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Understanding Patterns of Team Collaboration Employed to Solve Unique Problems / 13th International Command and Control Research & Technology Symposium, "C2 for Complex Endeavors"

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13th International Command and Control Research & Technology Symposium
"C2 for Complex Endeavors"

Understanding Patterns of Team Collaboration Employed To Solve Unique Problems

Tracks in priority order: Topic 4: Cognitive and Social Issues; Topic 1: C2 Concepts, Theory, and Policy; Topic 9: Collaborative Technologies for Network-Centric Operations

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14. ABSTRACT
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Understanding Patterns of Team Collaboration Employed To Solve Unique Problems

Susan G. Hutchins, Tony Kendall, and Alex Bordetsky

Abstract

'Macrocognition' is a nascent area of knowledge engineering that focuses on understanding how cognition emerges in natural environments. One goal for studying macrocognition is to understand the complexity entailed in inter- and intra-individual cognition. The goal of the research reported here is to better understand how team collaboration influences and facilitates the team's task performance. In this paper we describe our analysis of several complex team collaboration tasks: (a) firefighters from the Fire Department of New York on September 11, 2001, (b) air warfare teams on an Aegis ship, and (c) the team collaboration entailed in conducting Maritime Interdiction Operations. Team communications that transpired during three complex problem solving situations were analyzed to understand how teams collaborate to create new knowledge and decide on a course of action during complex, one-of-a-kind problems. Communications were analyzed using definitions of cognitive processes included in a conceptual model of team collaboration. These processes include: (1) individual knowledge building, (2) developing knowledge interoperability, (3) developing team shared understanding, and (4) team consensus. The way the team's cognitive behavior maps to the model of team collaboration is discussed along with differences in patterns of collaboration for different decision-making domains.

INTRODUCTION

'Macrocognition' is an emerging field within the area of cognitive engineering that describes the way cognition occurs in naturalistic, or real-world, decision-making events. Macrocognition is defined as the internalized and externalized high-level mental processes employed by teams to create new knowledge during complex, one-of-a kind, collaborative problem solving (Letsky, Warner, Fiore, Rosen, and Salas, 2007). The goal for this research is to understand the role of cognition in teams who are collaborating to solve complex, one-of-a kind problems, such as: (a) firefighters responding to the events of September 11, 2001, (b) a boarding party conducting Maritime Interdiction Operations (MIO), (c) a Navy shipboard combat information center team responding to air warfare threats, or (d) an ad hoc inter-agency team responding to a humanitarian assistance/ disaster relief situation. This research focuses on the contextually bound processes entailed in sense making, managing uncertainty, and related cognitive processes entailed in responding to emerging events that occur in dynamic decision-making situations (Fiore, Rosen, Salas, Burke, & Jentsch, 2008).

Team communications data from three decision-making situations (a series of field experiments, a series of laboratory experiments, and a real-real event) where a team of people collaborate to solve a complex problem were analyzed and reported on previously (Hutchins, Bordetsky, Kendall, and Garrity, 2007). This paper extends our analysis by examining similarities and differences in team collaboration patterns across three decision-making domains. In this series of studies we analyzed data obtained from teams and tasks characterized by the following descriptions. Team types include teams who employ asynchronous communications among distributed team members, may be culturally diverse, and where team members bring their heterogeneous knowledge to bear to solve the problem. In these complex situations each team member plays a unique role, team members operate within a command structure, and in some situations involve rotating team members. Collaborative problem-solving situations include time pressure, information/ knowledge uncertainty, dynamic information, large amounts of knowledge (cognitive overload), and human-agent interface complexity.

The purpose of this effort is to provide support to the Office of Naval Research (ONR) Collaboration and Knowledge Integration (CKI) Program's goal to improve the effectiveness of team decision making in complex, data-rich situations. This includes developing a better understanding of the cognitive processes employed when teams collaborate to solve problems. The focus is on FORCEnet type issues such as the MIO task that entails detecting a moving vessel emitting signs of ionizing radiation, followed by a boarding of that vessel. The vessel is boarded to take fingerprints or other biometrics and to perform a search for contraband. Results of the boarding may need to be communicated back to command elements on land and to remote experts for analysis. After successful analysis, key decision makers may collaborate to determine the appropriate course of action.

Team Collaboration

Collaborating teams are ubiquitous with examples of tasks requiring collaboration encompassing an ever increasing range of situations. Medical specialists in India provide second opinions and interpret medical results at times when medical specialists in the U.S. are in short supply (e.g., during weekends or in the middle of the night) (Friedman, 2006) and accountants half-way around the globe prepare income taxes at a fraction of the cost compared with U.S. accountants (Friedman, 2006). Scientists collaborate with researchers on a remote space station; and people on land collaborate with robotic geologists (Clancy, 2004). Military teams collaborate on plans and execution for a wide variety of mission areas. These teams all have characteristics in common – they engage in tasks that involve critical decisions and must often coordinate their activities to accomplish these tasks effectively.

Model of Team Collaboration

In this paper we report on research conducted to assist in evaluating and refining the ONR CKI Program's model of team collaboration developed by Warner, Letsky, and Cowen (2005). This conceptual model emphasizes the cognitive aspects of team collaboration and includes the major human decision-making processes used during team collaboration. Operational tasks performed by teams whose collaborative cognitive behavior was analyzed include team data processing, team decision making, course of action selection, and developing shared understanding. The goal for this research is to: (a) gain insight into where the model can be improved and (b) determine how the macrocognitive processes included in the model contribute to team performance. The focus of the collaboration model is on knowledge building among the team members and developing team consensus for selection of a course of action.

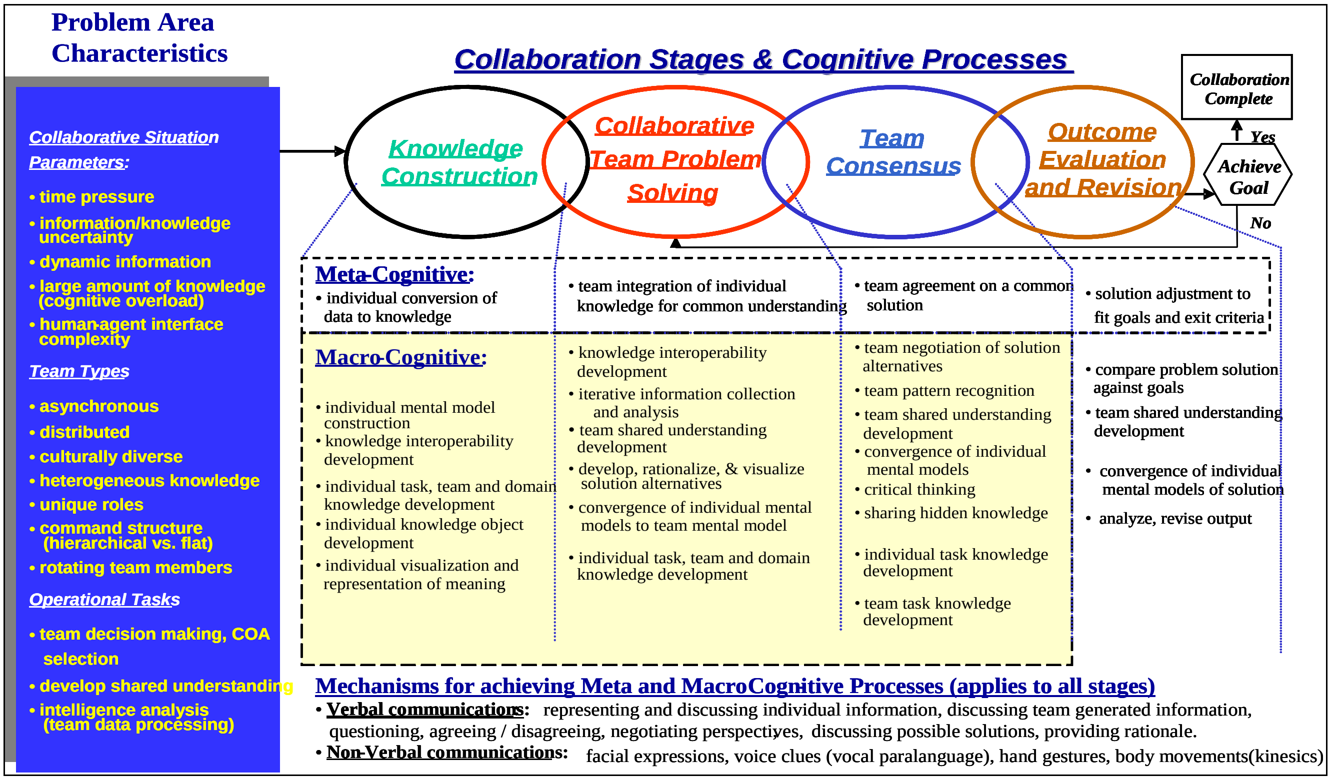


Figure 1. Model of Team Collaboration. (From Warner, Letsky, & Cowen, 2004).

Taking Actions as Part of Problem Solving

Many tasks require rapid and accurate coordination of information and behavior to successfully cope with the demands of time-compressed, ambiguous situations with the threat of fatal consequences. The types of tasks that are described by the model of team collaboration are naturalistic decision making tasks, that is, where the focus is on recognition of situations and reflection processes where there is a continuous shift between thought and action (Lipshitz and Ben Shaul, 1996; Espevik, Johnson, Eid, and Thayer, 2006). In naturalistic decision-making tasks, where a recognition-primed decision strategy is typically employed, the current situation is compared with previously encountered situations, and actions that were taken in past similar situations that were successful in those situations, and the associated outcomes that were produced are used to make rapid decisions. Decision makers use their previous experience to implement different solutions to a series of problems (Espevik et al, 2006).

Orasanu (1994) observes that team communications are used to accomplish tasks and also indicate the cognitive processes of individual team members. Following Orasanu, team communications serve three main functions related to problem solving: sharing information, directing actions, and reflecting thoughts. Sharing information, in the three decision-making domains covered in this paper, is used to inform the other team members of the evolving status of the situation regarding a team member's understanding of the situation and to update team members as the team takes various actions to deal with the problem. Depending on the decision-making domain, much of this communication relies on standard operating procedures to provide standardized ways of communicating, types of information to share, and pre-defined actions to be taken in response to specific situations.

Directing action is the second critical function of team communications. This includes direct commands for routine actions for a wide variety of situations. It also includes action commands for dealing with problems, such as gathering information for a decision. In line with Orasanu's analysis, the third function of team communications is sharing what one is thinking, as opposed to passing on information obtained from an external source. This type of communication is essential to developing a shared problem model among team members.

METHOD

Verbatim transcripts were analyzed from two series of experiments, and one real-world event where teams collaborated to solve a complex problem: (a) MIO, (b) air warfare decision making, and (c) the communications that transpired between the firefighters of the Fire Department of New York (FDNY), on Sept. 11, 2001 (Fire Department of the City of New York, 2001). Transcripts included communications that occurred between all team members as well as with decision makers at the distributed sites. Team communications data were analyzed and coded using the cognitive process definitions developed by Warner, et al., (2004). This research builds on previous work to validate this model (Warner, et al, 2004). The current effort uses a similar methodology applied to three different decisionmaking scenarios. For definitions of the macro-cognitive processes include in the model see Hutchins, Bordetsky, Kendall, and Garrity, 2007.

Team Collaboration Tasks

In all three problem-solving tasks decision making is difficult because the available information is often incomplete or ambiguous. Team members possess highly specialized knowledge that must be synthesized for all team members to develop a shared understanding of the problem: The inherent time pressure in these types of tactical situations creates a challenging decision-making situation. Problem solving situations that make use of multiple information sources and require collaborative analysis to develop a team shared understanding of the task, the environment, and the status of other collaborators, enhance the richness of the communications. A key enabler of collaborative decision making is a virtual aggregation of individuals, organizations, systems, infrastructure, and processes to create and share data, information, and knowledge that is needed for the team to plan, execute, and assess actions/operations. This team collaboration should enable a leader to make decisions better and faster than were previously possible.

Collaborative information environments are intended to transform collaborative planning and decision making from a relatively sequential, hierarchical process to a more parallel approach that allows 'virtual' collaborative interaction by all organizations regardless of their location. Important components of collaborative environments include collaborative decision support and situational awareness tools to support the overall task.

Cognitive Complexity of Scenarios

Brief descriptions of the decision-making domains analyzed for this effort are provided below.

Maritime Interdiction Operations. Scenarios used for the MIO experiments 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. A variety of benign sources, such as smoke detectors, radiant signs, mantles used for camping lanterns, and a container load of bananas all can cause radiation detectors to alarm. 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" (Schwoegler, 2006, p. 6).

Technical expertise, provided by remotely-located experts, is required to interpret the radiological signals emitted from complex detectors to enable on-site personnel to make the fine discriminations required. The boarding party is comprised of Coast Guard officers, as well as members of other local law enforcement agencies who collaborate with remotely-located experts. During a MIO, distributed experts collaborate to determine whether the detected material represents a risk and support the on-site operators in deciding how to handle suspect material. Performing these complex discriminations is made possible by the collaborative capability provided by the collaborative workspace in terms of bringing remote expertise to the vessel undergoing the search and the ability to rapidly send and receive communications and data files between a diverse team of experts who all bring their respective expertise to bear to deal with a potentially high-threat situation.

The objective of the MIO experiments is to evaluate the use of networks, advanced sensors, and collaborative technology for conducting *rapid* MIOs. Specifically, the ability of a boarding party to rapidly set up ship-to-ship and ship-to-shore communications in order to simultaneously search for radiation/ explosive sources and conduct biometrics identification while maintaining contact with the boarding vessel and remote collaborators. The goal is to enable geographically distributed command centers and subject matter experts to collaborate with the boarding party in real time, facilitating situational understanding, course of action selection, and execution (Bordetsky, Clement, and Vega, 2007).

Air Warfare. Air warfare decisionmaking is conducted in the combat information center (CIC) of a Navy ship. The team is responsible 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.

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. 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 (Hutchins, Morrison, & Kelly, 1996). 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 depicts the results of analysis of three collaboration tasks: four air warfare teams, three MIO teams, and the collaborative decision-making that transpired between firefighters from the FDNY. The percentage of speech turns for air warfare, MIO, and the 9-11 firefighting tasks coded as representing each of the macrocognitive processes included in the model is presented in Table 1. Analysis of the communications that transpired between firefighters and the dispatcher on September 11 indicates these firefighters used of more of the cognitive processes included in the model compared to teams during MIO experiments and air warfare decision making. (However, differences in the percentages of the cognitive processes used may also reflect the larger sample size of speech turns in the 9-11 data. The number of speech turns for each team is included in the bottom row of Table 1.)

In general, the large number of speech turns coded as categories 1-4 of Table 1 reflects the huge emphasis on individual *knowledge construction* that is required for all three tasks. Of particular interest is the large number of speech turns coded as *individual task knowledge* (*itk) development* which reflects the high degree of uncertainty inherent in all three decision-making tasks. (*Itk* is defined as a team member asking for clarification to data or information). These high percentages of use of *itk* by decision makers in all three task domains indicate these teams devoted a large amount of effort to trying to manage this task uncertainty.

Table 1. Percentage of Macrocognitive Processes Used by Teams for Three Different Tasks.

		Air Warfare Scenarios				MIO Scenarios			Sept. 11, 2001
	Macrocognitive Process Coding Categories	**Scen D Run A**	**Scen D Run B**	**CG 59**	**DDG 54**	**Nov 06**	**June 06**	**Sept 06**	**Firefighters[1] 9-11**
	Knowledge Construction								
1.	Data to information (dti)	02	04	-	22	03	13	-	<01 (2)
2.	Individual mental model (imm)	14	11	14	15	01	18	07	02 (14)
3.	Individual task knowledge development (itk)	43	29	24	17	52	18	40	41 (325)
4.	Team knowledge development (tk)	19	05	14	01	04	13	07	27 (210)
5.	Knowledge object development (ko)	-	-	-	-	-	05	07	-
6.	Visualization and representation (vrm)	-	-	-	-	-	-	-	-
	Collaborative Team Problem Solving								
7.	Common understanding (cu)	-	06	-		03	15	06	02 (16)
8.	Knowledge interoperability (kio)	-	05	-	01	03	-	08	01 (8)
9.	Iterative collection and analysis (ica)	02	11	-	-	09	10	12	-
10.	Team shared understanding (tsu)	02	16	22	20	04	05	03	<01 (6)
11.	Solution alternatives (sa)	-	03	-	-	09	-	-	02 (13)
12.	Convergence of mental models (cmm)	02	02	-	-	01	-	-	03 (22)

13.	Agreement on common solution (cs)	-	-	-	-		-	-	<01 (1)
	Team Consensus								
14.	Team negotiation (tn)	-	-	-	-	06	-	-	<01 (1)
15.	Team pattern recognition (tpr)	-	-	-	-	-	-	-	<01 (3)
16.	Critical thinking (ct)	-	-	-	-	-	-	-	<01 (3)
17.	Sharing hidden knowledge (shk)	-	02	-	-	-	-	-	<01 (5)
18.	Solution adjustment against goal (sag)	-	-	-	-		-	-	-
	Outcome Evaluation and Revision								
19.	Compare solution options against goals (csg)	-	01	-	-	-	-	-	<01 (2)
20.	Analyze, revise solutions (aro)	-	-	-	-	-	-	-	<01 (1)
21.	Miscellaneous (misc)	40	21	30	26	08	-	-	52 (849)
	Decision to Take Action								
22.	Issue order regarding course of action (coa)	12	05	13	22	-	-	02	12 (92)
23.	Request take action (rta)	05	02	14	05	01	05	09	07 (53)
	Total number of speech turns for each team	96	131	187	233	73	40	118	777

[1] Numbers in parentheses indicate the number of speech turns in each macrocognitive category.

A majority of the communications for 9-11 involved *knowledge construction* and significantly less team communications for the other stages: collaborative team problem solving, team consensus, and outcome evaluation and revision. Looking across all three decision-making domains, evidence was found for all seven macrocognitive processes that occur during the *collaborative team problem solving* phase (categories 7-13 in Table 1), where teams integrate individual knowledge to develop a team common understanding, indicating the role these cognitive processes play for teams who engaged in all three tasks. Far fewer speech turns were coded as representing processes included in the *team consensus* phase of collaboration (categories 14-18 in Table 1). The macrocognitive codes with the smaller percentages show that the FDNY did not reach the later stages included in the team collaboration model. Most of their efforts were aimed at trying to figure out what was going on around them, which focused on gathering information and developing knowledge, and creating a mental model within which they could work. The small percentage of speech turns that were coded as macro-cognitive processes associated with *team consensus* and *outcome evaluation and revision* indicated that the course of action selection phase of air warfare, in particular, and to a lesser degree, MIO and firefighting, is not conducted in a collaborative manner.

Patterns of Macrocognitive Processes Used by Firefighters

One striking difference between the 9-11 data and the data from the two experiments (air warfare and MIO) is the difference in the number of speech turns coded as *individual task knowledge* (*itk*) development. Twenty-six percent of the total number of speech turns for the combined air warfare and MIO experiments were coded *it*k compared to a significantly larger percentage, i.e., 41%, for 9-11 data ($p<.0001$, $z=6.5$, combined $n=1555$). The second largest difference in the use of the macrocognitive processes was, or *team knowledge* (*tk*) *development*, which comprised 7% for the combined experimental groups and 27% for the 9-11 data. Again, the difference was significant ($p<.0001$, $z=11.03$, $n=1555$). *Itk* and *tk* combined represent 32% of the experimental teams' speech turns and a majority of speech turns for the 9-11 team (69%). A majority of the communications for 9-11 involved *knowledge construction* because of the completely unanticipated nature of the unfolding terrorist attack scenario.

To see the full cycle of the collaboration stages and macrocognitive processes at work in the team collaboration for the FDNY on Sept. 11, the larger problem facing firefighters of search and rescue, and extinguishing the fire in the twin towers of the World Trade Center (WTC) needs to be broken into four smaller problems that correspond with each event that transpired that day. These events and the problems and resultant tasks to be performed to deal with each event are listed in Table 2. The FDNY team's cognitive processing of the tasks for each of these four events follows the collaboration stages in the team collaboration model. For example, when the first plane hit the WTC, the problem involved determining what happened and creating a mental model within which the FDNY could work. With each new event (each aircraft hitting the WTC towers, collapse of the North and South Towers) the team had to form a new team problem model.

Table 2. Events, Team Mental Model and Tasks for FDNY on Sept 11, 2001.

Time	Event	Team Mental Model	Situation/ Tasks
8:47-9:02	First plane hit the World Trade Center	Between plane impacts, it still could have been an accident	• Evacuate South Tower • Gain knowledge of situation • Assign units to respond to the scene
9:03-9:58	Second plane hit the World Trade Center	Definitely an attack but buildings could still withstand the impacts	• Had to divide their resources between the two tower lobbies for command posts
9:59-10:28	South Tower collapsed	Complete chaos	• How much was lost? • How many people were lost? • Complete loss of SA (including C2) • Evacuate the North Tower
10:29-11:07	North Tower collapsed	Complete chaos	• No idea of the breadth of the loss, shock and grief • Rescue for any lost in the rubble

Firefighters used 19 of the 23 macrocognitive processes, listed in Table 1, included in the model [Note: Table 1 includes the two new macrocognitive codes that were a product of this research, 22 and 23]. This includes all codes except: *knowledge object* (*ko*) *development*, which requires pictures and icons; *individual visualization and representation* of meaning (*vrm*), which requires visual aids; *iterative information collection and analysis* (*ica*), which entails collecting and analyzing information without mentioning a solution, and *solution adjustment against goal* (*saag*) and exit criteria, where the team compares the solution option against goal and exit criteria. These four macrocognitive processes did not pertain to the FDNY radio communications for either task- or standard operating procedures (SOP)-specific reasons.

Both *ko* and *vrm* are not possible on the radio (because the handie talkies do not include a video screen), but are used in the incident command center in the lobby of the two towers using the board with the location of the fire, operations post, staging area, and responding units, and also at the dispatcher's office with the map of the location of all the responding units. No communications were coded as *ica* because use of the FDNY highly-refined SOP dictates that firefighters always comment and collaborate towards a solution with each speech turn (in other words, they always noted what they were doing about a reported situation, as they reported on a situation), due to the inherent time crunch. In terms of use of *saag*, the firefighters did not think they needed to think about their exit strategy as they never got to complete their tasks.

Of the total 1620 total speech turns for the firefighters, 849 (52%) were coded as miscellaneous, and were thus removed from further analysis, leaving 771 speech turns. (Communications were coded as *misc* when it was simply an acknowledgement of receipt of the message, or an initial attempt to get the attention of the person for whom the message was intended. These misc communications are important for closed-loop communications, for example, where it is important to let the message sender know the message was received, e.g., "roger," or "10-4.")

The most frequently used macrocognitive processes, in order of usage included: (41%) *iterative team knowledge development* (*itk*): indicating the team was asking lots of questions. This raises the issue of how to alleviate the need for so many questions and the very high level message traffic? (27%) – *Developing team knowledge* (*tk*): which refers to sharing knowledge with fellow firefighters and passing knowledge back to the dispatcher; (12%) – *Course of action* (*coa*): telling the dispatcher and/or other responding units what to do; (7%) – *Request take action* (*rta*): Requesting something of the dispatcher or responding units; (3%) – *Constructing team mental model* (*cmm*): (2%) – Developing *common understanding* (*cu*); and (2%)– *Individual mental model* (*imm*): Individuals contributing to the team's mental model.

Taking Actions as Part of Problem Solving

Much of the radio communication revolves around asking fellow firefighters to respond or to do something towards the team's goal. This is seen in codes 22 and 23 in Table 1: *course of action* (*coa*, 12%) and *request to take action* (*rta*, 7%). These codes show the firefighters taking actions to move toward accomplishing their end goals, with the knowledge that they do not have to carry out the plan of action themselves with the capacity to ask for support from their fellow responders. These new macrocognitive categories both entail a decision by the team member that an action needs to be taken.

Patterns of Team Collaboration

Since the FDNY team communications data from Sept 11 is richer than what can be represented by numbers in a table, we developed a way to graphically depict the team's pattern of collaboration to represent their traversing through the stages of the model of team collaboration. One way to gain insight into a team's cognitive processes employed during collaboration is to examine the pattern of communications, reflecting the macrocognitive processes as they communicated and responded to the fires in the towers of the WTC. Following our decision to divide the 2.5 hours of team communications into four phases corresponding to the four major events of 9-11, a subset of the 771 speech turns was selected to characterize and graphically represent the team's cognitive processing of those events in relation to the macrocognitive processes included in the model. Criteria for selecting speech turns were when (a) a new topic was discussed or (b) a significant request was made for a team member to take action or a course of action was initiated. One of the authors read through the transcript and noted each time a new topic or event occurred in the transcript or a significant course of action was issued. A second author reviewed the communications selected for inclusion in these figures and made some minor adjustments.

Figures 2a and 2b depict this high-level representation of the firefighters' collaborative pattern as they responded to the first event: When the first plane hit the North Tower of the WTC. The goal was to show the order in which the firefighters used the macrocognitive processes during the first phase of the Sept. 11 attack to represent the flow of their team cognition in response to the situation. This figure (2a-b) represents the macrocognitive processes employed by the FDNY team during the first 16 minutes of the transcript which includes 209 speech turns: This equals a mean of 13 speech turns/minute, indicating the rate of communications was fairly dense. We see that the collaborative process was highly iterative in that the team moved back and forth many times between the knowledge construction stage and the other stages, and also initiated several actions (courses of action/ requests to take action) as depicted in the last column: decision to take action.

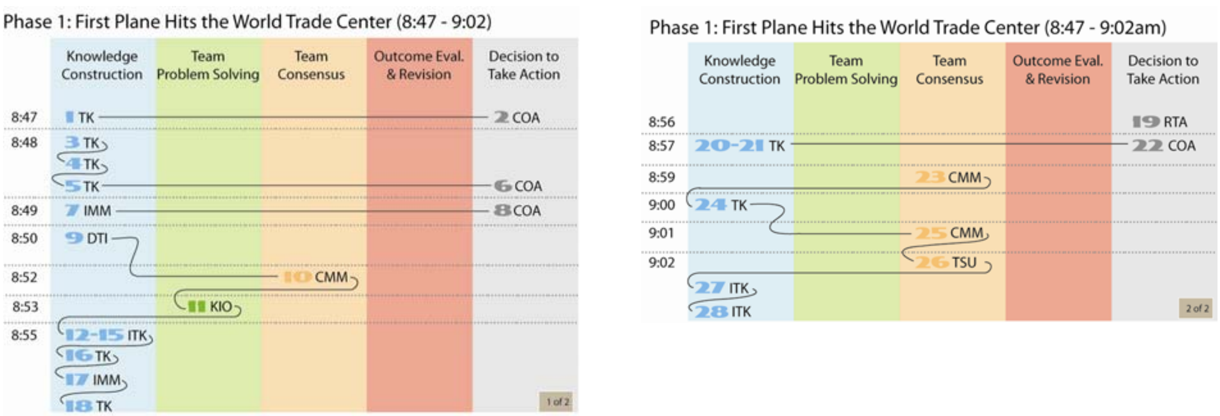


Figure 2a-b. Pattern of Team Collaboration Used by Firefighters on Sept. 11.

The lines represent the order in which the team moved through the macrocognitive stages included in the model. For example, in Figure 2a, the first speech turn involved the initial statement that "We just had a plane crash into upper floors of the World Trade Center." (*team knowledge*, *tk*) In this same speech turn, this firefighter issued the *course of action* to "Transmit a 2nd alarm and start relocating companies into the area." (Fire Department of the City of New York, 2001). This initial sizing up of the situation resulted in the immediate decision to do something about the situation (e.g., issue a *coa* to bring more firefighting assets to the scene).

The goal for developing this set of figures was to provide a sense of how the team progressed through the phases included in the model as they dealt with their task. Two new coding categories are included in these figures (these new categories were added as a result of the analysis conducted for the three tasks reported here). Issuing a *course of action* (*coa*) and *request take action* (*rta*) are the by-product of the previous cognitive processing that occurred up to the decision to issue the *coa*/*rta*. Therefore, *coa* and *rta* are represented in a fifth column – outside the four columns that represent the four stages included in the original model of team collaboration.

At 08:47 Battalion 1 called the Manhattan dispatcher to report the crash (*team knowledge development*, *tk*) and to request a second alarm, providing more units at the scene (*course of action*, *coa*). As more units called in to report the crash (various *tk*'s), the dispatcher was able to form a mental model of what had occurred. Relaying knowledge back to the dispatcher is critical as they are not located at the scene of the attack; anything the dispatcher knows comes from field reports from the firefighters.

Once on site it became clear to the firefighters that the crash might have been an intentional terror attack (*individual mental model construction*, (*imm*), and this caused the team's mental model to change (*convergence of individual mental model* (*cmm*) to a team mental model,). In a matter of minutes the FDNY moved through all four stages of the model of team collaboration: *knowledge construction* and *collaborative team problem solving* into *team consensus* and *taking action* as the team of firefighters agreed that more units were needed to save the many people trapped inside the buildings. Their speed of collecting information and making decisions saved countless lives in various buildings at the WTC Complex.

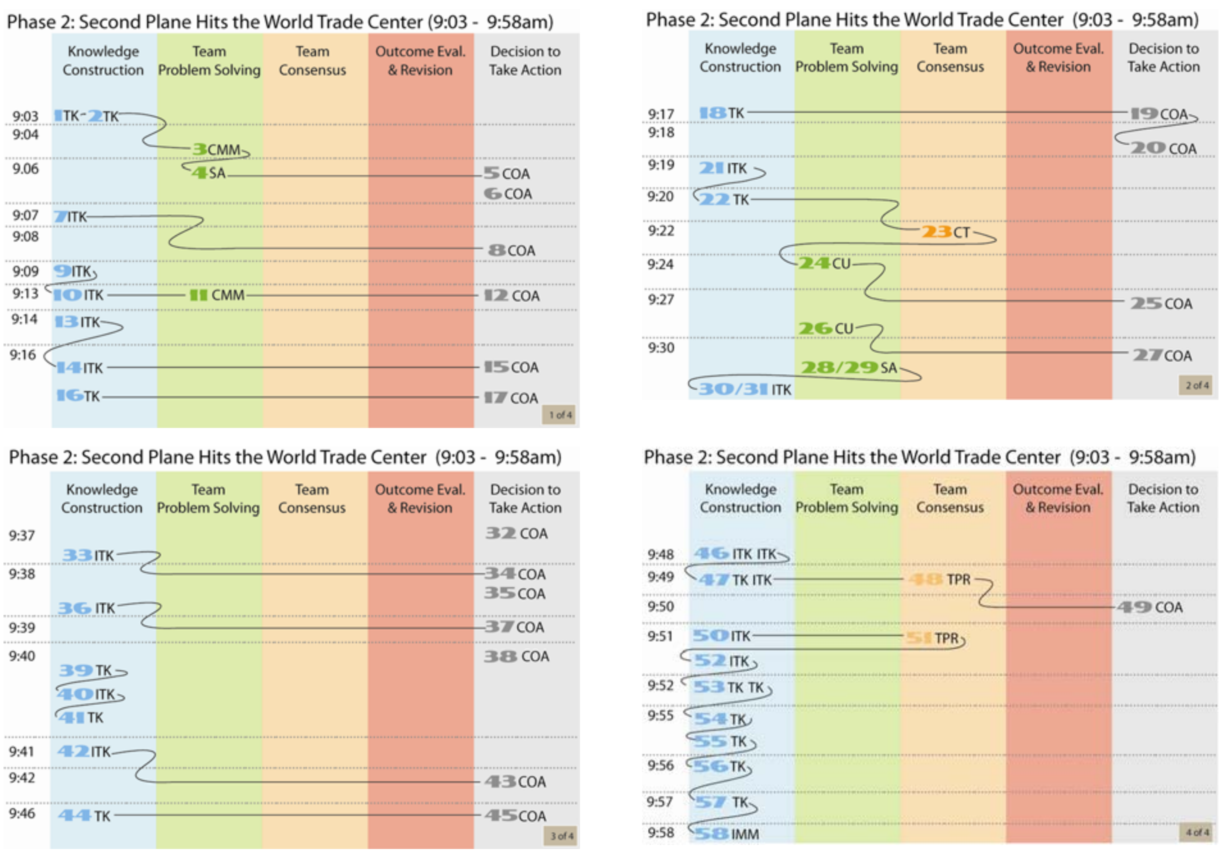


Figure 3a-d. Collaboration Pattern of Firefighters (2nd Plane hits North Tower).

Moving into *taking action*, they called for third and fourth alarms, revising their initial plan. Furthermore, when the second plane hit the South Tower, they had to further re-evaluate their solution, calling for a fifth alarm, and divide their resources between the two tower lobbies for command posts. Looking at the attack on the WTC on Sept. 11 as one large problem, the FDNY never reached the ultimate *outcome evaluation and revision* stage. Their mental model did not include the possibility that the buildings would completely collapse. The firefighters were under the impression that they were working within a much larger time frame.

Figures 3a–3d show a sample of the team communications during phase two of the attack on the WTC. For example, the communications for phase two began with the statement 'You have a second plane into the other tower of the World Trade Center, major fire.' (#1, in Figure 3 (*tk*). Table 3 includes the set of team communications selected for representation in the figure 3a-d that depict the team collaboration pattern for the FDNY during phase two, when the second plane hit the WTC. (These communications are a subset of the overall communications that that transpired during this phase (9:03-9:58) and were selected to represent the major topics discussed and actions taken during this time period.)

Table 3. Communications Selected to Represent Firefighters' Pattern of Team Collaboration During Phase 2 of the Attack on the World Trade Center.[1]

		9:02am United flight 175 flies into the South Tower of the WTC	
Turn #	**Time**	**Team Communication**	**Code**
1.	9:03	F. You have a second plane into the other tower of the Trade Center, major fire.	tk
2.	9:03	Be advised on the 83rd floor, room 8311, we have people trapped, room 8311, 83rd floor. Car 4 David acknowledge.	tk
3.	9:04	F. I'm on the F.D.R. Drive. Definitely something hit the second tower, possibly two-thirds of the way up. You've got visible fire showing out there.	cmm
4.	9:05	He would recommend you transmit a fifth alarm for that tower as well.	cs
5.	9:06	Best to have the [M.C.C.?] and have our personnel be secure here at this location.	sa
6.	9;06	D. All right. Engine 1-4 remain in service at this time. Standby.	coa
7.	9:06	F. All right, 10-4. Division 3 to Manhattan, call leader Car 4 David on the scene,	coa
8.	9:07	F. Did you give me the box that I'm being assigned to, K?	itk
9.	9:08	All units responding into No. 1 World Trade Center and No. 2 World Trade Center, bring all additional S.D.B.A.[?] bottles to the front of the building. All units to box 8087 and 998, No. 1 and No. 2 World Trade Center, bring your extra S.C.B.A. bottles to the front of the building, as per the division.	coa
10.	9:09	F. ... tower would you like us to be starting into, Tower 1 or Tower 2, K?	itk
11.	9:10	D. You're going to 2 World Trade Center, K, two.	itk
12.	9:10	F. I can't pick up the five units that you assigned to my system on. Have you got it in the computer yet, K?	itk
13.	9:11	F. ... 1-0, inform everyone assigned to the scene responding on West Street or Liberty Street not to pull up in front of the building. We have ambulances and everybody else pulling up and we've got debris falling from the building. They have to stop short of the building either north or south.	cmm
14.	9:13	F. Would you advise the mobile command vehicle to come in on West and Liberty Street, West and Liberty Street, K.	coa
15.	9:14	D. You want them over on the West Side?	itk
16.	9:16	D. Car 3 are you 84 the box? F. We are 10-84 the box. We are at West and Vessey, K.	itk
17.	9:16	D. All right. Listen I have some floors for you to check out	coa
18.	9:16	Car 3, in building two, the No. 8-2 floor, the No. 8-8 floor and No. 8-9 floor. On the 82nd floor it's the west. I have other floors.	tk
19.		D. O.K., the 83rd floor in building one; the 104th floor; the 103rd floor, northwest corner, room 103; 106th floor; 83rd floor is 8-3-1-1 room; and the 82nd floor, east side, in building one.	tk
20.		F. We're the marine division, we will position by the Brooklyn Bridge for a possible transport of men and equipment to Manhattan.	tk
21.	9:19	F. Have Field Comm. report in front of the Financial District Building on West Street ... American Express immediately.	coa

22.	9:19	F. Give me the company identifications that are coming to 2 World Trade Center. Just read them down. D. All right, 10-4: Engine 2-1-1, Ladder [interference], Engine 2-2, Engine 5-3, Engine 4-0, Division 3, Battalion 1-0, Battalion 1-2, Ladder 1-6, Ladder 2, Ladder 1-3, Engine 2-2-1, Engine 2-3, Engine 2-0-9, Engine 2-1-2, Engine 2-7-9, Engine 2-3-0, Engine 2-2-9, Engine 2-3-5, Engine 2-2-0, Engine 2-1-6, Engine 2-1-7, Engine 2-3-8, Engine 2-1-4, Ladder 12, Ladder 1-1-8, Ladder 7, Ladder 2-4, High Rise 1 and Battalion 1-1, Engine 7-4, Engine 7-6, Engine 4-7, Engine 5-8, Engine 9-1, Ladder 2-2, Ladder 2-5, Ladder 3-5, Four Truck and Ladder 2-1.	itk
23.	9:22	D. All right, Field Comm. No. 1 World Trade Center, the 1-0-3 floor, southwest corner and northwest corner, reported to be 100 people overcome at that location. Repeating, No. 1 World Trade Center, 103rd floor, northwest [interference] corner, reported to be 100 people in that location. Also, Ladder 3 is reporting on the 35th floor going up on the stairwell they've got numerous injuries, treating numerous injuries from burns occupied in the stairwell at this time. Field Comm. receive.	ct
24.	9:24	F. Brooklyn Dispatch. Urgent, people trapped, 5 World Trade on the 8-0 floor; 3 World Trade, that's the 1-0-1 floor and the 1-0-2 floor. Manhattan receive?	cu
25.	9:27	F. Have M.S.U. activate all their spares and bring all their spares and all spare bottles to the scene of the fifth alarm, No. 1 World Trade Center, K.	coa
26.	9:27	D. Field Comm., No. 2 World Trade Center on the 8-3 and the 8-4 floors and the 8-2 floor, people trapped at this time.	cu
27.	9:30	F. Contact the units, fifth alarm, coming down for No. 2 World Trade Center, contact them individually and get them to acknowledge the fact that they are to come to Liberty and West, Liberty and West, K.	coa
	9:30	F. Marine 6 to Manhattan, in the event of a transport problem into Manhattan we can establish a staging area at our quarters.	sa
		D. Is that going to be for No. 2 or No. 1 World Trade.	
		F. Wasn't sure. I'd say go with both.	

[1] (Fire Department of the City of New York, 2001.)

The focus of the collaboration is to keep all team members apprised of the situation so that all team members can maintain overall situation awareness, especially when dealing with as large a problem situation as the attack on the WTC. As was the case with air warfare and MIO teams, the 9-11 firefighters collaborated more about the 'front end' of the problem: 'What's going on?' A much smaller percentage of communications were devoted to collaboration during the team consensus and outcome evaluation and revision phases of the model. For both air warfare and the firefighters many decisions were made all along the way of dealing with the problem as opposed to making one big final decision (course of actions) and reaching a consensus on that course of action. If this same pattern holds for other examples of team collaboration it has implications for designing collaboration systems.

The iterative pattern of moving back and forth between the phases of the model continues during the second phase of the FDNY communications, depicted in Figure 3. The team moves between *knowledge construction* and *team problem solving* and many times issues a course of action and then moves back to building additional team knowledge. In some cases the team communications move into the team problem solving and team consensus stages, but the majority of communications entail knowledge construction and taking action.

The patterns included in Figures 2a-b and 3a-d depict the highly iterative process used by the FDNY. Each time they noticed something new they immediately issued a course of action to deal with their new understanding of the situation. This pattern reflects the finely-honed SOP that has evolved over many years of use and refinement. Firefighters are trained to ‘size up’ the situation and then report what they are doing about it. Information gathering was an on-going process throughout the event.

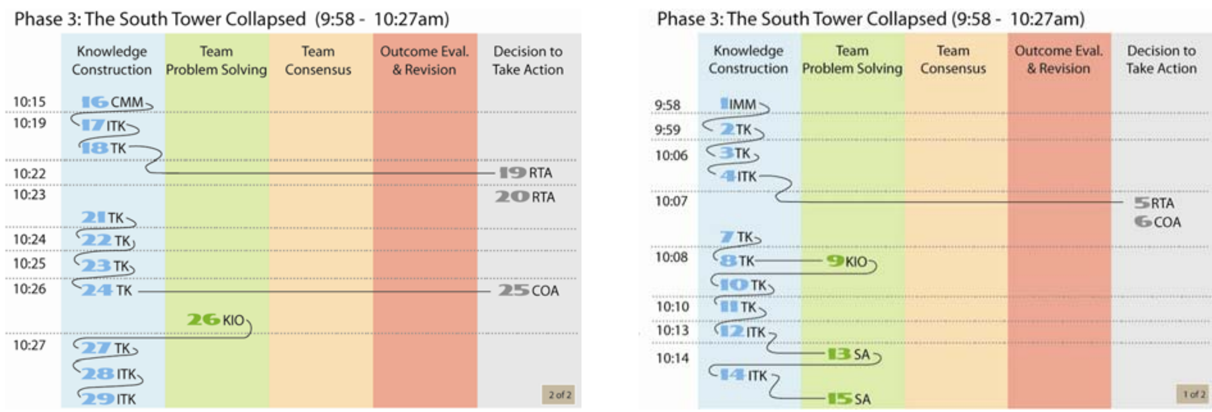
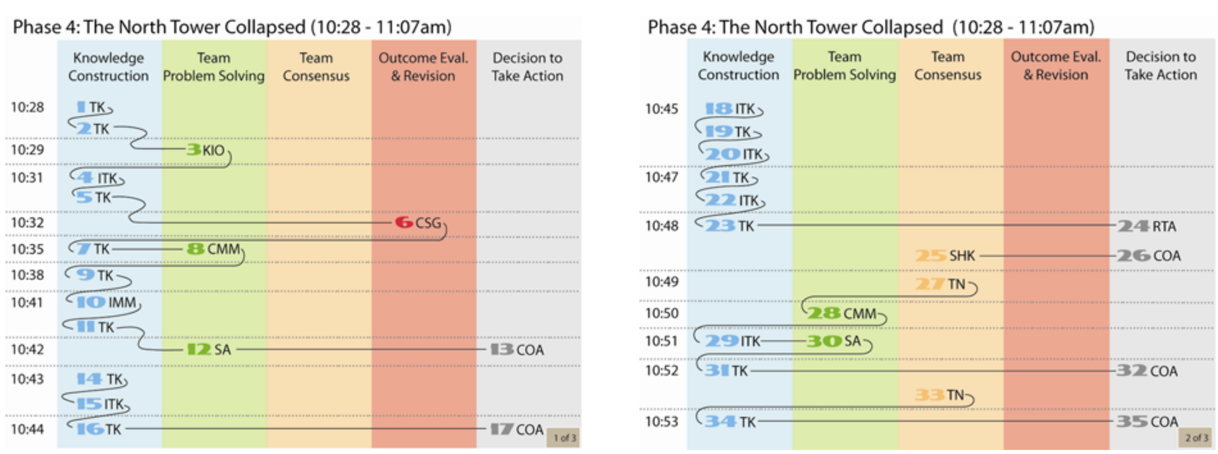


Figure 4a-b. Collaboration Pattern of Firefighters (The South Tower Collapsed).

As seen in both Figures 2a-b and 3a-d, the team’s collaboration involved a highly iterative process. The pattern shows that each time they noticed something new, that is, when the fire/situation had progressed to another stage, they often immediately issued a course of action to deal with their new understanding of the situation. For example the first utterance in Phase 1, shown in Figure 2, was to inform other team members that “We just had a plane crash into upper floors of the WTC.” (*team knowledge*, *tk*) In this same speech turn, this firefighter issues the course of action to “Transmit a 2nd alarm and start relocating companies into the area.” (*coa*) It is important to note that in the first speech turn they were taking action. During speech turns 3-5 (Figure 2) (*tk*) firefighters are describing the situation to others, the last one was “we have a number of floors on fire.” (*tk*) In speech turn #6 a team member issued another *coa*: “Transmit a third alarm throughout the staging area at Vessey and West St. As the third alarm assignment goes into that area, the second alarm assignment report to the bldg.” Speech turn #7 was: “…looked like it was intentional. Inform all units coming in from the back it could be a terror attack.” #8 followed: “Roll every available ambulance you’ve got to that position.” (*coa*)



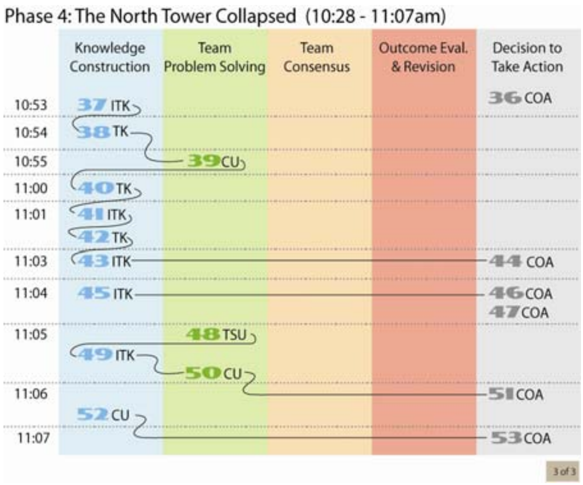


Figure 5a-c. Collaboration Pattern of Firefighters (The North Tower Collapsed).

The team kept moving back to the *knowledge construction* stage the entire time because they were constantly passing information and making mental model adjustments to keep each other and the dispatcher informed of changes at the scene. When the South tower collapsed the mission in the North tower became one of strict evacuation. Most of the *collaborative team problem solving* was done at the Incident Command posts, where the Chiefs collaborated to create a plan while they filtered information for currency and factualness.

Team Consensus. FDNY Chiefs at the scene were able to decide on solution options quickly because the FDNY SOP for regular response options was applicable for many instances. However, dealing with an attack on scale of Sept 11 meant there were cases were SOPs were not available. Fire chiefs moved between *collaborative team problem solving* and *team consensus* stages regarding solution options for various problems.

Outcome Evaluation and Revision. For smaller, more manageable problems, the FDNY was able to reach a consensus and go through entire collaborative cycle. For example, getting firefighters down via elevators usually works, but plans were modified to use stairs to climb to the fire. For the larger problem of evacuating civilians and putting out the fire, this final goal was never reached because buildings collapsed before they had time to see their solution through to completion.

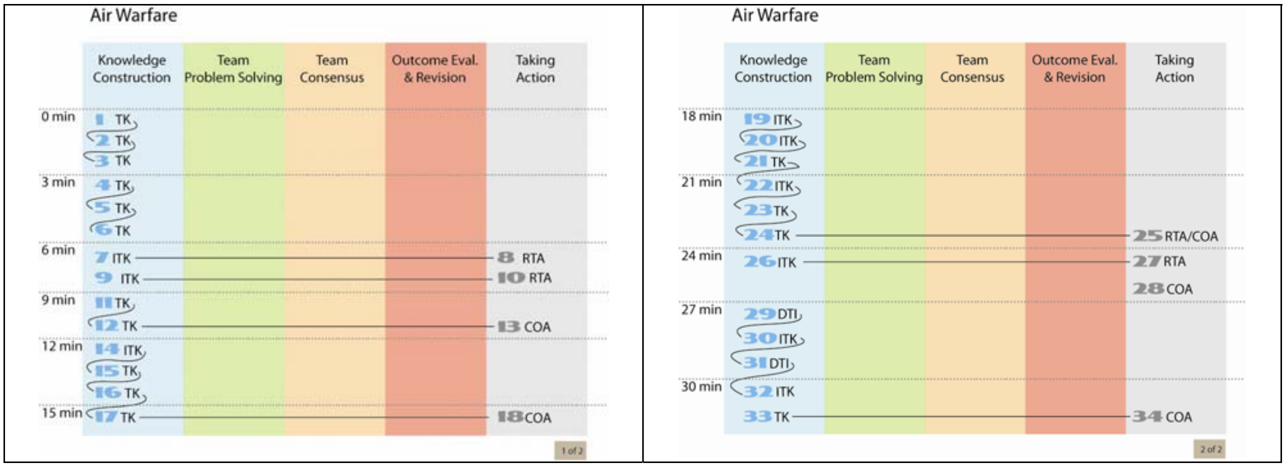


Figure 6a-c. Collaboration Pattern for Air Warfare Team.

A different pattern of collaboration is evident in figure 6a-c, which depicts a high-level representation of the macrocognitive processes employed by the air warfare team. The vast majority of their communications involved macrocognitive processes during the knowledge construction phase as well as several decisions to take action.

Figure 7a-c. Collaboration Pattern for Maritime Interdiction Operations Team.

As shown in Figure 7a-c, the MIO team engaged in more team problem solving in addition to knowledge construction and decision to take action.

New Coding Categories: Decision to Taking Action

Many critical tasks that involve team collaboration include team members taking action in addition to developing situation awareness and agreeing on a final COA. Various actions are taken as part of the overall information gathering process (e.g., MIOs, air warfare, firefighters, etc.). Problem-solving tasks also involve taking actions as part of the overall decision making and COA implementation. Many tasks involve a series of decision making and action taking in order to accomplish the mission. For example, in MIOs members of the boarding party physically search the ship using sensing equipment to take various readings which are sent to experts at reachback centers for analysis. In some cases, members of the boarding party are then asked to take additional readings to provide more fine-grained data that will help more precisely determine the type of cargo on the ship. Similarly, biometric data and video data is collected and sent back for analysis. This process of physically searching the ship for contraband cargo and suspect people entails a series of actions, thus, many speech turns involve requesting a team member to take an action. These requests can involve one team member to another (peer-to-peer situation) or a superior talking to a subordinate.

Two new coding categories were added to the set of macrocognitive process definitions that are included in the model. The first involves a person in command issuing an order 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 or locking-on with radar, developing a firing solution, covering with missiles, etc. Several examples for both of these new coding categories are listed in Tables 4 and 5 to illustrate the qualitative difference between issuing and order doe a COA and request take action – where one peer asks another peer to do something.

Distinctions between these two new categories that involve a decision to take action are the (1) relationship between the people and (2) the urgency the action requires. Issuing an order regarding a course of action involves a person with higher rank (e.g., commanding officer speaking to the tactical action officer (TAO), or the TAO speaking to one of the enlisted system operators), telling a subordinate to take some specific action against a potential threat track. Table 4 lists examples of courses of action (*coa*) found in the three decision-making domains analyzed. These actions might include issuing verbal warnings, illuminating or locking-on with radar, developing a firing solution, covering with missiles, etc. *Request a team member take action* refers to telling a team member to do something but it is not a direct action against a threat track. For example, "Can you try and change 7006 and 7005 to assumed hostile? I keep trying and can't get it to do it."

Table 4. Examples of Course of Action (coa) Macrocognitive Process.

9-11 Firefighters	Transmit a second alarm and start relocating companies into the area.
	Send every available ambulance, everything you've got, to the WTC.
	All units respond into West St. Transmit a 10-60 also.
	Get us a staging area…somewhere on West St.
	I want all but one of them here.
	Division to Manhattan calling Car 4 David K.
	Units calling Manhattan, one at a time.

	All incoming units into World 1 and World 2 are to bring additional cylinders.
MIO	Search team will report size of material and its current containment condition; then make recommendations.
	But, if you have plutonium, you need to confiscate.
Air Warfare	Cover tracks 7005 and 7006 with birds
	Cover 8032 (TN 7013) with standard missile also generate a SWG 1A solution.

The second new coding category is *request team member take an action,* which involves asking a team member to do something. Table 5 lists examples of *request take action* (*tra*) found in the three decision-making domains analyzed. The difference between these two categories is that the later does not involve a direct action against a threat track, e.g., 'Can you try and change 7006 and 7005 to assumed hostile?' Much of the radio communications for the firefighters also involves asking fellow firefighters to respond or do something towards the team's goal. Request take action involves asking a team member to take an action that will help move the problem along in terms of accomplishing the overall mission, e.g, 'Would you relocate the only rescue that's not going to the Trade Center, put them in Rescue 1 in Manhattan, please,' or: 'Will you call our bosses downtown and have them secure the MCC?' *Rta* is generally a type of action that has less urgency associated with it.

A *coa* involves a superior telling a subordinate to do something and the nature of the action is more severe (e.g., firing a missile) RTA is usually peer-to-peer request and the action requested is of a lesser consequence. Differences between a *coa* and *rta* center on the degree of authority held by the speaker and the urgency with which the action needs to be executed.

Table 5. Examples of Request Take Action (rta) Macrocognitive Process.

9-11 Firefighters	We're going to need the P.D. for security on the entire World Trade Center.
	Please have ambulances respond to West Street.
	Would you relocate the only rescue that's not going to the Trade Center, put them in Rescue 1 in Manhattan, please.
	Will you call our bosses downtown and have them secure the MCC?
MIO	Mark material for confiscation.
	Recommend material be confiscated.
	Make sure you handle carefully.
	Unless positive that destination is country under full-scope IAEA Safeguards, need to confiscate.
	Given multiple radiation hits and suspect equipment RECOMMEND Divert of entire ship to Friendly Port (If we are u/w) or detained and moved to a safe location (if in US)
Air Warfare	Let's investigate with (combat air patrol) CAP.
	Confirm that tracks originating from Iranian air space are designated unknown assumed hostile.
	Go ahead and tag 8037 and company assumed hostile.

DISCUSSION

Several trends are evident when examining the results depicted in Figures 2-7. First, all teams spent the majority of their time in the *knowledge construction* phase. The attack on the WTC was a very unique situation that did not resemble anything the FDNY had previously experienced. This high level of novelty more than likely contributed to the team needing to devote an inordinate amount of time to constructing their mental model of the situation.

The second noteworthy point is that for both the firefighters on Sept. 11, and the air warfare and MIO teams, the overall collaboration process did not culminate in one final outcome. While in other firefighting scenarios the final outcome is putting out the fire, the team does not necessarily collaborate to decide on the final outcome, i.e., whether one option/ final plan is better than another. (For example, the way a team of representatives from several cities who are collaborating to decide on the best final plan for where to locate a trash incinerator or a nuclear storage facility would.) A third important point is that for the kinds of tactical decision-making problems reported here, many actions are taken all along the entire process of dealing with the situation, whether it involves dealing with potential air threats, a MIO, or a fire – and all these decisions and associated *coa*s are critical to dealing with the situation. These may be considered mini-decisions in that they are not major or final decisions, however, they are all considered to be critical in terms of the teams' handling the problem situation.

CONCLUSIONS

For the 9-11 data, *individual task knowledge development (itk)* is by far the category with the greatest percentage of codes at 42%. Firefighters are asking a great deal of questions, and while asking questions is encouraged for exchanging team knowledge, it begs the question of whether there is a way to alleviate some of the questions by providing more information to the responding units and in providing a decision support tool. Many communications dealt with locations for staging areas. Incorporating a navigation system into the handie talkies could help a lot with map issues. This also applies to the category with the second highest number of codes, *team knowledge development (tk)*, with 210 out of 771 (27%).

Very few of the cognitive processes included in the team consensus stage were evident in the team communications that transpired during these three collaborative tasks. All three tasks are tactical level tasks; that is, these operations are conducted within a very short time period. Due to the speed of a potentially hostile aircraft, political/ economic pressure to conduct the MIO quickly, and for obvious reasons for the firefighters, these decisions need to be made within minutes, or even seconds, as the situation unfolds. In contrast, operational and strategic level operations occur over longer time intervals, e.g., weeks or months. More of the macrocognitive 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.

During the collaborative team problem solving stage the most frequently used process varied between all three decision-making domains. The macrocognitive processes with the highest use for each decision-making domain were: air warfare–team shared understanding; MIO–iterative collection and analysis; firefighting–convergence of mental models. These differences reflect differences in the tasks performed for these three domains. Air warfare teams focus on developing team shared situation awareness regarding the status (threat/non-threat) of the various tracks (air and surface) in the vicinity of the ship. MIO teams focus on iterative collection of data, and receiving feedback on results of analysis of this data which drives additional data collection until they are certain regarding the types of materials found on the vessel. For the 9-11 firefighting task, many completely unanticipated events occurred which made it necessary for the firefighters to develop a new mental model of the situation they were confronted with in response to each new event: a terrorist attack, the collapse of WTC 1, collapse of WTC 2, and not being able to rescue people due to the collapse of the two buildings.

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