2007-06

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Hutchins, Susan G., et al. "Evaluating a model of team collaboration via analysis of team communications." Proceedings of the Human Factors and Ergonomics Society Annual Meeting. Vol. 51. No. 4. Sage CA: Los Angeles, CA: SAGE Publications, 2007.
http://hdl.handle.net/10945/36395

Evaluating a Model of Team Collaboration via Analysis of Team Communications

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A model of team collaboration was developed that emphasizes the macro-cognitive processes entailed in collaboration and includes major processes that underlie this type of communication: (1) individual knowledge building, (2) developing knowledge inter-operability, (3) team shared understanding, and (4) developing team consensus. This paper describes research conducted to empirically validate this model. Team communications that transpired during two complex problem solving situations were coded using cognitive process definitions included in the model. Data was analyzed for three teams that conducted a Maritime Interdiction Operation (MIO) and four teams that engaged in air-warfare scenarios. MIO scenarios involve a boarding team that boards a suspect ship to search for contraband cargo (e.g. explosives, machinery) and possible terrorist suspects. Air-warfare scenarios involve identifying air contacts in the combat information center of an Aegis ship. The way the teams' behavior on the two scenarios maps to the model of team collaboration is discussed.

INTRODUCTION

Team collaboration and decisionmaking in complex, data-rich situations is being investigated to better understand the cognitive processes employed when teams collaborate to solve problems. These processes include (1) individual knowledge building, (2) developing knowledge inter-operability, (3) team shared understanding, and (4) developing team consensus. A cognitive model of team collaboration emphasizing the human decisionmaking processes used during team collaboration was developed by Warner, Letsky, & Cohen (2004). In this paper we describe research conducted to validate the model and determine how these processes contribute to team performance by analyzing two complex decisionmaking tasks.

The types of problem-solving situations this model describes are ill-structured decisionmaking tasks, characterized by time pressure, dynamic information, with high information uncertainty, high cognitive workload, and human-system interface complexity. The model focuses on three tasks: (1) team data processing, (2) developing a shared understanding among team members, and (3) team decisionmaking and course of action selection.

Team types described by the model include teams who operate asynchronously, whose members are distributed, and culturally diverse, where members possess heterogeneous knowledge, due to the unique roles played by each team member, and who operate in a hierarchical organizational command structure, and in some situations involve rotating team members (Warner, et al., 2004).

Four unique but interdependent stages of team collaboration are included in the model. As depicted in Figure 1, the stages include knowledge construction, collaborative team problem solving, team consensus, and outcome and evaluation and revision. Cognitive processes within each stage are represented at two levels: meta-cognitive processes, which guide the overall problem-solving process, and macro-cognitive processes, which support team members' activities within the respective collaboration stage. The model's macro-level definition of the cognitive processes permits empirical assessment of these cognitive processes with currently available measurement techniques (e.g., verbal protocol analysis, communication analysis). Analysis of data captured from teams performing their tasks in a collaborative environment can provide valuable insight into what constitutes effective collaboration performance.

METHOD

Verbatim transcripts were analyzed from two series of experiments where teams collaborated to solve a complex problem. Decisionmaking domains included Maritime Interdiction Operations (MIO) and air warfare decisionmaking scenarios. In both of these problem-solving tasks, assessment is particularly difficult due to time pressure, high workload, and because the available information is often incomplete or ambiguous. Transcripts included communications that occurred between all team members as well as with decision-makers at the distributed sites. Team communications data for four air warfare teams and three MIO teams was analyzed and coded using the cognitive process definitions developed by Warner, et al. (2004). The goal was to evaluate the model of team collaboration by determining which macro-cognitive processes are used and to refine the model based on empirical analysis.

Experiment I: Maritime Interdiction Operations

An experiment was conducted to test the technical and operational challenges of developing a global Maritime Domain Security testbed. A wireless network was developed for data sharing during a Maritime Interdiction Operations (MIO) scenario to facilitate expert reachback for radiation source analysis and biometric data analysis. Subject matter experts at geographically distributed command centers collaborated with a boarding party in near-real time to facilitate situational understanding and course of action selection.

The objective of this experiment was to evaluate the use of networks, advanced sensors, and collaborative technology for conducting rapid MIO. Specifically, the ability of a boarding party to rapidly set up ship-to-ship communications which permit them to search for radiation and explosive sources while maintaining contact with the mother ship, command and control organizations, and to collaborate with remotely located experts.

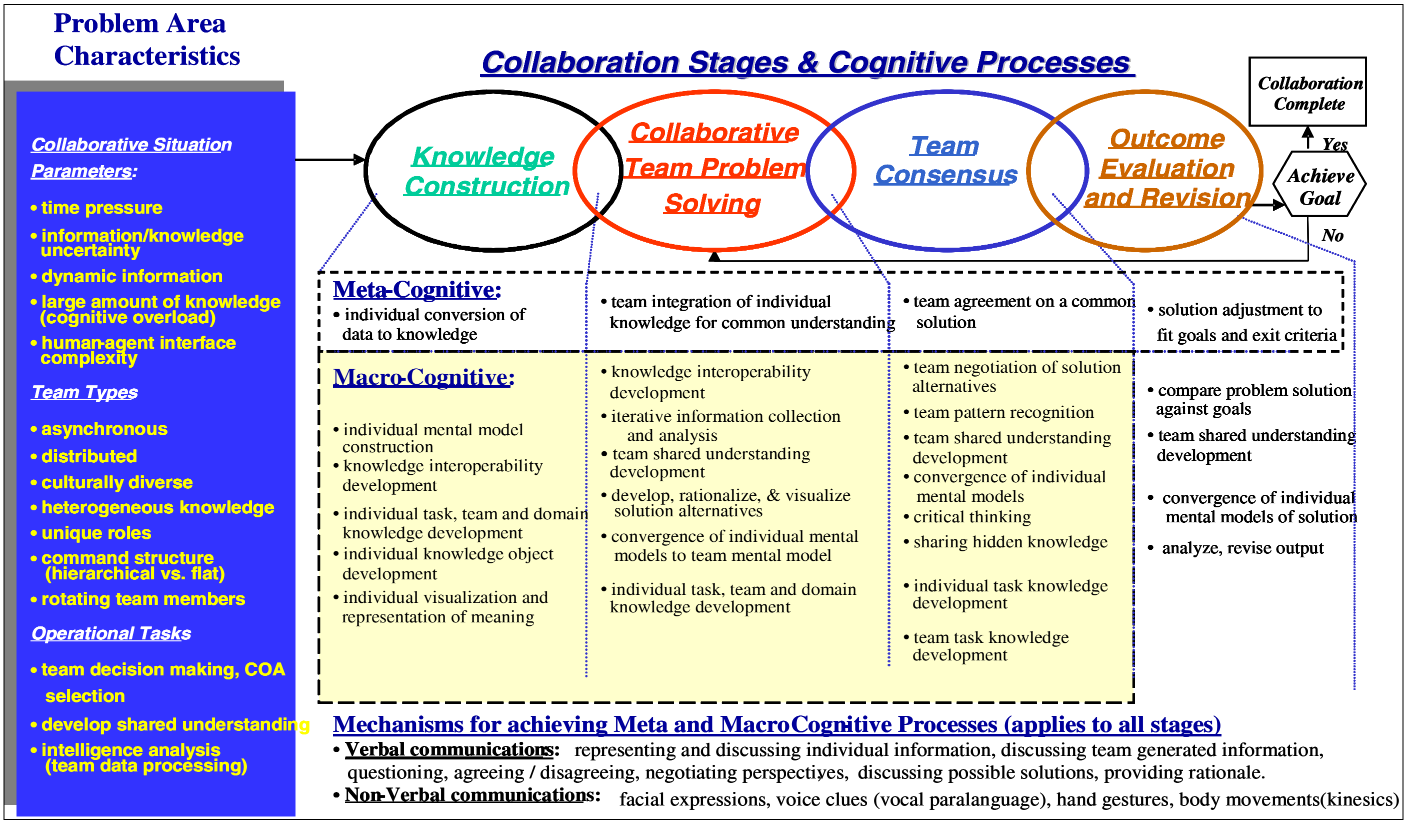

Figure 1. Model of Team Collaboration. (From Warner, Letsky, & Cowan, 2004).

Cognitive Complexity of Scenarios. Scenarios used for this research focus on detecting, identifying, and interdicting nuclear materials in open waters. The critical task involves the cognitively complex issue of discrimination, that is, how to determine the presence of contraband radiological material against a background containing multiple benign radiation sources. "Smoke detectors, radiant signs, and a container load of bananas all share the ability to be moved in commercial vehicles or vessels…and all three can cause radiation detectors to alarm." (Schwoegler, 206, p.4). For example, "smoke detectors contain small amounts of americium, radiant signs glow because they contain tritium, a radioactive hydrogen isotope, and bananas, contain a small fraction of potassium-40 which emits ionizing radiation." (ibid, p. 4).

Participants. The boarding officer boards the vessel with his laptop so he can collaborate with all other members of the team. This includes those who are located on the ship, but are physically spread out around different areas of the ship (while searching for contraband material and obtaining fingerprints of crew members), as well as the virtual members of the boarding team – the experts who are located at the different reachback centers. Since there are numerous commercial uses for certain radioactive sources, positive identification of the source in a short time is imperative. There is also pressure to conduct the MIO quickly so as to not detain the ship any longer than necessary.

Task. Data is collected on suspicious material, equipment, and people and sent to specific experts at distributed reachback centers. A network extension capability was utilized from the Coast Guard cutter to the boarding team; the network was able to reach back to Lawrence Livermore National Laboratory (LLNL) and Defense Threat Reduction Agency (DTRA) to assist in identification of suspect cargo. Support from the National Biometric Fusion Center was used to quickly and accurately discriminate between actual vessel crewmembers and non-crew suspect persons.

Experiment II: Air Warfare Decisionmaking

Air warfare decisionmaking is conducted in the combat information center (CIC) of a Navy ship. The team is responsibile for identifying and responding to a large number of air tracks under high time pressure. These air tracks can fit multiple hypotheses regarding the level of threat they pose to the battlegroup due to the high level of ambiguity associated with the data.

Incoming information arrives via various sensor systems (radar, electronic support measures system, identification friend or foe, etc.), and various reports, e.g., intelligence reports, passed by other platforms in the area. Communications between team members are passed as soon as information is received and updated reports are passed as soon as new information is obtained for any track. In a series of speech turns, five separate contacts may be discussed at various levels – initial reports, updated reports, sharing information on the response, or lack of response, by the contact to some action taken by the ship, etc.

Participants. Six collocated team members communicated with several non-collocated information sources, e.g., the battle group commander, the Saudi air tower, assets passing intelligence reports, other ships and friendly aircraft in the vicinity of the battlegroup, to gather additional information from them and keep them apprised of the unfolding scenario as they collaborated to identify air tracks.

Task. The global air warfare task involves identification and responding to numerous contacts. When an aircraft is detected, CIC personnel work as a team to determine the identity and to try to determine if the aircraft poses a threat. The high degree of ambiguity associated with contact information can often make threat assessment very difficult because many pieces of data can fit multiple hypotheses regarding threat assessment. The global response choices (that is, do nothing, monitor, take various actions to determine intent, or engage) are largely determined by the ship's orders and the current geopolitical situation. Specific actions depend on the local conditions and the relative positions of the inbound contact of interest and own ship.

RESULTS

Table 1 presents the number of speech turns for MIO and air-warfare tasks coded as representing each of the macro-cognitive processes included in the model. The large number of speech turns coded as categories 1-4 reflects the huge emphasis on individual knowledge construction that is required for both the MIO and air warfare tasks. Individual task development (itk) is defined as a team member asking for clarification to data or information, or response to a request for clarification. The large number of speech turns coded as itk (3) reflects the high degree of uncertainty inherent in both of these decisionmaking tasks.

An example of sharing hidden knowledge (17) occurred when the commanding officer (CO) issued an order to issue a verbal warning and "lock up" the inbound aircraft. The next speech turn involved the tactical action officer (TAO) replying "Yes, sir, we identified him as a com[mercial aircraft] earlier, we will go ahead and talk to him." In this situation, the TAO was gently reminding the CO of a critical piece of information that he had forgotten.

Evidence was found for all six categories that occur during the collaborative team problem solving phase (7-13), where teams integrate individual knowledge for team common understanding, indicating the role these cognitive processes play for teams who engaged in both tasks.

The small number of speech turns that were coded as cognitive processes that occur during the team consensus stage (14-18) and outcome evaluation and revision (19-21) stage indicates that course of action selection for air warfare and MIO tasks is not conducted in a collaborative manner.

Table 1. Cognitive Process Coding Tallies for Air Warfare and MIO Scenarios

	Macro-Cognitive Process Coding Categories	**Scen D-Run A**	**Scen D-Run B**	**CG -59**	**DDG-54**	**Nov 06**	**June 06**	**Sept 06**
	Knowledge Construction							
1.	Data to information (dti)	1	4	-	37	2	5	-
2.	Individual mental model (imm)	8	11	18	25	1	7	8
3.	Individual task knowledge development (itk)	25	30	31	29	35	7	47
4.	Team knowledge development (tk)	11	5	18	1	3	5	8
5.	Knowledge object development (ko)	-	-	-	-	-	2	8
6.	Visualization and representation (vrm)	-	-	-	-	-	-	-
	Collaborative Team Problem Solving							
7.	Common understanding (cu)	-	6	-		2	6	7
8.	Knowledge interoperability (kio)	-	5	-	1	2	-	10
9.	Iterative collection and analysis (ica)	1	11	-	-	6	4	14
10.	Team shared understanding (tsu)	1	17	28	34	3	2	3
11.	Solution alternatives (sa)	-	3	-	-	6	-	-
12.	Convergence of mental models (cmm)	1	-	-	-	1	-	-
13.	Agreement on common solution (cs)	-	2	-	-	1	-	-
	Team Consensus							
14.	Team negotiation (tn)	-	-	-	-	4	-	-
15.	Team pattern recognition (tpr)	-	-	-	-	-	-	-
16.	Critical thinking (ct)	-	-	-	-	-	-	-
17.	Sharing hidden knowledge (shk)	-	2	-	-	-	-	-
18.	Solution adjustment against goal (sag)	-	-	-	-		-	-
	Outcome Evaluation and Revision							
19.	Compare solution options against goals (csg)	-	1	-	-	-	-	-

20.	Analyze, revise solutions (aro)	-	-	-	-	-	-	-
21.	Miscellaneous (misc)	38	27	57	61	6	-	-
22.	Issue order regarding course of action (coa)	7	5	17	37	-	-	2
23.	Request take action (rta)	3	2	18	8	1	2	11
	Totals	96	131	187	233	73	40	118

New Coding Categories. Several new coding categories were added to the set of macro-cognitive process definitions that are included in the model. The first involves a person in command issuing an order (22, in Table 1) regarding a course of action, that is, a person with higher rank tells them to take some specific action against a potential threat track. This could include issuing verbal warnings, illuminating/ locking-on with radar, developing a firing solution, covering with missiles, etc. This category also includes reporting they have taken the action. A second new coding category is requesting a team member take some action (23) which involves telling or asking a team member to do something. The difference between these two categories is that the later does not involve a direct action against a threat and is not an order. An example is, "Can you try and change 7006 to assumed hostile."

Table 2 presents an excerpt of the communications coding from the MIO scenario where the team is developing solution alternatives by using data to justify a solution. First (1), individual team members (TMs) are developing team shared understanding by clarifying data regarding the degree of danger inherent in the material discovered and using data to justify a solution (2) and exchanging knowledge among each other, i.e., the material needs to be confiscated (3), based on information provided by one of the remote centers (the material needs to be handled carefully). An individual exchanges knowledge with other TMs (4) to develop knowledge interoperability regarding whether the Coast Guard ship has a suitable storage area for the confiscated material (5). Finally, TMs combine individual pieces of knowledge to achieve a common understanding (6) regarding the next action to be taken.

Table 3 presents an excerpt that represents the team developing knowledge interoperability and agreement on a final plan.

Table 2. Excerpt from MIO Scenario: Communications Coding for Developing Solution Alternatives

	MIO Team Communications		**Cognitive Process Coding**	
	Speaker		Code	
1	DTRA	Cesium 137 can be used to make an RDD. If there are no explosives, then it is not configured as a weapon yet. Recommend material be confiscated.	tsu sa	*Team shared understanding*: discussion among all team members on a particular topic or data item. Develop, rationalize and visualize *solution alternatives*; using data to justify a solution
2	BO	Roger will confiscate.	itk	*Individual task knowledge* development; individual TM clarifying data.
3	BO	Make sure you handle carefully. Cs-137 is an external gamma hazard.	kio	*Knowledge interoperability*: TMs exchanging *knowledge* among each other.
4	BO	Roger. Will take precautions.	kio	*Knowledge interoperability*: TMs exchanging *knowledge* among each other.
5	SOCOM	Does CG ship have proper storage area for material confiscated?	itk	*Individual task knowledge* development: individual TM clarifying data, asking for clarification.
6	SOCOM	Search team will report size of material and its current containment condition; then make recommendations.	cu	Team integration of individual TM knowledge for *common understanding*; one or more TMs combine individual pieces of knowledge to achieve common understanding.

Table 3. MIO Scenario: Knowledge Interoperability Development and Agreement on a Final Plan

	MIO Team Communications		**Cognitive Process Coding**	
	Speaker		Code	
1	BO	Negative for explosives Station 2.	kio	*Knowledge interoperability*: TMs exchanging *knowledge* among each other.
2	LLNL	Finally received RAD data from station 2.	kio	*Knowledge interoperability*: TMs exchanging *knowledge* among each other.
3	SOCOM	Will need to resolve RAD containment hazard if it exists.	cu	Team integration of individual TM knowledge for *common understanding*; one or more TMs combine individual pieces of knowledge to achieve common understanding.
4	DTRA	If you have plutonium, you need to confiscate. It's an alpha hazard, but still must be handled carefully.	ica	*Iterative information collection and analysis; collecting and analyzing information to come up with a solution but no specific solution exists.*
5	BO	Roger.	Misc	Acknowledge report.
6	DTRA	By the way, if plutonium is in solid metal	ica	Team shared understanding development – discussion among all

		form, your team can handle safely with rubber gloves and a dental face mask, depending on how much is there.		team members on a particular topic or data item.
7	BO	Talking to search team to see if this is within their capabilities or if we will need outside assets.	kio	*Iterative information collection and analysis; collecting and analyzing information to come up with a solution but no specific solution exists.*
8	LLNL	Hazard is probably minimal, can isolate and confiscate.	cs	*Team agreement on a common solution – all team members agree on the final plan.*

DISCUSSION

Course of action selection during the air warfare tasks tends to be done less collaboratively than in other decision-making domains, due to the inherent time pressure to make decisions and take actions. Decisions tend to be made unilaterally by the tactical action officer or the commanding officer — sometimes these two collaborate, but course of action decisions do not typically involve discussion with the rest of the team. Knowledge construction and collaborative team problem solving are done collaboratively but course of action selection entailed very little collaboration for the air warfare tasks due to the speed of the potential threat aircraft. When actions need to be taken very quickly in an attempt to determine the intent of an inbound track, and a series of gradually escalating actions are required, time is not available to discuss alternative courses of action.

Responding to air warfare scenarios consists of situation assessment and action selection. Klein (1989) found that when decisionmakers use a recognition-primed decision-making strategy, usually the situation itself either determines or constrains the response options and that experienced decisionmakers make up to 90% of all decisions without considering alternatives. If the situation appears similar to one that the decision maker has previously experienced, the pattern will be recognized and the course of action is usually immediately obvious. The recognition primed model of decisionmaking fuses two processes — situation assessment and mental simulation (Klein, 1993). In the simplest case the situation is recognized as familiar or prototypical, using feature matching, and the obvious response is implemented. In a more complex case the decisionmaker performs a conscious evaluation of the response, using mental simulation to uncover problems prior to implementing the response. In the most complex case the evaluation reveals flaws requiring modification, or the option is judged inadequate and rejected in favor of the next most typical reaction.

Very few of the cognitive processes included in the team consensus stage were evident in the team communications that transpired during these two collaborative tasks. Both air warfare and MIO tasks are considered to be tactical level tasks; that is, these operations are conducted within a very short time period, typically 24 hours or less. In contrast, operational and strategic level operations occur over longer time intervals, e.g., weeks or months. More of the macro-cognitive processes included in the collaborative team problem solving and team consensus stages may occur in collaborative problem-solving tasks that span a longer time period.

Anther possible explanation for the lack of evidence for the macro-cognitive processes associated with the team consensus and outcome evaluation and revision stages is that the MIO experiments have not focused on the command and control part of the overall task. The focus for the MIO experiments has been on assessing new technologies and not on human decisionmaking. In the most recent MIO experiment, conducted in June 2007, the human decisionmaking part of the MIO was included. We expect to see evidence for more of the macro-cognitive processes in follow-on MIO experiments.

CONCLUSIONS

Analysis of data captured from teams performing their tasks in a collaborative environment can provide valuable insight into what constitutes effective collaborative performance. This understanding can then be used to develop technology to support this cognitive activity, develop tools to reduce cognitive workload, and techniques and processes to improve information exchange among collaborating members. Future plans include additional analysis for different tasks and analysis of the contribution made by providing collaborative tools to support teams when performing these collaborative tasks.

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