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Maintaining Shared Mental Models Over Long-Duration Exploration Missions

Literature Review & Operational Assessment

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Part 1: Literature Review

A Review of the Critical Aspects of Team Cognition During Long-Duration Space Exploration Missions

We present a comprehensive review of research on team cognition as it relates to long-duration space exploration (LDSE). One of the three risks identified by NASA as affecting human behavioral health and performance is the *Team Risk*, defined as the risk of performance and behavioral health decrements due to inadequate cooperation, coordination, communication, and psychosocial adaptation within a team. The purpose of our review is to connect existing research on team cognition in general with the specific context of long-duration space exploration missions. Accordingly, the first step in our review was to develop an organizing framework for linking key aspects of the social context of space flight to specific study characteristics that, if present, would enable inferences to be drawn about team cognition during space flight. We then classified empirical studies of team cognition according to these taxonomic features relevant to space flight. And lastly, we summarize key findings regarding the state of the science of team cognition as it relates to team risks during space flight.

In our findings, we answer three questions relevant to team cognition-driven risks during long-duration space exploration. First, what conclusions *can* we draw based on the extant empirical research about how the context of space flight will affect team cognition? Second, what conclusions *can't* we draw based on the extant empirical research because the context under which team cognition has been studied does not exhibit adequate ecological validity to space flight? Third, what are the most critical areas for future research on team cognition?

Introduction

Among the risks that affect human health and performance during space exploration is the *Team Risk*: the risk of performance and behavioral health decrements due to inadequate cooperation, coordination, communication, and psychosocial adaptation within a team. The team risk reflects the reality that on long-duration space exploration (LDSE) missions, the astronauts and ground control members work in teams. The success of a space exploration mission hinges on collaboration within and among these teams. Research on small groups and teams has long recognized that teams create a context that affects the individual, and this context can both augment and stifle individual performance. When poorly designed or managed, teams can amount to less than the sum of their parts, a phenomenon termed process loss (Steiner, 1972; Latané, Williams, & Harkins, 1979). When well-coordinated, teams can amount to more than the sum of their parts, termed synergy. Research on groups and teams has examined both process loss and synergy for more than 50 years.

Research on team synergy and process loss has focused on identifying properties that characterize the dynamics/processes that occur in teams that may account for variations in team performance. Research on these properties (also called team emergent states) has identified two broad classes of group properties: (1) affective properties (e.g., cohesion, efficacy) and (2) cognitive properties (e.g., shared mental models, transactive memory). Affective properties are crystalized feelings among all members of a team (Beal, Cohen, Burke, & McLendon, 2003; Gully, Devine, & Whitney, 1995; Gully, Incalcaterra, Joshi, &Beaubien, 2002; Mullen & Copper, 1994). Well-studied affective properties relevant to team performance and viability include team cohesion (Mullen & Copper, 1994), team efficacy (Gully et al., 2002), team potency (Stajkovic, Lee, & Nyberg, 2009), team identity (Riketta, 2005), and team member satisfaction (Gully et al., 2002). Cognitive properties are mental representations that serve as a basis for individuals' actions and interactions within a team (DeChurch & Mesmer-Magnus, 2010; Mohammed, Klimoski, & Rentsch, 2000). Two streams of research have examined cognitive functioning in groups, one on transactive memory and a second on shared mental models. This review summarizes the extant research on team cognition, in both of these traditions. Our review identifies essential elements of the space flight context, and then cumulates prior empirical studies of team cognition according to their ecological relevance and deficiency with regard to space flight.

We use the terms ecological relevance and ecological deficiency to characterize the quality and concerns, respectively, in drawing inferences about the antecedents and consequences of team cognition during space flight based on a particular study. Ecological relevance characterizes the extent to which a study provides observations of team cognition for teams that operate in an environment that captures reasonably well the essential elements of space flight that would affect team cognition. Ecological deficiency characterizes the extent to which a study provides observations of team cognition in teams whose context differs in important ways from that of space flight, suggesting the generalizability of these findings to a space flight context may be questionable.

The overarching purpose of our review is to connect existing research on team cognition in general with the specific context of long duration space exploration missions. Accordingly, the first step in our review was to develop an organizing framework for linking key aspects of the social context of space flight to specific study characteristics. We then classified empirical studies of team cognition according to these taxonomic features relevant to space flight. And lastly, we summarize key findings regarding the state of the science of team cognition as it relates to team risks during space flight.

In our findings, we answer three questions relevant to team cognition-driven risks during long-duration space exploration. First, what conclusions can we draw based on the extant empirical research about how the context of space flight will affect team cognition? Second, what conclusions can't we draw based on the extant empirical research because the context under which team cognition has been studied does not exhibit adequate ecological validity to space flight? Third, what are the most critical areas for future research on team cognition?

Team Cognition in Space Exploration

The broad umbrella term team cognition refers to a variety of mental states among individuals that create a predisposition for their resulting behaviors. Team cognition serves an important role in enabling teams to adapt to unanticipated changes in the performance environment (Mohammed et al., 2000). DeChurch and Mesmer-Magnus (2010) offered an integrative conceptualization of team cognition, which we use as an organizing framework for our review. Team cognition has been shown in numerous reviews to be an important underpinning of team functioning and effectiveness (e.g., Bell, 2007; Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Mohammed et al., 2000). In their meta-analysis of the team cognition literature, DeChurch and Mesmer-Magnus differentiated team cognition based on three overarching dimensions: nature of emergence, form of cognition, and content of cognition.

Nature of emergence. The first dimension is the nature of emergence. Team cognition is what is commonly referred to in the team's research as an emergent construct. While the construct describes property of a team, the elemental content of this concept is the cognition in the minds of individual team members. Accordingly, team cognition differs along an underlying continuum of emergence (Kozlowski & Klein, 2000). At one end of this continuum is composition. Compositional emergence occurs when the manifest team cognition construct is comprised of similar cognition within the minds of the individual team members. At the other end of the emergence continuum is compilational emergence. This form of emergence reflects a team-level construct of the patterning in team- and/or task-related cognition among team members. Research on shared mental models, the extent to which team members have a similar understanding of the team and task, is a prototypical example of a team cognition construct that is compositional in nature. That is, each team member has the same mental model. Research on transactive memory systems, the extent to which the team develops a differentiated pattern of encoding and retrieving knowledge and information needed for the team to function and perform, is a prototypical example of a team cognition construct that is compilational in nature. Each team member has a different mental representation, and the team as a whole possesses all of the knowledge and information needed to perform its task and to function as a coherent whole. Research on team cognition shows that both aspects of team cognitive architecture are important to team functioning (e.g., Edwards, Day, Arthur, & Bell, 2006; Mathieu et al., 2000; Mohammed et al., 2000).

Form of cognition. The second dimension is the form of cognition. The form of cognition refers to the particular aspect of meaning contained in the cognition. More concretely, research can be differentiated based on cognition as individual's perceptions or cognition as individual's structured thought patterns. Research on team cognition shows that it is the latter (structured thought patterns) that are most predictive of team outcomes (DeChurch & Mesmer-Magnus, 2010).

Content of cognition. The third dimension is the content of knowledge represented. Team cognition can be distinguished based on the extent to which content is related to the task or related to the team. Task-related cognition refers to team members' understanding of the nature of the task and its related goals. Team-related cognition refers to team members' understanding of the nature of team interaction as dictated by member roles and responsibilities. Task-related cognition is believed to underlie effective teamwork because individuals can interpret information similarly and anticipate the behavior is needed of them in response to that information. In contrast, team-related cognition characterizes how team members are expected to interact, when interaction is needed. Research has demonstrated that both team and task content are important aspects of team cognition as related to team performance and viability (Edwards et al., 2006; Mathieu et al., 2000; Mohammed et al., 2000).

Criteria of Interest

We focus our review on understanding how team cognition affects two outcomes identified by NASA's Behavioral Health and Performance program: team performance and psychosocial adaptation. *Team performance* is defined as the degree to which a team meets the goal(s) for which it was formed. *Psychosocial adaptation* within a team is defined as team members' ability and motivation to perform needed teamwork and task-work behaviors and to remain on the team long enough to accomplish its goals. A classic example of the important role of psychosocial adaptation is the early termination of Russian space missions during the 1970s and 1980s (Cooper, 1976).

In 1976, during the Soyuz-21 mission to the Salyut-5 space station, the crew was brought home early after the cosmonauts complained of a pungent odor. No source for this odor was ever found, nor did other crews smell it. Since the crew had not been getting along, the odor may have been a hallucination (McPhee & Charles, 2009, p. 9).

Jack Stuster's (2010) analysis of the diaries of 10 astronauts reveals potential effects of team cognition on both performance and psychosocial adaptation. Throughout our review we draw on examples from this rich qualitative research to ground the explanations of our team phenomenon. The journals were those of astronauts in space aboard the International Space Station (ISS) for 150-200 days. They provide rich data to understand team functioning during space flight. Still, these diaries describe issues experienced in a period of less than 6 months. Long-duration space exploration missions could last 3 years. Some exemplar diary entries are as follows.

> ***Effects of team cognition on team performance***
> I was really surprised this morning to find that X had completely failed to perform a task yesterday, one required in order for me to perform a task this morning. I was quite angry and later apologized and accepted responsibility for not "monitoring" more closely. I'm still disappointed that X never took responsibility for the mistake. (Stuster, 2010, p. 22)
>
> Today is EVA day. I'm starting to have that I-think-I-must-be-forgetting-something feeling. MCCM just called to disallow me from using the ___. It's too close to the EVA to let myself get upset, but I can tell that I will be. It's all about "not invented here." (Stuster, 2010, p. 30)
>
> ***Effects of team cognition on psychosocial adaptation***
> Had a 5 minute break. Went to grab some coffee. Y has now decided not to have the water heater on continuously, so had no hot water. Again amazed by how inconsiderate Y is. (Stuster, 2010, p. 22)
>
> We did have a run-in one night. I was really livid after Z snapped at me quite viciously about something that wasn't my fault. I let Z have it, like I can't remember ever before in a professional relationship, and stormed off. (Stuster, 2010, p. 22)
>
> We moved some racks together today, in the morning and throughout that entire process U was barking at me constantly. (Stuster, 2010, p. 22)
>
> I'm finding myself losing tolerance for T. I can't explain exactly what it is that bothers me. (Stuster, 2010, p. 22)

Social Context in Space Exploration

In our review, we examined seven aspects of the social context astronauts will face during long-duration space exploration missions. These aspects of social context reflect the fact that the space crew is a small team working in:

1. concert with a larger multiteam system (multiteam)
2. an isolated environment (isolation)
3. a confined environment (confinement)
4. high tempo work conditions (high tempo)
5. low tempo work conditions (low tempo)

6. extended workload conditions (extended workload)
7. a team with one or more members who are dissimilar from themselves (composition)

Multiteam effects on team cognition. The six-member space crew will be working closely with ground control at various points in the mission. This places the space crew in a larger social context, which we define as a multiteam system. Multiteam systems (MTSs) are sets of teams, where each team pursues its own local goals while also working interdependently with other teams to accomplish global goals. The space crew can be thought of as one component team within a larger space exploration MTS (which also consists of the component teams working in mission control).

There are important implications of taking a multiteam perspective. MTSs exhibit tighter interdependence within a component team than across component teams. The implication of this for space flight is that the individuals within each team will have cognition that is more shared internally, but more dissimilar across the different component teams. There were multiple astronaut log entries reported by Stuster (2010) that illustrate how differences in team cognition between the space and ground crews affect the space crew members.

In fact differences in team cognition across MTS component teams can pose significant team risk. Imagine a situation where a ground control team has a different understanding of a system then does the flight crew. Because individuals communicate with one another and relay information based on their implicit understanding of how things work and the current situation, differences in these understandings across the members of different teams can lead to ineffective handoffs and breakdowns in coordination. NASA experienced the effect of such a breakdown of communication based on the dissimilarity of the underlying component team cognition when the failure to translate units between metric and English standard resulted in the multimillion-dollar loss of the Mars Climate Orbiter in 1999 (http://mars.jpl.nasa.gov/msp98/news/mco991110.html).

The quality of between team information sharing and coordination will likely affect the functioning and performance of the space crew (i.e., the team), and also the success of the larger space exploration mission (i.e., the MTS). There are likely to be many instances when the crew will need to rely on the ground for critical information and assistance and vice versa. This requires not only shared cognition within each team, but also shared cognition across the different component teams within the MTS.

The crew diaries analyzed and reported on by Jack Stuster (2010) suggest that team cognition particularly among the space crew and ground teams pose significant team risks due to both performance and psychosocial adaptation. There were numerous examples that point to misalignment in the cognition of the space and ground crews, which would likely affect the crew's performance.

Examples of how crew-ground team cognition can harm team performance:
I still get frustrated by the degree to which we get left out of the loop. This has been a perpetual problem in the ISS crew world. (Stuster, 2010, p.19)

Contrary to the briefing last night, the ground wanted to begin arm motion earlier than scheduled, prior to my availability. This certainly did nothing to give me confidence in the ground team and reinforces my belief that the ground too often fails to consider the crew when making decisions and taking action. (Stuster, 2010, p.19)

I continue to be amazed by the degree to which the ground has gotten into the habit of taking action and not informing the crew. (Stuster, 2010, p.30)

I am not sure I look forward to Holidays on ISS, especially those that are not followed by a weekend. The effort is made to be happy and people on the ground go out of their way to help each other and us, but the effect is to fill the Holiday with a lot of friendly social stuff, chatter on the air to ground, some expectancy for a little show from the crew, VIP telephones calls etc. **Meanwhile the things you really count on, like email updates, swift responses to your questions about work matters etc. degrade, because the ground teams have gone to [partial staffing].** Unlike on Earth where this would be enjoyable, because you do not have to work, here it is spoiled because there are always high priority work tasks that just cannot wait until the next day. (Stuster, 2010, p.30, emphasis added)

They can't imagine what it's like and what we have to deal with every day to make things work. It's not their fault, but they can't see it from our perspective. (Stuster, 2010, p.53)

Team cognition between the space and ground crew also affects astronauts' psychosocial adaptation. Exemplars from Stuster's (2010) diary study suggest that team cognition connecting the ground teams and the space crew have both positive and negative consequences for the astronaut's psychosocial adaptation.

Examples of how crew-ground team cognition can detract from psychosocial adaptation:
Stuff on the ground is also affecting my mood. (Stuster, 2010, p.18)

The comments he shared with me from the ground really hurt me. I have still not recovered and am not myself. I had been having quite a bit of fun up here, but the last few days have been far from fun. (Stuster, 2010, p.18)

Something that Houston has continued to do that is a little irritating, is cancel events for me because of a perception that I am too busy. Yes, I do have a full work schedule, but Houston is canceling fun events, like talking to celebrities and doing interviews. I sent our folks a polite note asking them to let me do these things. I am not too busy. (Stuster, 2010, p.19)

Examples of how crew-ground team cognition can benefit psychosocial adaptation:

> I am excited and feel very prepared for the journey ahead. I hope to make the ground teams proud of my crew and think that, at least on the U.S. side, we have a decent shot at accomplishing that. (Stuster, 2010, p.18)
>
> I don't feel uncomfortable at all. I feel like this is okay. There are lots of things I don't know, but I feel confident about handling issues that come up. I am surely glad the ground is watching our backs. That really makes me feel better. (Stuster, 2010, p.18)
>
> One thing that I am thankful of is that I haven't started noticing any resentment or anger toward the ground team or "management" or anybody else like many other crews have experienced. I continue to believe that everybody is pouring their heart into the mission. I received an email from a previous crew member that referred to the anger of several long-duration flyers. It is a major problem for sustaining this program and I hope to find a few "secrets" to apply as a countermeasure. It is largely the same anger and resentment that periodically crops up in the training environment and it tends to act as a poison among the entire group. (Stuster, 2010, p.19)
>
> I have regained my sense of humor and shrugged off the tedium. The Capcom has done a good job of disarming my potential for getting frustrated. (Stuster, 2010, p.19)

There has been some research that speaks to the general issue of how distributed teams maintain team cognition across different sub teams (e.g., Maynard et al., 2012). This research vein would suggest that there is greater risk for team decrements that stem from misalignment in cognition between teams, than of cognition within the space crew.

In order to consider them systematically, we have identified specific study characteristics with some level of fidelity at capturing the differences in team cognition that we would expect based on the multiteam structure of space exploration missions. Though this prior research has not been conducted in analog conditions, it has investigated team cognition under certain conditions (such as where teams are separated by time zones or teams who have been together for long durations) that allow us to anticipate some of the ways in which an MTS structure will affect the team cognition of the space crew. These study characteristics include: distributed teamwork, virtual teamwork, multiteam systems, task interdependence, external interdependence, and autonomy.

Effects of isolation on team cognition. The six-member space crew will be working in an extremely isolated environment. According to some scenarios, the six-member crew will have no physical contact with anyone except for their crewmates for as long as 3 years. The importance of managing isolation was well captured by this diary entry, "Thank goodness we have the IP phone and Email to keep in touch with our loved ones (Stuster, 2010, p.18)."

One of the most important aspects of isolation as it relates to team performance and psychosocial adaptation is the reality that team members interact only with their teammates and have no ability to leave the team for an extended period of time. This represents a unique feature of teamwork during space flight. The closest analog teams for this feature of the context of space flight are winter over teams in Antarctica and small special operations units in the military.

In order to consider the effects of isolation on team cognition, we have summarized research looking at the effects of psychological stress, temporal dispersion, and geographic dispersion on team cognition. Though this prior research has not been conducted in analog conditions, it has investigated team cognition under certain conditions, such as where teams are experiencing psychological stress, which would be a likely consequence of isolation (Baumeister & Leary, 1995). Temporal and geographic dispersion are other conditions that would affect team cognition in a way that is similar to the effects of isolation.

Effects of confinement on team cognition. The six-member space crew will be living and working under extreme confinement. The current estimate is that the space vehicle will provide between as little as 1.5 and as much as 14.8 cubic meters of space per astronaut. As a concrete comparison, each crew member's personal space in the spacecraft is approximately the same or far less that that afforded to the typical prisoner in an American prison who gets a cell of approximately 13.59 cubic meters in size (i.e., the typical prison cell is 6 feet by 8 feet by 10 feet; Grabianowski, 2007). As one astronaut put it: "Well, we're finally here. The launch met all my expectations. Damned small vehicle (Stuster, 2010, p.29)" In order to systematically consider the likely consequences of confinement on team cognition, we consider both the psychological stress brought on by confinement as well as the physical stress.

Effects of high tempo work on team cognition. The six-member space crew will have certain periods of high tempo workload. These high tempo work periods are likely to happen during the initial lift-off, early in the voyage (e.g., jettisons) and during various transitions (e.g., extravehicular activities [EVAs], landings, dockings). Team cognition is particularly important during these high tempo work periods because such tasks often occur during other less-than-optimal conditions (e.g., lack of sleep, physical or psychological stress), which places a severe strain on team functioning in general, and team cognition in particular.

There is been quite a bit of research conducted on what are called action teams. Action teams perform time urgent tasks that are often physically and mentally demanding, and require significant coordination among team members. Research on action teams provides a useful task-related analog to the high tempo work that will be faced by astronaut space crews; however, unfortunately much of this research has been conducted in settings that do not adequately mirror the high tempo work conditions that will be encountered in space.

A second study characteristic with some fidelity to understanding the effects of high tempo work on team cognition is research that has examined team cognition in teams with high levels of (often psychologically stressful) workload, such as those faced by first responder teams and nursing teams working in emergency rooms.

Effects of low tempo work on team cognition. In contrast to the high tempo work conditions, space crews will also face the effects of boredom, arising from sustained periods of low tempo work. In order to assess the extent to which low tempo work will affect team cognition, we have considered the extent to which prior work on team cognition has been conducted on teams that experience significant periods of boredom in conducting their tasks.

Effects of extended workload on team cognition. A third aspect of the work that constitutes the social context in which space crews will operate is extended workload. Extended workload describes the time where individuals are at a relatively high level of cognitive and emotional activation for an extended period of time, i.e., more than a typical workday. Extended workload conditions also accompany decrements in performance due to fatigue, physical exertion, and the build-up of work-related stress.

In order to systematically consider the possible effects of extended workload on team cognition in space crews, we have considered two properties of prior research. The first property is psychological stress, and the second is physical stress.

Effects of team composition on team cognition. A final but important aspect of the social context of space exploration is the composition of the team. Team composition, defined as the amount and diversity of team members' knowledge, skills, abilities, and other characteristics, has important implications for team cognition during space flight. A robust finding from research on individual differences is that many of the characteristics on which people differ, such as personality characteristics, play an important role in their cognitive schemas (e.g., Bell, 2007; Edwards et al., 2006). Any sources of diversity either within the six-person space crew, or between different teams in the larger space exploration multi-team system will have important implications for team cognition. Current estimates suggest there will be significant diversity on the space exploration team, both in terms of professional expertise and cultural/national groups, which is likely to have implications for the development and maintenance of team-level and MTS-level cognition.

Indeed, a number of the journal entries reviewed by Stuster (2010) point to issues that suggest how the teams are composed, both the space flight and ground teams, will play an important role in the development and maintenance of their team cognition. Some of these include team size, personality, cognitive styles, common language, friendship, and national identity reflected in each of the following diary entries:

> ***Team size.*** Suddenly I'm really appreciating the solitude that I have here. It does help to have control of your own environment if you're going to be isolated. I'm trying to picture what it would be like up here with a crew of 6. It would be totally, completely, absolutely different. It would be more fun at times, and there would be more camaraderie. That would be positive. But, the entire US segment is the equivalent of my house right now and sharing it would be huge difference. We are very lucky to be here a time when the Station is so huge, yet there are only 3 of us to share it. This is quite a luxury! (Stuster, 2010, p.19)

Personality and cognitive styles. It is good that we have this kind of relationship. This mission is so easy, since we are of like personality and thought. (Stuster, 2010, p.19)

Language. We have some inside jokes; we talk about the other cosmonauts and astronauts, which seems to be a favorite topic for him. We watch movies together on the weekend nights. S and I had some longer talks, but that is possible because his English is so good. (Stuster, 2010, p.19)

Friendship. One of the really neat things about this whole adventure is that by the time you're doing it, everyone you're doing it with is a long-time friend. This even holds true for the folks on the ground. Every voice I've heard on the radio so far has been someone who I know. (Stuster, 2010, p.19)

National identity. I get the feeling the US and Russian teams are a little stressed with each other. An incredibly unnecessary and pedantic US procedure to ___ should have no consequence to the Russian side, but my whole morning activity carrying out this procedure was cancelled, because it involved X helping me read a meter for 5 minutes, so opening the door to have the Russians review and probably ridicule the US procedure. Houston simply told me when I pressed them that the Russians had not blessed the procedure, and I jumped to these conclusions. It is probably a reaction by the Russians to Houston nagging Moscow about the upcoming ___, making them take a bit of their own medicine. I am not sure what X and I can do to ease all this. At least we can work together calmly and make that evident to Moscow and Houston. (Stuster, 2010, p.30)

I got a little terse with Y because he's not reading/following US procedures. He goes through Russian procedures with painful thoroughness, but just wings it with US procedures. (Stuster, 2010, p.40)

In order to systematically consider their likely effects of team composition on team cognition, we review research on team cognition based on the degree to which the focal teams were homogenous or heterogeneous.

Review Framework

Table 1 summarizes our taxonomy of the social context affecting team cognition during long-duration space exploration, and relevant characteristics of research that allow us to draw inferences about the likely effects of this particular aspect of context on team cognition.

Table 1. Literature Review Framework for Understanding the Impact of Team Mental Models Over Long-Duration Space Exploration Missions

Context of Long-Duration Exploration	**Features of Research with Relevance to Long-Duration Exploration**	**Exemplar Findings**
Small teams supported by larger teams on different schedules	Virtual teamwork	The effect of accuracy of SMMs on team process gets stronger as similarity of SMMs increases (Mathieu et al., 2005)
	Multiteam systems	---
	Task interdependence	The extent to which team members collectively understand management strategy impacts transition and interpersonal processes, and also influences team effectiveness even after controlling for transition processes (Mathieu & Shultz, 2006).
	External Interdependence	Expertise distribution among members, familiarity and face-to-face communication influences the development of TMSs while communication via email or telephone has no impact (Lewis, 2004).
	Autonomous teams	Collective understanding of how team members should work with one another improves mental and physical proficiency.
Teams operating in isolated settings	Psychological stress	High performing teams in a nuclear power plant can develop shared mental models during non-routine situations than low performing teams (Waller et al., 2004).
	Temporal Dispersion	Communication influences the development of TMS in the early stage of team process, which enables distributed teams to develop strategies and also directly impacts team performance (Yoo & Kanawattanachai, 2001).
	Geographical Dispersion	Frequency of task-oriented communication via email significantly impacted the development of TMSs among members in virtual teams in the early stage of their projects (Kanawattanachai & Yoo, 2007).

Context of Long-Duration Exploration	Features of Research with Relevance to Long-Duration Exploration	Exemplar Findings
Teams operating in confined settings	Psychological stress	Team monitoring can be detrimental to team performance in absence of team mental model similarity (Burtscher et al., 2011).
	Physical stress	Accuracy and similarity of team mental models positively influenced the performance of military teams which operated in a training combat circuit (Lim & Klein, 2006).
Teams operating in high tempo conditions	Action teams	Team and task MMs are critical determinants of team process (Mathieu et al, 2000).
	Periods of High Workload	As members develop understanding of other members' roles and expertise, shared mental models are likely to develop and influence coordination and backup processes (Marks et al., 2002).
Teams operating in low tempo conditions	Periods of Boredom	Effective planning influences the formation of SMMs, which enhances communication among team members (Stout et al, 1999).
Teams operating under extended workload	Psychological stress	Frequent meetings and phone calls positively influence the formation of TMSs while email has no impact.
	Physical stress	Familiarity, interdependence, communication and group potency are significant predictors of the formation of TMSs (Peltokorpi & Manka, 2008).
Team composition	Diversity	Team cognitive ability has a positive relationship with the development of MM accuracy (Edwards et al., 2006).

Literature Review Methodology

We thoroughly searched the extant literature on team cognition in an effort to explore the state of research on team cognition according to its relevance to long-duration space exploration. DeChurch and Mesmer-Magnus conducted a meta-analytic integration of the team cognition literature in 2008 (published in 2010). The process they used in constructing their meta-analytic database was thorough, so in building our database of studies for this project, we updated their original database using their search strategy and collected all studies published in the 5 years since their database was constructed. In particular, we conducted a search of PsycInfo, ABI Inform, and ERIC databases, and manually searched the references cited in studies identified as relevant for this review. Further, in an effort to ensure we captured relevant studies published literatures other than those canvassed by these databases, we also conducted a thorough search of the Google Scholar database. Sample search keywords included group OR team AND cognition, mental models, shared cognition, transactive memory, schemas, knowledge structure, cognitive structure, cognitive map, conceptual framework, and shared situation awareness. This search strategy identified an additional 37 **studies** to DeChurch and Mesmer-Magnus' original database of 65 studies, for a total of 102 studies of team cognition.

Inclusion Criteria

We included all studies relevant to team mental models and examined these in relation to the extent to which reported results may generalize to a long-duration space exploration context. As such, we sought to include studies on team cognition regardless of whether they were overtly related to long-duration space flight teams. Consistent with DeChurch and Mesmer-Magnus (2010), in addition to surveying literature on team mental models, we also captured studies of related team cognition constructs, including shared cognition and transactive memory. Then, using the social context features of LDSE teams summarized in Table 1, we coded the extant literature according to whether each study may provide insight into relevant aspects of the LDSE team context.

Coding Content and Procedure

As outlined in Table 1, various features of team cognition research conducted outside an LDSE context may be applicable to LDSE crews. We coded these aspects of the studies we collected on team cognition. In addition to summarizing the sample (e.g., teams of nurses, military/police, engineers, air traffic controllers, students), team's task (e.g., criminal investigation, medical simulation, case analyses, project design), and study setting (lab versus field), we also coded the type of team studied (e.g., action, project, management), average lifespan of the focal teams, task interdependence within the team, the external interdependence of the focal team, physical and psychological stress experienced by the team, contextual fidelity (realism) of the teamwork context, team autonomy, team diversity, and whether there (a) were periods of high workload, (b) periods of boredom, and (c) temporal and/or geographic dispersion. We also recorded the cognition constructs examined in the primary studies. Articles were coded by at least two authors to ensure coding reliability and validity. Table 2 summarizes the distribution of studies in our database relevant to the features of these studies that may affect generalizability to a space flight context.

Team type. We coded team type into three categories (action, management, and project) using taxonomies by Sundstrom, McIntyre, Halfhill, and Richards (2000) and Sundstrom, DeMeuse, and Futrell (1990) as guides. LDSE teams may be unique to those typically researched in that it may be difficult to determine whether crews are action, project, or management teams. *Action* teams are characterized by high levels of behavioral interdependence (e.g., sports teams, assembly teams, military combat teams). *Management* teams are characterized by high levels of informational interdependence (e.g., managerial teams involved in budgeting, joint planning). *Project* teams are characterized by high levels of both behavioral and informational interdependence (e.g., engineering teams, research groups, development teams). Depending on the point in the mission, space flight teams may fit different team type classifications. For example, during takeoff, landings, and EVAs, teams may behave more like action teams, likely action or project or a hybrid of the two. During ongoing scientific studies, teams may look more like project teams. The tasks and dynamics of the mission control teams may look most like management teams, though when members of mission control sub-teams work with members of the space crew on scientific projects, they may become more like project teams.

Average lifespan of the focal teams. LDSE teams are likely to have spent 2-3 years in training prior to embarking on a mission. As such, the development of these teams is more mature than that of teams who are more ad hoc in nature. Hence, we coded the lifespan of the focal teams in the primary studies. Team lifespan was coded as short, intermediate, or long duration. Short-duration teams were those who had been together less than a month. Intermediate-duration teams were those who had been together more than a month but less than a year. Long-duration teams were those who had been together longer than a year. Long-duration teams are more consistent with the nature of team development in long-duration space exploration than teams with shorter lifespans, so we pay particular attention findings gleaned from long-duration teams.

Interdependence. LDSE teams will have certain tasks in which they are highly interdependent with others in the crew (e.g., during takeoff, docking, EVAs) and other times wherein they are relatively independent from others on the crew (e.g., when they are working on their own research tasks). Thus, we sought to determine the proportion of primary studies exploring teams with varying levels of interdependence. Consistent with DeChurch and Mesmer-Magnus (2010), we coded *task interdependence* using Gully et al. (1995), Gully et al. (2002), and Campion, Medsker, and Higgs (1993) as guides. Teams wherein interdependence is *low* have task performance that is largely a function of individual effort and wherein feedback, rewards, and goals occur mainly at the individual level. *Moderately* interdependent teams have members who rely on one another for some information and resources but are able to complete a significant portion of the task individually. *Highly* interdependent teams have mutual or reciprocal dependencies among team members, members' performance is dependent on information or resources provided by other members, and team-level goals, outcomes, and feedback are emphasized over those of individual members. We also recorded the extent to which team members were interdependent with individuals or teams external to the focal team (*external interdependence*). External interdependence is consistent with the idea that space flight teams are interdependent with mission control teams in a broader multiteam system context.

Contextual realism and physical and/or psychological stress. As space flight teams often experience physical and psychological stress during at least parts of their mission, we sought to explore the extent to which focal teams in these team cognition studies faced realistic contexts (e.g., high-fidelity simulations, actual work situations in a field setting) and the extent to which they experienced physical and/or psychological stress during the course of their tasks.

Autonomy. As we move towards longer duration space exploration missions where communication delays with mission control may exceed 15-20 minutes each way and the potential increases for unexpected scenarios to arise, space flight teams will have to become more autonomous than they have had to be to date. We coded the primary studies as to the extent to which focal teams were autonomous.

Diversity. Space flight teams in long-duration space exploration missions are likely to be quite diverse in terms of culture, sex, personality, and educational, professional, and/or experiential backgrounds. Therefore, we coded the extent of diversity of the focal teams in the primary studies. Team cognition research has suggested that diversity has non-trivial implications for team performance (e.g., Bell, 2007; Edwards et al., 2006). As such, identifying the volume of research relevant to the development and maintenance team cognition in diverse teams is relevant to understanding the research needs for LDSE teams.

Workload tempo and potential for boredom. LDSE teams are projected to experience periods of heavy, high tempo workload interspersed with periods of low tempo workload wherein potential for boredom is high. The concern, clearly, is that team cognition may degrade over time with periods of relatively light workload. As such, we sorted studies on the basis of the extent to which the focal teams faced these workload dynamics (periods of high workload and periods of boredom).

Temporal and geographic dispersion. By their very nature, LDSE teams are temporally and geographically distant from others with whom they are interdependent (e.g., mission control and ground support teams). These teams operate much like geographically dispersed, virtual teams, as they have to make use of technology to communicate and deal with members of the crew or mission control working on different schedules. Thus, we coded the extent of these aspects of dispersion (virtuality, and temporal and geographic dispersion) in the focal teams within the primary studies.

Cognition constructs. Although they have historically been treated as interchangeable, team cognition constructs are operationalized in a number of different ways (e.g., team mental models, shared cognition, transactive memory, etc.; Cooke, Salas, Cannon- Bowers, & Stout, 2000; Mohammed, Klimoski, & Rentsch, 2000; Rentsch et al., 2008). The operationalization of the team cognition construct is non-trivial as DeChurch and Mesmer-Magnus (2010) find various interpretations of cognition have different implications for team performance and viability.

To aid in the interpretation of the potential relevance of various team cognition constructs to LDSE, we adopted DeChurch and Mesmer-Magnus' (2010) three underpinnings of team cognition, and coded the team cognition constructs according to their nature of emergence (i.e., form of similarity; compositional versus compilational), form of cognition (structured versus perceptual), and content of cognition (task versus team). The nature of emergence of team cognition was described as (a) *compositional* when either the *congruence* (degree of match among team members' mental models) or *accuracy* (degree of match between the team members' schemas and a "true score," usually an expert's mental model) was assessed, and (b) *compilational* when authors assessed the extent to which team members possessed complementary task- or team-relevant knowledge (i.e., transactive memory; e.g., Balkundi & Weinberg, 2008; Faraj & Sproull, 2000; He, Butler, & King, 2007; Thomas, 2006). The form of team cognition was coded as (a) *structured* when the organization of team knowledge was assessed (e.g., via Pathfinder, pairwise comparisons, multidimensional scaling), and (b) *perceptual* when shared cognition was assessed without any attempt to assess the structure of that cognition (e.g., via shared perceptions, Likert-type scales). Finally, the content of team cognition was coded as (a) *task* when cognition depicted the nature and components of the team's task(s), and (b) *team* when cognition included information related to team members' roles and responsibilities and facilitated members' expectations regarding how to interact with one another to accomplish team goals (e.g., Marks et al., 2000; Marks et al., 2002). Whereas task mental models depict what the team must do, teamwork mental models depict how the team should work together to do it (Marks et al., 2002).

Literature Review Findings

Team Cognition Literature Conducted in Contexts Relevant to LDSE

As outlined in Table 1, we coded the extant literature on team cognition to gain a clearer understanding of its relevance to long-duration space exploration teams. We summarize the number of studies that have been conducted on team cognition with relevancy to LDSE in Table 2. In this table, we further differentiate between studies conducted in laboratory versus field settings. In particular, although laboratory settings may offer greater experimental control, field settings may offer greater realism and generalizability. The majority of studies on team cognition have been conducted in laboratory settings, suggesting more research could be done in field settings with other contextual features similar to LDSE embedded. We discuss study setting in more detail later in this section.

Small teams embedded in larger systems. One defining characteristic of LDSE teams is that they are small teams (i.e., six-person space flight crews) supported by larger teams (i.e., mission control teams). This context suggests teams engage in distributed, virtual, and autonomous teamwork within a multiteam system, and are at times both interdependent within the team and externally interdependent with individuals/teams outside the space flight crew. The extant literature has not extensively examined this particular condition in relation to team cognition. Indeed, we were not able to identify any empirical studies that have examined team cognition in a multiteam system, indicating an important direction for future research relevant to LDSE. However, a few relevant aspects of this context have been examined.

Ninety-four studies examined team cognition in one or more related environments. Fifty-five of these studies were conducted in a laboratory setting and 39 were conducted in a field setting. The majority of these studies looked at team cognition in varying levels of team autonomy or team interdependence. Fewer studies have examined team cognition in teamwork that is virtual or distributed or when the team is externally interdependent suggesting these are also fruitful avenues for future research in relation to long-distance space exploration.

Isolation. A second defining characteristic of LDSE crews is that they are teams operating in isolated environments. In this context, these teams are under psychological stress and are temporally and geographically dispersed from external supports. Indeed, LDSE teams will operate in a level of isolation far from that which has been experienced on Earth. Although research on Antarctic teams on winter-over missions and submarine crews provide a useful analog to space exploration, these teams are still working on Earth, whereas LDSE teams may at times not be able to even see their home planet. Research on team cognition has not been conducted in settings with such extreme isolation. However, 49 studies have examined one or more aspects of an isolated teamwork context (geographically dispersed and/or psychologically stressful), 22 in a laboratory setting and 27 in a field setting. The majority of these studies have examined team cognition in environments that were at least moderately psychologically stressful, while relatively few have examined it in temporally or geographically dispersed environments.

Confinement. A third defining characteristic of LDSE teams is that they are teams operating in confined settings. Indeed, as described in the introduction, space crew members on LDSE missions will live and work in settings that are more confined than the average prisoner in a US prison. Although we could not find any research on team cognition within this specific, extreme context, there has been some research conducted on team cognition in settings with some of the same attributes. For example, our review identified 40 studies that have examined team cognition within teams facing psychologically or physically stressful conditions. Though all of these studies have been conducted in at least moderately psychologically stressful environments, relatively few (six studies) were conducted environments that were also physically stressful, suggesting more research may be called for in settings that place both psychological and physical stress on the focal teams.

Team tenure. A fourth defining characteristic of LDSE teams is that they will have been together for at least 2-3 years prior to their mission. These teams are more developed and experienced than many ad hoc teams that have been studied in a laboratory context given that pre-mission training is anticipated to be 3 or more years and mission duration is anticipated to be 2-3 years. Team tenure is relevant to the role of team cognition in mission success. For example, during high tempo work situations (e.g., lift off, tank jettison, landing, docking), LDSE teams will be action teams. Action teams with experience working together have been found to have stronger cognitive foundations for effective teamwork than less-tenured teams, and are thus likely to be more successful (DeChurch & Mesmer-Magnus, 2010).

As can be seen in Table 2, the lifespan of the focal teams was reported in 68 of the studies we coded. By comparing team duration with the study setting (laboratory versus field) we see that the majority of studies of team cognition have taken place in short-duration teams in a laboratory setting, with relatively little research conducted in field settings with teams who have been together longer than a few weeks. Similarly, few studies have been conducted on action teams in field settings. Both findings reveal important areas for future team cognition research relevant to LDSE crews.

Task tempos: Boredom, high workload, extended workload. Another contextual feature of LDSE teams is that their work tempo is not consistent across time. Rather, between periods of frenetic activity (e.g., lift off, EVAs), there are likely to be long durations of relatively lower tempo conditions (e.g., transit to/from Mars). Such low tempo work conditions suggest the LDSE teams may experience periods of boredom between high tempo work demands. Fourteen studies have examined team cognition in low tempo/boring work conditions. Approximately half of these studies have been conducted in field settings. Forty-two studies have examined teams operating under extended workload periods, only 11 of which were conducted in a field setting.

Table 2. Number of Empirical Studies Explicating the Role of Each Aspect of Social Context on Team Cognition

Social Context of Long-Duration Space Exploration	**Features of Research with Relevance to Long-Duration Space Exploration**	**# Lab Studies**	**# Field Studies**
Small teams supported by larger teams on different schedules	Distributed teamwork	1	2
	Virtual teamwork	2	8
	Multiteam systems	--	--
	Task interdependence	55	30
	External Interdependence	3	12
	Autonomous teams	34	31
	Total studies in this category = 94	**55**	**39**
Teams operating in isolated settings	Psychological stress	21	19
	Temporal Dispersion	0	4
	Geographical Dispersion	1	2
	Total studies in this category = 49	**22**	**27**
Teams operating in confined settings	Psychological stress	21	19
	Physical stress	1	5
	Total studies in this category = 40	**21**	**19**
Teams operating in high tempo conditions	Lifespan of team		
	< 1 day	33	0
	< 1 months	7	1
	< 3 months	3	5
	3-12 months	1	5
	> 1 year	2	11
	Action teams	35	10
Teams operating in low tempo conditions	Periods of Boredom	8	6
Teams operating under extended workload	Periods of High Workload	31	11

Settings in which Team Cognition has been Examined

In Table 3, we further explicate the settings in which team cognition has been explored to date. Of the 101 studies included in our database, 56 have been conducted in laboratory settings and 45 have been conducted in field settings. Within the laboratory setting, the majority of the studies have examined autonomous teams performing highly stimulating tasks, which is consistent with some aspects of LDSE. However, these studies were also focused on teams without external interdependencies working in low-fidelity contexts for short durations (i.e., an hour or less), which is inconsistent with the LDSE team context.

The field studies had somewhat greater generalizability to LDSE crews in that focal teams were autonomous and interdependent, and engaged in highly stimulating, high-fidelity tasks that posed moderate to high levels of psychological stress. A portion of these teams was also required to engage in moderate to high levels of external coordination. These dynamics would suggest that the field settings used in these studies may have more ecological relevance/validity to LDSE than is possible to replicate in a laboratory setting.

Figure 1 plots the number of studies conducted on team cognition by how long the team had been together. This data is further broken down according to the settings in which these studies have been set. As can be seen, typically the laboratory studies are of short-duration teams whereas the field studies are of long-duration teams. The interaction between setting and team duration is not unexpected given the logistics of data collection in these settings, but given that the dynamics within a team develop/mature over time, we may be able to draw more generalizable conclusions for LDSE crews from studies conducted in field settings.

Taken together, we can conclude that the extant laboratory research is generally relevant to understanding the team risk related to *team performance decrements,* and deficient in understanding the team risk due to *inadequate psychosocial adaptation.* Further, we can conclude that the extant field research is generally relevant to understanding the team risk related to both *team performance decrements and psychosocial adaptation,* and deficient for understanding the effects of *distributed teams in context* who are working under conditions of *high physical stress*.

Table 3. Settings in which Team Cognition has been Studied

Setting	# Studies	Ecological Relevance (Aspects of this research that are relevant to LDSE)	Ecological Deficiency (Aspects of LDSE that are not well-captured by this research)
Laboratory	56	The majority of studies were focused on autonomous teams that performed interdependent, highly stimulating tasks.	The majority of studies examined stand-alone, co-located teams performing low-fidelity, hour-long tasks under low physical and low-to-medium psychological stress levels.
		Conclusion 1: Extant laboratory research on team cognition is generally relevant to understanding the team risk related to *team performance decrements.*	**Conclusion 2:** Extant laboratory research on team cognition is generally deficient in understanding the team risk due to *inadequate psychosocial adaptation.*
Field	45	The majority of studies were focused on autonomous teams operating for a long time that performed interdependent, highly stimulating and high-fidelity tasks under medium-to-high psychological stress levels. About 30 percent of studied had tasks requiring medium-to-high levels of external coordination	The majority of studies examined stand-alone, co-located teams performing tasks under low physical stress levels.
		Conclusion 3: Extant field research on team cognition is generally relevant to understanding the team risk related to both *team performance decrements and psychosocial adaptation.*	**Conclusion 4:** Extant field research on team cognition is generally deficient for understanding the effects of *distributed teams in context* who are working under conditions of *high physical stress*.

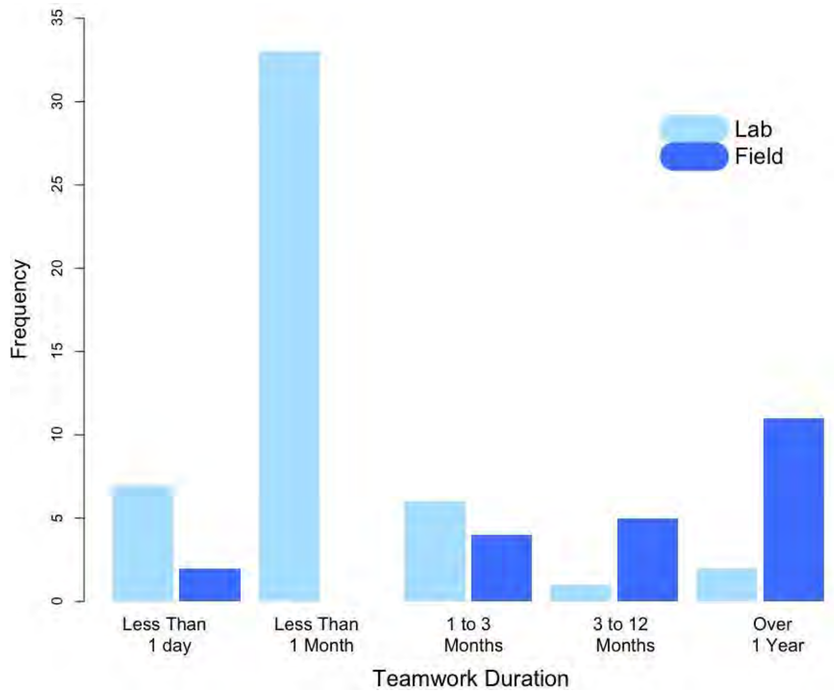


Figure 1. Sample settings within studies on team cognition organized by team duration.

Team Task Types Examined in the Team Cognition Literature

Table 4 summarizes the sorts of tasks that have been examined in relation to team cognition. We organized the tasks engaged in by teams in the primary literature into three categories using Sundstrom et al. (1990) and Cohen and Bailey (1997) as guides: (1) action teams, (2) project teams, and (3) management teams. Action teams are highly skilled and typically autonomous, specialist teams that are interdependent during high tempo situations that may require improvisation in the face of unanticipated situations (Sundstrom et al., 1990), and may mirror conditions faced by LDSE crews during high tempo work situations like those occurring during takeoff, landings, and EVAs.

As can be seen in Table 4, 45 studies have explored team cognition in action teams. Although the majority of these have been autonomous teams performing high tempo tasks under at least moderately psychologically stressful conditions (which would be consistent with LDSE crew conditions), most of these have been laboratory experiments wherein the teams performed fairly low fidelity, low physical stress tasks within ad hoc teams (which would be inconsistent with LDSE conditions).

Project teams are typically established for clear-cut tasks that involve considerable knowledge, judgment, and expertise on the part of the team members (Cohen & Bailey, 1997). LDSE crews may resemble project teams when they are working on on-going research projects outside the high tempo timeframes (e.g., takeoff, landings, dockings). Crew members may be part of project teams with their fellow crewmates, or with support personnel on the ground. This is another example of how an individual within an LDSE crew is a member of multiple teams and multiple multiteam systems. Thirty-one studies examined team cognition in project teams. Consistent with social contextual features of LDSE teams, the majority of these studies focused on autonomous field teams working on high-fidelity tasks. However, external interdependence was low for these teams, and they typically performed simple, low stress tasks, which would be inconsistent with the majority of tasks performed by LDSE teams.

Management teams coordinate and provide direction for sub-units under their direction (Cohen & Bailey, 1997). These sorts of teams may be more consistent with the mission control teams supporting the LDSE teams. Thirteen studies have examined aspects of team cognition in management teams. The majority of these focal teams were autonomous field teams of moderate duration.

Taken together, we can conclude that the extant research on action, project and management teams is generally relevant for understanding the team risks related to team performance decrements as well as inadequate psychosocial adaptation. However, the extant research on (1) action teams is generally deficient for understanding the effects of distributed team in a high fidelity, high physical stress context, (2) project teams is generally deficient for understanding LDSE *team performance decrements* when working within a MTS, and (3) management teams is generally deficient for understanding *team performance decrements* while working within a distributed or virtual MTS.

Table 4. Team Tasks Examined in the Team Cognition Literature

Team Tasks	# Studies	Description	Ecological Relevance (Aspects of this research that are relevant to LDSE)	Ecological Deficiency (Aspects of LDSE that are not well-captured by this research)
Action	45	Highly skilled specialist teams cooperating in brief performance events that require improvisation in unpredictable outcomes (Sundstrom et al., 1990, p. 121)	The majority of studies were focused on autonomous teams that performed stimulating interdependent tasks under conditions of medium-high psychological stress.	Most studies were laboratory-based with non-physically stressful tasks, and examined stand-alone, co-located teams operating only for a short time period that performed low fidelity tasks.
			Conclusion 5: Extant research on action teams is generally relevant to understanding the team risks related to *team performance decrements* as well as *inadequate psychosocial adaptation*.	**Conclusion 6:** Extant research on action teams is generally deficient for understanding the effects of *distributed teams in context* working on high fidelity tasks under conditions of high physical stress.
Project	31	Project teams are time-limited and produce one-time outputs. Their tasks are non-repetitive in nature and involve considerable application of knowledge, judgment, and expertise (Cohen & Bailey, 1997, p. 242)	The majority of studies were focused on autonomous teams operating in fields for months while performing stimulating, high fidelity tasks.	The majority of studies examined stand-alone, co-located teams operating under low physical stress levels performing simple tasks.
			Conclusion 7: Extant research on project teams is generally relevant to understanding team risks due to *team performance decrements* as well as *inadequate psychosocial adaptation*.	**Conclusion 8:** Extant research on project teams is generally deficient for understanding LDSE *team performance decrements* when working within a MTS.

Team Tasks	# Studies	Description	Ecological Relevance (Aspects of this research that are relevant to LDSE)	Ecological Deficiency (Aspects of LDSE that are not well-captured by this research)
Management	13	Management teams coordinate and provide and provide direction to the sub-units under their jurisdiction, laterally integrating interdependent sub-units across key business processes (Cohen & Bailey, 1997, p. 243)	The majority of studies were focused on autonomous teams operating in fields for months performing moderately psychologically stressful tasks.	The majority of studies examined stand-alone, co-located teams operating under low physical stress levels.
			Conclusion 9: Extant literature on management teams is generally relevant for understanding team risks due to *team performance decrements* as well as *inadequate psychosocial adaptation*.	**Conclusion 10:** Extant literature on management teams is generally deficient for understanding *team performance decrements* when working within a distributed or virtual MTS.

Samples in which Team Cognition has been Examined

Our review of 102 empirical studies on team cognition revealed seven types of samples in which team cognition has been studied. As can be seen in Table 5, approximately half of these studies have been samples of students performing interdependent low-fidelity tasks in a laboratory or classroom setting, raising some concern as to their ecological relevance to LDSE. Twenty-eight of these studies have been field samples of top management teams, "white collar workers", or engineers. These teams typically performed high-fidelity, moderately interdependent tasks requiring some external coordination. However, these tasks tended to be low in physical and psychological stress. Finally, thirteen of these samples examined military combat teams, air traffic control teams, or first responder teams (e.g., police officers, emergency workers). These teams were typically autonomous, long-duration teams engaged in high-fidelity tasks. Aspects of each of these sample types correlate with social contextual features of LDSE crews, though the non-laboratory/student samples tend to have more of the features in common with LDSE.

Taken together, we can conclude that the extant literature is generally relevant for understanding the role of team autonomy and interdependence in *team performance decrements.* Non-student/laboratory samples are likely to be highest in ecological validity, though deficient for understanding the role of team cognition in performance and psychosocial adaptation within distributed and virtual multiteam systems.

Table 5. Samples in which Team Cognition has been Examined

Samples	# of Studies	Description	Ecological Relevance (Aspects of this research that are relevant to LDSE)	Ecological Deficiency (Aspects of LDSE that are not well-captured by this research)
Aviation	3	Air Traffic Controller Teams	The majority of studies were focused on autonomous teams operating in fields for a long time period which performed high fidelity, interdependent tasks.	The majority of studies examined stand-alone, co-located teams operating under low physical stress levels.
Military	3	Combat Teams	The majority of studies were focused on autonomous teams operating in fields for a long time period which performed high fidelity, interdependent tasks.	The majority of studies examined stand-alone, co-located teams operating under low physical stress levels.
First Responder (Police, Fire, EMT)	7	FBI Nuclear Power Plant Operators; Police	The majority of studies were focused on autonomous teams operating for a long time period which performed high fidelity, interdependent tasks.	The majority of studies examined stand-alone, co-located teams operating under low physical stress levels.
Engineers	8	Software Development Teams; IT Teams	The majority of studies were focused on teams in fields performing high fidelity, somewhat interdependent tasks.	The majority of studies examined stand-alone, teams operating under low physical stress levels.
Students	57	Student project teams, class exercise	The majority of studies were focused on autonomous teams that performed interdependent tasks.	The majority of studies examined stand-alone, co-located teams performing low-fidelity tasks in laboratory settings under low physical stress levels.
White Collar	15	Teams in apparel, insurance companies, and high tech companies	The majority of studies were focused on teams that performed high fidelity, somewhat interdependent tasks some of which required external coordination.	The majority of studies examined co-located teams operating under low physical and low-to-medium psychological stress levels.
TMT	5	Top Management Teams	The majority of studies were focused on autonomous teams that performed high fidelity, somewhat interdependent tasks.	The majority of studies examined stand-alone, co-located teams operating under low physical and low-to-medium psychological stress levels.
			Conclusion 11: Extant literature across sample types is generally relevant for understanding the role of team autonomy and interdependence in *team performance decrements.* Non-student/laboratory samples are likely to be highest in ecological validity.	**Conclusion 12:** Regardless of sample type, extant literature is deficient for understanding the role of team cognition in performance and psychosocial adaptation within distributed and virtual multiteam systems.

Aspects of Team Cognition that Have Been Studied and Potential Relevance to LDSE

Table 6 reports the proportion of studies that have examined form of cognition (perceptual versus structured), form of similarity (compositional versus compilational) and content of cognition (task versus team) along with the potential relevance of these findings to LDSE. We also show the increase in number of studies conducted on each aspect of cognition since the last quantitative integration of the team cognition literature was conducted (DeChurch & Mesmer-Magnus, 2010). As can be seen, growth in research attention on these topics has been fairly consistent, with a relative balance in studies examining compositional and compilational cognition as well as teamwork versus taskwork-related team cognition.

Form of Cognition: Perceptual versus Structured. As can be seen in Table 6, the majority of studies have examined perceptual (k = 73) as opposed to structured (k = 29) cognition. Further, these studies have tended to examine perceptual cognition using long duration autonomous teams operating in realistic settings, which are also consistent with LDSE crews. Figures 2 thru 4 plot proportion of research on form of cognition (perceptual versus structured cognition) by team duration, task type, and geographic dispersion. Figure 2 depicts research on form of team cognition plotted by the duration of the focal team. As can be seen, perceptual cognition is most commonly assessed across time, with particular concentrations in short-duration and long-duration teams. Figure 3 depicts the balance of research on form of team cognition by teamwork type. As can be seen in this figure, regardless of team type the literature has consistently focused more on perceptual team cognition than structural cognition. Figure 4 depicts the proportion of research on form of team cognition by geographic dispersion of the focal team. As can be seen, the majority of research on form of cognition, whether perceptual or structured, has been conducted in collocated teams. Although the LDSE crew is collocated, its members are highly interdependent with distributed members/teams (i.e., ground control and support teams; multiteam systems). Importantly, what little has been done on team cognition in distributed and virtual environments has examined perceptual cognition.

Form of Cognitive Similarity: Compositional versus Compilational. The literature has reported research on team cognition in terms of whether the mental models held by team members are accurate and complete (compositional) as well as whether the mental models reflect complementary knowledge among team members (compilational). Compilational cognition is consistent with theories on transactive memory. Research on form of similarity of team cognition has been fairly balanced, with 56 studies exploring compositional cognition and 46 studies exploring compilational cognition. Figures 5 thru 7 plot proportion of research on form of cognitive similarity (compositional versus compilational cognition) by team duration, task type, and geographic dispersion. Figure 5 plots the volume of form of similarity research by team duration, and indicates attention to each aspect of team cognition has been fairly balanced over time as well, though with some greater emphasis on compositional cognition for shorter duration teams and on compilational cognition for longer duration teams. Figure 6 depicts the balance of attention on compositional versus compilational cognition by teamwork type examined in the primary studies. As we discussed above, LDSE crews resemble action teams when they are handling high tempo tasks like lift-off, landing, docking, and EVAs. As can be seen in Figure 6, research on action teams has typically explored compositional cognition with fewer than half examining compilational cognition. Arguably, a breakdown in compilational cognition (transactive memory) among LDSE crews has the potential to be just as disastrous as a breakdown in compositional cognition. As such, more research on transactive memory in action teams may be warranted. LDSE crews resemble project teams when they are working on ongoing research projects outside the high tempo activities involved with managing the spacecraft. Our figure suggests there has been a better balance of research on compositional and compilational research in project teams than with action teams. Figure 7 depicts the balance of research attention on compositional versus compilational cognition by geographic dispersion of the primary teams. Importantly, few studies have examined compositonal or compilational cognition in either virtual or distributed teams, suggesting this is an important area for future research attention for understanding the role of team cognition in long distance space exploration.

Content of cognition: Task-work versus teamwork. A third aspect of team cognition is the content of the cognition, or whether team cognitive models are about the task the team needs to work on versus about the team roles and responsibilities. Figures 8 thru 10 plot proportion of research on content of cognition (task-work versus teamwork cognition) by team duration, task type, and geographic dispersion. Figure 8 depicts the breakdown of research on team versus task mental models by the duration of the teams investigated. Equivalent research attention has been paid to both team and task mental models in ad hoc, short-duration teams. For longer duration teams, more research has focused on team-based mental models. Figure 9 depicts the proportion of research on team versus task mental models by the nature of tasks completed by the focal teams. As can be seen in this figure, attention on task and team mental models has been fairly balanced for action and management teams, though comparatively more attention has been focused on team cognitive models for project teams. Figure 10 depicts the proportion of research on team versus task mental models by the geographic dispersion of the focal teams. As can be seen in Figure 10, relatively little attention has been conducted in virtual or geographically dispersed teams, but typically team-based cognition has been assessed in these contexts.

Taken together, we can conclude that the extant literature on perceptual team cognition is generally relevant to understanding the team risk related to *team performance decrements* as well as *inadequate psychosocial adaptation*, whereas the extant research on structured team cognition may be relevant to team risk related to *team performance decrements* but is generally deficient for understanding risks due to *inadequate psychosocial adaptation.* With regards to the nature of emergence, we can conclude that extant research on compositional cognition, more so than compilational cognition, is generally relevant to understanding the team risk related to *inadequate psychosocial adaptation*. And, with regards to content of cognition, we can conclude that the extant literature on team-related team cognition is generally relevant for understanding the team risk related to *inadequate psychosocial adaptation*, whereas the extant literature on task-related team cognition is generally relevant to understanding *team performance decrements* within MTS, but is generally deficient for understanding the team risk related to *inadequate psychosocial adaptation*.

Table 6. Aspects of Team Mental Models that Have Been Studied

Team Cognition Construct		Relevance to Long-Duration Space Exploration	# Studies as of 2010 Meta-Analysis	# of Studies as of 12/31/2013
Form of Cognition	Perceptual	Numerous studies examined the perceptual forms of team cognition using autonomous teams operating for a long time period in realistic settings under conditions of moderate psychological stress.	54	73
	Structured	Numerous studies examined the structured forms of team cognition using interdependent teams operating for a short time period in laboratory settings.	18	29
		Conclusion 13: Extant research on perceptual team cognition is generally relevant to understanding the team risk related to *team performance decrements* as well as *inadequate psychosocial adaptation*. Extant research on structured team cognition may be relevant to team risk related to *team performance decrements* but is generally deficient for understanding risks due to *inadequate psychosocial adaptation.*		
Form of Similarity	Compos-itional	Numerous studies examined the compositional forms of team cognition using autonomous teams operating for a long time period in laboratory settings under medium psychological stress conditions.	40	56
	Compil-ational	Numerous studies examined the compilational forms of team cognition using autonomous teams operating for a long time period in realistic settings under low psychological stress conditions.	33	46
		Conclusion 14: Extant research on compositional cognition, more so than compilational cognition, is likely generally relevant to understanding the team risk related to *inadequate psychosocial adaptation*.		
Content	Team	Numerous studies examined team mental models using autonomous teams operating for a long period of time in realistic settings while performing interdependent tasks.	43	62
	Task	Numerous studies examined task mental models using autonomous teams operating in laboratory settings while performing interdependent tasks that require external collaboration.	32	43
		Conclusion 15: Extant literature on team-related team cognition is generally relevant for understanding the team risk related to *inadequate psychosocial adaptation*. Extant literature on task-related team cognition is generally relevant to understanding *team performance decrements* within MTS, but is generally deficient for understanding the team risk related to *inadequate psychosocial adaptation*.		

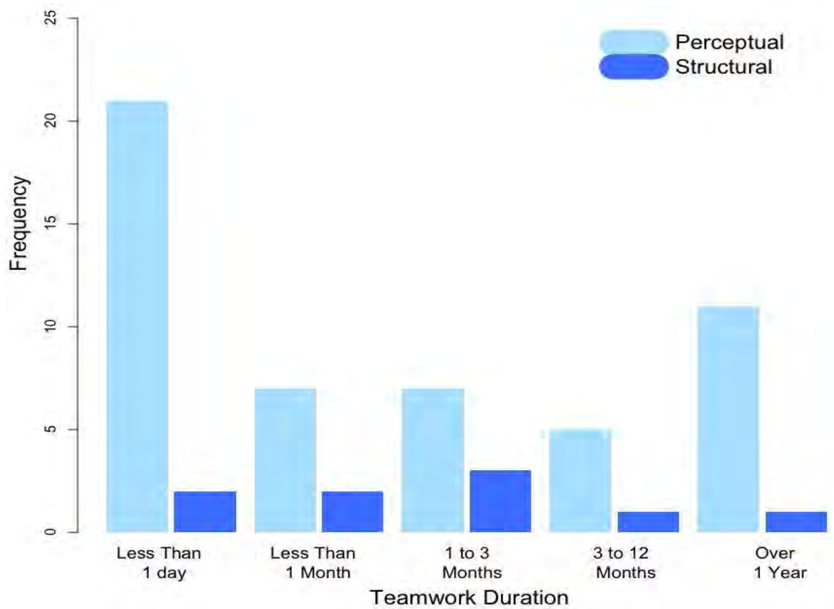


Figure 2. Form of team cognition and team duration.

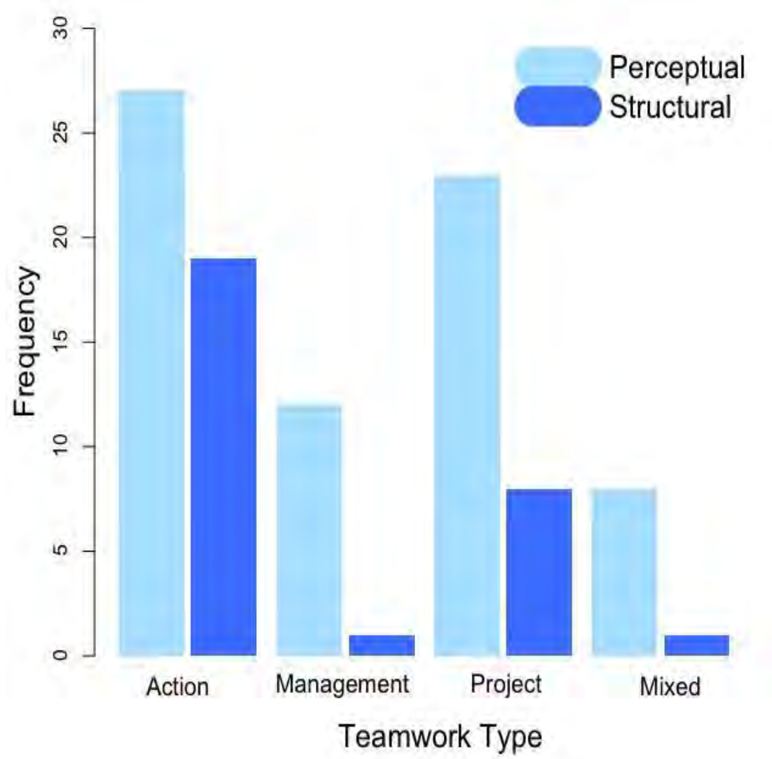


Figure 3. Form of team cognition and teamwork type.

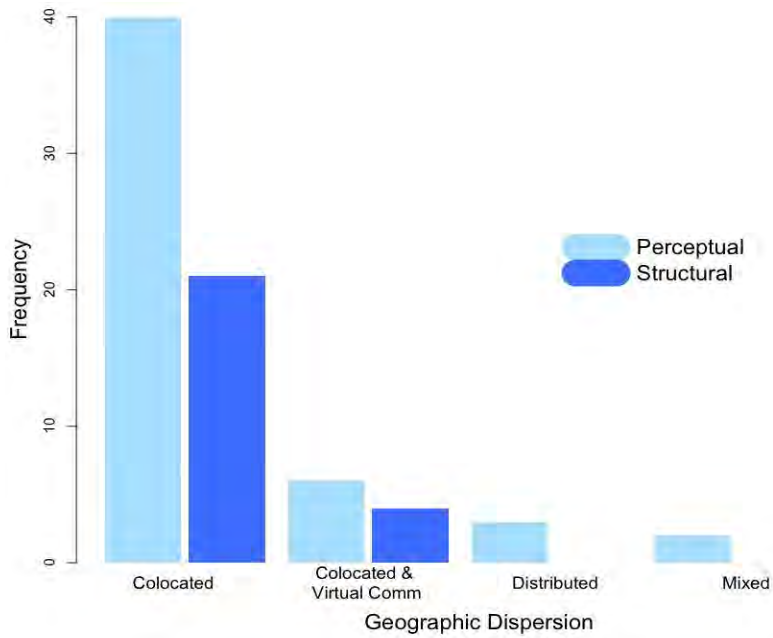


Figure 4. Form of team cognition and geographic dispersion.

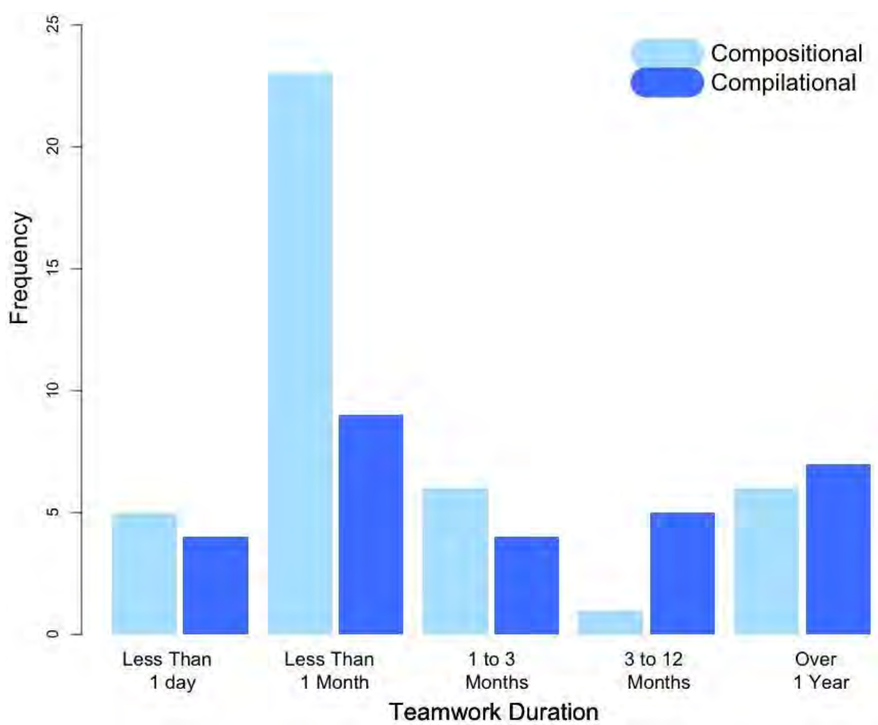


Figure 5. Form of team cognitive similarity and team duration.

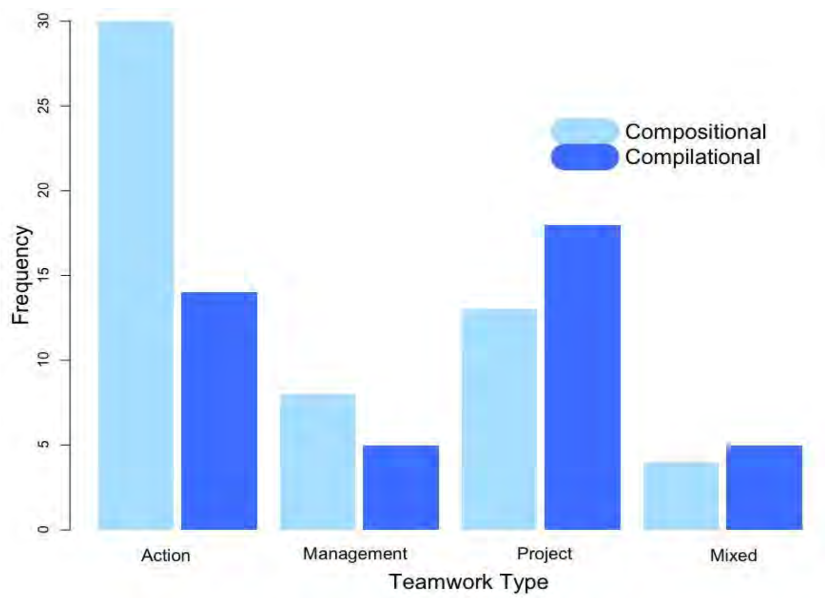


Figure 6. Form of team cognitive similarity and team type.

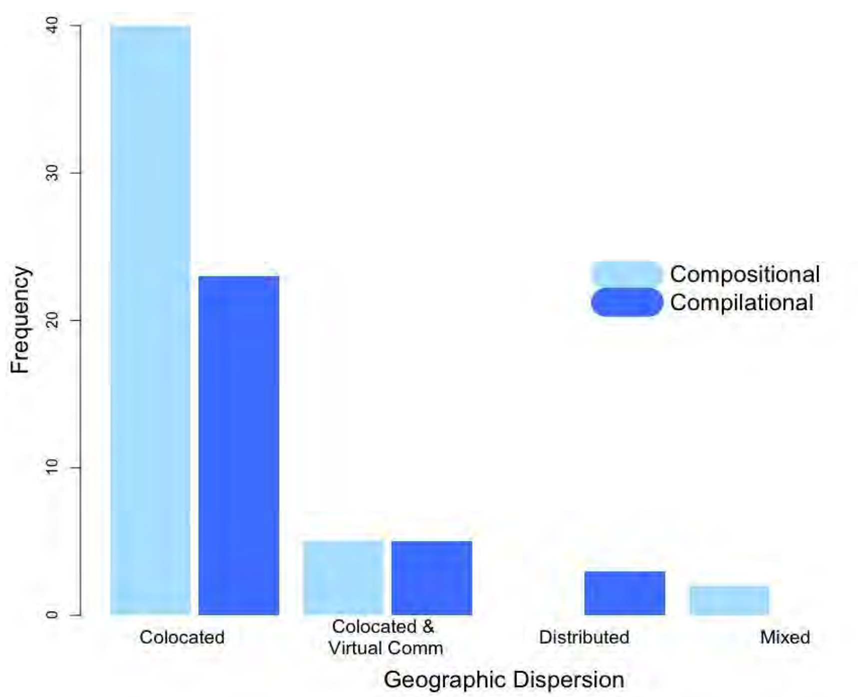


Figure 7. Form of team cognitive similarity and geographic dispersion.

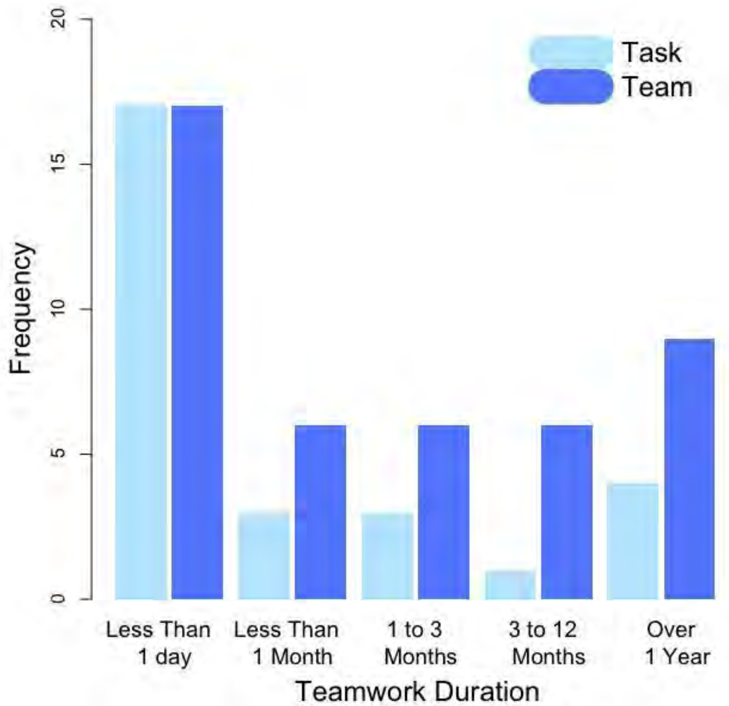


Figure 8. Content of team cognition and team duration.

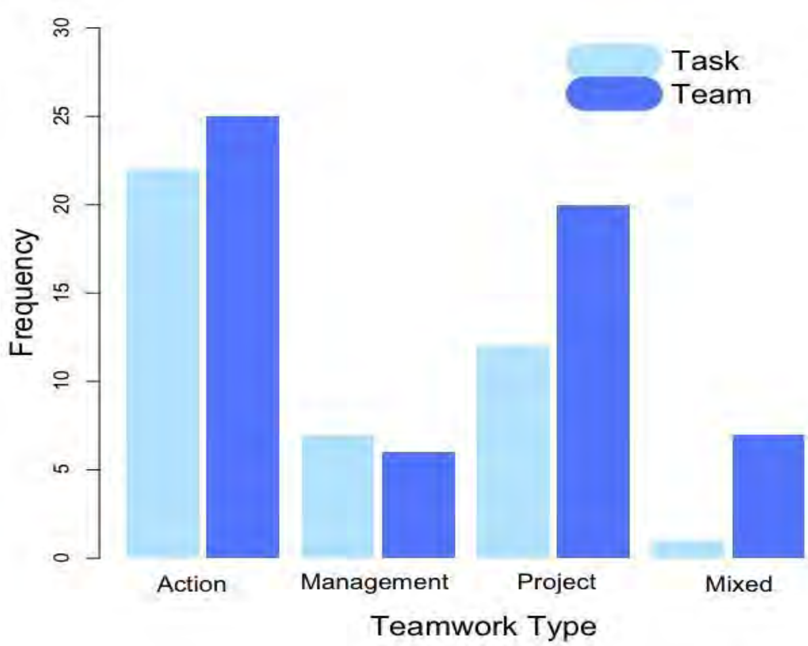


Figure 9. Content of team cognition and task type.

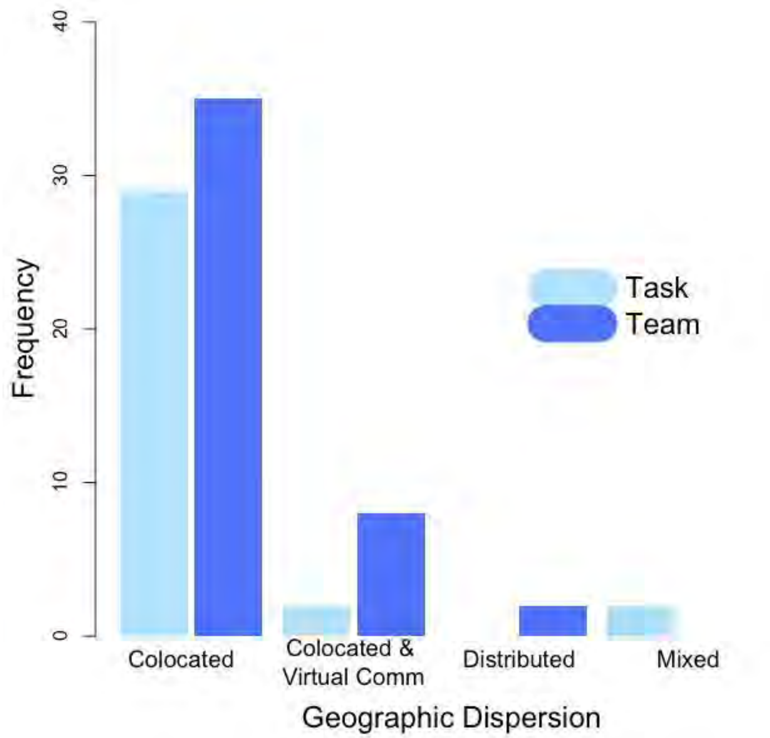


Figure 10. Content of team cognition and geographic dispersion.

Key Findings from Studies of Team Cognition in "Long-Duration" Teams

We identified nine studies of team cognition in teams that had been together for longer than one year; six of these studies investigated transactive memory systems (compilational cognition) and three of these studies investigated shared mental models (compositional cognition). We summarize these studies in terms of their sample characteristics, potential ecological relevance to LDSE crews, and their key findings in Table 7.

The studies of military, law enforcement, and air traffic control teams had the most similar contextual features to LDSE. However, studies on transactive memory within families/romantic couples should not be disregarded, as LDSE crew members are simultaneously part of work teams as well as family-like teams with their fellow crew members given the isolated and confined quarters they will coexist within for extended durations.

Conclusions drawn from the three studies on shared mental models (compositional cognition) in long-duration teams support the idea that accurate and similar shared mental models enhance team efficacy and team effectiveness. Conclusions drawn from the six studies on transactive memory (compilational cognition) in long-duration teams suggest transactive memory improves team performance, creativity, coordination, communication, and satisfaction, and reduces perceived work stress.

Table 7. Key Findings from Studies of "Long-Duration" Teams (i.e., teams with a lifespan > 1 year)

Study Citation	Sample Characteristics	Ecological Relevance to LDSE Crews	Cognition Construct Explored	Key Findings
Austin (2003)	Groups working together for an average of 2.5 years in a apparel company which were responsible for profit and loss, purchasing, and making new product recommendations	Long-duration interdependent project teams faced with periods of boredom and periods of high workload	Transactive Memory Systems	Transactive memory influenced the extent to which groups attained their financial and development goals, and enhanced the company's adaptability to its market as well as cross-department communication.
Child & Shumate (2007)	Work teams working together for an average of 3 years in various industries such as aerospace, hospitality, consulting, legal, and military	Long-duration teams with varied relevance to LDSE	Transactive Memory Systems	Transactive memory positively influenced team member satisfaction with their departmental decisions, team coordination, and project completion efficiency.
Maynard, Mathieu, Rapp, & Gilson (2012)	Global virtual supply chain teams working together in a large international IT company for an average of 4.9 years which were involved in the company's business transformation strategy and initiatives	Long-duration, interdependent, geographically dispersed, virtual project teams, with potential for external interdependence, period of boredom, and periods of high workload	Transactive Memory Systems	Preparation activities including goal specification, mission analysis, and strategy formulation influence transactive memory, which subsequently influenced team coordination.
Mathieu, Rapp, Maynard, & Mangos (2010)	Air traffic controller shift teams working together for an average of 1.8 years	Long-duration action teams, with external interdependence working in psychologically stressful environments with potential for periods of high workload as well as periods of boredom	Shared Mental Models	Task SMMs increased collective efficacy. Team and task SMMs interacted to influence team effectiveness such that task SMMs enhanced the effect of team SMMs on team effectiveness.

Study Citation	Sample Characteristics	Ecological Relevance to LDSE Crews	Cognition Construct Explored	Key Findings
Marques-Quinteiro et al. (2013)	Portuguese police special units working together for an average of 5.8 years which were responsible for performing hostage rescues and counterterrorism operations and engaging heavily armed criminals	Long-duration action teams operating in physically and psychologically stressful environments with potential for periods of high workload as well as periods of boredom	Transactive Memory Systems	Implicit coordination positively influenced TMSs, which subsequently enhanced the ways teams solved problems creatively, dealt with uncertain situations, and handled work stress.
Smith-Jentsch, Kraiger, Cannon-Bowers, & Salas (2009)	Commercial air traffic controller teams working together for an average of 26 months	Long-duration action teams, with external interdependence working in psychologically stressful environments with potential for periods of high workload as well as periods of boredom	Transactive Memory Systems	Teammate familiarity impacted TMS which affected the extent to which members on average asked for help and accepted help.
Lim & Klein (2006)	71 combat teams in the Singapore Armed Forces which worked together for an average of 13 months	Long-duration action teams, with external interdependence working in psychologically and physically stressful environments with potential for periods of high workload as well as periods of boredom	Shared Mental Models	Accuracy and similarity of team mental models positively influenced the performance of military teams which operated in a training combat circuit.
Wegner, Erber, & Raymond(1991)	Romantic couples who were together for an average of 19.6 months	Long-duration social teams which may relate to the social relationships formed in LDSE	Transactive Memory Systems	When participants were directed to memorize various pieces of information using a particular memory strategy, pairs of strangers outperformed natural couples. When there was no specific memorization style assigned, natural couples outperformed pairs of strangers.

Study Citation	Sample Characteristics	Ecological Relevance to LDSE Crews	Cognition Construct Explored	Key Findings
Smith-Jentsch, Mathieu, & Kariger (2005)	Commercial air traffic controller teams working together for an average of almost 6 years	Long-duration action teams, with external interdependence working in psychologically stressful environments with potential for periods of high workload as well as periods of boredom	Shared Mental Model	Two types of task SMMs, which capture the degree to which different strategies are effective in solving a critical incident and the degree to which goals associated with different roles are related to each other, inte racted with each other to influence team performance. When both SMMs are important, one type needs to be at the moderate level in order for the other to be effective.

Literature Review Conclusions

In systematically reviewing the literature on team cognition to assess what we know, and what we need to know about possible risks due to team failures that arise from breakdowns in team cognition, we draw out three areas: First, what conclusions *can* we draw based on the extant empirical research about how the context of space flight will affect team cognition? Second, what conclusions *can't* we draw based on the extant empirical research because the context under which team cognition has been studied does not exhibit adequate ecological validity to space flight? Third, what are the most critical areas for future research on team cognition?

Conclusions We Can Draw

Based on our systematic review of the literature on team cognition, there are a number of solid conclusions that we can draw about the role of team cognition during space flight.

The relevance of the existing research to LDSE. First, we identified seven contextual features of LDSE crews that could be used to organize the extant literature on team cognition. In particular, LDSE teams are (1) smaller teams supported by larger teams, (2) isolated, (3) confined, (4) long-duration teams, and were likely to face work contexts with (5) high tempo workload, (6) extended workload, and (7) periods of boredom. Using this framework, we find that:

- <u>Small teams supported by larger teams</u>: Although research conducted within autonomous and interdependent teams is generally relevant to LDSE teams, this research is deficient in understanding team risk due to team performance decrements and inadequate psychosocial adaptation within virtual or distributed teams as well as within teams who are externally interdependent with larger teams.
- <u>Isolated environments</u>: The extant literature conducted in geographically dispersed and/or psychologically stressful contexts is generally relevant to understanding this aspect of LDSE, however few studies have been conducted in contexts meeting *both* of these conditions and even research conducted in typical space flight analogs (e.g., Antarctic winter-over missions) does not adequately capture the extreme isolation that will be felt by crew members in LDSE missions.
- <u>Confinement</u>: The extant literature conducted in physically or psychologically stressful conditions provides some generalizability to LDSE, however little research has been conducted in contexts that are *both* physically and psychologically stressful.
- <u>Team tenure</u>: Research conducted within field settings with long-duration teams is generally relevant to LDSE, though since little research has examined action teams in this setting, this research is still somewhat deficient for understanding team risk due to team performance decrements.
- <u>Task tempo</u>: The extant literature is currently deficient in understanding the role of work tempo (high, extended, boredom) on team cognition as few studies have examined teams

in these conditions and fewer still have been conducted in an ecologically relevant field setting.

Further, we paid particular attention to (1) the settings in which team cognition research has been conducted (laboratory versus field settings), (2) the types of teams examined in relation to team cognition (as LDSE crew members are likely to be members of both action and project teams, and ground control support staff are likely to be members of both management and project teams), (3) the nature of cognition examined in these primary studies (shared mental models versus transactive memory systems, and team versus task-based cognitive structures), and (4) findings drawn from long-duration teams (as these teams are most likely to have faced similar social contextual features as LDSE teams). From these analyses, we can conclude the following:

- Setting: The extant laboratory research is generally relevant to understanding the team risk related to *team performance decrements,* but is deficient in understanding the team risk due to *inadequate psychosocial adaptation.* The extant field research is generally relevant to understanding the team risk related to both *team performance decrements and psychosocial adaptation,* and deficient for understanding the effects of *distributed teams in context* who are working under conditions of *high physical stress*. In sum, the extant non-student/non-laboratory research samples are likely to be highest in ecological validity, though deficient for understanding the role of team cognition in performance and psychosocial adaptation within distributed and virtual multiteam systems.
- Task type: The extant research on action, project, and management teams is generally relevant for understanding the team risks related to team performance decrements as well as inadequate psychosocial adaptation. However, the extant research on (1) action teams is generally deficient for understanding the effects of distributed team in a high fidelity, high physical stress context, (2) project teams is generally deficient for understanding LDSE *team performance decrements* when working within a MTS, and (3) management teams is generally deficient for understanding *team psychosocial adaptation.*
- Aspects of team cognition: The extant literature on perceptual team cognition is generally relevant to understanding the team risk related to *team performance decrements* as well as *inadequate psychosocial adaptation*, whereas the extant research on structured team cognition is generally deficient for understanding risks due to *inadequate psychosocial adaptation.* With regards to the nature of emergence, the extant research on compositional cognition, more so than compilational cognition, is generally relevant to understanding the team risk related to *inadequate psychosocial adaptation*. And, with regards to content of cognition, the extant literature on team-related team cognition is generally relevant for understanding the team risk related to *inadequate psychosocial adaptation*, whereas the extant literature on task-related team cognition is generally relevant to understanding *team performance decrements* within MTS.
- Long-duration teams: Research on team cognition within military, law enforcement and air traffic control teams had the most similar contextual features to LDSE. However,

research on transactive memory within families should not be disregarded. Conclusions drawn from the three studies on shared mental models (compositional cognition) in long-duration teams support the idea that accurate and similar shared mental models enhance team efficacy and team effectiveness. Conclusions drawn from the six studies on transactive memory (compilational cognition) in long-duration teams suggest transactive memory improves team performance.

The importance of transactive memory. An important conclusion we can draw from our literature review is that research on transactive memory systems is as relevant as research on team shared mental models to understanding the role of team cognition in team performance and viability during long-duration space exploration. Shared team mental models typically capture the similarity of the cognition among team members (e.g., what we know as a team, what we need to know, what our goals are, what we need to accomplish, what our roles and responsibilities are, etc.), whereas transactive memory systems typically capture the complementarity of that knowledge among members (e.g., who knows what, who is an expert at what, who can I rely on for what, who could be a backup for what, etc.). The nature of cognition relevant to transactive memory is highly relevant to team adaptation under stressful or unexpected conditions. Further, given the myriad social contexts the astronauts will operate in while on their LDSE mission, transactive memory is relevant to understanding the social structure of the crew and its interrelationships within and between various teams. Changes in the social context the astronauts will operate within will accompany changes in transactive memory systems. Taken together, we expect that the successful shifting among social contexts will be harder and more reliant on transactive memory shifting than on shared mental model shifting.

Conclusions We Cannot Draw

Based on our systematic review, and interpretation of NASA materials, we also point out aspects of the space flight context likely to affect team cognition that have not been adequately studied. These themes are the: (1) multiteam membership, (2) multiteam system, (3) dynamic nature of team cognition, and (4) inability of team members to leave the team. These four themes represent the most pressing areas in need of study in analog settings in order to adequately assess the risks due to team failures that would be likely to arise during long-duration space exploration missions.

The first two themes reflect somewhat of a misnomer in the label "team risk." In reality, an astronaut in a long-duration space exploration mission will be a part of *many* teams. At times s/he will work independently, at times as a member of a small team aboard the space craft, at times a member of a multiteam system with the ground control, at times in an international alliance, and at times as a member of a living group which more closely resembles a family than a team. All of these contexts require that the astronaut understand his/her role in the group, and how to switch in and out of roles as task demands necessitate that s/he transition between these collectives. The term team risk also obscures the reality that astronaut crews work in the context of a multiteam system with the various ground control teams, as well as the importance of the groups literature to understanding the social context in which LDSE crews operate.

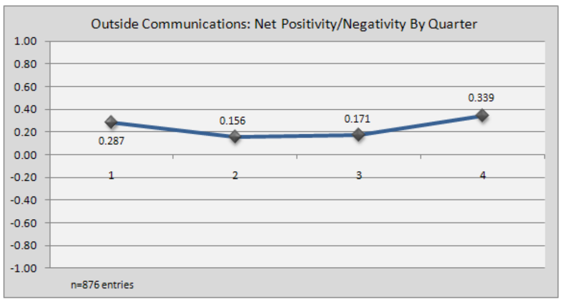
Theme 1: Multiteam membership (MTM). Astronauts will be living and working in about seven different types of collectives during long-duration space exploration (listed below), and they will be actively switching between them. A different cognitive architecture is needed for functioning/performance in each of these collectives. Meaningful measurement of team cognition and associated countermeasures will need to be sensitive to these changes, and to the possible "cognitive switching costs" associated with them. Accordingly, we identify team cognition in the context of multiteam membership as a top priority for future research. Such research is needed to assess the team risk associated with inadequate coordination, cooperation, and psychosocial adaptation within teams.

MTM is defined as "a situation in which individuals are concurrently members of two or more teams within a given period of time. The level of MTM within a social system is a function of the average number of team memberships held by individual members within that same time period. This definition of MTM includes three key components: team, membership, and time period (O'Leary, Mortenson, & Wooley, 2009)." Early research on MTM shows curvilinear relationships of MTM on a variety of outcomes including learning, performance, and satisfaction. In this way, leveraging a solid understanding of how MTM affects team cognition will provide a way to mitigate team risks. In our review of the literature, we noted seven different types of "collectives" astronauts will work in during space exploration missions. We note that this list increases exponentially when different subsets of the crew work on different teams.

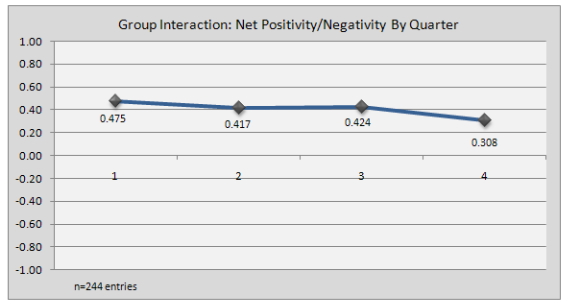
Examples of astronaut multiteam membership encountered during long-duration space exploration missions:

1. Astronauts working as a set of individuals
2. Astronauts working in a MTS
3. Astronauts working in different MTSs (e.g., US & Russian ground controls)
4. A team of astronauts
5. A team of astronauts working in a MTS
6. A team of astronauts working in a Multigroup-MTSs (e.g., US & Russian ground controls)
7. A group of astronauts (e.g., providing social support and caregiving, like a family)

Theme 2: Multiteam systems (MTSs). A second source of complexity in the structure of space explorations teams is their embeddedness within multiteam systems. We note that two figures presented in Stuster's (2010) report clearly show the criticality of MTSs during space flight. Figure 11 presents the balance of positivity to negativity in the journal entries of 10 ISS astronauts. Figure 11a shows the balance for outside communications; Figure 11b shows the balance for group interactions. Larger values indicate that positive entries outnumbered negative ones. The figures display these values at each of four time periods. Notably, the positivity is always higher when the crew is writing about the group (i.e., the space crew) than when they are writing about other teams in the MTS (i.e., the ground crew). The crew-ground relations are what MTS researchers have termed “between team process” (DeChurch & Marks, 2006; Marks et al., 2005). Interventions aimed at aligning team cognition in order to mitigate decrements in team performance and adaptation must focus at least as much attention to the between-team cognition as to the within-team cognition.



a. Balance of positivity/negativity in journal entries about the crew’s outside communications. Figure drawn from Stuster (2010, p.44)



b. Balance of positivity/negativity in journal entries about the crew’s internal interactions. Figure drawn from Stuster (2010, p.44)

Figure 11. Balance of positivity/negativity in ISS astronaut logs reported by Stuster (2010).

Theme 3: Dynamic cognition. A third important and under-researched aspect of team cognition relevant to space flight is the dynamism of team cognition. The extant research on team cognition measures team cognition as if it is a stable property of a team. Given the complexity of astronaut crews working both with multiteam membership and within multiteam systems, it is important to conceptualize cognition as a dynamic construct. Astronaut mental models will have some elements that will need to shift as s/he changes between groups, teams, tasks, and goals. Future research is needed that embraces this dynamic view of team cognition and develops high-resolution metrics that capture these shifts. One new approach to understanding team dynamics in “real time” that would be particularly appropriate for measuring dynamic team cognition is *relational event networks* (Leenders, DeChurch, & Contractor, 2014).

Theme 4: Inability of team members to leave the team. The fourth theme relevant to team cognition and the team risk in general is the reality that members of a long-duration space exploration team will not be able to leave the team. This aspect of the social context is apart from what is captured by isolation and confinement. It is the complete lack of individual agency. Astronauts will not be able to walk away, take time apart, and focus their efforts on other parts of their lives. They will be living the mission. Living it every day for as many as 3 years. This reality was well captured in the following journal entry:

> “I woke up this morning thinking, “OK I don’t want to ‘play’ anymore. I just want to be home sleeping in our bed, eating at the dining table, sitting in my recliner (Stuster, 2010, p. 19).”

Future research on team cognition needs to explore the effects of team cognition in teams with this same defining aspect of their existence.

Future Directions

Our review is designed to provide a roadmap to the NASA Behavioral Health and Performance group, connecting available evidence on team cognition to essential elements of the space flight context. We summarize this research with regard to its relevance to space flight, and, in doing so, identify areas where conclusions can be reasonably extrapolated from team cognition in settings such as military and first responders to space flight. We also submit the above four themes of team cognition research with the highest priority to mitigate team performance decrements and inadequate psychosocial adaptation in long distance space exploration.

Part 2: Measurement Review & Assessment

Measuring Team Cognition Over Long-Distance Space Exploration: A Five-Factor Framework

One of the most critical organizational challenges presented by a long-distance space exploration mission is the challenge of teamwork. Long-distance space exploration will push the limits of science on virtually every front: in human health, aerospace engineering, astrophysics, and bioengineering to name a few. On the organizational front, a successful long-distance space mission will push the boundaries of what we currently know about teamwork. The teamwork that will succeed or fail during long-distance space exploration pushes the boundaries of team size, requiring hundreds of individuals to work in a coordinated fashion. At the same time, these large teams will be highly specialized. Individuals will work in tightly coupled units with like-minded experts, whilst needing to coordinate with other teams of differently minded experts. And further complicating the issue, teams will exhibit a degree of virtuality unprecedented in modern exploration missions. Advances in information and cyber technologies have put large specialized teams in direct contact with each other, decaying many of the skills that would have been used in the times of Christopher Columbus and Marco Polo, when small groups of explorers were disconnected from assistance for long periods of time.

Modern exploration missions are characterized by immediate contact. As a case in point, exploration that occurs aboard the can be largely orchestrated and implemented by scientific teams located here on Earth. In some sense, the challenge of long-distance space exploration, missions that move beyond lower Earth orbit, will require the kind of independence that characterized the exploration conducted by Columbus and Polo. However, the sheer scientific complexity required to send a crew of six humans safely to Mars will necessitate a level of close interaction and interdependence that characterizes modern times.

Enabling high-performance teamwork under these extreme conditions will require an unprecedented level of precision in measuring and maintaining team processes. Rather than designing the set of teams that will carry out the mission, and hoping for the best, sophisticated in-situ data tracking systems will need to continuously monitor the functioning of the large system of teams involved in the mission and provide early warning diagnostics that can be used to anticipate likely breakdowns and adjust interactions accordingly.

This report considers one important construct of teamwork: team cognition. In our literature review we differentiated various types of team cognition and summarize the evidence regarding the importance of various aspects of team cognition during long-distance space exploration. In the current report, we provide an overview of existing measurement methods for assessing team cognition that would be critical in developing an early warning detection system for team breakdowns.

Our report is structured as follows. First, we present some of the key challenges in measuring team cognition. Second, we discuss the current best practices in measuring team cognition. Third, we develop a five-factor framework for selecting and/or developing team cognition measures for use in space exploration missions. Fourth, we summarize the measurement approaches that have been developed and reported in prior research, and evaluate them according to five factors. Fifth, we discuss a selection of methods used to measure team cognition in analogous populations, and evaluate them according to the five factors.

The Challenges of Measuring Team Cognition

Team cognition provides a valuable glimpse into the mind of a team. To what extent do team members share an understanding of key elements of their task, roles, resources, and constraints? Do team members know who in the team has what expertise? Being able to anticipate the needs of a teammate or access information needed to solve a novel problem requires a cognitive foundation. When individuals work alone on complex problems, they often have to combine disparate pieces of information, rely on their prior experiences, and connect previously disconnected ideas. The challenge of teamwork arises from the fact that the information needed to solve the problem is no longer resident within an individual, and rather requires that multiple individuals combine disparate information. Essentially *with teams, it is human social interaction as opposed to neural pathways that serve as the critical conduit through which problem-solving occurs*. The very notion of team cognition recognizes the need for cognitive architectures that span multiple individuals. As we note previously in our review, the construct of team cognition has been found to have some of the strongest predictive validity of team performance of any of the process and emergent state variables that have been studied in teams.

Capitalizing on the predictive utility of the team mental model construct requires that it be adequately measured in operational settings. This is perhaps the largest barrier to translating science to practice in the area of team cognition. Research on team shared cognition has raised concerns about how best to measure team shared mental models (Cannon-Bowers & Salas, 2001; Klimoski & Mohammed, 1994; Mohammed, Klimoski, & Rentsch, 2000; Smith-Jentsch, 2009), as there is a great deal of complexity involved with its operationalization (Cannon-Bowers & Salas, 2001; Klimoski & Mohammed, 1994; Mohammed, Klimoski, & Rentsch, 2000). Several research streams have addressed the measurement issue conceptually, and raised important considerations and methods for operationalizing team mental models (Cooke et al., 2007; Mohammed et al., 2000). Importantly, different operationalizations of the shared mental model construct vary by the extent to which they capture meaningful aspects of the nature and arrangement of shared cognition. These underlying differences are believed to impact the validity of cognition in predicting team process and performance (Klimoski & Mohammed, 1994; Mohammed et al., 2000; Smith-Jentsch, 2009). A cursory scan of the extant team mental model research shows substantial inter-study variation in the way in which team mental models are measured.

There are several reasons why measuring team cognition is particularly challenging, and more challenging than measuring many other team constructs such as conflict, communication, and coordination. First, measures of team cognition are task and context specific. Many psychological constructs have well validated measures that can be used to assess them. There are number of advantages to using a previously developed measure. First of all, it is essential for the reproducibility of science. If one wishes to measure a construct that has been shown to predict performance, it is desirable to use the exact same measure on which the basic research was conducted. In the case of team cognition, this is rarely possible. The two major team cognition research streams are team mental models (TMM) and transactive memory systems (TMS). Whereas validated survey measures of TMS are available, no such measures of TMM exist. Furthermore, research on team cognition shows that the very nature of the construct does not lend itself to assessment with a pre-existing and transportable measure. In fact, the ideal measurement approach is to capture team cognition in a way that is idiosyncratic to the context, the task, the roles, and the people of interest in a particular situation. This means that unique measures need to be developed for each application scenario. Whereas the measures need to be customized, fortunately there are some established guidelines in the development of team cognition measures that can be very useful in ensuring that reliable and valid measures are developed.

The second challenge in assessing team cognition is the need to model structure in addition to content. Meta-analytic research has shown that measures that capture structure are more valid than measures that do not capture structure (DeChurch & Mesmer-Magnus, 2010). Simply put, structure captures aspects of mental models such as how knowledge and information are mentally organized. It is not enough for two people to understand what the five critical life-support systems are, but they need to organize this information in terms of its relative importance, the interrelations among the life support systems, etc. in a similar manner. Aspects of structure that have been examined in prior research include hierarchy, sequencing, centrality, and other patterns of interrelations. When this information is obtained by directly asking individuals about their understanding, it can be extremely laborious. Thus, unobtrusive measures will need to be developed if they are to be realistically implemented in a long-distance exploration mission.

Third, measures of team cognition need to be taken repeatedly. Much of the research that has examined team cognition has done so by taking one measure and correlating it with antecedents (e.g., team composition) and consequences (e.g., team process). The reality in an operational setting is that mental models are highly dynamic, individuals are continuously updating their understanding of the situation as new information comes in and old models prove inaccurate, and as individuals refine their own models, they can become more similar or disparate from other individuals models. Thus, given the dynamic nature of the construct, it is necessary to develop a metric to capture team cognition that is sensitive enough to register small changes in individuals' understanding of the team and task situation.

Each of these challenges is particularly important to keep in mind when recommending measures of team cognition that can be used in long distance exploration missions. The reality is that measures will need to be highly detailed, and capture complex content, while at the same time be short and unobtrusive, requiring little effort of the astronauts and crew. Measures that will be most useful as early warnings detection systems will need to be taken frequently, and analyzed automatically in order to be diagnostically useful. We return to the specific operational needs of the long-distance space exploration context later in our report. We now turn to the state-of-the-art thinking on how best to assess team cognition.

Current Best Practices in Measuring Team Cognition

According to Mohammed and colleagues (2000), there are generally three important characteristics that permit the measurement of the degree of convergence or similarity among team members' shared cognition: (1) elicitation method, (2) structure representation, and (3) representation of emergence.

Elicitation method. The *elicitation method* refers to the technique used to determine the content or components of the model. Commonly used elicitation techniques are similarity ratings, concept maps, rating scales, and card sorting tasks (Mohammed et al., 2000). Ideally, these approaches to elicitation should be based on the results of a thorough task analysis that identifies the essential elements of the team's task. Different elicitation methods vary in the manner by which they present task information to participants. For example, a mental model of the task of completing an EVA could be elicited using any of the above approaches. Similarity ratings might be employed by presenting astronauts with a grid and then requesting they consider each pair of task nodes and report their perceptions of the relation between node pairs. A rating scale would elicit the content of the model by asking participants to respond to questions about the task on fixed-response formats (e.g., strongly agree to strongly disagree). A concept map would elicit content by asking participants to place actions into some meaningful organization scheme.

In our review of the team cognition measurement literature (DeChurch & Mesmer-Magnus, 2010), we found elicitation was typically assessed using similarity ratings, concept mapping or card sorting, questionnaires, or content analysis of cognitive maps. Importantly, researchers had two key approaches to eliciting mental models: (1) providing respondents pre-defined categories of cognitive content to rate/sort/map (i.e., similarity ratings, concept mapping/card sorting, questionnaire/rating), or (2) inducing respondents to provide their mental models without using pre-defined categories (i.e., cognitive map/content analysis). The key difference between the two approaches lies in whether the researcher generates the categories/components of the mental model for the respondent or whether they induce the respondent to provide their mental model content themselves. An example of the first approach might involve a researcher providing a respondent a list of task concepts and asking them to rate the similarity among concepts (e.g., Mathieu, Heffner, & Goodwin, 2005). An example of the second approach might involve a researcher content analyzing a respondent's description of their mental model (e.g., Fleming, Wood, Bader, & Zacarro, 2003).

We found that the elicitation method used to assess team cognition had implications for the strength of relationship between team cognition and team process as well as between team cognition and task performance (DeChurch & Mesmer-Magnus, 2010). Indeed, when shared mental models are elicited using similarity ratings, the relationship with team process is stronger than when they are assessed using either concept mapping/card sorting, or questionnaires or rating scales. Further, using cognitive mapping or content analysis yielded stronger links between team cognition and performance than either other method.

Structure representation. While elicitation methods capture the content of a mental model, they do not necessarily represent how that knowledge is structured. Structure representation operationalizes the shared mental model according to the degree of correspondence between how the knowledge contained in the model is represented in the mind, and how that knowledge representation is modeled by the researcher. As such, *structure representation* constitutes a second crucial aspect of team mental model measurement (Klimoski & Mohammed, 1994; Mohammed et al., 2000). Similarity ratings typically prompt respondents to think in terms of the degree of association between distinct components of their team or task. In this way, they capture associative networks of knowledge. At the other extreme, rating scales capture levels of knowledge, but do not model the structure or organization of that knowledge. Concept maps have been used to capture the sequencing of team actions; sequencing reflects an organization or structure of knowledge, though sequencing inherently models less structure than do network-based approaches (Marks et al., 2001).

In our review of the team cognition measurement literature (DeChurch & Mesmer-Magnus, 2010), we found structure representation was typically assessed using Pathfinder, UCINET, multidimensional scaling, concept mapping or card sorting. The objective of these approaches is to determine the way in which categories/concepts in the team's mental model is organized. Approximately half of the studies we surveyed did not report any attempt at structure representation. When we compared the strength of the team cognition - team process relationship, we found the strongest effects were evidenced using the Pathfinder PFNets. Positive, albeit smaller, effects were seen when structure was represented using a card sorting or concept mapping approach. When the method used to operationalize shared mental models did not enable the representation of structure, there was essentially no observed effect between shared mental models and team process. When examining the SMM-team performance relationships based on the representation of structure shows highly comparable estimates using Pathfinder, concept mapping/card sorting, and even estimates where mental model structure is not captured.

Representation of emergence. The third distinguishing aspect of how mental models are operationalized, *representation of emergence*, concerns how individuals' mental models are collectively considered as constituents of the team mental model (Kozlowski & Klein, 2000). Shared mental models align with Chan's (1998) description of a dispersion construct. When shared mental models are considered at the team level, it is typically the degree of similarity in models as opposed to the particular content of the team model that is of interest. Researchers have tended to index shared mental models at the team level using indices reflecting the level of similarity in the group. For example, in studies using pairwise comparison data, network analysis algorithms such as Pathfinder's C or UCINet's QAP correlation (Borgatti, Everett, & Freeman, 1992) are typically used to compare the overlap of team member's models. Rwg(j) (James, Demaree, & Wolf, 1984) has been used to reflect agreement within the team. Euclidean distance has been reported as a geometric representation of the separation or closeness of the model. Representation of emergence indexes the extent to which team members' mental models converge, and was typically accomplished using agreement indices (% overlap, rwg), team member consistency (r, ICC, alpha), a concept mapping scoring system, Pathfinder (C), UCINET Convergence indices (QAP), Euclidean Distance (MDS), or Consistency with Euclidean Distance (r, ICC, alpha, MDS).

Stronger effect sizes have been reported for the link between shared mental models and team process with Pathfinder "C" as well as with consistency or Euclidean distance indices as compared with others (DeChurch & Mesmer-Magnus, 2010). Interestingly, research suggests no relation between shared mental models and team process in studies using an index of within group agreement (DeChurch & Mesmer-Magnus, 2010). Research has more consistently reported positive effects across all compilation indices for the SMM-team performance relationship based on representation of emergence indices, though the strongest effects have been observed when either an index of agreement or a concept mapping scoring system was used, followed by either Pathfinder "C" or Euclidean distance (DeChurch & Mesmer-Magnus, 2010).

Perceptual measures. Perceptual cognition models team members' beliefs, attitudes, values, perceptions, prototypes, and expectations, but "does not provide a deep understanding of causal, relational, or explanatory links (Rentsch et al., 2008)." One form of perceptual cognition is "shared perception", like team-level climate. Other forms include shared beliefs and shared expectations (e.g., Xie & Johns, 2000). Typically, the way in which perceptual cognition is assessed means that it is more aligned with the content of cognition than the structure of that cognition. It does not provide deep understanding of causal, relational, or explanatory links among the content (Rentsch et al., 2008). Perceptual cognition tends to be measured using Likert-type scales assessing respondent perception of shared beliefs, attitudes, values, etc. For example, Lewis (2003) proffers a 15-item survey approach to assess three aspects of transactive memory: specialization, credibility, and coordination. Sample items for specialization include "each team member has specialized knowledge of some aspect of our project", "different team members are responsible for expertise in different areas", and "I know which team members have expertise in specific areas". Sample items for credibility include "I was comfortable accepting procedural suggestions from other team members", "I was confident relying on the information that other team members brought to the discussion", and "when other members gave information, I wanted to double-check it for myself (reversed)". Sample items for coordination include "our team worked together in a well-coordinated fashion", "we accomplished the task smoothly and efficiently", and "our team needed to backtrack and start over a lot (reversed)". Items are scored on a 5-point Likert-type scale ranging from 'strongly disagree' to 'strongly agree'.

Faraj and Sproull (2000) designed an 11-item questionnaire assessing three aspects of transactive memory: expertise location, expertise needed, and expertise provided. Sample items for expertise location include “the team has a good ‘map’ of each others’ talents and skills”, “team members are assigned to tasks commensurate with their task-relevant knowledge and skill”, and “team members know who on the team has specialized skills and knowledge that is relevant to their work”. Sample items for expertise needed include “some team members lack certain specialized knowledge that is necessary to do their task”, “some team members do not have the necessary knowledge and skill to perform well - regardless of how hard they try”, and “some people on our team do not have enough knowledge and skill to do their part of the team task”. Sample items for expertise provided include “people in our team share their special knowledge and expertise with one another”, “if someone in our team has some special knowledge about how to perform the team task, he or she is not likely to tell the other member about it (reversed)”, and “more knowledgeable team members freely provide other members with hard-to-find knowledge or specialized skills”.

In their 2010 article published in the Academy of Management Review, Huber and Lewis articulate a team cognition-related construct called ‘cross-understanding’. Cross-understanding refers to the extent to which team members possess an accurate understanding of the mental models of other members. They articulate two methods by which researchers can index cross-understanding within a team, a perceptual approach and a behavioral manifestation approach. The perceptual approach involves assessing each team member’s perception of the extent to which they have accurate knowledge of each other member’s mental model using a questionnaire-based approach. Questionnaire items would be constructed to measure how well each member “perceives that he or she understands what it is that each other member knows, believes, is sensitive to, and prefers”. Sample items might include “for each member of your group, to what extent do you think you understand what it is that this focal member believes with respect to the cause-effect relationships relevant to the task?” or “to what extent do you believe you understand what this focal member prefers, expects or demands with respect to the group’s products?”

Assessing cross-understanding using the behavioral manifestation approach involves eliciting from each team member a set of relevant behaviors they observe in their teammates. In particular, assuming the focal member had an extensive and accurate understanding of the respondent’s mental models, then there are certain behaviors the focal member would be expected to exhibit toward the respondent and the respondent would be expected to observe these behaviors. Assessment of cross-understanding using the behavioral manifestation approach would also be questionnaire-based. Questionnaire items would be constructed to assess the behaviors of each other team member with regards to communication effectiveness [e.g., sample items may include “this member chooses concepts and words I understand”, “this member tailors communications to refer to concepts, terms, and perspectives that we have in common”, “this member makes arguments that are technically, politically, or otherwise unacceptable to me (reversed)”], knowledge elaboration (e.g., sample items may include “this member inquires about the reasons underlying my knowledge, beliefs, or preferences”, “this member often asks for clarification or elaboration on issues related to my knowledge, beliefs, or preferences", "this member prompts me to surface and discuss what I know, believe, or prefer", "this member helps me to better understand the group's task or task situation"), and collaboration (e.g., sample items may include "this member seems to anticipate what I will do or say", "this member does a good job of coordinating his/her actions with mine", "this member seems to recognize when our knowledge, beliefs, and preferences differ"). Huber and Lewis suggest the behavioral manifestation approach may be more valid than the perceptual approach because it is based on something the respondent can observe rather than what they perceive.

Structural measures. Structured cognition refers to the organization/structure of the team's knowledge, and incorporates causal, relational, or explanatory links among the content of the mental model. According to Rentsch et al. (2008), "underlying characteristics of structured cognition include integration, differentiation, centrality, density, and content and directionality of linkages", though have not been the subject of much research to date.

Conversely, structured cognition attempts to capture the organization of a team's knowledge without modeling the content or amount of a given type of perception. Structured cognition focuses on the pattern of knowledge arrangement, and then models the collection of knowledge patterns within a team. Often, structured cognition is assessed using Pathfinder (Schvaneveldt, 1990), multidimensional scaling, or pair-wise comparisons.

Conclusion. Research suggests the method used to measure team shared cognition has implications for the understanding of team cognition's role in team processes (DeChurch & Mesmer-Magnus, 2010). The results of their meta-analysis suggest shared mental models only predict team process when the measurement technique enables the structure of individuals' mental models to be revealed. In contrast, shared mental models predict team performance across measurement techniques. With team process, the strongest relationships were evident when similarity ratings were used to elicit the content of the model, the Pathfinder network analysis algorithm was used to represent the structure of the model, and Pathfinder's C was used as an index of team mental model similarity. Weaker, but positive validity coefficients were also obtained when researchers elicited the mental model using a concept map or card-sorting task, represented structure using an SME-constructed scoring system, and indexed team similarity with a consistency metric. Traditional rating scale techniques did not show a relationship between mental model similarity and team process, which may be due in part to their deficiency in representing the knowledge structure (Mohammed et al., 2000). In sum, the extant literature suggests that while *knowledge structure* is predictive of both team process and team performance, *knowledge content* is predictive of team performance but not team process.

Table 8. Five Criteria and Key Questions for Evaluating Team Cognition Metrics for Use in Operational Settings

Decision Criteria	**Criteria 1: Predictive Validity**	**Criteria 2: Operational Feasibility**	**Criteria 3: Temporal Sensitivity**	**Criteria 4: Unobtrusiveness**	**Criteria 5: Transportability**
Key Question(s)	Does the measure predict individuals' psychosocial adaptation within teams? Does the measure predict team process and performance?	How easy is it to administer the measure in a naturalistic setting? How much researcher direction is required to administer the measure with fidelity? How automated is data processing?	Is the measure sensitive to changes in mental models over minutes, days, or weeks?	Does the measure produce reactivity from those taking it (reverse coded)? Do respondents easily fake the measure (reverse coded)?	Does the measure need to be customized to a specific situation/context/content domain (reverse coded)?

Five-Factors for Evaluating Measures of Team Cognition for Space Exploration Missions

We suggest five factors, or criteria, for evaluating the utility of team cognition metrics for use in space exploration missions. These include predictive validity, operational feasibility, temporal sensitivity, potential for reactance, and transportability. Table 1 presents some illustrative questions that can be used to classify measure in terms of their utility on each of these five dimensions.

Factor #1: Predictive validity. The first criterion that must be met for any measure of team cognition is predictive validity. Predictive validity is an aspect of construct validity, the extent to which measures tap into intended constructs. A primary aspect of construct validity is the extent to which measures of a focal construct predict other focal constructs as laid out in theoretical models. Central to models of team cognition and team performance are the strong positive relationships expected between the cognitive architecture of the team on the one hand, and the quality of team member interactions and their collective access, on the other. Predictive validity is defined as the degree to which a measure correlates with valued outcomes. Regardless of how operationally feasible a given measure might be, if it fails to evidence substantial predictive validity with regard to important outcomes identified by NASA in the team risk, these measures are not advisable.

Based on the NASA HRP sourcebook (McPhee & Charles, 2009), team cognition metrics need to predict a variety of metrics related to team functioning. Using existing teamwork taxonomies, we categorize these as: interaction processes (e.g., behavioral coordination, collective leadership, interpersonal conflict processes), affective states (e.g., cohesion, interpersonal conflict states), motivational states (e.g., collective efficacy), and outcomes (e.g., individual & team errors, individual and team performance). The predictive validity of a team cognition metric should be benchmarked against all four sets of criteria. Thus, the first question to be answered in choosing team cognition metrics is:

Question 1: Which measures of team cognition are the most predictive of important outcomes (e.g., individual psychosocial adaptation, team performance)?

Factor #2: Operational feasibility. The second primary consideration for any measure of team cognition is its operational feasibility. Whereas basic researchers have the luxury of administering laborious, mentally intensive measurement devices to research subjects, administering such measures to astronauts and flight crew members is impractical. Operational feasibility in a space flight setting has many aspects to it. Some but certainly not all of these include the time it takes participants to complete the measure (administration time), the mode of administration of the measure (administration mode), and the degree of automation that is possible in scoring the measure so that it can be linked to team facilitation software (scoring automation).

A measure that will be feasible in space flight will need to require little *administration time*.

Given the large number of crew, ground control, and other backroom team members who are crucial to mission success, a feasible measure will need to tap into mental processes of a large number of individuals without requiring time and effort. Team cognition measures need to be administered in a naturalistic setting, capturing cognition within large distributed teams. Hence, the *administration mode* needs to require minimal researcher involvement, be self-explanatory to participants, and not easily subject to misinterpretation that would affect the validity of findings. Many existing team cognition metrics require substantial explanation and training from a researcher familiar with the purpose of the measure; this is not feasible for use in space exploration missions. Likewise, measure high on operational feasibility will enable automatic data capture and scoring so that information can be used in countermeasure development (scoring automation). The value of measuring team variables such as team cognition, is to be able to use these as diagnostic indicators of psychosocial adaptation within the team. Without sufficient automation in data processing, these metrics cannot be used for advanced attention of team dysfunction, nor can they be used to trigger potential countermeasures.

As with predictive validity, operational feasibility is a sine non qua for measuring team cognition during space exploration. Regardless of how predictively valid a given measure might be, if it fails to evidence substantial operational feasibility, these measures are not advisable. Based on the preceding, the second question to be answered in choosing measures of team cognition is:

Question 2: Which measures of team cognition are the most feasible for use in an operational environment during space exploration missions?

In addition to predictive validity and operational feasibility, there are three additional criteria that should be considered in choosing or developing a team cognition metric for use on space exploration missions. These include temporal sensitivity, unobtrusiveness, and transportability.

Factor #3: Temporal sensitivity. The third consideration for any measure of team cognition is its ability to capture meaningful shifts in cognitive structures. This factor concerns the extent to which a measure of team cognition is sensitive enough to register changes in mental models and/or transactive memory systems (Cronin, Weingart, & Todorova, 2011). There may be extended periods of time during space exploration missions over which team cognitive architectures change little. However, there can also be periods of hours or even minutes where cognition is changing rapidly, and potentially getting out of sync in a way that harms psychosocial adaptation and/or task performance.

A situation described frequently in our interviews with NASA personnel involves crew members who have immediate access to rich information developing an understanding of a problem that differs markedly from the understanding of the expert teams on the ground. As members work on different schedules and time horizons, they stand to develop diverging mental models. A temporally sensitive metric is needed to detect these changes soon enough so that psychosocial functioning and task performance are preserved. And so, the third question to be answered in choosing measures of team cognition is:

Question 3: Which measures of team cognition exhibit adequate temporal sensitivity to capture shifts in cognition on an appropriate timescale for use in space exploration missions?

Factor #4: Unobtrusiveness. The fourth consideration for any measure of team cognition is the degree to which it is unobtrusive (Campbell, Schwartz, & Sechrest, 1966). This has been a longstanding challenge in social science: how do we measure properties of individuals' inner thoughts and feelings without directly asking them about their thoughts and feelings? Campbell and colleagues provide a classic reference on the topic of unobtrusive measures, and the potential issues surrounding their use. However, in the case of space exploration, unobtrusive measures are preferable to direct measures despite their potential tradeoffs. With team cognition, the reality is that it is possible to reliably and validly assess the construct unobtrusively. Doing so is efficient in terms of time, reactance, and fakability. And so, the fourth question to be answered in choosing measures of team cognition is:

Question 4: Which measures of team cognition are sufficiently unobtrusive for use in space exploration missions?

Factor #5: Transportability. The fifth consideration for any measure of team cognition is its transportability. A measure is transportable when it can be utilized to assess team cognition in a wide range of settings, tasks, and/or teams. Many of the existing measures are not transportable, that is, they are specific to a particular task, to a given setting, and to a particular team. This means that multiple measures would need to be developed and validated. Furthermore, this impedes the comparability of metrics obtained across tasks, settings, and teams, since scores also contain heterogeneity due to the measures that may or may not be perfectly parallel. Ideally, measures of team cognition will be developed that use the same elicitation method (e.g., digital traces of communication) and representation of structure (e.g., a lexical indicator). And so, the fifth question to be answered in choosing measures of team cognition is:

Question 5: Which measures of team cognition are the most transportable across the different tasks, equipment, teams, and contexts that will be encountered during space exploration?

Review of Cognition Measures

We now use the above five-factor framework as a lens for considering the appropriateness of existing methods of assessing team cognition that have been reported in prior research. First, we begin by discussing the methods used in existing research on team cognition, based on the body of work reviewed in our first report. There was a subset of studies identified in our review that consisted of teams who were more analogous to LDSE teams than is typical in that literature. Second, we elaborate the types of metrics used in each of those studies in Table 2. Third, we use the framework to evaluate team cognition metrics that were used in a set of articles considering teams that perform tasks which as comparable as possible to LDSE.

Cognition measures in the broad team cognition literature. We begin by considering the appropriateness of four well-established measurement methods for assessing team cognition. Our focus in this section is on how these methods fare against the five factors critical to any measure to be used in long-distance space exploration.

Factor #1: Predictive validity. A recent meta-analysis compared the predictive validity of team cognition measures relative to interaction processes and outcomes (DeChurch & Mesmer-Magnus, 2010). For predicting team process, measures that elicit cognition using similarity ratings or Pathfinder algorithms (Schvaneveldt, 1990) are the most valid. For predicting team performance, measures that elicit cognition using cognitive maps, content analysis, or questionnaires are the most valid. One important qualifier is that research suggests team mental models and team transactive memory systems need to be assessed differently. Whereas questionnaires are likely valid for eliciting transactive memory systems, they are not likely as valid for eliciting shared mental models. Indeed, Resick and his colleagues (2010) published a validity study of shared mental models and found very little validity in questionnaire-based measures of shared mental models.

Based on the meta-analysis and Resick's validity study, we can reasonably conclude that at present, there are essentially four measurement methods for capturing team cognition with strong predictive validity of team process and performance (Mesmer-Magnus & DeChurch, 2010; Resick et al., 2010). These methods are: (1) cognitive maps, (2) questionnaires, (3) similarity grids, and (4) content analysis.

Factor #2: Operational feasibility. Of the four existing methods for measuring team cognition with strong predictive validity: cognitive maps, questionnaires, similarity grids, and content analysis, all four present challenges with operational feasibility. All four can be time-consuming to complete. Cognitive maps, as currently used in research, are laborious to complete, require substantial researcher instruction during the administration, and require some researcher involvement in the scoring. However, both cognitive maps and similarity grids could be built into a module or game; in essence, they could be gamified (Deterding et al., 2011a, 2011b) to make administration easier. This would enable them to be used in automated data processing as well. Content analysis is likely to be the most operationally feasible, though will require substantial researcher interpretation during analysis. Though, like cognitive maps and similarity grids, to the extent content analysis can be automated based on lexical analysis (e.g., via sentiment analysis or topic modeling), it may require little researcher involvement during interpretation.

Factor #3: Temporal sensitivity. All four existing methods are limited in their temporal sensitivity, with questionnaire being the most limited. Questionnaires are not sensitive enough to capture meaningful shifts in cognitive processes because they require first that the respondent is aware of the change in cognition, and second that they report it. Many of the complex tasks that will be involved in space exploration will entail rapid shifts in individuals' cognition that cannot easily be tracked in questionnaires that could, at best, be administered daily or weekly. Cognitive maps and similarity grids are similarly limited in their temporal sensitivity because they require an activity to be performed in order for cognition to be measured. This is not possible during periods of intensive and/or extended workload. Content analysis, if it is based on automated, lexical analysis such as topic modeling or sentiment analysis, would have high sensitivity, potentially detecting cognitive shifts within a speaking turn.

Factor #4: Unobtrusiveness. Three of the four existing methods are obtrusive. As with temporal sensitivity the questionnaire is the most obtrusive. Questionnaires are both reactive and fakeable, both of which undermine their validity. Cognitive maps and similarity grids are similarly obtrusive, they require individuals to perform a task that runs in parallel to their primary work so that a measure can be taken. This often produces fatigue and reactance. Content analysis, on the other hand, is the least obtrusive, reactive, or fakeable as it can be accomplished behind the scenes without requiring team members to consciously complete tasks unique to the data collection.

Factor #5: Transportability. Questionnaire methods, such as those used to measure TMS, have the advantage of being highly transportable. Cognitive maps and similarity grids are less transportable and need to be customized to the range of situations, tasks, and teams individuals will work with during a mission. Both cognitive maps and similarity grids require substantial a priori development of content. The utility of these measures ultimately hinges on the extent to which a researcher can develop content in advance that will adequately represent all possible scenarios the teams face. Ironically, the likelihood of this happening goes down in highly unpredictable situations where the content needed in the model cannot be anticipated a priori. Similarly, in highly dynamic situations, the utility of these measures may be limited to the extent that the researcher who developed the content on the front end was unable to anticipate the situation requiring adaptation. Content analysis, on the other hand, is highly transportable as it can be continued to be used to the extent team members are communicating with one another.

Cognition measures from analogous populations. Not surprisingly, we found very little in the way of published research on team cognition measurement conducted on populations that were highly analogous to long distance space exploration teams. However, we identified research that proposes cognition assessments appropriate for analogous populations as well as studies conducted in analogous populations. Populations might be considered “analogous” in one of two ways. One way is that the team works on tasks which are highly analogous to those faced by LDSE teams (e.g., tasks faced by military, aviation teams, search and rescue teams, etc.) Another way these populations can be considered analogous to LDSE teams is if they’ve worked as a team for a long time (i.e., long-duration teams, which we define as those that have worked together at least a year). In the next sections, we review measures of team cognition reported in studies of these types of analogous populations.

Cognition measures in teams with analogous longevity. Table 2 summarizes the cognition measures used in the nine studies of long-duration teams we summarized in our literature review. Within these studies, questionnaires were the most commonly used elicitation methods, followed by similarity ratings. Three of these studies used both questionnaires and similarity ratings (Austin, 2003; Mathieu et al., 2010; Smith-Jentsch et al., 2005). We did not find instances of concept mapping in studies of teams with analogous longevity.

Cognition measurement methods outlined in studies of teams with analogous task characteristics. Here, we review seven methods for team cognition measurement that have been either proposed for use in or implemented in analogous teams, and evaluate their utility for LDSE according to the five factors of validity, feasibility, sensitivity, unobtrusiveness, and transportability.

Method #1: Closed-loop communication analysis. Salas, Rosen, Burke, Nicholson, and Howse (2007) suggest diagnosing team cognition in military and aviation teams by assessing the shared information processing that occurs during complex and dynamic interactions which indicate the presence or absence of requisite cognitive or behavioral process. Salas et al. identify three aspects of shared mental models (closed-loop communication, mutual performance monitoring, and adaptive and supportive behavior) and two aspects of shared situation assessment (problem identification and conceptualization, and plan execution) that can guide assessment of team cognition in field settings. For example, markers of closed loop communication may include "team members use implicit communication appropriately" and "team members engage in confirming and cross checking information". Markers of mutual performance monitoring may include "team members recognize when another team member makes a mistake" and "team members offer relevant information before it is requested". Markers of adaptive and supportive behavior may include "team members dynamically reallocate workload" and "team members step in and help out other teammates when needed." Markers of problem identification and conceptualization may include "team members rapidly identify a problem or a potential problem" and "team members engage in overt strategizing while maintaining accurate awareness of the situation". And, markers of plan execution may include "team members take corrective action when interrupted" and "team members avoid, abandon, or modify standard operating procedures appropriately."

*Five factor evaluation***.** Salas et al. did not report on any actual implementation of this method for detecting team cognition, so we do not yet know its validity in assessing team cognition nor its *predictive validity* for team process or performance. The *operational feasibility* of this approach depends on the extent to which designated personnel can be monitoring and coding team communications within these markers of team cognition. To the extent that this communication analysis can be automated, the requirement for external real-time monitoring may be diminished, though methods of automatization were not outlined in the article and so would need to be developed. Given the need for expert observation and coding, we would expect operational feasibility to be low. Because of the expert coding required, the *temporal sensitivity* of this method is also low. This method would not realistically register fine-grained changes in cognitive processes. These data are *unobtrusive* in that they are gathered in the background as individuals complete their work, and are therefore not reactive or fakeable. The *transportability* is a potential limitation of these measures because coding of communications along the proposed markers cannot remain stagnant if it is to take into consideration necessary changes in cognition and tasks over time. As such, analysis needs to be able to distinguish cases where individuals change their actions because of task demands (without resulting changes in their cognition), from cases where changes in cognitive processes have occurred.

Method #2: Behavioral/team action analyses. Soos and Juhasz (2010) explored the role of team cognition in team performance using a sample of 16 nuclear power plant operator teams in Budapest. In this study, they cite the difficulties in measuring team cognition, and point to the potential you can learn about a team's cognition by assessing the actions made by the unit. Indeed, teams interact, communicate, distribute information, coordinate their behavior, and take joint action. Through these interactions, they are sharing their joint knowledge, and by monitoring these interactions, researchers can learn about the team's shared cognition. In particular, the authors used *communication analyses* to assess team cognition. In communication analysis, it is important to assess both the quantitative and qualitative aspects of communication. For example, the authors answered the questions: "what has been said", "how has the information been distributed", and "who is the center of communication". They also assess "physical" (duration of communication, sequencing, timing, duration of speech by team member, etc.) vs. "content" (focus is on *what* is being said and coded using a relevant coding scheme) data, and "static" (evaluating team communication at a given point in time) vs. "sequential" (assessing ongoing stream of communication exchange/interaction) data.

Five factor evaluation. Soos and Juhasz did not compare the proposed communication analyses with other methods of cognition assessment, however did find some evidence in support of the hypothesized link with team performance that is suggestive of a moderate *predictive validity*. The *operational feasibility* of this particular method of communication analysis is low because it requires observation and expert coding of communication. Because of the expert coding required, the *temporal sensitivity* of this method is also low. This method would not realistically register fine-grained changes in cognitive processes. The method is relatively *unobtrusive* in that it relies on existing communication data; to the extent that communication is observable, this method could be used to assess team cognition in a way that is non-reactive and difficult to fake. One caveat with reactance is that in general, observing communication can produce guarded behavior by respondents. This may not be a concern for members of the crew who are used to be observed, but it could be a concern for members of ground control and the many backroom teams who one may also want to measure in order to ensure cognition is functional across the full range of teams involved in the mission. The *transportability* is generally high given that this method can be used so long as people are communicating, and this communication can be observed across different situations, teams, and tasks.

Method #3: Linguistic analysis. Fischer, McDonnell and Orasanu (2007) assess team cognition of simulated search and rescue teams via linguistic analyses of task and social team communication. For example, prior linguistic analyses have found that the use of plural pronouns ("we" or "us") during discussion is more indicative of team cohesion and long-term viability than when more first person singular is used ("I"; e.g., Buehlman, Gottman & Katz, 1992). In this study, authors coded task-related communication (e.g., information sharing about tasks or logistics, problem solving like setting goals or making plans, meta-cognition like monitoring team progress and assessing team performance, and team coordination like directing others' actions and stating one's intentions) as well as affect-related communication (e.g., humor, praise, positive reinforcement, politeness, mediation, apology, insult, blame). Results suggested successful teams spent more time in positive communication sharing information than did unsuccessful teams.

Five factor evaluation. Fischer et al.'s findings support the hypothesized link between dispersion of team member contribution and team performance. Their results confirm that one or a few team members tend to contribute to conversations in unsuccessful teams, whereas in more successful teams the communication is more shared across team members. The reported correlation between the variability of team member contributions and team success was -.44, suggesting that overall, linguistic analysis has moderate *predictive validity*. The *operational feasibility* of this method is good so long as the communication traces needed for lexical analysis can be obtained. The communication would occur as a part of normal task operations and social interactions, and so there would not be additional time required to administer the measure. The measure does require the capture and storage of large amounts of communication data for analysis. The *temporal sensitivity* is also quite good in that changes in pronoun use could be detected quite quickly in a communication stream. This measure fares well on *unobtrusiveness*; it relies on existing communication traces, and is not reactive or fakeable unless one knows the algorithm being used in the analysis. For example, if the team-training program taught crew and ground control members to use collective pronouns, this would negate the value of this particular lexical indicator. An advantage of lexical indicators of communication is that, relative to other communication-based metrics, they protect the privacy of personnel. Lexical indicators use information about word usage, the structure of communication, the connections among concepts, or the topics or emotions present in a corpus to compute diagnostic indicators. In this way they are less reactive to personnel than are communication-based metrics that involve expert coding where communication is directly and fully observable. The *transportability* is high to the extent that the pronouns used in the lexical analysis reporter here are valid across situations, teams, and tasks. This is an open question. However, we do note that once lexical indicators, such as the frequency of reliance on plural pronouns, are validated across situations, they are highly transportable.

Method #4: Analysis of communication breakdowns to index discrepancies in TMS and SMM. Bearman et al. (2010) report on the results of a *quantitative and qualitative analysis* of the transcripts of NASA's Apollo 13 mission. They assessed sharedness of team cognition (which incorporated the astronauts as well as ground control support personnel) via the number and type of *communication breakdowns* during the mission. They proffered a taxonomy of breakdowns, which included (a) operational breakdowns (e.g., "we don't want to do X", "Can you/we do X instead of Y", "we can't carry out X"), (b) informational breakdowns (e.g., "we didn't know that", "you didn't tell us about x", "that makes sense now that we know x"), and (c) evaluative breakdowns (e.g., "I don't agree with that", "why are we doing x?", "we think there may have been a misunderstanding"). The results of this analysis suggests that evaluative breakdowns represent a more significant deficit in the team's cognition, is harder to resolve, and results in more negative outcomes. This taxonomy of evaluating communication exchanges has high ecological and operational validity to NASA LDSE.

Five factor evaluation. The results of this study suggest evaluative breakdowns have moderate to strong *predictive validity* for team performance, though more research is needed to determine the extent to which various communication breakdowns have utility in predicting team process. The *operational feasibility* of this method is high to the extent that it can be used to derive lexical indicators of these breakdowns in communication traces. The use of such a measure would not require personnel to complete additional tasks just for the sake of data collection. The *temporal sensitivity* of a lexical indicator based on the breakdown metric of team cognition would also be quite good; the only caveat being that breakdowns need to be overt and explicit in order to be detected. A breakdown that is thought but not discussed would not register on this metric. But then again, this work could be extended to develop lexical indicators of breakdowns that are evidenced by either unreciprocated communication, lags in communication responses, or overall communication silences. It is entirely possible that pauses and silences can be used as indicators of cognitive breakdowns between people. A lexical indicator of breakdowns would be *unobtrusive* in that communication data are already being gathered, and so this measures would be non-reactive and not easily faked. The caveat of course being that if training is aimed at minimizing communication pauses, or matching communication styles, it would undermine the utility of such an indicator. Lastly, the *transportability* of a breakdown based lexical indicator is also quite good. To the extent that the semantic structure of a breakdown is similar across settings, tasks, and teams, similar indicators could be usefully applied across the range of settings, tasks, and teams involved in a space exploration mission.

Method #5: Combination of (1) inter-positional knowledge questionnaire, (2) analyses of oral and physical interactions between team members of attack submarine crews, and (3) physiological arousal via heart rate monitors. Espevik et al. (2006) studied submarine attack crews during simulated attacks to explore the role of transactive memory in team performance and found that knowledge of teammates explained variance in team performance over that which could be explained by operational skills alone. This project was an extension of the TADMUS project (1998), which investigated aspects of team cognition and coordination in high-stakes military team performance (i.e., antiair warfare on U.S. Navy vessels). The TADMUS project concluded that the information exchange strategies used by effective teams were an index of team cognition, as the team's shared mental model enabled the team members to give each other information in a proper and orderly manner without the receiver having to request it. The TADMUS study identified shared mental models for (a) the equipment, (b) the task, (c) team interaction, and (d) team type. The 'team type' SMM related to team members' knowledge of one another's competencies, skills, abilities, preferences, and tendencies. The Espevik et al. study used the total population of attack teams on the Norwegian ULA class submarines, and studied team cognition over the course of attack simulations. Team mental models were assessed via an (1) *inter-positional knowledge questionnaire*, which assessed team members' knowledge of different roles, responsibilities, and duties in attack teams, as well as what procedures the team should take under different attack scenarios, (2) *qualitative and quantitative analyses of video and audio tape recordings* of information exchange, communication, supporting behavior, and team initiative, and (3) *heart rate monitoring* to assess physiological arousal.

Five factor evaluation. Espevik et al. found that team performance as well as team member psychophysiological arousal (as indexed by heart rate) were more favorable in teams with more developed team cognition (as assessed via inter-positional knowledge questionnaire and communication analyses), though the physiological arousal metric was only weakly related to either team cognition and performance. Preliminary results suggest inter-positional knowledge questionnaires and communication analyses have weak to moderate *predictive validity* for team performance. The *operational feasibility* of communication analyses is high given that this information is typically already being collected, through its interpretation and use will require designated and trained personnel. The operational feasibility of inter-positional knowledge questionnaires is lower in that they are more obtrusive and will require personnel to set aside time for lengthy and cumbersome questionnaire completion. Although heart rate monitoring is commonplace for team members on the spacecraft, it is not as typical with ground personnel. Given its reportedly weak utility for predicting team performance, it is not likely worth the effort to collect it with ground personnel. The *temporal sensitivity* of inter-positional knowledge questionnaires is likely low given the survey nature of the instrument; it is less likely to be sensitive enough to capture changes in cognition. The temporal sensitivity of the communication analysis is intermediate as it requires dedicated and trained personnel to monitor and interpret communications and the interpretation framework will need to be adapted to accommodate changes in team knowledge structures that will naturally need to occur over time. The temporal sensitivity of the heart rate monitoring is likely high given it can detect immediate changes in heart rate, though the interpretation of the cause of heart rate fluctuations will require more attention. Heart rate monitoring and communication analyses are unobtrusive as both can be conducted behind the scenes. The *unobtrusiveness* of inter-positional knowledge questionnaires is low given their questionnaire-like format. The *transportability* for the communication analyses is generally high given that this method can be used so long as people are communicating, and this communication can be observed across different situations, teams, and tasks. The transportability of the inter-positional knowledge questionnaire is likely lower as it will likely need to be redesigned as team tasks and communication structures change over time.

Method #6: Checklists and evaluations of recovery from errors. Cooke et al. (2014) proposed the use of event-based checklists (e.g., TARGETS; Fowlkes, Dwyer, Oser & Salas, 1998) for indexing team cognition by (1) grounding observations of team interactions in contextually-relevant events (e.g., instead of rating team communication, check whether or not a specific piece of information was passed between team members at a given event), and (2) assessing the sequencing and timing of the team process behaviors that underlie team cognition (Proctor, Panko, & Donovan, 2003). They also discuss the use of communication analysis to assess team cognition (Kiekel, Cooke, Foltz, Gorman, & Martin, 2002) which involves measuring communication content or flow data. However, they allow that communication analyses may be operationally prohibitive because analyses of content data can be extremely cumbersome in terms of the time and effort required to record, code, and analyze data. A new method, CAST (Coordinated Awareness of Situation by Teams; Gorman et al., 2005) assesses the coordinated perception and action that emerges from team member interactions (beyond the static knowledge of team members) when faced with unusual situation constraints or "road blocks"; this approach begins to address the time/effort constraints of communication analyses by assessing the extent to which the team identifies and understands instances of communication failures. Alternatively, the CAST approach can be used to streamline communication analyses by specifically noting (a) which team members independently noted the glitch, (b) which team members discussed the glitch, (c) actions taken to circumvent the glitch (which also corresponds to firsthand perception, coordinated perception, and coordinated action in response to the glitch), and (d) whether or not the team overcame the roadblock.

Five factor evaluation. Although Gorman et al. (2005) report moderate *predictive validity* for CAST analyses in predicting team performance, the *operational feasibility* of the TARGETS or CAST methodologies is generally weak. This method would be cumbersome to implement across a wide range of teams performing over a long period of time. The temporal sensitivity depends on how frequently TARGETS or CAST can be tracked. The *temporal sensitivity* is intermediate. The timeframe on which such a measure could register meaningful changes in team cognition is certainly better than would be afforded by a questionnaire measure, but is not as fine-grained as a metric based on digital traces. An advantage of the TARGETS or CAST methodology is that it is *unobtrusive*, captures team cognition without requiring personnel to complete measures. A weakness is the lack of *transportability* of these measures. Unique measures have to be constructed for all of the relevant scenarios that incorporate specific instances that can be observed to represent shared/unshared or accurate/inaccurate cognition.

Method #7: Sequence analysis of digital traces. A novel approach to capturing team cognition through automated analysis of digital trace data is being developed by Murase et al. (2014). The idea behind the measure is that individuals' patterns of behaviors reflect their underlying cognitive schema about the activities and interactions they are engaging in. Thus, digital traces left behind in server logs that capture individuals' actions and interactions can be used to develop metrics of team cognition.

Murase and colleagues present an illustration of the method. Drawing on the idea of scripted behavior (Gioia & Poole 1984; Gioia & Manz, 1985), this study proposes that individuals' hold cognitive representations of how they should act, and their cognitive scripts are manifested in the sequence of behaviors in which they engage. They report the results of a sequence analysis used to capture patterns of behavior revealed in server log files based on 70, 6-person multiteam systems performing a computer-based task in the laboratory. Behavioral sequence analysis was conducted with the TraMineR package in R (Gabadinho et al., 2011). They technique began with a data-driven approach, identifying 4.5 million distinct sequences involving up to 3 behavioral shifts (e.g., communicate with a teammate followed by engage an enemy), and retained those observed in at least 5% of the sample of MTSs. The result was a set of 250,000 distinct sequences, which were grouped into 37 activity categories. Next, they used a theory-driven approach, having subject matter experts group sequences based on the collective loci (i.e., team, MTS, both) and collective functions (e.g., MTS goal, team communication). The predictive validity of these sequence-based metrics was then validated against MTS performance metrics using (a) survey measures of process, and (b) Pathfinder metrics of team cognition. Quasi-Poisson regressions show trace measures significantly predict both the Pathfinder cognition metric and MTS performance, and the trace measure predicts MTS performance significantly better than the Pathfinder metric.

Five factor evaluation. The *validity* coefficient for the sequence measure of team cognition showed strong effect sizes both in correlating with a similarity grid-type team cognition measure and to a team performance measures. The *operational feasibility* of this approach depends on the extent to which adequate digital traces can be identified, and algorithms such as those used to train this data, can be developed in advance of and during a space exploration mission. If digital traces can be identified, this measure fares well on operational feasibility because it does not require individuals to do a parallel task to provide the data, the data comes from tasks they are already doing. This data is ideal on *temporal sensitivity*, providing very high-resolution data that can detect changes in cognitive processes quickly. Because the data are collected every time someone interacts with a system or tool, changes can be detected quickly. These data are *unobtrusive* in that they are gathered in the background as individuals complete their work, and are therefore not reactive or fakeable. The *transportability* is a potential limitation of these measures because the analysis needs to be able to distinguish cases where individuals change their sequences because of task demands, without changing their cognition, from cases where changes in cognitive processes have occurred (Braun, Kuljanin, & DeShon, 2013; Kuljanin, Braun, & DeShon, 2011). Doing so will require that large, representative training data sets are available on which to develop team cognition metrics.

Cognition measurement methods outlined in studies of teams with analogous longevity (i.e., long-duration teams): In Table 2 (below), we summarize team cognition measures used in published research conducted on teams of analogous duration, though not necessarily analogous task characteristics. These studies were preliminarily reviewed in our literature review with regards to the relevance of their key findings to LDSE teams. Here, we describe in more detail their methodology with regards to assessing team cognition.

Table 9. Team Cognition Measurement Methods Used in Populations of Analogous Duration

Study Citation	Cognition Construct	Measures Used
Austin (2003)	Transactive Memory Systems	**Questionnaire, Similarity Ratings** Task TMS: consensus was assessed by computing the group's consensus on which team member was the expert for each of 11 identified skills (e.g., competitor product knowledge, budgeting and financial planning, product testing, team coordination); accuracy was assessed by correlating the extent to which others rated expertise of a focal individual similarly to the focal individual's self-ratings of expertise on each of 11 identified skills. External relationship TMS: consensus was measured using group agreement about which group member had the closest relationship with each of the 10 identified external stakeholders (e.g., suppliers, SVP merchandising, budget director); accuracy was measured by correlating the extent to which others rated relationship closeness of external stakeholders similarly to the ratings by the external stakeholders.
Child & Shumate (2007)	Transactive Memory Systems	**Questionnaire** Participants answered items pertaining to their own and group members' understanding of knowledge expertise, responding to statements such as "my group members know a lot about my expertise", "my group members know a lot about one another's expertise", "I know a lot about the expertise of my group members." Responses were made on a 5-point Likert-type scale ranging from 'strongly disagree' to 'strongly agree'. Items were averaged and used as a composite score for understanding of knowledge expertise.
Maynard, Mathieu, Rapp, & Gilson (2012)	Transactive Memory Systems	**Questionnaire** Used Lewis' (2013) scale of transactive memory, measuring (1) specialization (e.g., "each team member has specialized knowledge of some aspect of our team's task", "the specialized knowledge of several different team members is needed to complete the team's deliverables", and "team members know which other team members have expertise in specific areas", (2) credibility (e.g., "team members are comfortable accepting procedural suggestions from other team members", "team members trust that other members' knowledge about the team's task is credible", and "team members are confident relying on the information other team members bring to the discussion", and (3) coordination (e.g., "team members can get the information they need from other members in a timely fashion", "we can easily determine who in the team is most appropriate for answering questions or for solving problems", and "we can align our collective knowledge and efforts with task demands").

Study Citation	Cognition Construct	Measures Used
Mathieu, Rapp, Maynard, & Mangos (2010)	Shared Mental Models	**Questionnaire, Similarity Ratings** Conducted a task analysis by interviewing Navy air traffic control teams to identify elements that were critical to the task and team shared mental models and used results to develop task and team shared mental model measures. Task SMM – based on the cue-strategy association SMM measure developed by Smith-Jentsch et al. (2001; 2005). Created three scenarios describing a challenging event and detailed four potential courses of action. Then asked the respondent to rate how likely they would be to execute each course of action on a 6-point Likert-type scale ranging from 'highly unlikely' to 'highly likely', yielding a total of 12 responses which were then correlated with the responses of each other team member. Sample scenario: "A pilot requests an opposite direction departure. You are working ground. You would (1) coordinate the request with the local controller, (2) evaluate local's traffic and then decide whether to make the request, (3) deny the request regardless of local's traffic, or (4) not pass or coordinate the request at all." Team SMM – assessed using a measure of positional-goal interdependencies developed by Smith-Jentsch et al. (2005) which indexes team members' understanding of the influence of actions taken by one controller on the operations of other members. The measure focuses on information about team member roles and interaction patterns among team members. Four scenarios were crafted and respondents rated how the actions taken by the local controller in each scenario would influence the operations of other constituents, like the ground, local, and approach. Sample scenario: "At this facility, as Local Control takes steps to minimize delays in landings what impact can this have on Local's, Ground's, and Approach's ability to effectively move ground vehicles about the airport?" Respondents used a 7-point Likert-type scale ranging from 'strong negative impact' to 'strong positive impact'. Average inter-member correlations were computed within each team.
Marques-Quinteiro et al. (2013)	Transactive Memory Systems	**Questionnaire** Used an abbreviated version of Lewis' (2003) TMS scale. Items included "each team member has specialized knowledge of some aspect of our project", "different team members are responsible for expertise in different areas", "I know which team members have expertise in specific areas", "team members were comfortable accepting procedural suggestions from other team members", "I trusted that other team members' knowledge about the mission was credible", "I did not have much faith in other members expertise (reverse-coded)", "our team had very few misunderstandings about what to do", "we accomplished the tasks smoothly and efficiently", and "our team worked well in a coordinated fashion". Participants rated how much they agreed with each sentence using a 7-point Likert-type scale ranging from 'totally disagree' to 'totally agree'.

Study Citation	Cognition Construct	Measures Used
Smith-Jentsch, Kraiger, Cannon-Bowers, & Salas (2009)	Transactive Memory Systems	**Questionnaire** Participants responded to 10 items designed to tap knowledge of their teammates' experience (e.g., working with military aircraft) and abilities (e.g., maintaining separation between aircraft) using a 6-point Likert-type scale. Euclidean distance scores on each of the items were calculated by comparing ratings a participant assigned to each team member and those assigned by his teammates.
Lim & Klein (2006)	Shared Mental Models	**Similarity Ratings** Respondents were asked to judge the relatedness of 14 statements describing team task work (to assess task work mental models) and 14 statements describing teamwork (to assess teamwork mental models) using a 7-point Likert-type response scale ranging from 'unrelated' to 'highly related'. Since each statement is paired with each other statement, respondents assess the relatedness of 91 pairs of statements to assess task work mental models and another 91 pairs of statements to assess teamwork mental models. Sample task work statements included "team members conduct routine maintenance of their equipment and weapons in the field", "team members are cross-trained to carry out other members' tasks", and "team members have a good understanding of the characteristics of the enemy's weapons". Sample teamwork statements included "team members trust each other", "team members accept decisions made by the leader", "team members communicate openly with each other", and "team members are aware of other team members' abilities". To assess accuracy of team mental models, three subject matter experts completed both inventories; their ratings were averaged to determine the expert task work mental model as well as the expert teamwork mental model. The task- and team-work statements were developed using Cannon-Bowers et al. (1993) descriptions of team mental models and by consulting with five subject matter experts from Singapore Armed Forces regarding the characteristics critical for team effectiveness. Pathfinder was used to create the structural model of each team member's taskwork and teamwork mental model. Team mental model similarity as well as accuracy (as compared with the expert mental model) was computed.

Study Citation	Cognition Construct	Measures Used
Smith-Jentsch, Mathieu, & Kariger (2005)	Shared Mental Models	**Questionnaire, Similarity Ratings** Task SMM were assessed using a cue-strategy association SMM measure. Created a scenario describing a challenging event for an air traffic controller and detailed potential courses of action. Then asked the respondent to rate how likely the strategies would be effective in resolving the issue using an 11-point Likert-type scale ranging from '0% likelihood of success' to '100% likelihood of success', yielding a set of responses which were then correlated with the responses of each other team member. Scenario: (paraphrased) A plane taxis onto the same runway as an inbound plane will be using without clearance. Three attempts have not reached the errant plane. Respondents rate the likelihood six different strategies will be successful. They then rate these same strategies under three different conditions (e.g., it is night). Team SMM were assessed using a measure of positional-goal interdependencies which indexes team members' understanding of the influence of actions taken by one air traffic controller on the operations of other members. The measure focuses on information about team member roles and interaction patterns among team members. Sample situation developed: "At this facility, as local control takes steps to minimize delays in landings [i.e., minimizing delays in takeoffs, ensuring separation standards for successive departures, and ensuring separation for arriving aircraft], what impact can this have on ground's, approach's, and departure's ability to…." Respondents rate on a 5-point Likert-type scale from 'strong negative impact' to 'strong positive impact' for Ground (e.g., "minimize delays in moving inbound aircraft from the runways to the ramp"), Approach (e.g., "maintain separations between inbound and outbound aircraft"), and Departure (e.g., "maintain standard separation for outbound aircraft"). The scenarios were developed based on semi-structured interviews with ATC and other subject matter experts to develop task analyses and understanding of critical incidents.
Wegner, Erber, & Raymond (1991)	Transactive Memory Systems	**Questionnaire** Assessed the transactive memory systems of dating couples by asking respondents to make forced choices about whether they or their partner were more the expert in the areas of science, food, spelling, alcohol, history, television, and psychology.

Novel Measures of Team Cognition

The NASA BHP is currently supporting two research streams that could be useful in measuring team cognition. These include sensors and lexical analysis. Neither sensors nor lexical analysis provides a measure of team cognition, each provides a technology that facilitates one aspect of measuring team cognition: elicitation, representation, and/or emergence. We now consider how each of these developments may foster the assessment of team cognition.

Wearable sensors. Wearable sensors are a promising data source for measuring teamwork processes that are gaining increased attention. Sensors provide a way to overcome the challenge of capturing the very fine-grained behavioral data needed to understand dynamic team processes such as cognition. Sociometric badges like the ones created by Sandy Pentland at the MIT Media Lab, can be used to capture real-time collaboration; something that traditional questionnaire tools and methods of observation cannot accurately detail (Kim et al., 2012).

Factor #1: Predictive validity. Predictive validity is the open question for wearable sensors. Using sensor data to tap into team cognitive processes will require a blend of theory and data driven methods to develop algorithms from sensor-captured interactions that reliably capture team cognition, and do so in a way that has predictive validity in anticipating the quality of team interaction processes (e.g., behavioral coordination, collective leadership, interpersonal conflict processes), affective states (e.g., cohesion, interpersonal conflict states), motivational states (e.g., collective efficacy), and outcomes (e.g., individual & team errors, individual and team performance). The use of sensors for capturing team behavioral process is one-step easier than using them to capture cognition, because processes are directly captured by sensors as member interactions. The research on teams conducted thus far has focused on behavioral interaction processes, and so using them to capture cognitive processes will require significant development effort.

Factor #2: Operational feasibility. The first advantage of sensors such as sociometric badges is their operational feasibility. Sensors capture information on how people interact with one another, which holds valuable clues for how they think about their teammates and tasks. Other attempts to capturing rich detail about group interactions, such as recording or observing these interactions, would not be feasible operationally (Kim et al., 2012). Sociometric badges represent a viable alternative to these labor-intensive methods. Furthermore, these badges offer researchers the ability to study collaboration in large, distributed teams in real-time. Wearable sensors can be used to collect data from a large number of individuals located in different locations in a manner that is both time and cost effective.

Factor #3: Temporal sensitivity. Wearable sensors hold great promise for eliciting the building blocks of a team cognition metric that has good temporal sensitivity. These badges generate at least one hundred data points per minute. The level of detail in communication patterns afforded by sociometric badges could not possibly be achieved through traditional self-report questionnaire methods or non-technologically enabled observation methods. Pure reliance on self-report questionnaire measures for depictions of relationships and influence patterns can be misleading and inaccurate (Kim et al., 2012). Sensor data provides a clearer picture of the communication patterns, illuminating collaboration and influence where it occurs.

Factor #4: Unobtrusiveness. Wearable sensors have the advantage of being unobtrusive. These badges allow researchers to observe both verbal and non-verbal communication patterns, making them both nonreactive and difficult to fake. Information recorded by sociometric badges includes patterns of speech and body movements, but does not include the content of communication or facial expressions. Data can be collected that includes participants' tone of voice; body positioning; gestures; frequency of speech, and tendency to listen or interrupt during conversation.

Factor #5: Transportability. Wearable sensors can support the development of metrics that can be used across situations. Whereas the algorithms for transforming sensor data on behavioral interactions into team cognition metrics would need to be situationally-validated, the modality of eliciting behavioral interaction with sensors is transportable. Once individuals wear the device, and they become transparent, they can capture the data needed to represent team cognition in a variety of nominal and off-nominal situations.

Digital traces. Digital traces reflect any type of communication or activity data that is logged as individuals interact with hardware and software systems. Digital traces can include communication traces, patterns of activity, or both. Examples of communication traces are those captured when individuals communicate through virtual tools such as email, chat logs, smart phones, video conferencing, or project management software systems. An example of activity traces that was specifically used to assess team cognition was the study by Murase et al. (2014). Murase et al. used server logs that capture team members' interaction with a piece of task software that logs their actions such as accessing or sharing files, marking locations, viewing map viewers, and making decisions. The sequences within which a given individual engages in certain activities is used to represent certain cognitive processes. The advantage of communication traces is that they lend themselves to lexical analysis such as topic modeling (Ramage, Rosen, Chuang, Manning, & McFarland, 2009) and sentiment analysis (Pang & Lee, 2008), which can be useful for representing individuals' cognitive and emotional processes. Across the five factors, digital trace data offer many advantages for measuring team cognition.

Factor #1: Predictive validity. There is evidence that digital traces can produce measures of team cognition that predict team interaction processes (e.g., behavioral coordination, collective leadership, interpersonal conflict processes), affective states (e.g., cohesion, interpersonal conflict states), motivational states (e.g., collective efficacy), and outcomes (e.g., individual & team errors, individual and team performance). In addition to the Murase et al. (2010) study described earlier, much research has used structural communicate traces to develop metrics of both TMMs (Cooke, Gorman, Duran, & Taylor, 2007; Kiekel, Cooke, Foltz, & Shope, 2001; Kiekel, Cooke, Foltz, Gorman, & Martin, 2002; Kiekel, Gorman, & Cooke, 2004) and transactive memory systems (Palazzolo, Serb, She, Su, & Contractor, 2006; Palazzolo, 2005; Yuan, Fulk, Monge, & Contractor, 2009).

Factor #2: Operational feasibility. Digital trace data is voluminous and is automatically recorded (Williams, Contractor, Poole, Srivastava & Cai, 2011), making it well-suited to use in operational settings. Furthermore, trace data is often readily available through interactions that individuals are already engaging in, and so they economize administration time. Rather than produced through traditional data collection methods (e.g., questionnaires), trace data is often pre-existing, thus simplifying data collection (Howison, Crowston, & Wiggins, 2011).

There are also a few caveats that bear mentioning when using trace data in an operational setting. First, many digital trace data sets are overwhelmingly large, and therefore can be difficult and very time consuming to manage and analyze (Williams et al., 2011). Second, it can be challenging for researchers to move from trace data to meaningful psychological constructs when they analyze digital trace data. One must be cautious in understanding what phenomena the traces reflect (Howison et al., 2011). Third, researchers should be careful to use appropriate data analytic techniques and address issues of internal validity (Howison et al., 2011). Fourth, in order for social scientists to leverage these sources, they need to leverage computationally-intensive analytic procedures (Ilgen & Hulin, 2000; see an exception by Palazzolo, Serb, She, Su & Contractor, 2006) that are often outside the wheelhouses of most social science laboratories.

Factor #3: Temporal sensitivity. Digital trace data represent discrete events as they occur over time, lending them nicely to developing team cognition metrics with adequate temporal sensitivity. Such longitudinal data present researchers with more precise windows into the interactions of large virtual teams. Digital trace data captures team cognitive processes at exceptionally high levels of resolution, enabling shifts in cognitive processes to be meaningfully captured.

Factor #4: Unobtrusiveness. Digital trace data are unobtrusive. The data is collected without interfering with participants' daily lives and primary work tasks. Participants are not required to fill out time-consuming questionnaires, and, as such, the data may more accurately reflect behavioral reality.

Factor #5: Transportability. Digital traces may or may not be transportable depending on the extent to which individuals interact with similar tools and systems as they work on different tasks with different individuals. For example, if individuals switch communication methods when working on nominal and off-nominal events, metrics will be need to be developed based on multiple data streams in order to adequately assess team cognition. Additionally, it will be important to develop algorithms based on digital data streams that capture the full range of possible actions and interactions. To the extent that metrics are developed on training and other data sets that are not representative of the full range of space exploration situations, they cannot be certain to capture team cognition in new situations.

Conclusion

Since the initial discovery of team cognitive constructs (e.g., transactive memory, shared mental models), researchers and practitioners have been trying to read the minds of teams. The strong connection between how team members think about each other, their tasks, and their operating environment and how they behave, provides a crucial window into the team. This window allows scientists and practitioners to anticipate the actions and reactions of the team in a wide variety of situations. Although team cognitive processes provide one of the most predictive aspects of team functioning, they are perhaps the most challenging aspect of teamwork to assess. Team cognition is particularly difficult to assess in large collectives operating in dynamic environments, exactly the type of collective that will be needed for successful space exploration missions. Our report considers the measurement considerations - the five factors - inherent in selecting and developing metrics of team cognition that will be useful in mitigating team risks. We have described the range of metrics used in prior research, in research on analogous teams, and have applied the five factors to evaluating these metrics. Although our evaluation of these specific metrics may be useful in the short term, it is our hope that elaborating these five factors will provide a useful framework for designing metrics in the future as new data, tools, and methods become available for capturing team cognitive processes.

Part 3: Operational Assessment

Operational Assessment of Shared Team Mental Model Maintenance Relevant to Long-Distance Space Exploration

This report presents the results of our operational assessment. We conducted ten interviews by either teleconference or videoconference (Skype) in order to gain a deeper understanding of the issues related to shared mental model maintenance during space exploration missions. This summary report describes: (1) our interviewees who provided the insight into NASA operations needed for the operational assessment, (2) a high level overview of our methodology, and (3) a discussion of our key findings. Our interview protocol is contained in Appendix A.

Methodology

Interviewees

We interviewed ten individuals between April 30, 2014 and September 2, 2014. The interviewees were selected by BHP personnel. Due to requirements for anonymity and confidentiality, we do not provide names of the interviewees, but instead will summarize their prior experience, which included astronaut, flight planner/director, station training, CAPCOM, Mission Operations, BHP Operations, aviation psychologist, flight operations, analog participant, and engineering.

Methodology

Our operational assessment was designed to address the question of: *What issues related to shared mental models are present in training prior to launch as well as during space flight?* We used our literature review (Milestone 1) to design the interview protocol. In addition to probing Milestone 1 themes, we asked questions to help us understand differences in mental model alignment in nominal and off-nominal events, differences that might be anticipated in long-duration/long-distance missions, and asked about the role of training and technology tools in maintaining shared mental models. Our protocol was developed to complement that of Dr. Steve Fiore, so that we could conduct the interviews together gaining the needed insight for both of our respective reports.

Nine of our interviews were conducted by teleconference, and a final interview was conducted via videoconference (using Skype) because the teleconference bridge failed. All interviews were conducted by Leslie DeChurch and Steve Fiore, with Jessica Mesmer-Magnus as the lead observer and transcriber. DeChurch, Fiore, and Mesmer-Magnus were assisted by two student research assistants, Elizabeth Sanz and Travis Wiltshire.

We used our transcribed notes from the interviews to pull out exemplar quotes that illustrate each of the specific issues of concern identified in our first Milestone report. In particular, we probed issues of mental model alignment across different component teams involved in space exploration (i.e., multiteam systems) and issues to mental model alignment presented by multiteam membership.

Operational Assessment Findings

Our questions were designed to probe the themes identified in our first report, and we provide an overview and specific quotes from the operational assessment that illustrate the issues identified in our interviews related to each theme. In addition, several other themes emerged that may have implications for crew success on long distance missions as well as for developing, measuring, and maintaining shared team cognition over time. We also discuss these themes in this section.

Theme 1: Team Cognition and Multi-Team Systems

Theme 1 captures instances of between-team coordination, information sharing, and integration across teams. Collaboration at NASA often occurs between different teams. Interactions between the crew and ground were the most commonly cited as being critical for the execution of any mission or training exercise.

> *"The crew is our eyes and the ground is the brain"*
>
> *"The crew depends on the ground to analyze the data and to tell them what they need to know to execute the missions, from liftoff to landing."*

In addition there are other teams involved in information exchange, which can also play a large role in the execution of a mission.

> *"When we are sitting in the main flight control room, one thing not so obvious is that there are lots of back-room teams. Those teams help create a pure flow in making decisions. This approach really works well."*

Another example illustrates the different mental models of the crew and ground that occur even with the "easier to integrate" ISS missions:

> *"... [seeing the big picture] it helps to remind the ground of the crew members' perspective, because they see buttons not the stuff behind them..."*

Many of our interviews suggest that shared cognition between teams is maintained through advance planning and training, such as through the creation of a mission schedule, and also through key roles, such as the CAPCOM during the mission. Our interviewees discussed the role of the CAPCOM in maintaining shared cognition across teams during a mission:

> *"You do a mind meld with the crew you are leading, and get the communication going between teams."*
>
> *"One thing I do as a CAPCOM on space missions is to try to make all the participants like* ***one team****...*

When asked about the CAPCOM role during long distance space exploration missions, interviewees were quick to mention that the communication hurdles pose significant motivational and coordinative challenges to the mission:

> *"In order for the crew to be heavily involved in the decision making and communication processes and to review things like the schedule and the science for the week, we hold a weekly private tag up with the lead CAPCOM… [this is an] opportunity for the crew to complain about things and also to say what went well… These mechanisms are not going to work on a long distance mission… because you can't talk…"*

> *"We use video both ways (up and back). We put cameras over the crew member's shoulders so they can show us what they are seeing on their laptops so we can fix issues for them… This approach relies on them having [real-time] video, which we won't have on the long distance missions… this is really key to figure out how to overcome these challenges…"*

Because of the complex nature of the tasks and the physical distance between teams, cognition in MTSs comes with its challenges. There is translation that needs to occur across cultures, as well as translation that needs to occur from the crew in orbit to the ground crew.

> *"There were issues on trying to get procedures because of the contracts and different parties involved. NASA wrote procedures in English and then the Russians would translate them into Russian, but when they would come back to us (retranslated to English) they wouldn't be very good."*

> *"…as individuals get on orbit, they are surprised by what it is like to be a remote crew member with ground and how quickly you can get off kilter with the ground… Ground can see you, but you are in a fish bowl so when you look out you have a distorted idea of what is going on outside your bowl…"*

Part of this barrier is motivational; our operational assessment revealed an in-group / out-group mentality with many of the different groups involved in a space operation. For example:

> *"The crew expects it to be an integrated team, but it's really more of a confederation"*

Our operational assessment suggests the most significant issue related to the maintenance of SMMs will be in the cognition between these groups. As one interviewee noted:

> *"You have to realize that the space station was never designed to be autonomous. You get control from the ground… but a big breaker is the culture of the ground controllers. They are in charge of the mission and the astronauts are the worker bees…"*

When asked about how crew members decided whether to involve the ground, one respondent said it depended on:

"How much time do you have to execute...do you have the luxury of getting their information"

"If you were working under a communication delay, we could communicate only very basic things. So it would be difficult, if you were under communication delays, to work on payloads, for example, as you would tend to not ask ground control for small details, you will just try to figure them out yourselves because communicating with a time delay of 10 minutes would be less efficient…there would be fewer communications going on with the ground."

Given that long distance missions will rarely afford the "luxury of their information," this is a critical issue in maintaining shared mental models. It is important to realize that this is not only an issue of communication technology (i.e., communication delay), but also an issue of intergroup relations. **In short, crew members need to have not only the *capability* to communicate across functional groups but they also need the *motivation* to do so.** The extreme distance that will be presented by long-duration exploration means that both issues must be overcome. As communication delays increase, the crew's perception of what the ground will be able to help with will change. With these changes there may come a decreased motivation to engage in communication on issues with ground control. This quote taken from a participant in an analog with communication delays, and shows the type of motivational issues that will compound the logistical issues presented by the communication delays:

"... [the ground] tends to be very nice to you when you make a mistake or do something wrong and tends not to tell you that [something you did] was wrong…. this creates a little anxiety, like 'why didn't they tell me this?', and 'maybe I'm doing other things wrong and they are not telling me'... so that builds stress and makes [work and interaction] difficult…"

Theme 2: Team Cognition and Multi-Team Membership (MTM)

Theme 2 captures statements that highlight participation in multiple teams. Interviewees acknowledged that they participated in multiple teams.

"…there is overlap in these teams… just because you are in one team doesn't mean you can't be part of other teams…"

The most often cited challenge associated with MTM work that interviewees described related to **changes in team membership**. Although long-duration missions will likely not involve crew swaps the way that ISS missions do, they will involve rotation of ground crew members. And so issues of MTM have the potential to exacerbate issues of mental model alignment between crew and ground during long-duration missions.

"…every 3 months it is a 'changing group'... politically the commander changes every 3 months… It is not really a big change but the commander makes important decisions, and

then each astronaut also has his or her own schedule and own space center…"

"The new Russian crew Member A and Member B showed up, originally I wasn't supposed to be there for a crew swap… I knew Member A, but I had never met Member B. I met Member B for the first time on orbit."

For the astronauts, the crew in orbit was one team, and their partnership with people on the ground at NASA was another team. Their team at NASA usually involves the people that help with any experiments the astronaut is required to do while in orbit. The separate objectives between the astronauts and cosmonauts render them as being part of separate teams. However, when a task in orbit required collaboration, the crew worked as a team.

"We got instructions at night and then Person A said what you needed to do… [the amount of] coordination depended on the task… for [my] experiments on board I was independent on those and worked alone, but sometimes I would need help from other guys and they would come in to help me do that… [but when we did] EVAs, that was a very integrated team task, while they were outside, I was inside doing the com, etc."

Theme 3: Team Cognition Dynamics - Transition and Action Processes

Theme 3 captures transition and action processes within a given mission that underscore the team cognition dynamics over the course of the mission. This theme also highlights the synchronizing of behaviors through scheduling and coordination. Our interviewees described recurring phases that they experience during missions that can be described as transition periods and action periods.

Transition - In a transition period, members are gaining a shared understanding through careful planning. Planning is a major phase of each mission, and occurs both on the ground in advance of the mission and also in situ in response to events.

"Preflight planning is published and available to all. It is extremely valuable for understanding our shared framework and the rationale for a given objective, why we are doing it a certain way and what the tradeoffs would be."

Pre-flight planning is one of the major ways that different teams within the mission can hold shared mental models as the mission progresses. Most interviewees discussed the important role the timeline takes on as follows:

"The timeline is the sheet music, the reference point that people use"

Another interviewee described the timeline as follows:

"What are the coordination mechanisms to integrate? Well a tremendous amount of prep occurs before the mission and outside the control room to make sure plans are all synchronized … not just that the activities are synchronized, but also that all the power is

synchronized. a lot of work going on inside and beyond the control room… and getting feedback from the crew all along to make sure it is working from their perspective as well….”

Action - The second period of activity is the action phase. During the mission, coordination is also critical. Activities at NASA are very scheduled. Keeping everyone in-sync is a large part of what goes on during a mission.

"How do we understand who is supposed to be doing what at a particular point in time? How do we engage in handoffs at particular point in time? The schedule. We are choreographed/coordinated for those things...everyone is trained in the pool or simulation… and this training is engrained after having been training this way for a year or more…"

"We keep the crew informed of what we're doing every day. When the crew goes to sleep at night the ground creates a series of messages to the space crew of the status of the mission, the status of the vehicle, etc. to keep them up to date. We have regular voice contact with the crew. We ask the crew to look at things and be our eyes, and their inputs are important. We want to make sure they are comfortable with actions. The space crew also has a representative on the ground to advocate for them."

The crew works very long days and resets their schedules for next day each evening. This "schedule reset" appears to be a daily transition process that helps align crew mental models for the next days' work. Presumably, this sort of coordination/planning would still be possible on a long distance exploration mission, and in light of communication delays throughout the day, may take on heightened importance. However, given the differing capacities and motivations associated with communications over the course of long distance missions, there is also an increased chance that crew and ground will have become out of sync over the course of the day, suggesting these end-of-day planning sessions may be an important opportunity to identify breakdowns in mental model sharedness.

"Every day, the flights plans come up in the evening, so the commander would hold it up and say tomorrow we need to do this, this, and this. We would organize what everyone would be doing. At the end of the day we would look at the flight plan and the ground would put it out with certain times we were supposed to do certain things."

Theme 4: Team Cognition Shifts

Theme 4 captures shifts from nominal, routine events to off-nominal events. This theme highlights how the ground and crew prepares for, detects, and handles off-nominal events. Training for off-nominal events is critical for the ground and crew. Although they cannot anticipate every off-nominal event, NASA uses previous events to train the ground and crew on potential failures.

"The art of the simulation is needed to ask the right questions in the simulation… put in a credible failure and ask the right questions and they may crash or they may come up with a genius solution… on the days they fail, they work the simulation until they find a way around it… on flight day, they should be able to not be surprised by these sorts of problems…."

Shifts from nominal to off-nominal events can often occur during a mission, and interviewees described some of the things they may experience. These off-nominal events required the crew to come together as a team.

"the crew was sleeping when the computers went down and the alarm went off, so they needed the crew to go do such and such. We had to wake up the crew, and they said well we're already there, so the ground and the crew worked together."

Because the crew often considered themselves as being on separate teams (American or Russian), off-nominal events posed a challenge when all teams had to come together to solve a problem. These challenges appeared to have been a problem not only with the crew but also on the ground.

"when we did emergency exercises we realized that the most challenging part was that the control centers weren't interacting effectively, not sharing info, and telling crew contradictory things."

Theme 5: In It Together

Theme 5 captures how the interviewees had to overcome barriers and work together in order to make a mission successful. The US does not have control over what personnel the Russians choose, or vice versa. Therefore, it's important to get along when living in close quarters for extended periods of time. For every mission or assignment, the crew has to come together to make it work.

"…all EVAs are challenging and you really have to have a camaraderie with the crew… you have to figure it out… not all are better than others… in the end everything has to be accomplished… can't say that one way or another is more efficient, you just have to find a way to work within that crew."

The difference in cultures also means differences in the way that work was done. The crew has to create a shared understanding of how the other team works, and accommodate when needed in order to ensure that the mission goes smoothly.

"A couple hours before we went out, Member A said that there needs to be commands to the solar arrays, and these are the commands that you need to use, and he starts listing the #'s...in Russian of course. I had to stop him and have him write them down."

The difference in cultures can come with difference in opinions on various issues, which presents opportunities for conflict. The crew must maintain a healthy working relationship while on a mission, and this can be challenging.

> *"In terms of the conflict, typically crews are multinational and so there is always the potential for cross cultural misunderstanding so things from the earth may creep into the crews. The crew members are like people on an elevator knowing they have to be together so trying to get along. If an opportunity comes up, they will try not to talk about it, particularly if it is not work related. So frequently groups from different countries will just focus on what they agree on… (there are always) cross cultural and gender role issues and leadership and followership perceptions across cultures that seep into gender and leadership roles and assigned roles…"*

It is important to note that one participant described the shared cognition issues between the crew and ground as "orders of magnitude" more difficult than communicating across language and cultural barriers:

> *"We were also mindreading with the crew members speaking Russian, but you can communicate more easily with them than you can with the ground, one or more orders of magnitude easier than communication with ground when on a delay."*

Theme 6: Selecting Individuals for Long Distance Missions

Two overarching selection-related themes emerged from participant interviews: (1) identifying individual characteristics that suit the unique challenges of long-duration space missions, and (2) addressing the challenges associated with selecting the right individuals for the job. It is important to note that many of the selected examples could possibly be addressed by training as well (e.g., training in teamwork skills).

> "*I'm talking about task-work - from my small straw - we will have to form teams that have not worked together much that can really solve complex novel problems in an asynchronous manner; we have to figure out how to train them to do this*"

Long distance and duration space missions present unique challenges that some individuals may be able to handle better than others. First, although astronauts are typically engineers by training, and possess the skills to successfully accomplish task-work for the mission, concerns were raised regarding "soft skills" required to work effectively with other team members. The ability to work well with others may become a crucial characteristic for individuals forced to spend 24 hours a day with other crew members throughout the entire mission (which, including travel time, could last over 1.5 years). This individual trait may not only be beneficial for maintaining cohesion within the crew, but also between ground control and the crew. For example:

> "*... [they] think if you are smart you will also have the needed team skills, but that's not necessarily true…*"

Second, astronauts will likely be subjected to unfavorable conditions, which some may be able to handle better than others:

> "*people's cognition may or may not change over the mission…you find some people report space fog… anecdotally they report things like going over the checklist more times to make sure doing right… you feel fuzzy sometimes at beginning, middle, or end of mission… don't have a good grasp of this or that... but not everyone reports space fog…*"

Furthermore, some responses suggest that the challenge of keeping astronauts entertained on LD flights could be addressed through selection:

> "*Need to pick people who can entertain themselves and give them those self-entertaining things to do… e.g., computer geek astronaut…*"

Interview responses also revealed challenges associated with the current mission assignment procedures. For example,:

> "*they are always on their best behavior when being observed .*"

Theme 7: Training

Several training themes emerged from the interview responses including training in a team setting, in situ and just-in-time training, current training practices, analog training facilities (e.g., NEEMO, FMARS, MDRS), outsourced training programs (e.g., National Outdoor Leadership School; NOLS), training challenges, trade-offs associated with training for teamwork versus task-work, and training for stressful situations.

Some responses reflected support for training as a team:

> "*well that's kind of a given [that astronauts on the ISS are a group], they've trained together...the crew up there changes...three old and three new faces...the crew work together because they trained together.*"

Teams were also trained in the capsule itself:

> "*Get the crews together; put them in a capsule, make them work together repeatedly as an intact crew, exercise their roles and responsibility. In the ISS, the crews do mainly their individual tasks, and they only come together infrequently for intact activities*."

Training as a team was believed to facilitate the level of autonomy required on long distance missions (during which communication with ground will be limited) as well as allow trainers to identify possible communication barriers:

> "*getting the crews together and putting them together in a capsule/simulator in close quarters and make them work together repeatedly exercising regular responsibilities would be helpful to develop them… currently they are often trained individually and*

come together only for discrete training opportunities… for long distance mission, they really need to build up the team dynamic with the intact crew… if we are going to have multinational crews, then we need to put them together and get them to use their language skills and develop them to promote cohesion… language barrier may be problem, but focuses on what to develop…"

Furthermore, including instructors from multiple departments in team training was, anecdotally, found to be a positive experience:

"*Where they interact is in the "Day in the Life Simulation" - here we get multiple instructors together; they have all the information at once, they have to integrate the training*"

This "training as a team" approach is also leveraged in perturbation scenarios in which teams are required to respond to an off-nominal event:

"*multiple instructors get together and give crew members a scenario… instructors watch how will they react… [From there, the training team would be in a room together monitoring what they say in response to the malfunction and then debrief/respond on good/bad solutions… various training scenarios throughout their training flow like this. The emergency scenarios are very important…*"

Discussions regarding in situ and just-in-time (JIT) training highlighted training practices such as refresher training on-board the vehicle to keep astronauts engaged and prevent boredom, staffing on-call trainers that can provide specialized training to the crew as needed, on-board video libraries to "refresh" the astronauts' memory of process and procedures, and on-board video systems capable of recording tasks as they are carried out and sending the recordings to ground for feedback. Additionally, the possibility of including JIT training for special tasks, such as EVAs, was well received by one of the astronauts interviewed for this study:

"*EVAs are usually trained extensively so this just-in-time training would be really interesting for you to elaborate on. For example, I trained extensively with Member A, but we didn't train with the Russians before we launched. We came together on orbit.*"

Many of the training challenges identified by interviewees revolved around training for time delays and developing autonomy in LDSE crews due to the resulting communication barriers between ground and crew. Ideas to address these challenges (that are described in detail in the "future challenges" section) included having the crew complete third-party training programs (e.g., NOLS) without ground involvement and training in off-site facilities (e.g., NEEMO, FMARS, MDRS) that could serve as an analog for time delays expected on LDSE missions. Although many interviewees were optimistic about the benefits of analog training, one interviewee was not convinced that it was the ideal solution:

"[analog training] is a good idea, but it is not the same as being in space. You learn

different things in each environment… e.g., being in a space analog for 4 months isn't as good as being in Antarctic analog for a year".

Another training theme addressed challenges associated with seeing how individual actions affected the system as a whole. One interviewee, proffered the possibility of training for such a "system-level thinking" approach to the crew:

> "*the are comfortable working on technical issues but are uncomfortable working with soft skills… I'm not sure how a team that is on a 40 minutes delay is going to work with a team that faces a problem that was not anticipated before launch…*"

A related theme was identifying tradeoffs (i.e., team coordination versus individual-level expertise) for addressing particular problems that may arise on the mission. Specifically, interviewees discussed when team coordination skills were critical and when individual-level expertise should be leveraged to address technological problems (i.e., transactive memory systems; teamwork versus task-work). One interviewee made the following comment:

> " *[Training] really has to be focused on the interplay among people to force coordination among team members… ensuring the functionality of a particular person's knowledge of their own system is a "waste" of time for the whole team to have to do … For example, in a simulation, a power operator may want to do a power down and move power from one system to the other (and from a technical sense, you should assume they know how to do that), but the exercise becomes more challenging when other operators have their own reasons for not wanting to do that right now. When they build the cases, the team members' objectives have to be in direct opposition and need to require them to have to go to arbitration with flight director to determine the smartest path forward given the challenges everyone is managing…*"

Additional training considerations included higher order cognition skill training, training under stress, and the time required to train for extended missions. One interviewee voiced concerns regarding a lack of standardized training to teach problem solving skills:

> "*SFRM is evolving into a modified team dimensional training model. It's a good model, with a lot of fundamental enabling skills (communications, leadership, followership, etc.) but I don't see how those 4 competencies turn into problem solving skills…"*

Interview responses also suggested that in order to deal with the stress brought about by carrying out a mission in space, trainers should elicit the same affective responses when training astronauts:

> "*What you are describing is affective or emotion preparation for stressful missions, training combined with high stress scenarios. We would train first to do the procedures, and that was very stressful because everyone wanted to look like they knew what they were doing, but going through it was very valuable. Integrated simulations where*

everyone was involved are crucial. One person would be putting in a malfunction telling what problem was supposed to happen and those can be very stressful."

Additionally, the time required to train astronauts was a concern:

> "*the problem with our training, even now, is that it takes 18 months to train an astronaut. It trains them how to operate the system safely, and to some level fix the certain things for which there are predefined procedures. But to train the crew for something more than that is hard to do. The schedulers own those astronauts when they are trained, and if they want to take a day off then the coordinator has to reschedule everything.*"

Theme 8: Future Challenges

Interview responses related to future challenges for LDSE missions revolved around developing autonomy within a crew that will be relatively isolated from ground control due to communication delays, articulating research programs that will investigate possible issues such as cultural friction between members and remedial actions for ineffective teams, identifying possible challenges associated with integrating third party contractors into the mission plan (e.g., SpaceX), and addressing knowledge base gaps associated with new vehicles and equipment that have not previously been used by NASA.

Due to communication delays between ground control and the crew during LDSE missions, ground control will be forced to give up much of the direct control over the crew's day-to-day activities, and the crew will need to maintain the required motivation and competencies to carry out objectives without relying on ground control for constant support and guidance. For example, an aerospace psychologist commented that

> "*It will be a big adjustment for ground control who is used to running mission and for astronauts who are used to waiting for ground to tell them what to do… (e.g., "now you can turn on that panel")... now [ground] will need to let that go… They can't just send up signals and have a panel turn on anymore. The culture of ground control of being in charge all the time [will have to change]…"*

Interview responses highlighted the need for research investigating the impact of cultural dynamics across particular disciplines and nationalities. For example, interviewees were concerned that sub-cultures may develop between pilots and other crew members as pilots "*understand and gravitate to other pilots.*" Additionally, because these programs are multinational, preferred training practices (e.g., involving the entire team in training exercises) may not be possible due to the lack of funding in some countries. This would not only limit training options, but may lead to the ostracism of crew members who are unable to attend early phases of training. Another challenge specific to teams research is how to address a situation in which a team is no longer functional. One interviewee made the following recommendation:

> "*If you have to do a replacement, then you should replace the whole crew*"

Interviewees expressed concerns about outsourcing operations to commercial space organizations. For example, an interviewee made the following comment:

> "[*It would be interesting to see if* "[commercial space organization] *could run a long duration mission or even one to an asteroid because once you add a crew to something and then you have to save their hides when things start not going well. NASA's processes are cumbersome because we really think that this stuff is required if we are going to keep the crew safe and get the mission done.*"

As described by interviewees, LDSE vehicles will be drastically different than vehicles used in previous programs. Responses alluded to the fact that LDSE vehicles will be simpler than ISS components (e.g., will have fewer modules) because they will be smaller in size. Some interviewees expressed that there may be fewer off-nominal events during LDSE missions than during ISS missions because of the simpler design of the LDSE vehicles. However, the main concern is the unknown unknowns that accompany the use of all new equipment. Because "*the new vehicle will be new everything: new vehicle, new ops, new crew, new training, new everything*", ground control and crew members will not be able to leverage experience or an existing knowledge base to address off-nominal events.

Theme 9: Technology Used To Accomplish Work or Solve Problems

Five technology-related themes identified in the responses are (1) psychological testing technology, (2) training technology, (3) equipment and information sharing technology, (4) special equipment, and (5) LDSE vehicles.

An aerospace psychologist discussed the "Winscat" technology as a tool to screen for psychological abnormalities that may arise during the mission.

> "*Winscat was developed as a quick cognitive screening tool to look at an individual's cognitive ability. A fire on MIR drove this because what happened to the crew was they inhaled a number of contaminants but when they said they were ok, they were still concerned with what they inhaled and what it would do to them…*"

When asked if this screening technology could be adapted to analyze team constructs, this person commented that it would be a "leap to take Winscat and turn into something that would show team cognition."

Technologies used by teams to accomplish their goals ranged from simple planning and brainstorming tools such as whiteboard sketches used to develop team-training exercises:

> "*The SIM team's process is to come into the room with a blank sheet of paper, a flight board which is basically a whiteboard with timeline for day with major events and then lead a brainstorming session. The training lead adjudicates and his perspective is to build a clever and challenging case to stress the entire team the most… Their goal is they*

want to promote communication among the team…"

At the other extreme are the sophisticated simulation training tools capable of calculating the impact of team actions on the system:

"*once they've come up with the script from the brainstorming session, they print a copy and everyone goes back to desks with their case, go into database and start entering details about how to make that happen in the simulator… exact terms, values, times, etc. to make the failure to happen… this is done electronically with the SIM team…*"

However, one interviewee expressed frustrations with the current software used to simulate off-nominal events:

"*Software drives the instructors crazy because it's supposed to make life simple but it requires a tremendous amount of training.*"

Technologies used to facilitate and record information sharing among team members were discussed. A training technology referred to as JEDI links a number of databases and contains 20 tools that allow crew members to reference a common timeline, access a database of common procedures and reference documentation, upload daily messages to the crew, etc. Additionally, the JEDI system records team member interactions, which are indexed and searchable by keywords, time stamps, etc. An information sharing challenge related to prioritizing electronic communications seemed to be due to timing issues with high priority emails and a high volume of low priority emails:

"*we had a problem with high quality emails coming out rarely (like 2am before the lead got home before bed) and lower quality more frequent emails that folks would jump in with lots of challenges, etc. We were bouncing between high quality but less frequent emails and low quality but more frequent emails…*"

Many of the interviewees referred to two formal information sharing technologies used for coordination and information sharing across the system: (1) an interactive timeline software including "sync points" documenting individual team actions is available to teams across the system, and (2) a common communication channel (i.e., "flight loop") over which important messages from the flight director that could impact various teams across the system is monitored. An interviewee described the timeline software:

"*Processes are designed such that there are a series of points where there are documented records of decision processes.*"

The "flight loop" (i.e., flight director loop) common communication channel is used by the flight director to communicate off-nominal events that may impact the flight deck, managers, engineers, etc.

Interviewees indicated that for informal or one-on-one communication, email is typically used:

"*Email is considered informal as is one-on-one communication… emails and phone calls don't have formal implications until sanctioned by the largest group*"

Other information sharing technologies used by some (but not all) teams included SharePoint, file-sharing software, and email list serves. However, one interviewee indicated that list serves may not always be reliable:

"*The flight director was sending out the emails to this team and was using a distribution list he thought was correct. But he realized that the email list didn't get to the people he needed it to get to*"

Interviewees described equipment challenges resulting from the smaller, more modular LDSE vehicles. For example, one interviewee pointed out that research sample storage equipment designed to protect samples from contamination were bulky, and would take up a significant amount of space on the relatively small vehicles. He also indicated another possible concern regarding the small form factor of LDSE vehicles regarding private space for individuals from different cultures.Additionally, the modular structure of the vehicle could create more opportunities for error in design as modules (which may be designed by different companies) have to fit together perfectly to function properly.

Theme 10: Vigilance and Travel Time

Travel time for LDSE missions to distant planets (i.e., Mars) will take significantly longer than previous missions. Some estimate that travel time to mars could be 6 months both ways. If the mission itself lasts 18 months, the total time for the mission could be over 2.5 years. One interviewee expressed concerns about the mental health of individuals who do not have meaningful work to keep their mind active during the 8 month travel time:

"*Time needs to be filled with meaningful work so that they are not bored for the ride.*"

Although maintenance activities may help with this issue, the interviewee recommended that refresher training (e.g., on how to execute EVA tasks) be provided during the travel periods.

This interviewee pointed out that there is a state of the art laboratory on the ISS to keep the crew engaged, but that will not be the case on LDSE missions. The interviewee sees this problem as particularly problematic after the mission is over and the crew is on its return trip back to Earth.

Theme 11: Acceptable Levels of Risk and Planning with Resilience in Mind

Interviewee responses highlighted NASA's awareness of the unknown unknowns that can arise throughout a mission. Because all accidents cannot be anticipated, interviewees discussed planning in terms of acceptable levels of risk:

"*safety is a delayed term… mission success happens now… accident may not happen in the future… not directly related… no absolute bar for 'safe' and although we may both* *value safety and mission success, acceptable levels of risk differ across groups…*"

One prescriptive method for facilitating the early detection of errors is to create a culture in which employees feel comfortable sharing mistakes and errors. This requires a proactive effort on the part of management to ensure that employees will not be ridiculed or reprimanded for openly admitting mistakes or reporting errors. Although interviewees indicate that this is not always the case:

> "*Crew will not tell ground everything. If they made a mistake they may think 'let's not tell the ground that we did this because we fixed it'…*"

One interviewee discussed an approach to open communication with management introduced by NASA after the Columbia incident:

> "*if the crew calls down to ask for a private management conference tends to get folks attention… after Columbia, NASA started a standing management conference to disguise that it might be "special". They spend a fair amount of time with the crew before the mission so the crew feels comfortable talking with them.*"

One flight director manager described tools that flight directors use incorporate acceptable level of risk into planning processes:

> "*you can continue down "the fault tree" with what-ifs until you are down in the very low probability outcomes so have to temper your efforts to be thorough with what is your best bang for your buck… As flight director, you need to ferret out the probabilities that are the biggest impact on flight plan…*"

After these probabilistic risk assessment measures are taken, the representatives from each discipline work together to

> "*You have to develop a flight ops plan with the best margins to make the timeline as resilient to failures as possible, so you can respond to off nominal situations to get everything done. The importance of the activities is also balanced with prioritizing crew safety…*"

This approach allows experts of various disciplines to weigh in on tradeoffs involving efficiency, effectiveness, and safety, and the working plan is placed on a shared timeline.

Another approach for promoting resilience during mission planning was to adhere to "flight rules":

> "*Handful of basic tenets to be used in response to a failure*"

One interviewee explains that the benefits of using such tenants comes from the process of developing the rules and not simply applying them to address particular off-nominal events:

> "*Part of the planning and flight rule development process is really about developing the principles for how to make decisions rather than the actual decisions themselves*".

In this way, crew members learn how to problem solve in the event of an unexpected failure for which there is no prescribed solution.

Summary

In our literature review and measurement methodology assessments, we identified themes associated with maintenance of shared team cognition that may raise unique challenges for long distance exploration missions, including the relevance of multi-team systems, multi-team membership, shifts in cognition, team transition and action processes that build/maintain shared cognition, and the inability to leave the team (the crew is 'in it together"). Our questions revolved around collecting information on current and future operations relevant to those themes. In particular, a few comments surfaced during our operational assessment interviews that were enlightening as they underscored the importance of communication for detecting team cognition shifts. One interviewee mentioned that to the crew needed to not only have the method/opportunity to regularly communicate with the ground, but they also needed to have the motivation to so. Further, other interviewees raised concerns that the ground would not always inform them of their errors despite their wanting to know if something was done incorrectly, as well as there being a possibility/tendency to want to withhold reporting on crew errors if they were subsequently fixed by the crew, which may be increasingly a possibility in long distance missions when communication delays increase.

In addition to exploring the themes we identified in our literature review and methodology assessments, several other themes emerged related to the unique circumstances long distance space exploration missions. These issues merit future research as well as special consideration for designing operational best practices, and include selection and training issues as well as technology use and best practices which will be unique to long distance missions.

Part 4: Conclusions & Recommendations

Operational Recommendations

Based on our literature review and operational assessment, we make three operational recommendations concerning the importance of team cognitive processes to the smooth operation of long-duration space exploration missions. These recommendations are based on the robust finding supported in the literature that team cognitive processes (i.e., shared mental models and transactive memory systems) are strongly associated with the quality of team interaction processes such as communication and coordination, and that they are predictive of team outcomes including performance, member satisfaction, and viability.

As part of our review, we explicitly considered the degree to which findings from the literature can be appropriately generalized to the long-duration space flight context. Much of the extant literature is not generalizable in one or more ways to LDSE, however, we are confident in drawing these three recommendations for two reasons. First, they are supported by the few studies conducted on teams that are comparable in a many ways to LDSE teams. Second, the conclusions link team cognition to performance outcomes, and the associated credibility intervals for these effects do not include zero. So the open question is just how important are they, but the fact that they are important does not appear to be in question based on existing research (DeChurch & Mesmer-Magnus, 2010).

In our recommendations, we refer to the Space Exploration Multiteam System (SE-MTS) to encompass the teams and sub-teams that minimally include the flight crew, mission control, and flight operations. As our operational assessment revealed, many of the back room teams are also a part of the highly interdependent "team" that will ultimately enable a long duration space exploration mission to succeed. Accordingly, we recommend the following:

1. Given its demonstrated association with team process and performance, two aspects of team cognition: shared mental models and transactive memory systems, **need to be developed and regularly updated** among members of the flight crew, mission control, and flight operations (i.e., the SE-MTS) throughout LDSE missions.
2. Given its demonstrated association with team process and performance, team cognition within and between component teams throughout the SE-MTS should be **continuously assessed before and during this mission and used as a trigger for countermeasures.**
3. Given its demonstrated association with team process and performance, **team cognition should be one criterion on which decisions are based** for SE-MTS personnel selection, crew composition, training, information technology, leadership, and communication protocols

Research Recommendations

Based on our literature review and operational assessment, we make three recommendations for areas of research that are likely to be most critical in understanding the specific nature of how team cognition affects individual psychosocial adaptation and team performance during LDSE missions. Each of these represent aspects of space flight where the literature on team cognition is not sufficiently developed.

1. **Multiteam membership (MTM) and team cognition**. Astronauts will be living and working in different groups during long-duration space exploration, and they will be actively switching between them. Thus, research is needed that explores the positive and negative consequences of team switches on team cognitive processes.
2. **Multiteam systems (MTSs) and team cognition.** Interventions aimed at aligning team cognition in order to mitigate decrements in team performance and adaptation must focus at least as much attention to the between-team cognition (e.g., between the crew and ground), as to the within-team cognition. Research is needed that explores the notion of MTS cognition, detailing what elements of cognition within and between teams need to be shared and which need to be distributed. Research is needed to identify the optimization points for within and between team cognitive processes that maximize *individual* psychosocial adaptation, *team* functioning, and *system* effectiveness. Research is needed that identifies specific thresholds for within and between team cognition beyond which the risks of poor integration dramatically increase.
3. **Dynamics of team cognition.** Existing research on team cognition is based largely on single estimate effect sizes between cognition and its antecedents, correlates, and consequences. The development of early warning detection systems that can be paired with countermeasures will require an in depth understanding of how cognitive processes shift over time. Basic research on the development and adaptation of team cognitive processes, and how they are affected by MTM and MTS are essential to apply research on team cognition to an LDSE mission.

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13. ABSTRACT *(Maximum 200 words)*

We summarize the results of a (1) comprehensive literature review on team cognition relevant for LDSE, (2) review of relevant team cognition measurement methodologies, and (3) operational assessment of NASA practices as they relate to development and maintenance of team cognition. The literature review findings are used to identify the (1) conclusions that can be drawn based on the extant empirical research about how the context of spaceflight will affect team cognition, (2) conclusions that can't be drawn based on the extant empirical research because the context under which team cognition has been studied does not exhibit adequate ecological validity to spaceflight, and (3) the most critical areas for future research on team cognition. We evaluate team cognition measures along five-factors relevant to LDSE, and summarize the measurement approaches that have been developed and reported in prior research. The results of our operational assessment include three operational recommendations concerning the importance of team cognitive processes to the smooth operation of long duration space exploration missions as well as three research recommendations likely to be most critical in understanding the specific nature of how team cognition affects individual psychosocial adaptation and team performance during LDSE missions.

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