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Design Directions for Support of Submarine Commanding Officer Decision Making

ABSTRACT

The Commanding Officer (CO) on a submarine makes numerous subtle perceptual judgments, assessments of complex situations, and decisions under conditions of time pressure, high stakes, shifting goals, dynamic conditions, and uncertainty. The objective of our project was to deeply understand and clarify the nature of the decisions made by a CO so that we could develop recommendations for a potential large-screen display to directly support CO decision making. To form our recommendations, in addition to reviewing relevant literature, we undertook at-sea observations and interviews, and also conducted interviews with 19 additional COs using cognitive task analysis elicitation methods. Through thematic analysis of the data collected, we identified six major cognitive challenges that COs face. We developed design directions addressing each of these cognitive challenges. The design directions involved providing a CO with active, future-oriented support; a vital signs display; an integrated vertical slice; simplified contact management; ability to spot leverage points; and what-if planning support.

INTRODUCTION

Submarine systems have changed tremendously over the past 30 years with the advent of new sensor, fire control, and navigation systems, among others. But is a submarine's Commanding Officer (CO) able to make better decisions as a result of these upgrades? Can they form a clearer picture of their operating environment and better anticipate how a given maneuver will play out with the addition of 10 new flat-screen displays? Do more sensitive sensors change how a CO commands his ship? This research sought to address two key issues stemming from these questions. First, we needed to understand the cognitive challenges that COs face in their day-to-day operations, both deployed and nondeployed. From this understanding, we were asked to develop recommendations for the design of technologies to support CO decision making.

A primary impetus driving this research was the implementation on newer submarines of a flat-screen display devoted to supporting the CO in the control room. The main question we heard was, "If you gave the CO a dedicated display, what should go on the glass?" Clearly, the glass itself does nothing unless what is portrayed there is configured to directly support a CO's information needs. It was our task to research what information would most directly support CO needs on such a display.

There were three data collection approaches used in this research: a review of the literature pertaining to large-screen display design for command centers, a series of ride-alongs on submarine training missions, and interviews with current or very recent commanding officers. Most of the design directions we developed were supported by more than one of our data gathering approaches. After describing our research process more completely below, the remainder of this paper will be devoted to explaining the six major cognitive challenges facing COs, along with design directions to mitigate those challenges.

RESEARCH PROCESS

First, throughout this effort we gathered and assessed relevant literature to help inform our work. The team read several general background sources describing submarine operations and missions, and delved into cognitive research to determine what others had found. This review provided direct insight into the cognitive challenges and strategies of submariners (Kirschenbaum 2001), the nature of uncertainty in general, expert strategies for dealing with uncertainty and dynamic change, the usefulness and configuration of large-screen displays in command centers, and the importance of navigation and contact management in submarine operations.

In the second part of the research process, we also sought to understand the submarine CO's perspective through direct observations and Cognitive Task Analysis (CTA) interviews. Two team members rode as observers on separate submarine training missions. During this time, we observed prospective COs (PCOs) undergoing their at-sea training evolutions, as well as actual COs operating in tightly constrained navigational waters. The combination of access to training and normal operations, and the opportunity to continually observe and question crew members was perhaps the most critical contributor to our understanding.

The third part of this process involved analyzing each interview and identifying design directions. The notes from each interview were analyzed by extracting, in table format, the cognitive challenges identified and how the CO mitigated or addressed each challenge, and by identifying design ideas from these facts where appropriate. Six preliminary design directions were developed from these analyses.

LITERATURE REVIEW

We undertook a literature review with three main purposes. We wanted to be familiar with the established literature about situation awareness displays to better inform our display recommendations. We wanted to provide SUBDEVRON with valuable principles or examples related to situation awareness displays, and also provide lessons learned about successful and not-so-successful situation awareness display recommendations or uses. Finally, we wanted to back up our display recommendations with research-based data whenever possible.

Large-screen displays have held great promise for improving situation awareness and battlespace visualization. However, research has not always supported the claim that large screens will improve the awareness and visualization capabilities of users.

Barnes' (2003) in-depth review of battlespace visualization research and design issues argues that visualization does not occur simply when battlespace information is depicted; visualization means the commander can understand this information well enough to see options and predict outcomes. Thus, information technology must do more than simply display information; it must be designed with an understanding of users' work and expertise.

So under what circumstances are large-screen displays (LSDs) useful in command centers or control rooms? First, an LSD (or data wall) should be used to illustrate higher-order patterns and relationships among disparate but related pieces of information in support of sensemaking. Submarine examples include permitting a CO to directly visualize patterns of contact behavior that could reveal intent, or overlaying relationships by depth. "The ability of an expert to adapt to new problem sets depends on a rich interconnectedness among the expert's knowledge structures, allowing generalization to the problem space" (Barnes 2003, 22). An LSD can be designed to reflect the expert CO's knowledge structures, explicitly showing the patterns and relationships among data that he has previously compiled in his head.

Large-screen displays also can be used to share information among team members, creating common ground and a basis for coordination. Roth et al. (1998) suggest that a group view display, if it is to support shared situation awareness of teams, should meet the following requirements:

1. Provide a common reference which leads to shared awareness of the system and tasks underway,
2. Permit users to understand how their own actions impact tasks that others are accomplishing,
3. Allow understanding of how other team members' work impacts what one member is trying to do,
4. Enable supervisors to keep tabs on specific team members' actions and whether those actions meet expectations

In summary, enabling team members to understand how their actions impact each others' efforts, thereby enhancing coordination of work, is critical for a shared information display.

However, LSDs can also be used as repeater screens, which research has shown is a poor approach, making life more difficult for command center personnel. Darling and Means (2005), observing both Homeland Security FEMA operations and a two-day Joint Expeditionary Forces Experiment, found a number of issues with the employment and use of the LSD. People entering the room did not look at the screen to gain situation awareness; a workstation's screen was repeated on the LSD but often entered screensaver mode due to inactivity; security status would change to "red" but not be reflected on the "power point rotisserie" being shown on the LSD; and people on the main floor rarely, if ever, referred to the large screen when in conversation away from their workstations. Darling and Means (2005) recommend that a data wall should not be used to mirror an existing workstation in a control room. They also recommend development of preset display configurations that can be switched on or off depending on the current situation.

DIRECT OBSERVATIONS AND INTERVIEWS

During at-sea observations, our primary data collection methodology consisted of gathering narratives of specific instances which served to illustrate the challenges of CO decision making. These narratives were taken from direct observations and follow-up interviews with the watchstanders, PCOs, instructors, and COs to clarify the events.

During these missions, the researchers shadowed the PCO, who acted as the CO during the exercise as he moved around the control room. We recorded what the PCO did, said, looked at, and asked about. Because the less-experienced PCOs were the focus of the exercise, the researchers paid particular attention to what the expert decision makers (the instructor and the CO of the submarine) attended to. The researchers recorded what these COs did, what they looked at, and what they questioned along a timeline of the exercise. An off-duty PCO stood with each researcher during the exercise to explain the situation and the tactics that were being employed.

After their day of command, we conducted brief interviews with the PCOs. The researchers used the timeline they created during the exercise to select a critical or challenging event that the PCO faced while acting as the CO. We focused the interview on understanding what the PCO was thinking about, where he was getting information, and how he made sense of what was going on during the critical event. In this example the CO needed to determine if his submarine could get to a photo point and take a picture safely before a ship closed within the safety range:

> *Sonar called out classification and contact ID, so I could gauge speed. I first went to the sphere display which told me we have the contact right now and was a good source for bearing rate. Then (I went) to the CEP to get the bearing source, it is much more readable, and the time scale is longer so you can see more history. Then back to the Ops Summary display to select the contact ID and read the estimated course, speed, and range on the read out. Then I checked our course and speed using the analog displays above piloting. Then to the navigation plot, where I can ask for the time to the next photo point, then I add X minutes for photo and quality check, then use the three-minute rule to calculate how close contact would get. Then I compare that number to see if it is within my go deep range* (CO).

The above example illustrates one of the challenges that COs face when trying to gather vital signs—data integration from dispersed sources.

THEMATIC ANALYSIS OF COGNITIVE TASK ANALYSIS DATA

We gathered data through CTA procedures and then applied thematic analysis to the data. Cognitive Task Analysis methods are designed to examine cognitive processes and to understand how people make judgments and decisions. We applied a variety of CTA interview methods towards interviews of current and recent COs. We conducted 19 interviews, each approximately two hours long. Methods used included the Critical Decision Method (Klein, Calderwood, and MacGregor 1989), Knowledge Audit (Klein and Militello 2004) and Wagon Wheel Team CTA interviews (to identify and understand team performance challenges). In each two-hour interview, we applied either a single method or a combination of methods.

Our approach to analyzing the CTA data we collected centered on examining command decision-making incidents for key decisions, cognitive strategies, and information flow by gathering and analyzing incident data generated from Critical Decision Method (CDM) interviews. After isolating and documenting key incidents, we identified cognitively complex decisions and actions made by the decision makers in each incident. We also noted shifts in situation awareness or points where the decision makers revised their understanding of the situation at hand. We noted indications of cues and factors that decision makers considered when assessing the situation. In addition to incident and situation awareness analysis, we devoted time to analyzing command decision-making expertise to investigate the nature of expertise with regard to uncertainty management and skill development.

This CTA enabled identification of six main design directions for better supporting CO decision making; these are elaborated and linked to cognitive challenges in the Table below, but are listed here for clarity:

1. Active, Future-Oriented Support
2. Vital Signs Display
3. Integrated Vertical Slice
4. Simplified Contact Management
5. Spotting Leverage Point Identification
6. “What-If”Planning Support

Thematic analysis is a common method for analyzing qualitative data collected through interviews and observations. It is often used to analyze ethnographic interviews (Spradley 1979, Taylor and Bogdan 1984) and focuses on identifiable themes and patterns of behavior or work (including cognitive performance).

Themes were defined as units derived from patterns such as conversation topics, recurring activities (with humans or systems), meanings, and maxims (Taylor and Bogdan 1984). Themes that emerged from individual interviews and observations were pieced together to form a more comprehensive picture of the CO’s collective experience, and were then re-stated as cognitive challenges for COs. We corroborated these cognitive challenges by comparing them to the findings of the literature review and cognitive task analysis findings. This catalog of cognitive challenges was used to inform and organize our display recommendations.

FINDINGS: COGNITIVE CHALLENGES AND DESIGN DIRECTIONS

The challenges identified, along with their associated design directions are listed in Table 1.

Cognitive Challenges	Design Directions
1. Projecting current data into the future: COs strive for a future-oriented big picture understanding, but often are pulled into the details of the current situation. Right now displays are designed for specialists and consequently only present current and immediate past information. This, in conjunction with the CO’s inability to actively engage with displays, makes it difficult for the CO to focus on the future. Additionally, because information is spread across multiple displays, the CO has to constantly gather and integrate disparate pieces of information in his head to maintain the current picture. This leaves less time for the CO to think about the future, spot weaknesses in a course of action, or identify pop-up opportunities.	**Active, Future-Oriented Support.** A display with future-oriented timescales and scenarios would permit a CO to take anticipation out of his head so as to visualize how different parts of the picture might fit together, how track history has developed and might play out in the future, and how that would permit data projection and playback (e.g., satellite weather map cycle information).
2. Quickly getting and integrating vital ownship, contact, and environmental information to make a decision under time pressure and high stress: Currently vital signs	**Vital Signs Display.** Since vital signs are dispersed across displays and locations, the CO is forced to manually integrate the collective picture in his head. A by-product of this fragmentation is

Cognitive Challenges	Design Directions
are dispersed across numerous displays that are not designed to be viewed by a user who is standing several feet away from the display. So, in addition to having to manually integrate a collective picture in his head and mentally track tripwires, the CO needs to constantly move around to gather vital information. Under time pressure, high stress, and in fully manned situations, this leaves less time to make decisions and evaluate a course of action.	the need for redundancy and constant verbal and written exchange of information between the CO and his watchstanders. A vital signs display would enable the CO to continuously get vital ownship information as well as vital information for contacts, without having to gather and integrate the pieces from multiple locations.
3. Building and maintaining a vertical picture of the operating space in high stress situations, especially littoral environments: Another picture that the CO must mentally form is the vertical operating picture. Data from our own observations, as well as from many critical incidents, identified the challenges inherent in creating a mental picture of the vertical waterspace. This picture is especially important in littoral environments, where the chance of grounding the submarine increases.	**Integrated Vertical Slice.** The vertical picture of the operating space is built from information such as Depth Tripwires, Charted Depth, Fathometer Depth, Depth Envelope, Ownship Depth, Array Depth, and Depth History. A vertical slice display would provide explicit visualization of the vertical space surrounding a submarine's operations. Given adequate interoperability of systems onboard a submarine, this vertical picture information should be integrated, displayed together, and automatically updated.
4. Effectively organizing and prioritizing contacts in high-density environments: Navigation and contact management are anything but simple in a submarine's current operating environment. Getting underway, preparing to come to periscope depth, coming into port, and transiting highly constrained and congested waterways all present extremely high risk for collisions, groundings, and unintended detection. The ability of the CO to continuously make sense of the constantly changing variables and act accordingly is cognitively challenging.	**Simplified Contact Management.** COs use repeated practice drills, extensive planning, and deliberate time cushions to deal with these challenges. Design direction #4 would leverage extensive research done in other domains (such as Free Flight) to present a simplified, projective contact management/navigation picture. A critical feature would permit triage of the contact picture in high-density environments by highlighting priority contacts, grouping contacts, and monitoring all contacts and tripwires.
5. Spotting leverage points and managing uncertainty in highly dynamic environments: Given the nature of subsurface operations, technology will not reduce uncertainty to zero. In fact, COs do not need total certainty to execute operations, but COs do need to gauge how the submarine's actions will increase or decrease tactical uncertainty. The cognitive challenge that COs currently face is incorporating uncertainly into critical decisions like: is the target within range, have we been detected, or do we shoot or not shoot. Supporting the CO's ability to understand how actions will increase or decrease	**Leverage Point Identification.** Uncertainty management is the key theme for this direction. The Goal Pyramid (Safety, Stealth, Mission) is fraught with gray areas and tradeoffs, the most basic of which is, "Are we safe and stealthy enough to proceed with the mission?" This design direction seeks to help a CO spot leverage points in hostile environments through showing how a maneuver affects the target solution: does maneuver X increase or decrease the cloud of uncertainty around the contact? Overlaying actual sensor data with derived data from the fire control system (FCS) would further permit COs

Cognitive Challenges	Design Directions
uncertainty will help COs spot leverage points for reducing uncertainty and present a truer picture of what is known about the current situation.	to see how the system's algorithms are working and reduce related uncertainty.
6. Performing "what-if" analyses during re-planning sessions: In challenging, time-pressured situations, COs gather the Department Heads to elicit recommendations and identify a workable course of action. COs typically gather around the navigation plot, so that a view of the situation can inform the discussion. However, the plot does not support the COs' and Department Heads' ability to understand how a recommended course of action would play out under different circumstances. Consequently, it is challenging for the CO to identify the small differences that can indicate the way a situation will unfold and cause a course of action to become unworkable.	**"What-If" Planning Support.** A theme from interviews with highly seasoned COs was their reliance on their people. To support CO and Department Head interaction around the navigation plot, this design direction would lead to a tool affording option simulation and visualization, projecting contacts into the future, and a timeline development tool to help build flex time into a plan within operational constraints. Such a tool should support sharing of each team member's ideas and concerns, and permit innovative development of solutions outside of routine process execution.

Table 1. Cognitive challenges COs face, along with associated design directions.

CONCLUSION

The pace of technology advancement puts advanced sensor and algorithmic capabilities in the hands of COs, but from a commander's perspective, the challenges of knowledge integration and uncertainty management remain extreme. This in-depth but quick examination of how to improve support to a CO through interface technology has yielded design directions that are preliminary and only briefly developed. Further exploration and evaluation of the concepts and their implementation forms is necessary in order to prioritize and achieve confidence in their payoff.

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