Navy HSI Symposium Submission

Cynthia O. Dominguez, Cognitive Solutions Division of Applied Research Associates
14 Blackford Drive, Exeter, NH 03833; 603-778-7765; cdominguez@ara.com

Christopher Nemeth, Cognitive Solutions Division of Applied Research Associates
1750 Commerce Center Blvd N., Fairborn, OH 45324-6333; 937-825-0707;
cnemeth@ara.com

Robert Strouse, Cognitive Solutions Division of Applied Research Associates
1750 Commerce Center Blvd N., Fairborn, OH 45324-6333, 937-873-8166
rstrouse@ara.com

Matthew O'Connor, Naval Surface Warfare Center, Dam Neck, VA; 757-286-9378;
matthew.oconnor@navy.mil

Beyond Behavior: Making Cognitive Systems Engineering Part of Navy Acquisition

Associated Symposium Topic: 3rd Leg of the Stool: Integrating the Human into the Total System

ABSTRACT

Although much of the work that Navy operators undertake is cognitive in nature, involving tasks such as sensemaking, planning, decision making, and attention management, most of the human factors work done in Navy systems acquisition is task-based, or behavioral in nature. Neither the JCIDS process (per DAU Guidebook) nor the Navy Instruction 5000.2 incorporates processes for cognitive engineering, although DoDI 5000.2 specifically calls for cognitive engineering in its human systems integration chapter. Despite Navy Tactical Decision Making under Stress (TADMUS) work in the 1990s, which created much of the impetus and progress in cognitive engineering, it is a challenge to find current evidence of cognitive engineering work ongoing in Navy acquisition. This paper describes a year and a half effort on behalf of OPNAV N857 to show how cognitive systems engineering (CSE) can be used for requirements development and redesign of command and control displays. The effort showed how to merge CSE into systems acquisition phases, and developed requirements based on operational needs of two of the eleven commands in Naval Expeditionary Combat Command, Maritime Expeditionary Security Force and Riverine Force. The project also created a C2 display to provide deployed expeditionary forces with a common operating picture and developed a 60-page guidebook to document the process for system development managers and engineers. We will describe the CSE process in this project, from preparation and data collection/analysis through requirements development, display design, and validation. The addition of cognitive systems engineering to Navy human systems integration promises to improve greatly how technology supports Navy officer and enlisted crewmember cognitive work for ACAT IV and smaller system development efforts.

INTRODUCTION

Although much of the work that Navy operators undertake is cognitive in nature, involving tasks such as sensemaking, planning, decision making, and attention management, most of the human factors work done in Navy systems acquisition is task-based, or behavioral in nature. Neither the US military's joint capability integration and development system (JCIDS) process nor the Navy Instruction 5000.2 incorporates processes for cognitive engineering, although DoDI 5000.2 specifically calls for cognitive engineering in its human systems integration chapter. After the shoot down of an Iranian Airbus by the USS Vincennes and subsequent congressional hearings aimed at understanding the cause of this tragedy, the US Navy put significant resources into the Tactical Decision Making under Stress (TADMUS) program in the 1990s. The TADMUS program created funding, impetus, and progress in cognitive engineering towards design of displays and training (cf. Cannon-Bowers & Salas, 1998). Despite this and early work on the original DDX program (Bisantz et al., 2003), at present day it is a challenge to find evidence of cognitive engineering work being integrated into systems engineering in Navy acquisition.

In 2009, the US Navy (OPNAV N857) was interested in improving the command and control displays that support its' deployed troops protecting harbors and rivers overseas, and wanted to explicitly ensure that cognitive requirements of users were fully supported by the new displays. They commissioned a study to undertake, in parallel, the cognitive systems engineering effort to research and identify design requirements for a new command and control display, along with the documentation and integration effort to capture how CSE is done and integrated into Navy acquisition for small scale (ACAT IV and below) development. This paper describes the approach taken, the methods for data collection, analysis, and requirements development used, and the products that resulted from that effort, demonstrating how requirements developed through cognitive analysis translate into display design concepts, which directly support the cognitive work of users.

BACKGROUND

The Naval Expeditionary Combat Command (NECC) was established in 2006 to manage, train, and equip forces who conduct maritime security and joint contingency operations in expeditionary environments. The command is comprised of multiple component commands that provide maritime port security, naval construction, littoral and coastal warfare and patrol, Riverine warfare, explosive ordnance disposal (EOD), and expeditionary diving and combat salvage. NECC's component commands are designed to be scalable, and are deployed to support joint forces and coalition partners as needed across the globe. The expeditionary nature of the NECC, as well as the variety of possible force configurations and missions they face, means that NECC command and control (C2) requirements are multifaceted and complex. Adding to the complexity, the force structure and concepts of operations have continued to evolve as the command defines its capabilities and determines how to best support maritime security operations around the world. Given the unique C2 challenges facing NECC, this new and evolving force requires systems that support differing mission requirements and complex cognitive activity involved in C2 of its component commands across multiple theatres of operation.

To demonstrate the value of CSE in this context, we employed Cognitive Task Analysis (CTA) methods to understand the cognitive work and information needs of NECC operators up and down the C2 hierarchy. We focused on two component commands with the highest operations tempo and most complex tactical coordination requirements: Marine Expeditionary Security Forces (MESF) and Riverine Forces. MESF provide port and harbor defense, protecting US high-value assets in port areas; Riverine Forces secure inland waterways and perform peacekeeping missions.
Numerous papers have demonstrated the ability of CSE methods such as CTA and cognitive

work analysis (CWA) to develop design-relevant artifacts, models, and design seeds (cf. Bisantz et al., 2003; C. O. Dominguez, Long, Miller, & Wiggins, 2006; Hutton, Miller, & Thordsen, 2003). The Navy expressed the need for a guidebook which would explain the process, outcome, and payoff resulting from incorporating cognitive task analysis into military system development efforts. In the next section, we describe the project for which we undertook to execute and capture the CTA process in order to develop such a guidebook, and illustrate the display concepts resulting from the requirements development process involved.

METHODS AND RESULTS

The approach we followed to understand cognitive performance in NECC and develop design requirements and solutions followed the stages of decision-centered design (DCD) (Crandall, Klein, & Hoffman, 2006; Hutton et al., 2003). Decision-centered design is one of many CSE methods. Although each method has its own description and process flow, the DCD stages are broad enough so that the reader will recognize the steps that any CSE development effort undertakes. Those stages are:

- Preparation
- Knowledge Elicitation
- Analysis and Representation
- Application Design
- Evaluation

Each one of these stages reveals essential elements and builds on the stage before. A description and representation of the flow of these stages is shown in Figure 1; each stage will be described in detail in subsequent sections.

Stage 1: Preparation/Framing

As our team became familiar with the NECC component commands, documentation, and operating environments and prepared for data

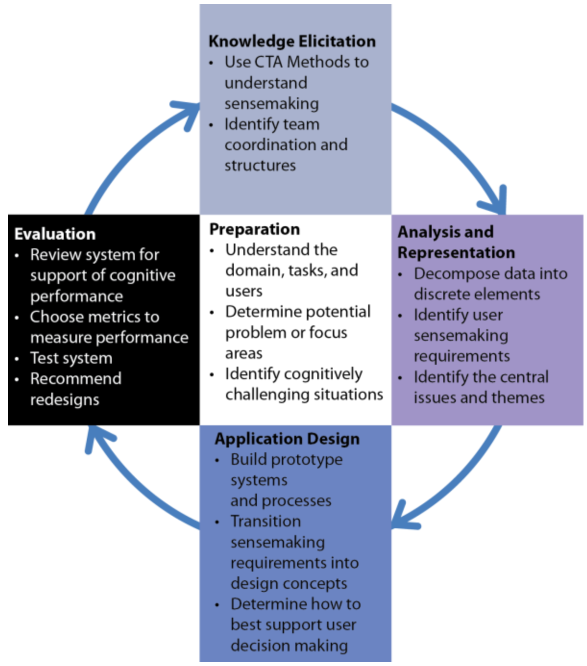

Figure 1. Stages of Decision Centered Design

.

collection, we identified the tasks, goals, and criteria for each stage. Our goals were to understand the work domain, to identify where to focus our limited resources, to select CTA methods, and to identify preferred participants.

We became familiar with the domain through the use of several documents provided and prioritized by our customer. We read, summarized, and discussed a wide range of CONOPS (concept of operations)-type documents for MESF and Riverine forces. NECC contacts provided us with organizational diagrams and subject-matter experts (SMEs) who described how NECC forces operate. Before doing formal data collection, we conducted five telephone interviews with SMEs who were familiar with NECC requirements and operations or who had been deployed with NECC forces. As we began planning for data collection, we had a fledgling understanding of organizations, missions, and tasks undertaken by NECC.

Stage 2: Knowledge Elicitation/Data Collection

Over the course of a four-month period, the four data collection opportunities we had were a visit to an east coast Riverine squadron, visits to both east coast and west coast MESF squadrons, and observation at a west coast exercise, Trident Warrior 2010. We conducted CTA interviews with recently deployed sailors at each of those visits, 14 Riverine and 23 MESF interviews in all. The interviewees had had command and control experience as either patrol leaders, C2 specialists, or watch officers at deployed locations in Iraq, Kuwait, UAE, and Haiti. We used CTA methods to conduct an in-depth collection of data reflecting key decisions, cognitive processes, and cognitively complex tasks; we also identified team structure, coordination tasks and communication patterns. During our first set of interviews with both Riverine and MESF forces, we needed to deepen on our understanding of these commands' principal functions and missions, and on the kinds of challenges they face in general. Therefore, we structured the interview guides we developed and used around three primary segments: 1) questions about functions and missions, 2) questions about the interviewees' roles and experience in NECC, and 3) an abbreviated version of a Critical Decision Method (Klein, Calderwood, & MacGregor, 1989) interview. We shortened the functions and missions segment and put more emphasis on the CDM segment as we gained a stronger understanding of the former in the early interviews.

Stage 3: Analysis and Representation

We followed a systematic, yet iterative, analysis process that enabled refinement of structure and content as new data were collected and incorporated throughout the process. The ability to link the eventual recommendations and application back to the raw data through a series of interim analysis products, its traceability, was critical in the analysis process.

We first pulled **preliminary insights** out of the data set. Following each data collection event, the research team met to discuss key take-aways and initial impressions gleaned during the interview process. These insights served as an initial organizing mechanism for subsequent analysis, including the identification of prominent themes and analysis categories of interest.

The next step was **systematic review and categorization** of interview notes. Through several structured 'passes' through the interview notes, we organized data into a flow which specified the driving mission requirements at the top level. We then identified cognitive demands, such as understanding the operational picture, barriers to effective performance, such as unreliable communications equipment, and finally, a set of resulting information needs, such as the need for an accurate, integrated real-time contact picture that included a number of specific information elements. The analysis resulting in categorization of data in this manner involved several iterations, discussions, and representations. One of several methods used for this analysis was a card sort technique, where we grouped data elements based on similarity in content, and the analysts labeled and described the resulting categories based on consideration of the data comprising them.

Finally, we undertook to **develop requirements** from the organized data**.** Once the data had been organized into a traceable set of cognitive challenges and barriers & gaps, it took the form of data tables, which we called a 'data hub' (see Dominguez et al., 2011, for a detailed description of this analysis process and the resulting cognitive demands, barriers, and gaps). For each cognitive requirement, we created a data hub table clearly representing the following information:

- A description of each cognitive demand or barrier/gap category
- Details about what a given requirement enables operators to do related to mission performance
- Costs or operational impact of the barriers and gaps

- Example quotes and incidents from SMEs' operational experience
- Preliminary requirements (including information needs) for supporting those cognitive demands and overcoming the barriers or gaps.

The data hub contained fifteen tables, elaborating on relationships between demands, gaps, and requirements that result from the data collected. A snapshot of Table A of the data hub is shown in Table 2 below. The names of each data hub table are shown in Table 1.

Cognitive Demands	**Barriers, Gaps, Glitches**
Table A. Understanding the operational picture	Table J. Unreliable communications
Table B. Maintain and repair common ground	Table K. Inadequate tools and equipment
Table C. Information sharing	Table L. Boredom/Cognitive underload
Table D. Collaboration and coordination	Table M. Organizational issues
Table E. Detect and assess potential threats	Table N. Training gaps
Table F. Manage communications	Table O. Information flow issues
Table G. Anticipate and plan	
Table H. Detect and solve problems	
Table I. Maintain vigilance	

Table 1. List of Data Hub Table Content Areas.

Data Hub GUIDANCE - this file contains the following:
1) Cognitive Demands Table; 2) Findings unique to the Riverines for this category ; 3) Notebook space for recording record insights, questions about the table/findings, additional issues, etc. Please feel free to add to it, please note your name and the date with any content you add; 4) Interview excerpts—from our most recent data pull (July 2010) these are segments of MESF interview data that provide illustration of the particular cognitive demand category

CGD TABLE A: Understanding the Operational Picture

This individual-level activity involves **building and maintaining an understanding of the operational situation,** including **status and capability of assets; potential threats; and schedules and movement of other craft**. .....it is a sensemaking activity that involves tracking, filtering, and integrating information from multiple sources, and constantly updating one's understanding.

A-1 Cognitive Demands Inventory

Need to be able to *Understand operational picture* in order to...	**If can't do this then... (costs)**	**Things that get in the way...(glitches/challenges)**	**Requirements - in order to do this they need...**
(from MOC perspective) ➢ Provide info relay between the JOC and the water ➢ Understand implications of information they're receiving ➢ Accurately interpret what the PL reports about the status of boats, ➢ Know what action to take to ensure mission continues ➢ Provide 'oversight' – grasp implications of specific events for the overall mission picture ➢ Step in and drive the situation if/when the PL actions are inconsistent with	➢ Watch officer cannot make timely, effective, appropriate decisions, ➢ WO cannot provide guidance/direction to the PLs re accomplishing the mission. ➢ Watch officer will not know implications of patrol craft status for security plan and ongoing mission ➢ WO are "behind the curve" --Response time is shorter; lose ability to anticipate or react ➢ JOC Watch officer not able to provide CO/XO with	➢ Unreliable radio comms ➢ No sensors ➢ Delayed/distorted information from boats ➢ Vessels not submitting their movements ➢ Delayed (or lack of) communication from host nation Port Authority about schedule and vessels coming in/out of port ➢ Difficulty finding the person who has the info you need	➢ Need reliable radio comms for info-sharing and updating ➢ Need accurate, timely info from other links in the C2 chain ➢ Need information that is real-time (not time-delayed), or capability that allows operators to check recency of info update ➢ Need integration of both perspectives – boat/water perspective and bigger picture (MOC) ➢ Need understanding of capabilities and status of all patrol craft, with respect to current environmental conditions (e.g., sea state). ➢ Need to know what the available human resources are: who has what information and how they can be reached ➢ Need ability to distinguish contacts on radar (many returns are ambiguous) ➢ CO (Sq WO) needs to know what his patrol boats

Table 2. Sample Data Hub Table, Showing Cognitive Demand Table A, "Understanding the Operational Picture."

A major task involved in creating the data hub representation was thinking about what information or support sailors need to be able to address the cognitive challenges and mitigate the barriers and gaps they face in operational settings. Those requirements on the right column of each data hub table needed to undergo a streamlining process, being written in plain language rather than the 'system shall…' requirements language. In addition, across the 15 data hub tables there were many overlapping requirements. One team member culled and cross-checked all of the information requirements from these tables to create a list of streamlined requirements, which went through multiple iterations over time, and eventually formed recommendations to NECC on which requirements should be Key System Attributes (KSAs), language for a Key Performance Parameter, and a detailed set of evaluation criteria for the eventual system.

Stage 4. Application Design/ Concept Ideation

With a set of streamlined requirements, a four-person analysis team who was completely familiar with the data set went through a two-day structured design workshop to transform requirements into design concepts. A team member who is a design professional facilitated the workshop; this team member brought design experience and several ground rules into the process, such as encouraging a proliferation of rough sketches, discouraging perfection in sketches, and keeping any judgments at bay. The ideation sessions began with exercises intended to expand our thinking, and concluded with a set of exercises devised to narrow the design concept space.

Starting with the most specific requirements, influenced heavily by their exposure to the interview data, the design group individually made sketches of how they would satisfy each requirement. This phase of the ideation session generated multiple sketches for each requirement. We began the subsequent narrowing process with many ideas posted on the wall. The design team revisited each set of sketches (still organized by requirements) and discussed as a group the best concepts. Familiarity with the interview data allowed the design team to use mental simulation to evaluate each concept within the context of the data. Elements of individual concepts were combined with each other to create composite designs supporting multiple information requirements. After the ideation sessions, our team's designer/developer continued the aggregation of concepts and began to arrange them as parts of a single, unified product.

Finally, during the refinement process, unified products were presented internally to the research and design team in a backwards check ensuring the requirements from the primary research were addressed. We included discussion of usability issues in this review. We circled through twice before presenting prototypes to SMEs in a cognitive wall walk, discussed next.

As an example, the requirement which was most heavily supported by the data involved providing an operational picture with specific attributes (see Table 3). These requirements were nominated as KSAs due to their mission-essential nature. The source column indicates all

Information Requirements	Source
1. **KSA (MESF):** The system shall provide an operational picture that integrates information from both MOC and boats and provides each C2 node with an understanding of the operational picture that others in the C2 chain see simultaneously. (Referred to as "Operational Picture" in requirements below)	A, B, E, G, H, O

Table 3. Example of an information requirement nominated as Key System Attribute (KSA), which was related to specific details needed in the C2 display's operational picture.

of the Data Hub tables that document and validate this requirement. This KSA, relevant to MESF, requires providing an operational picture that all three nodes in the C2 chain—Squadron, Watch officer, and Patrol boat—can see simultaneously. This requirement was derived from two perspectives: MESF watch officers in the maritime operations center (MOC) who needed to get a clear picture of what patrol boats were seeing on the water, and patrol leaders on the water who needed access to the operational picture on the C2 display shown at the MOC.

Design concepts to support these requirements needed to address each perspective. For the patrol leaders, the design concept was architectural, providing a feed of the C2 display on the patrol boat, which was architecturally feasible but which had not been done previously. For the MOC watch officers, the solution was to provide detailed information on status of each patrol boat on the water (and off), with a clickable camera icon next to each on-water patrol boat which provided live feed from an on-boat camera (see Figure 2).

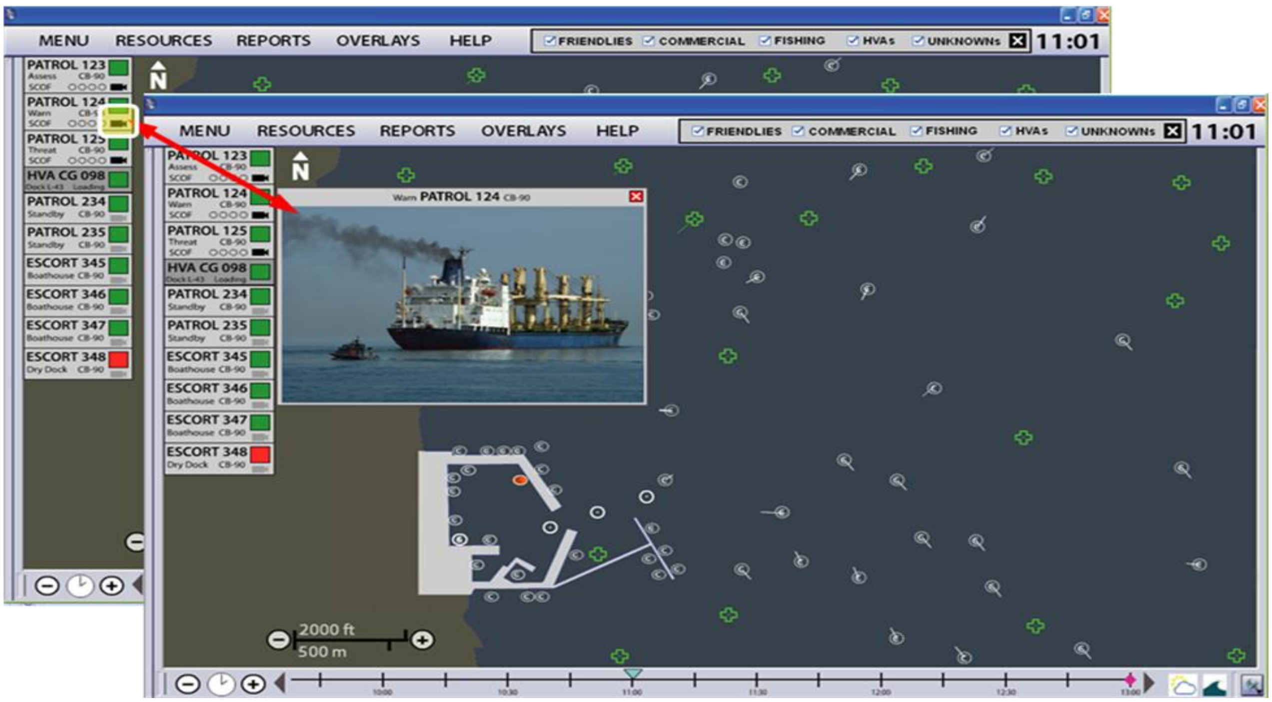

Figure 2. Camera icon in list of Patrol Boat information linked to camera on that patrol boat; reflects requirement for watch officers in the MOC to see the on-water view of patrol boats to aid in decision making.

Stage 5. Evaluation

In addition to validating/improving designs, the evaluation involves validating the requirements generated from the analysis stage. The designs created in Stage 4 were prototyped as paper-based storyboards and set within a realistic scenarios (one each for MESF and Riverines) for SME evaluation in a cognitive wall walk event. NECC sent three MESF and three Riverine SMEs to participate in this event. We held a half-day meeting describing the background and process of this research to the SME participants, and then spent a day walking through the scenarios, eliciting feedback about both the scenarios and the design components. Including both MESF and Riverine forces together in the room enabled us to receive specific feedback about requirements which might be shared across both forces, a key element to our tasking. The wall walk event also allowed the design team to further refine the design requirements that were used to guide the development of a prototype system. The prototype system was then presented to four individual SMEs from the MESRON and RIVRON forces via four WebEx sessions for further validation.

DISCUSSION

This project enabled both application of cognitive systems engineering methods through requirements development and design/evaluation of prototypes as well as documentation of the detailed process involved in applying CSE, specifically within the military acquisition context. The feedback from the evaluation sessions with sailors yielded excellent suggestions for improvement of both requirements and display designs, and in addition provided comments, which validated the usefulness of the approach. Examples of these comments included “This display provides me with everything I need all in one place.” In addition, the Data Hub product was used by Navy programming/budgeting staff involved in the project to advocate for and justify the need for capabilities spelled out in the requirements. Finally, the Guidebook delivered at the end of this project spells out in detail how to link the stages of decision-centered design described here with the stages of the military acquisition process.

CONCLUSIONS

There are costs to using a CSE approach; it requires dedication of subject-matter expert time in order to conduct data collection and evaluation, and requires considerable analysis and documentation effort. However, the approach’s emphasis on the cognitive challenges and barriers inherent in the deployed operating environment results in display designs which are effective in overcoming those challenges. This paper spells out specific steps which enable designers to incorporate cognitive challenges into design. In a companion paper, Dominguez et al. (2011), we include details on reasonable scientific criteria, which can be applied to ensure these CTA processes are undertaken with appropriate rigor. We endorse the use of these approaches more frequently to support display design in US Navy acquisition. When published, the Guidebook product promises to help Navy program managers to incorporate these approaches and to include the cognitive engineers who can execute them in the systems acquisition process.

REFERENCES

Bisantz, A., Roth, E., Brickman, B., Gosbee, L., Hettinger, L., & McKinney, J. (2003). Integrating cognitive analyses in a large-scale system design process. *International Journal of Human-Computer Studies, 58*, 177-206.

Cannon-Bowers, J. A., & Salas, E. (Eds.). (1998). *Making decisions under stress: Implications for individual and team training*. Washington, D.C.: American Psychological Association.

Crandall, B., Klein, G., & Hoffman, R. R. (2006). *Working minds: A practitioner's guide to Cognitive Task Analysis*. Cambridge, MA: The MIT Press.

Dominguez, C., Grome, A., Strouse, R., Crandall, B., Nemeth, C., & O'Connor, M. (2011, June). *Linking cognitive data to design in U.S. Navy command and control*. Paper presented at the Proceedings of the 13th Annual International Symposium. International Council on Systems Engineering. , Denver (Also invited paper in INCOSE Special Session of IEEE Systems Symposium [2011, April] Montreal).

Dominguez, C. O., Long, W. G., Miller, T. E., & Wiggins, S. L. (2006, June 6-8). *Design directions for support of submarine commanding officer decision making*. Paper presented at the Undersea HSI Symposium Mystic, CT.

Hutton, R. J. B., Miller, T. E., & Thordsen, M. L. (2003). Decision centered design: Leveraging CTA in design. In E. Hollnagel (Ed.), *Handbook of cognitive task design* (pp. 383-416). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Klein, G. A., Calderwood, R., & MacGregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on*

Systems, Man, and Cybernetics, 19(3), 462-472.

Acknowledgements

The authors are grateful to the Department of the Navy (OPNAV N-857) for guidance and funding, to NECC for facilitation of this research, and to the NECC Futures Working Group for support and guidance.

Biographies

Cynthia Dominguez, PhD, is a Principal Scientist at Applied Research Associates. She participates in applied research studying how to support human cognitive performance in high-stakes military and civilian settings. She has supported development and use of cognitive performance indicators and other cognitive metrics for assessment of technology.

Christopher Nemeth, PhD, CHFP, is a Principal Scientist and Group Leader for Cognitive Systems Engineering at the Cognitive Solutions Division of Applied Research Associates. Recent research interests include technical work in complex high stakes settings, research methods in individual and distributed cognition, and understanding how information technology erodes or enhances system resilience.

Robert Strouse, M.F.A., is a Designer at Applied Research Associates. Mr. Strouse is currently involved in projects to better understand the decision making processes in command and control environments, including the Naval Expeditionary Combat Command and Submarine Warfare. In addition, he works with other members of ARA to develop prototypes and visualizations that capture and convey the insights gained through cognitive research.