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Extending the Dynamic Model of Situated Cognition to Submarine Command and Control

ABSTRACT

A necessary step in the process of enhancing Sea Warrior performance is the ability to analyze performance via a comprehensive Human – System approach. Such an approach to Human – System performance has been espoused by researchers (Miller & Shattuck, 2004) in the study of military command and control. Citing the gap between the focus of analysis of human factors practitioners and systems analysts, Miller and Shattuck describe a dynamic model of situated cognition (DMSC) in which cognitive activities are based on the data which flow from the environment through the machine portions of a complex system. This approach overcomes the limitations of measures used to assess cognitive performance, such as some situational awareness (SA) metrics, that implicitly depict the activity as a state rather than a dynamic process. Moreover, by utilizing the DMSC, military accidents can be analyzed retrospectively to pinpoint root causes and identify ways to improve future performance. As an example, this paper applies the DMSC to two Naval submarine mishaps.

INTRODUCTION

The ability to analyze performance in complex systems is vital to the successful design and operation of such systems. Analysts and designers should include the human and machine components. Such an approach has been espoused by researchers in the study of military command and control (Miller & Shattuck, 2004). Citing the gap between the focus of analysis of human factors practitioners and systems analysts, Miller and Shattuck describe a dynamic model of situated cognition (DMSC) in which data flow from the environment, through sensors and other machine agents to the human agents in the system. This approach overcomes the biases which are inherent in analytical methods focusing almost exclusively either on machine agents or on human agents. In addition, this approach overcomes some of the limitations inherent in the measurement of cognitive performance because it examines the evolving system processes rather than a series of discrete system states. The associated metrics used in the DMSC also emphasize process over state. The Dynamic Model of Situated Cognition also appears to be a valuable framework for the retrospective analysis of military accidents. This framework facilitates the identification of root causes and potential areas for improvement of human performance.

On the afternoon of February 9, 2001, the *USS Greeneville* (SSN 772) collided with the Japanese Motor Vessel *Ehime Maru* off the coast of Oahu, Hawaii while performing an emergency surfacing maneuver. Nine civilians were lost. In a separate incident, the *USS Hartford* (SSN 768) ran aground off the coast of Italy on October 25, 2003, costing the Navy $9.4 million in repairs. While the first incident involved submerged operations and the second involved surface navigation, there are similarities, revealed by the dynamic model of situated cognition, as described below.

THE DYNAMIC MODEL OF SITUATED COGNITION

The DMSC posits that there are various stages of technological and cognitive system performance (see Figure 1). On the technological side, all the data in the environment, data detected by technological systems (e.g., sensors), and data available on local command and control systems (C2; e.g., workstations) are included. Each of these stages includes a subset of what was included in the preceding stage. Building upon this technology

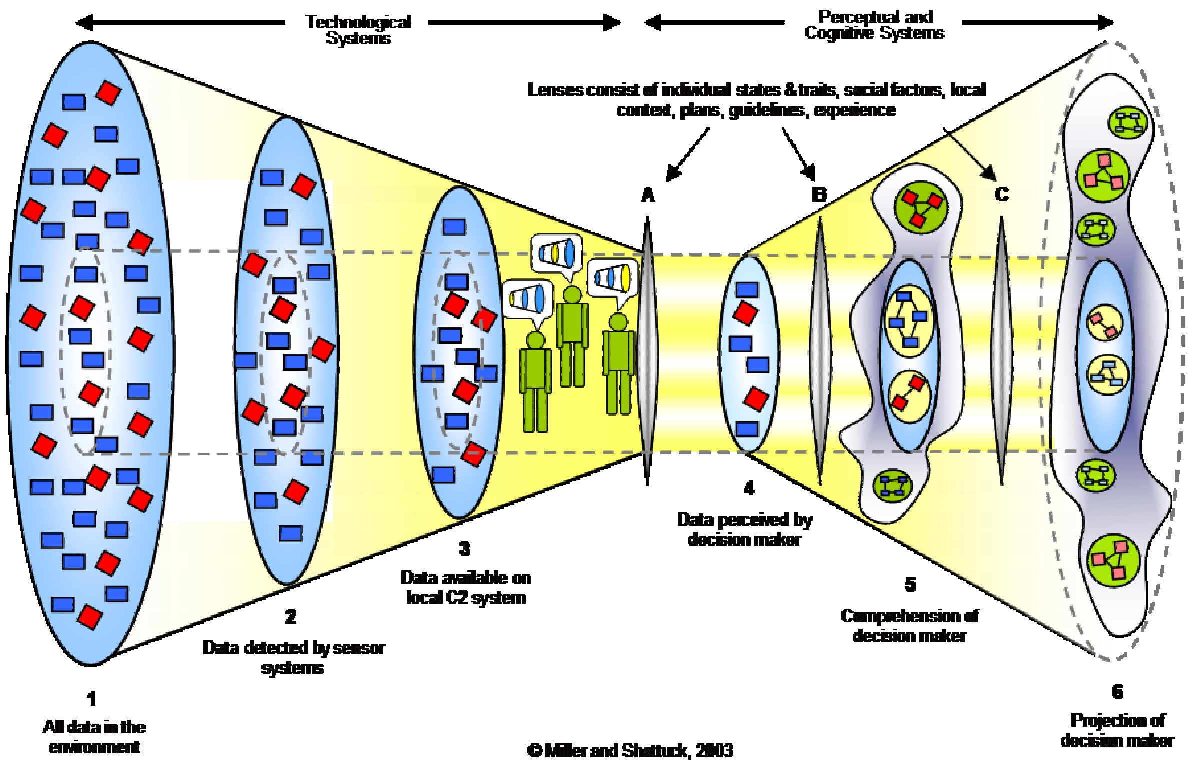

FIGURE 1. Dynamic Model of Situated Cognition

are the perceptual and cognitive systems offered by the human operator. These include data perceived by the decision maker, comprehension of the decision maker and, finally, projection/ prediction of the decision maker. These cognitive stages equate to the three levels of SA discussed by Endsley (2000). Embedded between these stages are lenses, which serve to focus (or distort) an individual's cognitive processes. Such lenses embody the context in which the situation occurs, and include the individual's unique experiences and cultural background, the local situation and, in military situations, may include the operation order, military doctrine, and rules of engagement.

Technological Aspect of the System

The large oval on the left side of Figure 1 (Oval 1) depicts ground truth, (i.e., everything in the world). Ground truth is dynamic in nature, changing with spatial and temporal progression although it may be captured at points in time. There is no error or uncertainty inherent in Oval 1. Simulations allow for the accurate representation of ground truth. In the real world, however, it is understood that Oval 1 cannot be measured with total precision and accuracy. The blue rectangles and red diamonds in Oval 1 represent individual data elements for friendly and enemy entities. While other things are present in the world (e.g., noncombatants, weather, terrain, friendly and enemy intent), they have been excluded from the figure for simplification.

The next oval (Oval 2) shows the elements detected by the technological portion of the system. Note that this oval is depicted as a subset of the first oval. However, it is not apparent what portions of ground truth are being detected and what items remain undetected. Error or uncertainty can first enter the model at Oval 2, taking various forms. Oval 2 is a subset of Oval 1 for a variety of reasons.

- Not enough sensors available to cover environment
- Sensors unable to detect due to lack of sensitivity or specificity
- Enemy activity designed to deceive
- Sensors may malfunction.

Inaccuracy or uncertainty in Oval 2 can result in error that may be propagated throughout the rest of the model.

Oval 3 depicts what is displayed on the decision maker's workstation. These data are a subset of what is represented in Oval 2. Users are able to tailor their displays to suit their individual preferences. If the user has the display settings adjusted on the C2 screens such that information is not displayed, it is possible that important, perhaps vital, information may be hidden or concealed. It may not be obvious to the user which data have been excluded. Oval 3 represents yet another entry point for error or uncertainty into the model.

Perceptual and Cognitive Aspects of the System

The technological aspect feeds into the perceptual and cognitive aspects of the DMSC. On right side of the model, three lenses are depicted (see Figure 1). Each individual has a unique lens. The lens is continually updated and is present at three points in the model (see A, B, and C in Figure 1) to focus the decision maker, to reflect the unique perspective of the decision maker, and to provide context. In a military context, the lenses are comprised of the following information and attributes: experience (societal, cultural and individual), states or performance characteristics (system/team and individual), specific plans (micro level - the temporal context in the days and hours preceding the incident), and rules of engagement or doctrine (macro level - the temporal context in the months preceding the incident). Together, these classes of information influence what is perceived by the user or decision maker.

Oval 4 represents all the data actually perceived by the decision maker, contains only a portion of the data available in previous ovals and may include some distortion, a potential source of system error. Perceived data are a small subset of the data available in the environment, the sensor array, the configuration of the local C2 display, and are based on the characteristics of the decision maker's lens.

Perceived data are of little value to the decision maker until they are processed. The same lens components that directed attention and led to perception also influence comprehension. The friendly and enemy icons in Oval 5 have been linked and reorganized, suggesting that they have been processed, represent the comprehension of the data elements that were perceived. The oval is embedded in an amorphous shape, suggesting that there are other possible ways the data could be linked and reorganized that would lead to alternative mental representations (e.g., situational models) of the data.

The final oval (Oval 6) represents the decision maker's projection into the future or his prediction. Alternate views of the battlefield within the amorphous shape but outside of Oval 5 do not contribute to or influence the prediction of the decision maker. Note that the amorphous shape that surrounds Oval 6 is larger than that which surrounds Oval 5 and contains even more alternatives. This representation depicts the idea that there is much greater uncertainty associated with prediction.

Description of the DMSC thus far implies that processing occurs in a linear fashion from the technological side to the perceptual and cognitive side. However, there are feedback loops within the model (not shown in Figure 1). For example, a projection (Oval 6) can lead the decision maker to modify sensor coverage (Oval 2) or a local C2 display (Oval 3), influence perception of data (Oval 4), or influence comprehension of data (Oval 5). Moreover, both projection (Oval 6) and comprehension (Oval 5) can shape the contents and contours of the decision maker's lenses (A, B, and C).

APPLYING THE DYNAMIC MODEL OF SITUATED COGNITION TO SUBMARINE MISHAPS

To further explicate the DMSC, the authors applied it retrospectively to two actual submarine command and control mishaps on the *USS Greeneville* and the *USS Hartford*. We employed a process tracing methodology to demonstrate the use of the DMSC model and to pinpoint where and when the C2 process went awry. We then continue the process trace to follow the path that lead to the faulty decisions that ultimately resulted in mishaps with tragic consequences. These analyses offer guidance on how to deter similar events from happening in the future.

USS Greeneville (SSN 772)

On February 9, 2001, the U.S. Navy submarine *USS Greeneville* collided with the Japanese motor vessel *Ehime Maru* off the coast of Oahu, Hawaii. The submarine was demonstrating an emergency surfacing maneuver for civilian guests onboard for a seven-hour distinguished visitor cruise. As it rose to the surface, the submarine struck the fishing vessel's aft port quarter, causing the ship to sink in less than 10 minutes. Of the 35 Japanese crew, instructors, and students onboard the *Ehime Maru*, 26 were rescued while nine remain unaccounted for, presumed dead (Executive Summary of USS Greenville collision, retrieved 04/14/2005 from http://www.cpf.navy.mil/greeneville.html).

The problems started when the submarine fell behind schedule by 30 minutes and had less than an hour to get to a pre-designated location. There were three surface ships in the vicinity of the submarine. The *Ehime Maru* was closing on the *USS Greeneville* but at this point this information only resided in Oval 1 (ground truth or data in the environment) and in Oval 2 (data detected by sensors) of the DMSC. The information on the closing rate of the *Ehime Maru* was not in Oval 3 (data available on the C2 system) because a critical display system was not working. The Analog Video Signal Display Unit (AVSDU), located in the control room of the submarine where it provides a remote display of sonar data used for surface contact analysis, was inoperative. Since information on the proximity of the *Ehime Maru* was not available in Oval 3 from the AVSDU, it could not be propagated throughout the rest of the model. At this point, the commanding officer (CO) of the *USS Greeneville* made a series of decisions and issued orders that created an artificial sense of urgency in crewmembers in the control room. This elevated time pressure affected the individual lenses (Lens A, B and C on the right side of the model) of the crewmembers, adversely impacting their ability to accurately process the information residing in Oval 4 though Oval 6 (perception, comprehension, and projection).

One of the decisions made by the CO was to prepare to come to periscope depth. Mandatory procedures for a submarine to come to periscope depth (PD) require that the Officer of the Deck (OOD) hold a periscope briefing with watchstanders, conduct two good target motion analysis (TMA) legs of about three minutes on each surface contact, provide the necessary report and obtain the CO's permission to proceed to PD. These procedures were known to all crewmen and were part of their lenses The CO, however, abbreviated these procedures used by the crew to maintain their SA during the PD maneuver. The CO's decision not only compromised the procedures, it virtually assured that the data in the environment (Oval 1) detected by the sensors (Oval 2) would be inaccurate or incomplete. Hence, the data displayed on the C2 workstations (Oval 3) would also be inconsistent with Oval 1; and the perception, comprehension, and projection (Ovals 4, 5, and 6) of the crewmembers with regard to the surface contacts would be formulated based on erroneous data.

Prior to the CO's decision to surface, the sonar technician reported a new contact to the control team. This information from the human agent either did not pass through Lens A in the model or was skewed as it passed through. The result was that neither the CO nor the OOD perceived

(Oval 4) the situation properly; they did not recognize that the sonar report was information on a new contact. The CO then announced to Control that he had a good feel for the contact picture and ordered the OOD to proceed to PD on the same course. The OOD was not given enough time to develop an accurate picture of the surface contact situation. He did not conduct the required periscope brief with watchstanders, missing a valuable opportunity to receive and critically assess important contact information from the sonar. He was deprived of input from both the technological agents and the human agents in the system.

Additionally, other crewmembers were not given enough time to do their jobs properly. Upon hearing the sonar technician's report of the new contact, the FTOW (fire control technician of the watch) rushed to complete his analysis of three surface contacts prior to PD, overlooking an updated 4000 yard closing solution on one of the old contacts (the ill-fated *Ehime Maru*). His focus was entirely on a 'new' contact which he considered to be the primary contact of interest. The FTOW's lens was skewed by the false sense of urgency established by the CO which could very well have narrowed the FTOW's focus of attention. Further, when the FTOW heard the CO say he had a good feel for the contact picture, he assumed the CO was referring to all contacts, including the new one. This provides further evidence of a skewed lens on the part of the FTOW, which may have contributed to his decision to remain silent, failing to provide the CO with corrective information.

The CO's erroneous perception led to an incorrect comprehension (Oval 5) of the situation and an inaccurate projection (Oval 6) of where the vessels would be in the future. At no time did the CO discuss the surface picture with the contact management team to verify a common understanding of the surface contacts (Ovals 5 and 6, comprehension and projection). His own SA of contacts was based on two brief walk-throughs of the sonar room and a single review of fire control displays. He was overly confident and pressed for time, and failed to properly use both the technological agents and the human agents in the system to build his understanding of the surface picture. The decision to proceed to PD represents a feedback loop from Oval 6 (projection) to Oval 1 (environment). As the submarine ascended to PD, the contents of Oval 1 were changed and new data were available for propagation through the model.

While at PD, the CO decided to interrupt the OOD's periscope search and performed his own abbreviated visual search for surface contacts. After the periscope searches by the OOD and CO, the FTOW cycled back through his surface contacts and correctly calculated a dangerous closing solution for one of the contacts, the *Ehime Maru*. However, the OOD had just stated he had seen no close contacts at PD, and the CO also said he had no visual contacts. These pronouncements so skewed the lens of the FTOW that he doubted his comprehension (Oval 5) of the situation (that there was a surface contact in close proximity to the submarine). The FTOW's erroneous comprehension generated a decision and a feedback loop from Oval 5 (comprehension) to Oval 3 (C2 workstation). He manually overrode the correct solution presented by his workstation, physically changing the distance of the surface contact (*Ehime Maru*) from 4000 to 9000 yards, reflecting the distance to the visual horizon. The FTOW entered this erroneous information into the fire control system. The result of this action was that the speed solution of the surface contact resulted in an impossible speed solution of 99 knots. After the periscope searches, the boat went "emergency deep", proceeded to 400 feet, and conducted an emergency main ballast tank blow. The ship surfaced underneath the *Ehime Maru*, causing major flooding on that ship which sunk rapidly.

USS Hartford (SSN 768)

On October 25, 2003, the *USS Hartford* ran aground east of the island of Caprera near Sardinia, Italy while piloting out of the harbor. During submarine piloting, the CO and OOD are stationed on the bridge, while the other navigation and contact management team watchstanders are in the control room.

The Naval Mishap Investigation Report indicated that the primary causes of the incident included:

- Inability of the piloting party to accurately fix the position of the ship (poor comprehension in Oval 5, which was most likely based on inaccurate data in Oval 3).
- Failure to use available charts and equipment on the bridge to effectively pilot the vessel (failure to use information in Oval 3 which led to lack of understanding in Oval 5).
- Inadequate planning and application of basic navigation principles in the piloting plan to assure success and provide the proper warning that the ship was heading into danger (biased lenses affecting perceptual and cognitive processing).

The plan for the *USS Hartford* on October 25, 2003 was to take a four "leg" journey out of the harbor. After leaving the pier, the voyage management system (VMS - an automatic electronic navigation aid) froze and had to be rebooted. This is considered a major technological malfunction. All of the pre-entered voyage plan data was lost upon rebooting. The boat increased in speed, and an operator noticed that there was an inconsistency between the Ring Laser Gyro Navigator (RLGN) and the Global Positioning System (GPS). Essentially these two sensor systems (Oval 2) were providing conflicting data to C2 workstations (Oval 3) needed to conduct operations. The fact that an operator noticed the conflict is evidence that the data were perceived (Oval 4) and comprehended (Oval 5) by at least one crewmember.

When the submarine turned into its second leg, the navigational fixes seemed accurate. Thus, the system inconsistency perceived and comprehended earlier were disregarded. No feedback loop was generated to Oval 2 (sensor systems) or Oval 3 (workstations). However, the boat increased speed again, and two people left the control room to check on the system inconsistency. This time, the perception and comprehension did generate a feedback loop. This occurred without the CO or XO knowing that key personnel left the control room.

The CO then ordered a turn that was almost 500 yards short of the plan that he discussed earlier with the Navigator (NAV), suggesting a failure in Oval 6, projection into the future based on what was comprehended (Oval 5). At this point a GPS waypoint was erroneously plotted on the primary plot. The Assistant Navigator (ANAV) instructed the watchstander to enter the waypoint for the next turn into the GPS, but it was entered in a different reference unit than instructed, making the position entered different from desired. The watchstander's inaccurate comprehension led to an erroneous feedback loop, which incorrectly updated the data on the chart (e.g., his workstation in Oval 3).

The early turn caused confusion because it was ordered from the bridge without warning. In addition, because the leg was short, it resulted in a turn point that was several hundred yards off from what was planned and it required the plan to be revised significantly in order to accurately fix the boat's position. Even though crewmembers could not get a good fix, no one reported the problem to the bridge or recommended that they slow down until a fix was gotten. After the early turn, the control room became increasingly confused as to the actual location of the boat. Erroneous perceptions (Oval 4), comprehensions (Oval 5), and projections (Oval 6) resulted in decisions and feedback loops which altered the environment (Oval 1), the sensors (Oval 2), and the C2 displays (Oval 3) in unexpected ways, leading to more mistakes and confusion.

During the same leg, another operator incorrectly placed the submarine 400 yards from its actual location. A minute later, they passed the revised waypoint for the next turn, but nobody on the bridge was aware that they were off track. In the control room they were still trying to fix the plot, and they were now not only off course, they were completely off the chart. The chart that they should have been using contained a warning about shoal water. But, the crew still tried to plot a fix on the previous chart. Again, the incorrect perceptions, comprehensions, and projections led to erroneous decisions and feedback loops, which influenced the technological portion of the system. The confusion they experienced was a result of the mismatch between what they were experiencing and what they thought should happen based on the contents of their lenses. As a result, they focused their attention (i.e., directed their lenses) to resolving the problem and missed the fact that they were on the wrong chart.

Confounding these series of unrecognized errors, the submarine turned onto the fourth leg. The water began shoaling, and the fathometer showed 100 feet after previously consistent 150 foot soundings. The fathometer operator gave a three minute warning, more than enough time to do something to avoid grounding. When the fathometer reading went from 83 feet to 50 feet, the fathometer operator provided another warning. At this point there had not been an accurate navigational fix for 14 minutes, even though fixes are to be updated every three minutes. This warning was significant enough to divert the attention away from the navigational problem. It finally re-directed the lens of the OOD and allowed him to perceive (Oval 4) and comprehend (Oval 5) the gravity of the situation. In anticipation of what would happen if they remained on course (Oval 6), the OOD ordered all back full, but the boat grounded 1,100 yards off Isola delle Bisce. After the boat ran aground, the Squadron Commodore took command (he was on the bridge during the transit), and said “speed on” without a full understanding or knowledge of the *USS Hartford’s* position, going against procedure.

Repairs on the submarine cost about $9.4 million, and many days of operational readiness were compromised. The CO of the *USS Hartford* and the Commander of Submarine Squadron 22 who was onboard as a pilot were both relieved of command. Six other crewmen were charged with dereliction of duty and received various administrative punishments.

CONCLUSION

We have demonstrated the utility of the DMSC with respect to accident investigation by reviewing two recent submarine mishaps involving the *USS Greeneville* and the *USS Hartford*. Analysis of both cases reveals that the technological (e.g., sensor coverage and workstation display) and perceptual/cognitive (e.g., perception, comprehension, and projection) systems, along with experience and doctrine, all played an important role in the unfolding of events. For further information on the role of situational models and mental models in submarine navigational mishaps, see Shobe and Severinghaus (2004).

These analyses, along with previous extensions of the model to the *USS Stark* (FFG 31) and *USS Vincennes* (CG 49) mishaps (Shattuck & Miller 2004), further support the usefulness of a human - systems performance approach. Ultimately, this approach can inform system designers about weaknesses or vulnerabilities in a current or planned system and give them data they need to make modifications to the design, which, in turn will result in better systems and reduced risk to humans. Future incidents may be averted if designers, system analysts, and human factors practitioners adopt the DMSC to in their work.

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