Complex Collaborative Problem-Solving Processes in Mission Control

Stephen M. Fiore, Travis J. Wiltshire, James M. Oglesby, William S. O'Keefe, and Eduardo Salas

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Introduction: NASA's Mission Control Center (MCC) is responsible for control of the International Space Station (ISS), which includes responding to problems that obstruct the functioning of the ISS and that may pose a threat to the health and well-being of the flight crew. These problems are often complex, requiring individuals, teams, and multiteam systems, to work collaboratively. Research is warranted to examine individual and collaborative problem-solving processes in this context. Specifically, focus is placed on how Mission Control personnel—each with their own skills and responsibilities—exchange information to gain a shared understanding of the problem. The Macrocognition in Teams Model describes the processes that individuals and teams undertake in order to solve problems and may be applicable to Mission Control teams. ***Method:*** Semistructured interviews centering on a recent complex problem were conducted with seven MCC professionals. In order to assess collaborative problem-solving processes in MCC with those predicted by the Macrocognition in Teams Model, a coding scheme was developed to analyze the interview transcriptions. ***Results:*** Findings are supported with excerpts from participant transcriptions and suggest that team knowledge-building processes accounted for approximately 50% of all coded data and are essential for successful collaborative problem solving in mission control. Support for the internalized and externalized team knowledge was also found (19% and 20%, respectively). ***Discussion:*** The Macrocognition in Teams Model was shown to be a useful depiction of collaborative problem solving in mission control and further research with this as a guiding framework is warranted.

Keywords: collaborative problem solving, distributed teams, macrocognition in teams, mission control.

To ensure safe spaceflight missions, effective decision-making and problem-solving processes must be established for successfully addressing complex issues that may arise. In support of astronauts during spaceflight, Mission Control teams work in a complex domain characterized by ambiguity, uncertainty, ill-structured problems, dynamic conditions, high risk, and time pressure (8). Complex situations include malfunctioning equipment on the spacecraft, sickness or injury of a crewmember, or novel incidents where procedures for addressing the problem have not been established (8).

Broadly, Mission Control personnel are responsible for the monitoring and maintenance of the International Space Station (ISS), and must address any problems or issues that can impact the functionality of the orbiting facility to ensure crewmember safety. This task requires collaborative efforts between individuals and across teams that may have different skills, knowledge of technical systems, responsibilities, and different priorities. Given the diverse backgrounds and perspectives across Mission Control teams, they must collaborate, share information, and develop solutions to fix problems onboard the ISS to ensure mission success.

Many problems faced by mission controllers and spaceflight crews are characterized by complexity as a function of the number of interconnected elements across technical systems, high degrees of uncertainty, shifting task priorities, and dynamic systems and conditions (4). Teamwork and collaboration are thus essential to ensure successful spaceflight missions, especially in the context of addressing novel problems that involve time pressure and high stakes (8). That is, members are required to exhibit team level competencies in order for Mission Control Center teams to collaboratively develop an understanding of the problem and identify possible solutions. While technical or systems knowledge is an important component for problem solving in this context, this goes beyond an individual's knowledge about his/her own system. As such, developing a shared problem model is essential to complex and collaborative problem solving (2). Shared problem models include both situation and task relevant strategies for understanding and effectively coordinating with a team toward appropriate problem solutions (9).

Strategies do exist to improve performance on complex tasks that teams collectively conduct, including crew resource management. This is a well-established approach used in aviation and the military (12), and focuses primarily on team decision making, situational awareness, conflict management, and communication (5). But, in the context of Mission Control teams, additional requirements arise because teams often engage in individual and collective knowledge building for solving novel problems, collaborating with specialists with unique knowledge and skills, and adapting to new situations and incoming information.

From the University of Central Florida, Orlando, FL, and the United Space Alliance, LLC, Houston, TX.

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Address correspondence and reprint requests to: Stephen M. Fiore, M.S., Ph.D., University of Central Florida, 3100 Technology Parkway, Ste. 140, Orlando, FL 32826; sfiore@ist.ucf.edu.

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Therefore, essential to understanding the collaborative development of shared problem models across individual and team levels during complex problem solving contexts is the Macrocognition in Teams Model (3). The Macrocognition in Teams Model relies upon a multidisciplinary approach to explicate the cognitive processes team members undertake to address novel and complex problems requiring interpersonal collaboration. Specifically, the Macrocognition in Teams Model is founded upon theories of externalized cognition, team cognition, group communication and problem solving, and collaborative learning (3). **Fig. 1** illustrates the model's five components that describe cognitive processes and actions a problem solving team exhibits in complex collaborative problem solving. A full review of the components and subprocesses of each component are beyond the scope of this paper (3); rather, brief summaries of the components and subprocesses are provided.

Individual Knowledge Building (IKB) refers to processes and actions involved in expanding one's own knowledge base during problem solving. IKB represents the actions that an individual personally takes (e.g., enhance role relevant understanding) which can contribute to subsequent collaborative actions taken by team members. The subprocesses included in this component are individual information gathering, individual information synthesis, and knowledge object development (3).

Team Knowledge Building (TKB) refers to actions that team members exhibit in order to develop actionable team-level knowledge related to the problem-solving situation. TKB directly contributes to the development of a shared problem model (i.e., the agreed upon representation of the problem elements). The subprocesses include team information exchange, team knowledge sharing, team solution option generation, team evaluation and negotiation of alternatives, and team process and plan regulation (3).

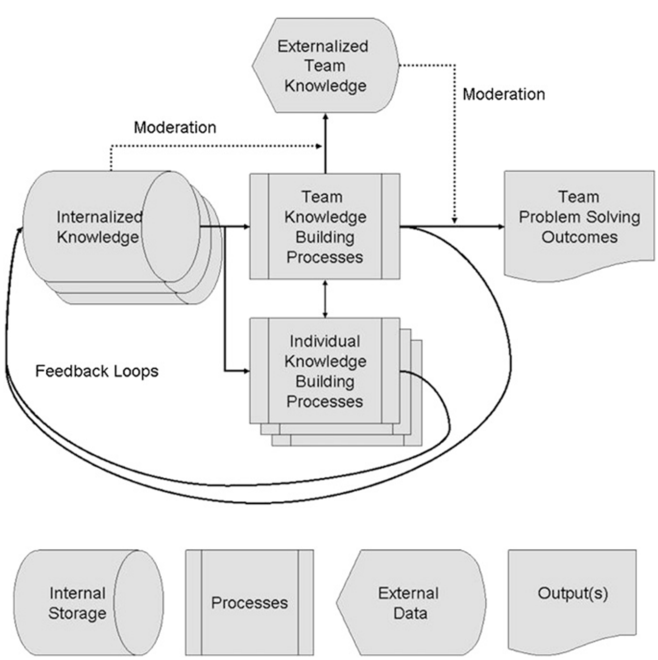

Fig. 1. The Macrocognition in Teams Model (3).

Internalized Team Knowledge (ITK) refers to the knowledge base of each individual involved in the team and knowledge not yet shared on the team level. ITK may include specialized knowledge about the systems and resources of which an individual is in control, as well as their knowledge about the skills and responsibilities of fellow team members. The subprocesses included are team knowledge similarity and team knowledge resources (3).

Externalized Team Knowledge (ETK) refers to knowledge that is shared across the members of the team. ETK contributes to the creation of artifacts associated with a shared understanding of the problem and situation. Examples of processes associated with ETK include changing strategies based on the perception of problem cues, and the recognition of certain patterns and trends that project future states of the situation. The subprocesses associated with this component include externalized cue-strategy associations, pattern recognition and trend analysis, and uncertainty resolution (3).

Team Problem Solving Outcomes (TPSO) addresses the actual final state of the problem resulting from the collaboration within the team. Indicators of TPSO include the success/failure of the generated solution and specific subprocesses of this component include quality of plan, efficiency of planning process, and efficiency of plan execution (3,4).

Prior research detailed decision-making processes inherent to spaceflight crews (8) as well as agent-based functional models of problem solving in Mission Control (7). Accordingly, the unique contribution of this paper is to examine the complex nature of collaborative problem solving within the context of Mission Control. Two specific goals relevant to spaceflight missions are addressed: 1) to identify problem solving processes elicited by Mission Control personnel facing a novel and complex problem requiring multidisciplinary collaboration; and 2) to determine the degree to which complex collaborative problem solving processes made explicit by the Macrocognition in Teams Model are present.

In order to investigate the collaborative problem solving processes emergent during a novel and complex problem faced by Mission Control personnel, a naturalistic study was conducted. In particular, the failure of the main bus switching unit (MBSU) on the ISS served as a rich and suitable problem context for our analyses. This problem involved the identification by individuals of data suggesting the MBSU was likely to fail, the team knowledge building efforts across Mission Control teams, collaboration to develop a shared problem model, and the generation and execution of solutions.

METHODS

Subjects

Semistructured critical incident interviews were conducted with seven experienced ISS Mission Control personnel. These interviews and the subsequent analyses were approved for research purposes by the NASA JSC Director of the Mission Operations Directorate and subjects were informed of the interview purposes. Subjects included flight controllers, engineers, and managerial level individuals. Abbreviated titles of these individuals are as follows: IMMT Chair, Increment Flight Director, Increment Phalcon, Increment PRO, Increment OSO, OSO-EPS-SME, and MER-EPS-SME (Descriptions shown in **Table I**). Subjects average number of years in a role supporting the ISS was 8.7 (SD = 6; range 5–18 yr) and the average number of years in their current role was 3.4 (SD = 4; range 1–12 yr).

Procedure

The focus of the semistructured interviews was to gain insight into how subjects, both hierarchically and across disciplines, collaboratively contributed to solving the MBSU problem. Interviews were conduct individually over a period of 21 d. Each interview lasted approximately 2 h, during which subjects were prompted to recount their perspective of how the MBSU problem was approached. Open-ended and probe questions were used to encourage subjects to provide more detail regarding their interaction with others involved in the collaborative problem solving process. All interviews were digitally recorded and all recorded interview data was transcribed from audio to text.

The semistructured interviews were guided by a set of predefined questions. The ordering of the questions varied based upon interviewee responses. The topics covered in the semistructured interviews included: a walkthrough of the MBSU problem event timeline (i.e., "From the 50 thousand foot level, could you explain your view of the technical issue with the MBSU 1?"), problem solving and decision makings processes at an individual and team level (i.e., "Can you explain to me why a decision was made to continue de-crew* [De-crewing is an important aspect of the MBSU problem as it meant that the ISS would be left completely unmanned for a period of time, which is not typical in normal operations of the space station.] efforts, even after the Soyuz launch?"), interactions with team members and other teams (i.e., "Your job had to do a lot of integration with a number of people—can you tell me who you had to work with, who you had to talk to, or coordinate with, for the MBSU problem?"), lessons learned from the event (i.e., "Were there any lessons learned or anything that you were going to carry forward, if you had a second opportunity to have to work this sort of thing?"), and how training efforts can be improved (i.e., "…What would you recommend to the training [organizations] to train this set of operators to be as good as the specialists that work with you in solving a problem of this breadth and depth?").

Analyses

Several steps were taken in order to analyze the transcriptions from the MBSU event using a top-down (i.e., from theory) and bottom-up (i.e., preliminary data analysis) approach (1). First, a review of complex problem solving literature was conducted. Next, an initial coding scheme was developed that synthesized a coding framework developed for analysis of real-time team problem solving interaction (10), additional complex collaborative processes of macrocognition in teams (3), and patterns emergent in preliminary data analysis. Then the coding scheme and the associated operational definitions for each code were refined by the two coders and the principal investigator throughout the coding process. Revisions to the coding scheme were conducted through systematic discussions comparing theory, emergent

TABLE I. ACRONYMS FOR THE MACROCOGNITION IN TEAMS MODEL AND MISSION CONTROL SPECIALISTS TECHNICAL POSITIONS AND DESCRIPTIONS.

Macrocognition in Teams Model Acronyms	
Acronym	**Acronym Defined**
IKB	Internal Knowledge Building
TKB	Team Knowledge Building
ITK	Internalized Team Knowledge
ETK	Externalized Team Knowledge
TPSO	Team Problem Solving Outcomes
Mission Control Specialists Technical Position Acronyms	
Acronym	**Acronym Defined and Position Description**
IMMT Chair	International Space Station Mission Management Team (IMMT) Chair – Responsible for program management through a management team composed of all the international partners and primary directorates. The IMMT determines program priorities and provides guidance to Operations.
Increment Flight Director	Increment Flight Director - Responsible for the entire increment including planning, forecasting and integrating to make sure current activities in the flight control room support increment objectives.
Increment PHALCON	Increment Power, Heating, Articulation, Lighting Control Officer (PHALCON) – Responsible for increment planning and organization of console activities for the electrical power system.
Increment PRO	Increment Power Resource Officer (PRO) – Responsible for increment planning for electrical power use and balancing.
Increment OSO	Increment Operations Support Officer (OSO) – Responsible for increment planning and organization regarding maintenance and the mechanisms onboard the space station.
OSO-EPS-SME	Operations Support Officer Electrical Power System Subject Matter Expert (OSO-EPS-SME) - Responsible for the maintenance of electrical power system mechanisms onboard the space station.
MER-EPS-SME	Mission Evaluation Room Subject Electrical Power System Matter Expert (MER EPS SME) – Responsible for leading an engineering team that provides troubleshooting and problem resolution support for the electrical power system.

patterns in the data, and examples for each code. In addition, proposed refinements of the operational definitions and criteria for using codes were systematically discussed and transcriptions were revisited as changes were made. The final coding scheme comprised 23 codes representing the collaborative problem solving processes specified by Fiore and colleagues (3).

An iterative coding process was conducted between two coders where each iteration was conducted independently and was followed with systematic refinement to the coding scheme and operational definitions such that the codes were descriptively representative of the data. Discrepancies in the initial coding were compared and reconciled based on a comparison of the two assigned codes for a given data element. From this, a reconciled reliability analysis was conducted. Finally, because of the low number of transcripts, the highly technical nature of the MBSU event, and the complexity of the coding scheme, a comprehensive collaborative analysis of each transcription was conducted by both coders to reach a final and complete consensus on all coding ($\kappa = 1.00$).

RESULTS

Table II shows that a majority of coded instances from the MBSU transcriptions were accounted for under the Macrocognition in Teams Model. Approximately half of these instances were assigned to the TKB component. Next, ITK and ETK represented approximately one-fifth of the data. Lastly, IKB and TPSO represented the smallest percentages of the data that, when combined, account for approximately 10% of the data. In the subsequent sections, descriptive details are provided for the most prevalent components of the model (e.g., TKB, ITK, and ETK). Although the interviews and coding produced a rich data set, due to page constraints, we provide a more general summary of the findings (refer to Table II and **Table III** for further detail).

Team knowledge building codes accounted for 50% ($N = 613$) of all coded data and was present across all 7 transcriptions. Again, TKB processes are those in which an individual takes action to disseminate information and to transform that information into actionable knowledge for team members. For example, one participant stated: "Those are the people I'm passing information down to… this is the timeline we're looking at, these are the constraints we're under, and we need this procedure by this time." Another participant stated: "As far as communicating up the chain, basically whenever I got some of that high-level data from their procedure about how long it would take, or what accessing or safing impacts there were, we had a presentation that we took to the JOP [Joint Operations Panel] and explained how that was going to happen."

The second most prevalent component of the Macrocognition in Teams Model within the MBSU transcriptions was ITK, which accounted for 20% ($N = 244$) of all coded data and was present across all 7 transcriptions. These codes represented instances in which knowledge held by individual members of the team was referred to in the transcriptions. For example, one participant stated: "So, OSO-EPS-SME and OSO-EPS-SME-in-training are both our SMEs, our subject matter experts, for the EPS system. So they're the ones who really understand the system in and out more than I do. My role as an increment lead is more of just coordinating their efforts, making sure that we're going to be able to get our procedure developed on time."

The third most prevalent component of the Macrocognition in Teams Model was ETK, which accounted for 19% ($N = 235$) of all coded data and was present across all 7 transcriptions. These codes were assigned to instances in which subjects referred to facts, relationships, and concepts that have been explicitly agreed upon or not openly challenged by factions of the team. For example, one participant recounted: "You could barely do anything on the space station, but we had a plan together that the crew could do if they saw all the lights go out. They could do this and do this and wait for the cavalry to send the commands on the ground to build things back up again."

Finally, when considering the subprocesses, as listed in Table III, the two most frequently assigned codes were both under the TKB component and included team process and plan regulation as well as team knowledge sharing. Following this, the third most frequently assigned code was the ITK code. And the fourth most frequently assigned code was the externalized cue-strategy association under the ETK component.

TABLE II. FREQUENCIES AND PERCENTAGES OF THE MAJOR COMPONENTS OF THE MACROCOGNITION IN TEAMS MODEL EMERGENT IN THE MBSU TRANSCRIPTIONS.

Code	Coding Frequencies	Coding Percentages
Individual Knowledge Building	75	6%
Team Knowledge Building	613	50%
Internalized Team Knowledge	244	20%
Externalized Team Knowledge	235	19%
Team Problem Solving Outcomes	49	4%
Other (Reflection)	11	1%
TOTAL	1227	100%

DISCUSSION

We set out to provide a theoretically derived and descriptive account of the complex cognitive processes occurring across individuals and teams participating in collaborative problem solving for Mission Control. The prevalence of TKB processes, as well as both ITK and ETK across all subjects' transcriptions, suggests support for the Macrocognition in Teams Model as a useful depiction of the complex collaborative processes arising in this context.

In addition, the results serve to highlight the interdependencies occurring between these components. First, the notion that ITK, initially held only by individuals, provides the substance for which TKB processes are founded upon. Specifically, the TKB process represents the synthesis of information and knowledge, once held only by individual members of the team, and now available

TABLE III. PERCENTAGE OF MINOR COMPONENTS OF MACROCOGNITION IN TEAMS CODES.

Component of Macrocognition in Teams Model	Code	Coding Frequencies	Approximate Coding Percentages
Individual Knowledge Building	Individual Knowledge Building	20	2%
	Individual Information Gathering	20	2%
	Individual Information Synthesis	19	2%
	Knowledge Object Development	16	1%
Team Knowledge Building	Team Knowledge Building	13	1%
	Team Information Exchange Provision/Request	34	3%
	Team Knowledge Sharing Provision/Request	171	14%
	Ambiguous Team Sharing Provision/Request	89	7%
	Team Solution Option Generation	54	4%
	Team Evaluation and Negotiation of Alternatives	70	6%
	Team Process and Plan Regulation	182	15%
Internalized Team Knowledge	Internalized Team Knowledge	118	10%
	Team Knowledge Similarity	90	7%
	Team Knowledge Resources	36	3%
Externalized Team Knowledge	Externalized Team Knowledge	63	5%
	Externalized Cue-strategy Association/Goal Orientation	111	9%
	Pattern Recognition and Trend Analysis	12	1%
	Uncertainty Resolution	49	4%
Team Problem Solving Outcomes	Team Problem Solving Outcomes	0	0%
	Quality of Plan (problem-solving solution)	25	2%
	Efficiency in Planning Process	11	1%
	Efficiency of Plan Execution	13	1%
Supplementary Code	Reflection	11	1%
Total		1227	100%

to the entire team. In support of theory on shared cognition, the data from the MBSU event shows that ITK and, in particular, knowing which team members or other teams possess certain knowledge, is essential to collaborative problem solving. TKB processes then provide the basis for ITK to take the form of ETK. Specifically, the agreed upon and ETK arising during TKB processes contributes to the formation of the team's problem representation and leads to consensus or a shared problem model. In the context of the MBSU event, many meetings types (e.g., Failure Investigation Teams) were held in service of building the team knowledge such that a shared problem model was developed by those in attendance spanning each Mission Control discipline.

In sum, this work was done to illustrate the collaborative problem-solving processes that Mission Control specialists require when facing novel problems. In addition, it serves as empirical support for the Macrocognition in Teams Model and provides a means through which to identify more specific problem-solving training areas for future space missions. The method used in this paper has been able to make explicit collaborative problem-solving processes predicted by the Macrocognition in Teams Model in the context of a novel problem that Mission Control specialists faced. Due to lack of control and the retrospective nature of semistructured interviews, some degree of bias and inaccuracy may be inherent to the data. However, this is one of the prominent methodologies for collecting data to gain an understanding of problem-solving processes in complex real-world contexts (8). Though, given access and resources to study a complex problem over the duration in which it occurs, other measurement methods and indices would be appropriate (3).

Future research will corroborate and extend the findings of this study with other novel problems occurring in the Mission Control and spaceflight contexts. In addition, the Macrocognition in Teams Model will be extended to include relevant teamwork processes that mediate and facilitate collaborative problem solving processes. Further, data from this study requires additional examination to identify predicted problem solving phases (3) as well as recommendations for potential training methods (11). Lastly, the model must also be refined to account for the roles associated with collaborative problem solving when increasingly intelligent automated systems comprise part of the team. In the current model, data from sensors and knowledge repositories are used in the problem solving. But, from the human-systems integration perspective, as technologies evolve, the contributions (and limitations) of these will need to be more closely scrutinized (6).

In conclusion, this paper provided an overview of the Macrocognition in Teams Model and examined this in the context of collaborative problem solving processes inherent to Mission Control. In support of the importance of knowledge building in problem solving contexts, TKB processes were most evident during the transcriptions of the MBSU event. In addition, ITK and ETK components were evident and manifested themselves as necessary components of the TKB. As such, this effort explicates the emergent collaborative processes during a complex problem faced by Mission Control teams and future efforts need to extend this work and specify the associated subprocesses and problem solving phases.

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Authors and affiliations: Stephen M. Fiore, M.S., Ph.D., Travis J. Wiltshire, B.S., M.S., James M. Oglesby, B.S., and Eduardo Salas, University of Central Florida, Orlando, FL, and Williams S. O'Keefe, B.S., M.S., United Space Alliance, LLC, Houston, TX.

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