# MEASURING THE IMPACT OF ADVANCED TECHNOLOGY ON MANNING COMBAT INFORMATION CENTERS

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## ABSTRACT

In anticipation of shrinking budgets, the Navy has begun to examine technologies that will support a reduction in the manning requirements, and hence increase the affordability, of 21$^{st}$ century surface combatants. Because more work per warfighter is not viable, reduced manning implies an increased use of technologies that offset the increased workload that would otherwise be placed on future warfighters. Advanced human-computer interfaces and software-based intelligent agents have the potential to alleviate the workload associated with the use of current systems. If these advanced technologies are designed and applied correctly, future systems will allow cognitive resources to be focused on the task of accomplishing the mission rather than on the tasks of interacting with systems and synthesizing data.

However, with the introduction of these new technologies, a basic question arises as to whether the new systems actually support the decisions and task strategies necessary for mission success. It must not be assumed that a new system will support a reduced combat team simply because it uses advanced technologies. To address the question of systems effectiveness, this paper will describe a framework for evaluating the effectiveness of new systems, an experimental paradigm for collecting data, and the types of performance measurement that are needed to assess the impact of thse new technologies on human performance in a combat information center. Evaluating the impact of advanced technologies on system effectiveness and manning requirements is difficult, but critically important, and this paper will present a theoretically-based approach to this problem.

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## INTRODUCTION

Reducing crew size by 23 combat systems personnel can save an estimated 1.3 billion dollars in direct costs during the acquisition and operation of 32 DD-21 class ships over a 35-year lifecycle. If indirect costs (e.g., training and support of operating force personnel) are included, the savings are almost doubled (cf. Naval Center for Cost Analysis, 1998). Estimates like this make it easy to see why the Navy is interested in manning reductions as a solution to budgetary constraints.

The notion of reducing the size of an already overworked crew, however, is untenable if it is approached as a downsizing. The inadequacy of a simple downsizing approach is further underscored when it is noted that the Navy's mission is actually increasing in complexity. Tomorrow's battle groups will seldom be stationed in open waters to support U.S. interests. Instead, naval assets will tend to be stationed in coastal regions, 50-75 miles offshore. As littoral warfare becomes the norm, the relative safety of open-water operations will be lost. In its place, tomorrow's surface combatants will find themselves in time-compressed battle-spaces that require rapid responses to the additional threats present in littoral waters (e.g., mines, land-based aircraft, and small watercraft). They will also be expected to use an increasingly sophisticated cache of sensors and soft- and hard-kill weapons to conduct land attacks while simultaneously controlling air space and coastal seas.

The push to reduce manning and dominate littoral waters will obviously impact the design of 21st century surface combatants (e.g., DD-21). Warfighters can no longer be expected to adapt to piece-meal systems developed through stove-piped programs because of the simple fact that the Navy can no longer afford it.

## HUMAN-CENTERED DESIGN

A fundamental assumption behind the Science and Technology Manning Affordability Initiative is that crew size on today's ships is, to a large extent, a product of stove-piped acquisition – a problem created, in part, by a technology-centered design focus. As is often the case, new weapons, sensors, and other technological advances are developed in isolation and then integrated with existing systems late in the design process, or simply deployed as standalone systems. In either case, the warfighter's information and control requirements are usually considered only in the context of operating the new system. Technology-centered design such as this seldom considers the warfighter's requirements in the context of their total mission – missions that may require the coordinated use of families of sensors, weapons, and other systems to achieve mission objectives. As a consequence, late integration and standalone deployment tend to produce new systems with idiosyncratic displays, controls, and procedures. This creates additional training requirements and additional workload for the warfighters. And, in the extreme, if the added workload is too great, new billets must be created to operate the new systems.

In contrast to the design practices behind currently deployed ships, the Manning Affordability Initiative further assumes that the challenges posed by reduced manning requirements and increased mission complexity can be met by adopting a design approach that is human-centered. In this view, technology must be fit to the human as opposed to forcing the human to adapt to the shortcomings of technology. Warfighters must be involved throughout the design process to ensure that new systems meet their needs. It is believed that increased involvement will lead to the development of new systems that better support the decisions necessary for mission success --

systems that help warfighters understand and control their situation by providing them with the external representational support (i.e., cognitive artifacts) they need.

The principles of human-centered design are relatively simple, though difficult to implement. Firstly, a system is viewed as including both human and machine. Secondly, machines are built to provide humans with the information and controls needed to accomplish their task. Thirdly, and importantly, extra care is taken to ensure that machines are as easy for humans to use as is possible. And finally, if the task is so complex that it requires a team of humans to accomplish it, team structure and processes must be organized for optimal information exchange and coordination / command.

In line with human-centered design principles, the system to be optimized, as we acquire surface combatants of the 21$^{st}$ century, includes the ship and crew, and all relevant interactions. Generically, the interactions include human-human, human-machine, and machine-machine interactions. More specifically, the 21$^{st}$ century surface combatant system will include external communications (e.g., ship-to-ship and ship-to-shore interactions), ship-to-crew interactions (i.e., how the ship provides information from sensors and other equipment to the crew), crew-to-ship interactions (i.e., how the crew controls and operates the ship, including sensors and weapons), and crew-to-crew interactions (essentially, the organization).

For the Manning Affordability Initiative, the human-centered design problem has been bounded by considering the system to be that part of the Combat Information Center (CIC) and the crew required to conduct Air Defense Warfare (ADW). Furthermore, project success has been defined as a demonstration showing that crews half the size of those required to conduct ADW in a state-of-the-art Aegis CIC can perform successfully when a new CIC designed according to human-centered principles is used.

The new CIC will be designed to provide the information and controls warfighters need to accomplish their mission more efficiently. It will be designed primarily to reduce the demands associated with the various aspects of ADW, thus requiring fewer warfighters for mission success. This primarily requires reducing the demands associated with operating ADW

equipment, and those associated with communication and coordination among team members.

Importantly, our approach is not an evolutionary one in which the technology-centered shortcomings of the Aegis system are fixed. Instead, our approach is a revolutionary one in which a human-centered system is designed from the ground up. It starts with warfighters and builds a CIC around them. More specifically, it starts with the warfighter's mission and builds a CIC around warfighters accomplishing that mission – the mission as conceived by warfighters, not as conceived by the developers of the system.

## HUMAN-CENTERED TECHNOLOGIES

Advances in computing and cognitive engineering have yielded two types of human-centered technologies that may allow significant manning reductions without adversely impacting operational performance. One technology consists of executable, computational models of humans performing tasks and interacting with the equipment used to accomplish their tasks. The other consists of human-centered applications of advanced Human-Computer Interface (HCI) technology.

### Human Performance Models

A common, knee-jerk approach to meeting reduced manning requirements is to increase automation. Few would argue with the basic horse sense behind using computers to perform mundane tasks, thereby freeing up humans for more complex tasks. The basic goal is to shift workload from humans to machines. However, automation cannot be conceived of as a one-for-one substitute for humans.

Automation cannot be used as a simple replacement for humans because of the simple fact that the technology to build artificially intelligent machines that perform at a par with humans does not exist (cf. Sarter, Woods, & Billings, 1997). The basic problem is that automation is best suited to routine tasks, exactly the kinds of tasks that place little burden on human information processing resources. This means that only pieces of a more complex task can be automated, leaving human operators to take care of the rest of the task.

The effect of this type of automation, if done improperly, is a system that produces (very) low workload during routine phases, but potentially (very) high workload when things get tough. Furthermore, in a partially automated system, humans must monitor the automation to make sure it is working right, and if something does go wrong, the human is put in the position of diagnosing the problem. Both of these activities (monitoring and diagnosis) may add workload, and can interfere with accomplishing mission objectives. Thus, instead of simply removing workload, automation can actually increase it. It also has the potential to exacerbate times of low or high workload by pushing it to one extreme or the other.

Automation changes the human's job to the degree that his or her performance depends on the output from the automation. For our purposes, automation changes the warfighter's task to the degree that a malfunction in the automation would impact his or her situation awareness. Automation, therefore, is a technology that can range from being a very useful mechanism for controlling workload to one that can produce mission failure. It will be useful only to the degree that it meets the warfighter's information and control requirements on the way to mission success.

To avoid clumsy automation, the current project is exploring the development of software-based, Human Performance Models (HPMs) that can be deployed as intelligent agents. HPMs provide automation that is more human-centered in that they are designed to operate in a manner analogous to warfighters. The development of HPMs requires detailed input from warfighters because HPMs are basically computer representations of how experts understand and execute specific tasks. By representing and executing mission-related tasks like warfighters, HPMs should more closely match the mental models warfighters have of their tasks. As a consequence, they should tend to operate in a more intuitive fashion.

Among the benefits of this approach is the potential HPMs have for reducing workload associated monitoring and diagnosis, besides that associated with offloading workload from humans. Because they are organized in a manner similar to warfighter knowledge,

- HPMs naturally lend themselves to human interaction.

For example, they can provide situation reports to facilitate monitoring activities. Similarly, they could respond to warfighter queries with explanation facilities that represent the situation like their human counterparts, thereby facilitating trouble-shooting activities, or providing decision support by presenting logical, context-specific alternatives.

In addition to being deployed as intelligent agents in operational systems,

- HPMs of warfighters can be used by systems engineers during design.

That is, executable HPMs of warfighters can be used to support a human-centered, simulation-based design process. With simulations of warfighters performing mission-related tasks, system engineers gain a capability for exploring the impact of various design options using virtual prototypes, thus avoiding the cost of actually building one or more prototypes and conducting human-in-loop experimentation.

The HPMs discussed thus far model individual warfighters. The basic goal of these individual-level HPMs is to manage workload by offloading aspects of the warfighter's task to intelligent agents that are designed in a fashion that also minimizes the demands associated with monitoring and diagnosing their behavior. These warfighter-level HPMs are but one of at least three types of HPMs that are being explored as human-centered design tools for simulation-based design.

- HPMs can be used to design systems that optimally distribute workload in at least three ways.

As described above, individual-level HPMs can be used to address the issue of distributing tasks between human and machine. They can then be deployed as intelligent agents. In the bigger picture, workload can be distributed among humans in a team, in addition to being distributed between human and machine. This requires a different type of HPM that represents human performance at a team level.

Given that the majority of tasks in today's Navy are complex enough to mandate teams of warfighters, it seems likely that HPMs of

warfighter teams will be needed to design systems that optimally distribute workload among the warfighters in a team, and between the team and any relevant intelligent agents. In contrast to individual-level HPMs, team-level HPMs do not include information about how an individual's tasks are performed (i.e., task-work). Instead, team-level HPMs focus on the communication and coordination requirements specifically associated with teamwork (MacMillan, Paley, Serfaty & Levchuk, 1999). As a result, team-level HPMs tend to be designed at a coarser level of granularity than their individual-level counterparts.

Given their granularity, team-level HPMs can be made available to systems engineers earlier in the design process than the more detailed individual-level HPMs. With simulations of teams of warfighters performing mission-related tasks, system engineers gain a human-centered design tool that assists them in the optimization of team structures and processes. The tool can also provide information about areas of high pay-off for individual-level modeling efforts (i.e., software-based intelligent agents).

The team optimization design tool currently being explored uses a three-part allocation process to minimize some of the workload associated with teamwork. Generally, the process first requires input from warfighters in order to decompose a given mission into tasks. These tasks are then divided into functional groups based on the resources required to accomplish them (e.g., sensors and weapons). Following this, the functional task groupings are assigned to members of a team, which is then overlaid with command and communication processes. The basic goal is to provide individuals with direct access to the resources required to accomplish their given tasks, thereby minimizing communication requirements within the team and hence reducing team-associated workload.

For the purposes of the current project, the team optimization design tool is being used to minimize the communication and coordination requirements given a team half the size of a comparable Aegis team. The optimized team structure that is output by this process is then used to develop a simulation based on task-network modeling technology (see Laughery & Corker, 1997). Thus, a team optimization design tool is being used in tandem with a task-

network modeling tool to create team-level HPMs that simulate optimized teams as they fight the ship or perform other missions – which in our case is ADW.

Among the advantages of using task-network models in the implementation of team-level HPMs is that they provide indices of the workload imposed on individual warfighters, and the team as a whole, over the time course of a mission. These metrics can then be used as feedback for the team optimization design process so that if workload does not appear to be adequately balanced among team members, the team can be redesigned to correct deficiencies in an iterative manner.

Just as task-network models can be constructed at the level of granularity required for team-level HPMs, they can also be constructed at a much finer grain of detail to provide simulations of humans interacting with specific components of the HCI. This is the third type of HPM being explored by this project.

Thus far, HPMs of warfighters and teams of warfighters have been discussed as human-centered design tools that can be used by systems engineers to examine the impact of design options on human performance. These HPMs are being designed to manage workload in a significantly reduced crew by dividing mission-related tasks between humans and machines, and among warfighters in a team, respectively.

A final area in which HPMs are being used to examine the demands associated with ADW concerns the workload required to interact with the equipment / computers required to conduct ADW. These micro-HPMs are being designed at a level of analysis appropriate for simulating a human's interaction with computer input and output devices (e.g., trackballs, keyboards, pull-down menus, etc.). These micro-level HPMs differ from the HPMs discussed above in that they do not simulate warfighters performing mission-related tasks. Instead, they simulate warfighters performing input/output tasks associated solely with the equipment they use. These micro-HPMs provide the systems engineer with the third of a triad of human-centered design tools based on HPM technology, and are meant to facilitate design decisions that whittle away the workload placed

on warfighters by the workstations they must operate.

## Multi-Modal Watch Station

The second general type of human-centered technology being explored as a means for optimizing manning requirements involves the application and development of advanced hardware, software, and interface design technologies. By developing HCI principles and guidelines for future CIC watchstations, Multi-Modal WatchStation (MMWS) technology will provide an integrated foundation for managing warfighter workload through human-centered, mission-related design.

MMWS technology will deliver to warfighters the superior automation and decision support that arises from HPM technology. It will use various sensory modalities, visualization and information grouping techniques, intelligent agents, and workload management tools to augment, fuse and deliver information in an advanced HCI paradigm.

Among the planned features of the MMWS are:

- a single watchstation that provides a consistent interface for mission planning, execution, monitoring, or engagement using any of a family of sensors and weapons,

- an expanded, multi-modal display space created from a combination of flat-panel and non-immersive, head-mounted visual displays, and three-dimensional audio displays,

- multi-modal controls that allow touch, speech, and natural language input, in addition to standard input devices,

- information management technologies that provide mechanisms for temporarily storing and retrieving verbal communications, and translating information from one modality to another (e.g., verbal to written communications), and

- task and workload management tools that assist warfighters by providing them with intelligent task aiding, attention alerting mechanisms, and workload planning, management, and allocation assistance.

The workload-saving principles underlying MMWS technology stem, in part, from multiple resource theories of attention (e.g., Wickens, 1980). In line with these theories, humans have different attentional resources associated with each of the sensory modalities. As a consequence, humans can process more information if it is distributed across sensory modalities than when it is all presented in one modality[1]. The MMWS thus manages warfighter workload by using multi-modal input to distribute information throughout his or her cognitive system.

Workload is further distributed throughout the warfighter's cognitive system by providing multi-modal control options. This provides warfighters with response options so they can naturally manage their workload using different attentional resources for the execution of actions.

The extended display space is also intended to reduce workload associated with manipulating the HCI. The enlarged visual display allows warfighters to display the various tasks he or she is executing side-by-side. This alleviates the need to open and close hundreds of windows over the time course of a watch.

The MMWS further assists warfighters in managing workload through attentional alerting mechanisms and task management strategies, plus support for dynamic task allocation among warfighters in the CIC.

## FRAMEWORK FOR TESTING

Our evaluative framework for examining the value-added by HPM and MMWS technologies can be divided into two dimensions. Organized along one dimension are research efforts associated with three levels of analysis. As analysis shifts from the highest to the lowest level, the focus of research shifts from the human-machine system to the human-computer interface, and finally to specific system components (see Table 1 below).

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[1] Gains in information throughput are, of course, limited by a variety of factors including the human's total attentional capacity, and the coherence of the items being held in short-term memory.

Table 1. Levels of Analysis in Manning Affordability Initiative Research Efforts.

| Level of Analysis | Research Effort |
|---|---|
| System | Effectiveness Evaluations |
| Interface | Usability Studies |
| Component | Verification & Validation Activities |

Table 2. Research Approaches to each Level of Analysis.

| | Approach | |
|---|---|---|
| Level of Analysis | Empirical | Analytical |
| System | | |
| Interface | | |
| Component | | |

Examinations at the system level evaluate the effectiveness of the human-machine system. Effort at this level examines end-user performance in the context of real-world tasks. This would include, for example, experiments that examine warfighter performance in the context of operational tasks.

At an intermediate level of analysis are research efforts concerned with the HCI. Effort at this level examines the usability of specific interface components. Among the various efforts included at this level are, for example, usability studies that compare the efficiency of stylus versus touch-screen input, or user preferences. This level of analysis does not necessarily require the involvement of the targeted user-group (e.g., warfighters). Thus, comparing input devices, for example, does not necessarily require warfighters, whereas assessments of user preference probably should.

Specific system components are examined at the lowest level of analysis. Verification and Validation (V&V) activities are among the efforts encompassed at this level. Verifying whether a particular component was built according to specifications, or examining whether HPMs accurately portray human performance are examples of component-level activity.

Along the second dimension of the framework are two approaches for the various research efforts. Accordingly, each level of analysis can be approached as an empirical or analytic research effort (see Table 2 below). Empirical efforts require that performance data of some sort be collected for comparison to standard, baseline, or other conditions. Analytical efforts involve collecting data about what is essentially expert opinion (see Pejtersen & Rasmussen, 1997, for a more thorough description).

Recall that a central goal of the Science and Technology Manning Affordability Initiative is to demonstrate to the fleet how human-centered technologies can be used to cut manning requirements in an Aegis CIC in half. To meet this goal, we will execute an Aegis-MMWS comparison as a quasi-experiment that addresses the basic research question of whether we can demonstrate equal or better performance in CIC with half the warfighters. HPM and MMWS technologies will be used to create two versions of an improved CIC that differ from an Aegis CIC in terms of team size, job design, HCI, task management tools, and automation. The two versions of the new, improved MMWS CIC to be created -- basic and advanced -- will differ in the degree to which they incorporate HPM and MMWS technologies.

The Aegis-MMWS comparison is being approached as an empirical, system effectiveness evaluation. As such, our observations are designed to determine whether the new MMWS combat systems support mission performance, as well as, or better than the Aegis system. The evaluation will be empirical in that data will be collected from warfighters performing ADW using one of the three combat systems.

Aspects of performance to be measured were selected based on the combat system improvements expected from HPM and MMWS technologies. Although performance measure development began by examining improvements expected from system components, these component-level metrics were rolled up into more abstract constructs to create measures appropriate for examining performance of the human-machine system. This process was straightforward given our human-centered approach.

The hypothesized improvements roll up into the constructs of task-work, teamwork, workload, and situation awareness. As for task-work, MMWS technology, with its attention management tools (e.g., alerts and deadlines suggested by the task manager), is expected to impact performance by decreasing response times, and increasing decision windows and accuracy. Changes in teamwork due to team redesign (via HPMs of warfighter teams) and shared information spaces (via MMWS display technology) are expected to be manifested in enhanced communications and coordination. Team redesign and the multimodal HCI of the MMWS are also expected to create more balanced workloads among and within the warfighters in CIC. And finally, the improvements in task-work, teamwork, and workload management are expected to result in an enhanced situation awareness.

Our empirical paradigm, at this level of analysis, relies on (1) comparisons to a current baseline (i.e., the Aegis CIC), and (2) event-based measurement. The comparison to a current standard is necessary for demonstrating value-added. Event-based measurement simplifies data collection and analysis activities without compromising data quality. That is, the event-based methodology, developed by researchers examining team decision-making processes in tactical environments, focuses measurement activities on specific critical events within a tactical scenario. Selective measurement of this small set of critical events has been shown to provide results consistent with those based on measurements from all scenario events (Johnston, Cannon-Bowers & Smith-Jentsch, 1995).

A large amount of effort has gone into preparing for the Aegis-MMWS comparison, and much effort is yet to be expended in the collection and analysis of the system effectiveness data. To mitigate threats to success in a research effort of this magnitude, other types of evaluations have been, and are being, conducted as we prepare for the full-up, empirical, Aegis-MMWS system effectiveness comparison.

At the HCI level, for example, warfighters have been involved throughout the design process, and have thus provided much input and feedback on the various pieces of the MMWS interface. This type of involvement produces data for analytical HCI evaluations. Among

these analytical efforts are included cognitive walkthroughs and other heuristic usability methods performed by warfighters or HCI specialists. Where necessary, empirical studies comparing various pieces of the MMWS interface have been conducted to elaborate on, or cross-check, warfighter / HCI specialist opinion, preference, and judgment of utility. Empirical usability studies have also been used to compare the efficiency of two or more input devices.

At the system component level, warfighters have again been involved, especially for HPM development. This has provided opportunities for analytic evaluations of the validity of various HPMs. As an example, the output of our HPMs of warfighter teams has been iteratively critiqued by warfighters as to whether the redesigned teams from the model make sense. The HPMs are then adjusted based on warfighter feedback and the redesign process continues.

The importance of validating HPMs cannot be overemphasized. Once an HPM has been validated, it can be used time and time again to perform empirical evaluations of design options by simulating human performance, thus avoiding the cost of human-in-the-loop experimentation. Because of the potential gains in cost-effectiveness and design quality, the Manning Affordability Initiative has gone to great lengths to gather empirical data, in addition to analytical data, for the purpose of validating HPMs. Indeed, human performance data from each level of analysis in our evaluation framework has been, and will be, fed down to the systems component level to test the validity of HPMs.

## SUMMARY

Future manning reductions in the Navy require reducing the workload associated with performing tasks of today, so that each warfighter can perform a greater proportion of their mission. To meet this challenge, the current project has been developing and systematically testing advanced technologies to facilitate the design of systems centered on warfighters' requirements. HPM technology holds promise as a means for optimizing the distribution of workload among warfighters and between warfighters and the machines they must operate. It also holds great promise in reducing the costs associated with testing the

value-added by new systems by providing a means for simulation-based evaluation, thus avoiding much of the cost associated with empirical approaches to systems evaluation, namely human-in-loop experimentation. MMWS technology holds promise as an integrated, advanced HCI that distributes workload throughout a warfighter's cognitive system, and delivers the advanced automation made possible by HPMs.

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