneuver of squad elements across terrain.[12] Self-synchronization is evident in line-of-sight-enabled small-unit operations where individual soldiers, seeing their comrades, maneuver toward an objective (self-synchronize) in support.

Self-synchronization leads to emergent properties and efficiencies unachievable with top-down direction. Network-centric warfare, rather than being a revolution in an absolute sense, takes advantage of innate human abilities and propensities to maneuver in support of other unit members to achieve a common objective. Historically this has depended on unaided line of sight. Creating a virtual line-of-sight connectivity, extending well beyond the actual line of sight, enables self-synchronization to extend beyond the small unit and provides the adaptability and flexibility of self-synchronization at higher levels of command and control and across much greater unit size and dispersion. The fluidity and real-time adaptability with which small infantry units or armor units maneuver and fire to take an objective would be impossible with pure top-down direction. Network-centric warfare extends such innate human talents for self-synchronization to larger, more widely dispersed units and higher echelons of command and control.

New Operational Capabilities

As battlespace information is made available via networking and digitization across all echelons of command and control, the ability to self-synchronize will spread from small units (e.g., the 21 armored vehicles representing the lead troop of the 2d Armored Cavalry Regiment) to increasingly larger units, and finally will characterize joint operations. The value of the synchronization across larger units is clearly exemplified by the decisive US victory in Afghanistan. This victory resulted from attacks by waves of Air Force, Navy, and Marine combat aircraft on al Qaeda and Taliban fortifications, coordinated with the insertion of Army Rangers, Marine expeditionary units, Navy SEALs, and Delta Force carrying out a variety of combat missions—to include reconnaissance that improved the precision of airstrikes.[13]

Fred Stein has outlined the "new operational capabilities for force employment" enabled within the "shooter grid" of the network-centric environment.[14] These include:

- The ability to be proactive in the planning process to avoid direct confrontation (by employing alternative means), to be prepared to react and exploit opportunities when direct confrontation must occur, and to shape expected actions to stay inside an enemy's decision cycle and keep him outside of ours; and the ability to rehearse, evaluate, and adapt plans rapidly (predictive planning and preemption).
- The ability to achieve dynamic synchronization of missions and resources from components and coalitions; and to synchronize distributed force operations (integrated force management).
- The ability to enable rapid target search and acquisition, battle coordination and target selection, handoff, and rapid engagement of briefly available targets (execution of time-critical missions).

These operational capabilities are not new, but without the technological advances now available (e.g., the Joint Surveillance Target Attack Radar System [JSTARS]), their scope was for all intents and purposes restricted to those elements that were within the warfighter's line of sight. The Battle of 73 Easting highlights the importance of these operational capabilities to successful operational outcomes—capabilities which taken as a whole constitute cognitive readiness or the skillful application of technology in real time to exploit opportunities as they emerge. The Battle of 73 Easting is an example of a group having information in common and adopting a common mental model of what constitutes a successful outcome and working in concert to achieve this outcome. Network-centric capabilities expand access to information and the opportunity to form common mental models from smaller units (individual, squad, and platoon) to increasingly larger units (company, battalion, brigade) operating beyond simple line of sight. While the Stein taxonomy is based on his observations of the functional capacities enabled by the networked force, it is fully compatible with cognitive executive functions, typically involving the brain's prefrontal cortex—the seat of anticipation, planning, initiative, the integration of reason and emotion, and self-synchronization.

Implications for Operational (Cognitive) Capabilities

Effective operational outcomes generally depend on speed of responding and attention to context directed toward accomplishing the commander's intent (*Auftragstaktik*). The ability to implement *Auftragstaktik* (task tactics) in turn depends upon the ability to perform complex mental operations—cognitive integration at the highest levels.

Although on the surface the point of greatest vulnerability in network-centric operations might appear to be the hardware and software constituting the network itself, it is worth bearing in mind that the hardware constituting the networks is decentralized—and as a result is relatively resilient to localized node (connection) failures because signals can be transmitted along a multitude of routes. Therefore, by default, it is the operator's (warfighter's) ability to make use of the information provided by the network (i.e., to facilitate predictive planning and preemption; integrated force management; execution of time-critical missions—all of which effectively translate into *Auftragstaktik*) that becomes the point of greatest vulnerability. And this vulnerability is potentially compounded by reduced human redundancy in modern military operations.

The mental abilities required to achieve *Auftragstaktik* are those facilitated by a networked force—and include situational awareness, adaptability, mental agility, judgment, initiative, anticipation, planning, and course-of-action determination—abilities that are known to be impaired by the various stressors to which today's warfighter is routinely exposed, including environmental extremes (heat, cold), dehydration, high operational tempo, and sleep loss. This does not, however, mean that the cognitive resources of soldiers in a network-centric operation will necessarily be taxed to a greater extent than they are in a non-network-centric environment, nor that operational performance will necessarily be more vulnerable (on an absolute scale) to the effects of those operational stressors. Rather, it means that the importance and salience of the warfighter's cognitive performance status is likely to be relatively increased against a backdrop of global, network-centric-enhanced warfighting prowess. In fact, as discussed below, it is conceivable that network-centric capabilities will confer increased resilience in the face of some operational stressors known to affect cognitive performance.

The Impact of Sleep Loss

Of the stressors affecting warfighter cognitive performance, sleep loss (which directly affects prefrontal cortex function) is the most thoroughly characterized. Acute, total sleep deprivation and chronic sleep restriction (the latter is probably a far more common problem than acute, total sleep deprivation in the operational setting) impair cognitive performance, including the general speed of responding on simple psychomotor tasks.[15] However, complex mental operations—including the ability to anticipate, generate, and execute a plan of action; maintenance of situational awareness; and critical reasoning (executive functions associated with the brain's prefrontal cortex)—also are impaired by sleep loss.[16] Such findings are consistent with the results of our debriefings of friendly-fire incidents during the 1990-91 Gulf War, which indicated that friendly-fire incidents often result from the loss of situational awareness (orientation to the battlefield and hence the ability to distinguish friend from foe—a complex cognitive ability).[17] Functional brain imaging studies show that sleep loss selectively deactivates the pre-frontal cortex,[18] the brain region where anticipation, planning, and situational awareness culminate. The implications of these findings are clear: even in well-equipped, well-trained, highly motivated soldiers operating within cohesive units with good morale, sleep remains a critical factor for maintaining the operational capabilities enabled (and required) by a network-centric environment.

Thus, it would be expected that the better-rested the soldier, the better and faster that soldier will be able to grasp and capitalize upon the information provided by the network—an advantage that could be critical when the opposing force also has network-centric warfare capabilities. However, in situations in which the opposing force is without such capabilities (the more likely situation for the near term), it is conceivable that network-centric capabilities will mitigate some of the consequences of sleep loss. For example, the functionally extended "line of sight" that this technology provides means that the warfighter—even the sleepy warfighter whose cognitive abilities have slowed considerably—is likely to "see" the enemy long before the enemy is aware of that warfighter's position, effectively extending the time that the warfighter has available to decide upon the correct course of action.

Revolution—or Evolution—in Military Affairs?

Although Cebrowski and Garstka described network-centric warfare as the "next revolution in military affairs,"[19] as we have outlined in this article, network-centric operations might be better viewed as a technological evolution of the line-of-sight capability on which military operations have always depended.

By expanding line of sight, network-centric operations revolutionize the extent to which maintaining cognitive capabilities in each individual soldier or operator becomes critical to successful outcomes, an issue implicitly recognized as one of six essential components crucial for Objective Force Warrior fielding in 2010.[20] Collaborative situational understanding (a common relevant operational picture) is targeted as one of the two most critical components (the other being netted fire) into which maximum focus and resources should be applied, because these two items allow the soldier to know what the system knows (collaborative situational understanding) and apply the power of the force (netted fire).

Managing New Operational Capabilities

Maintaining cognitive capabilities critical to a networked force will require that they and the factors sustaining them be managed. These factors can be viewed as analogous to items of logistical resupply. To be effectively managed, a quantity must first be measured. Historically, attempts to measure cognitive capabilities in the field have met with minimal success due to the inherent difficulties in quantifying effective performance in the operational environment. Under these circumstances, possible solutions include: measuring other, intermediate factors that account for variability in mental performance; using metrics or tests from which operational performance capability can be inferred; or some synthesis of these two solutions. The salient point is that these solutions enable cognitive performance quantification (indirectly or directly)—which in turn opens the possibility of modeling (predicting) operational capacities. Components of the Warfighter Physiological Status Monitor (WPSM) exemplify these alternative solutions, as discussed next.

Measuring Intermediate Factors

As an example, sleep loss directly decreases operationally relevant cognitive capacities. Therefore, knowing an individual's sleep history confers some ability to estimate cognitive capacity. Because technology is currently available for measuring and recording sleep information in the field unobtrusively by having individuals wear a device on their wrist, it is currently possible to predict cognitive readiness.

The Sleep Watch Actigraph component of the WPSM is a wrist-worn, wear-and-forget, stand-alone, digital signal-processing device that measures and records arm movement data. From that data it determines one's history of being awake and being asleep, and can predict performance, information that can be either stored or transmitted. The next version of the device will have the full functionality of a sports watch and will constitute a true wristwatch replacement.

Metrics from which Operational Performance Capability Can Be Inferred

An example of inferring operational performance capability from fieldable metrics is provided by the application of a simple vigilance task for assessing current cognitive readiness in the field. The Psychomotor Vigilance Task (PVT) is a simple, five- or ten-minute reaction-time task developed by David Dinges and John Powell.[21] A reaction-time test in its most general form measures the time it takes for a person to respond to the presentation of new information, or more simply, the time it takes to detect and respond to a change in the environment. Because the PVT has demonstrated sensitivity to even slight restrictions in daily sleep amounts well in advance of errors and accidents,[22] it has been adapted for the field via implementation on a personal data assistant (PDA). The actual test involves holding the PDA with a right or left thumb poised over the appropriate right or left button on the PDA, and when a bull's-eye target appears, pressing the button. The score is the time it takes (latency) to press the button after the bull's-eye appears. Using this test, researchers have shown that one's speed of responding on the PVT correlates with vigilance in shooting on a firing range and vigilance in detecting enemy movement in a MOUT (Military Operations on Urbanized Terrain) field training exercise.[23]

But can one generalize from performance on the PVT to performance in network-centric operations? While this is an empirical question, the strategic and tactical analysis of combat operations put forward by Colonel John Boyd suggests that the answer is yes. Colonel Boyd developed the notion of the "observe, orient, decide, act" cycle or "OODA Loop."[24] In Boyd's conceptualization, "observe," "decide," and "act" are self-explanatory. By "orient," Boyd meant analysis and synthesis based on new information, previous experience, cultural tradition, and genetic heritage, to shape "the way we interact with the environment—hence orientation shapes the way we observe, the way we decide, the way we act."[25] Orienting is the central and most complex element of Boyd's Loop. It represents the complex cognition largely localized to the prefrontal cortex, as discussed above.

Colonel Boyd viewed time (and its reciprocal, speed) as the critical element of decision making at all levels of operational command and control. Operational success, in Colonel Boyd's view, depends on being inside the opponent's decision cycle—that is, completing the OODA Loop faster than the enemy. In this context, PVT (a measure of reaction speed) seems an appropriate, albeit basic, match to the elegant simplicity of Boyd's conception of the basis for operational success at all levels of command and control. Similarly, Clausewitz wrote of friction in operations, with friction slowing the tempo of operations and leading to operational failure.[26] The simple reaction time measured by the PVT may be a measure of the human-in-the-loop's contribution to Clausewitzian friction.

Synthesis of Solutions—Predicting Cognitive Readiness

The ideal solution would be synthesis of the measurement of sleep history using the actigraph and performance metrics using either the PVT or embedded-in-the-operation measures to create a mathematical model individualized to the soldier that predicts cognitive readiness on the basis of the soldier's sleep history. Such a model, the Fatigue Intervention and Recovery Model (FIRM), is under development. Recent hardware advances make it possible to implement the FIRM on the Sleep Watch, which will enable the soldier to access real-time quantitative estimates of individual performance capacity (cognitive readiness) from the on-wrist Sleep Watch display. These estimates will also be transmitted to commanders through the Future Force Warrior network, providing commanders with individual and aggregated-to-group performance estimates for purposes of mission planning.

Planned optimizations include automatic integration of PVT output to individualize FIRM predictions for more accurate, real-time individual performance capability predictions. The Sleep Watch with FIRM will be an intelligent sensor which—when integrated into the Warfighter Physiological Status Monitor, Objective Force Warrior, Future Force Warrior, and other soldier systems—will provide the remote monitoring capabilities needed to predict those aspects of soldier performance capacity that are critical in a networked force, and will do so at a low cost in terms of power, weight, volume, and computational capacity. Sleep will become another consumable, like fuel, and commanders will be able to manage operations to provide for timely resupply.

Work Needed

Future work will link PVT metrics to cognitive capabilities underlying the warfighter's ability to rapidly recognize and capitalize upon emergent battlefield opportunities in the network-centric environment. Consider the following scenario: An M1 tank is engaged in a battle. The commander is scanning for possible targets; finding one, he confirms its identity as friend or foe. Once he identifies the target as foe, he passes the target to his gunner. This process involves a positive hand-off in which both commander and gunner confirm to their mutual satisfaction that they are looking at the same thing. The gunner then ranges the target, decides the round, and communicates this to the loader. The loader loads the round. The gunner fires the gun.

This entire process takes time: less time when an otherwise well-trained and experienced crew is rested, and more time when the crew is fatigued. The process itself can be broken down into a series of latencies—e.g., latency of the commander to acquire the target, latency to pass to the gunner, etc. The sum of these temporal latencies (literally the time taken for each task) equals the total time required to execute the task. If, for any given target, the crew of the M1 is able to complete its series of tasks in less time than it takes for the enemy to do the same, the outcome will be favorable; the tank crew will be operating inside the opponent's decision loop and will destroy the opponent.

It should be possible in the simulation environment to correlate PVT performance with the latencies to accomplish these real-world tasks— and by predicting and summing these latencies, predict actual operational performance from the PVT. Further, it may be possible to measure these latencies directly in operations, and to use them as input to a performance prediction model.

Summary and Conclusions

Network-centric warfare is the basis of doctrine and operations for the US Army, Navy, and Air Force. Fundamental to network-centric warfare is the availability of accurate, detailed, real-time information at all levels of command and control. This information provides the basis for self-synchronization, in which coordination proceeds without overt communication as the natural consequence of having information in common and having common mental models of the current state and the desired end-state. Such self-synchronization shifts the balance between bottom-up organization and top-down control in favor of bottom-up organization.

Network-centric operations and the associated self-synchronization put a premium on the performance of individual soldiers and small teams at all levels of command and control. A critical component of such performance is the ability to integrate information, anticipate, and plan. These executive mental functions depend on the prefrontal cortex of the brain for successful execution.

Various physiological stressors degrade cognitive performance. These include carrying excessive loads, dehydration, hypothermia, sleep loss (which degrades prefrontal cortex function directly), and nutritional or caloric deficiencies. Soldiers in the network-centric force will have sensors and software constituting a warfighter physiological status monitor (WPSM) incorporated into the individual soldier computer, linking them through the network-centric warfare network. These will provide information on their biomedical status with respect to these performance-degrading stressors. This information will be used by commanders to manage biomedical resupply (water, food, sleep, etc.) to sustain performance. Embedded and other measures of cognitive performance will be included in the suite of sensors and software. With these systems in place, commanders will have the tools at hand to sustain individual and unit performance in the networked force.

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Supporting Data:

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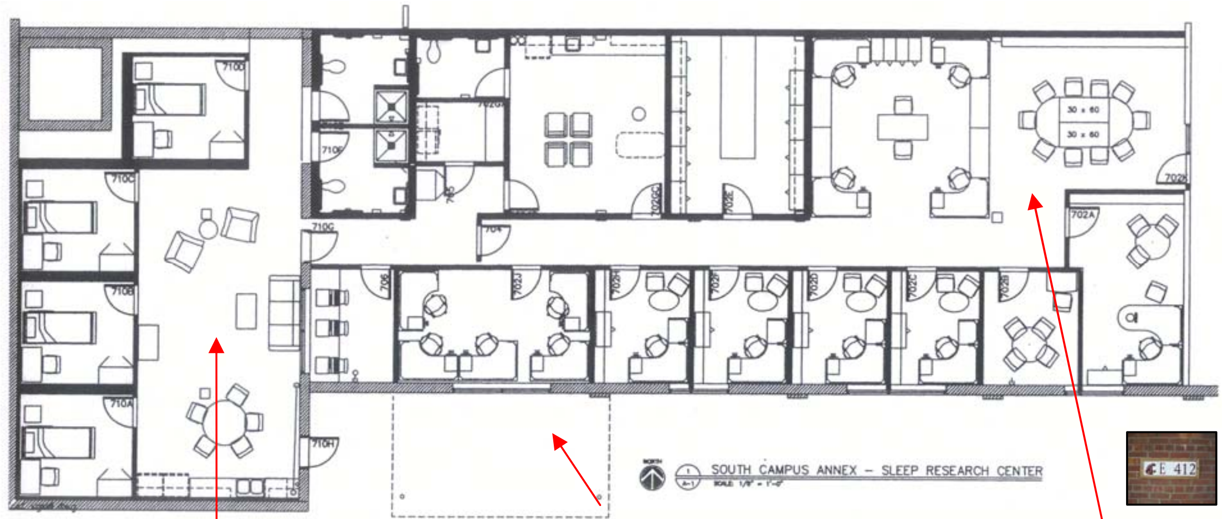

SPRC Sleep Suite

SPRC Exterior

SPRC Office Bay Space