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Critical Team Cognitive Processes for Long-Duration Exploration Missions

Final Report

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Executive Summary

Teams conducting long-duration spaceflight missions face the pervasive risk of team performance decrements due to inadequate cooperation, coordination, communication, and psychosocial adaptation within the spaceflight crew itself, as well as between and across Mission Control teams. Future space exploration missions will be characterized by extended periods of isolation and confinement as well as communication constraints caused by the extreme distances involved. Accordingly, these teams will need to operate under a much greater level of autonomy than current spaceflight crews. Given that team cognition has been shown to be a significant predictor of team performance across a number of domains and tasks, it is critical to understand how team cognition occurs under these specific conditions, how it shifts over time, and how to implement countermeasures to improve team-level cognitive processes such as planning, decision making, and collaborative problem solving. These team processes have generally been well studied; however, research into team processes under conditions of isolation, confinement, danger, high autonomy, and long durations is limited.

In an effort to support the need for further understanding of the issues surrounding team cognition for future space exploration missions, this project is taking a multidisciplinary perspective, coupled with operational assessments, to identify the key team cognition factors that are most likely to affect the maintenance of effective and adaptive team performance and overall crew well-being. We address the research that has studied team cognition in long-duration spaceflight missions and appropriate spaceflight analogues while recognizing that little research has been conducted on team cognition in this context. As such, we evaluate issues related to, or supporting, team cognitive processes, and current methods used to address these in other relevant domains (e.g., nuclear power, organizational settings). Results from our literature review and operational assessment will be presented as initial operational recommendations for training, selection, composition, and monitoring as well as suggestions for future research.

This report is broken into four main parts. The objective of Part I of the Final Report is to provide an overview of our extensive review of research conducted in space and spaceflight analogues examining individual cognition. Here we aim to summarize and interpret these results. In Part II, we provide a general overview of team cognition and then systematically focus on a set of critical team cognitive processes and knowledge structures (shared mental models, transactive memory systems, collaborative problem solving, team decision making, and team planning). Within each of these we highlight the major concepts and research surrounding these team cognitive processes and then postulate on the ways in which findings from individual cognition in spaceflight and close analogues could scale up to affect the specific team-level cognitive process under discussion. In Part III, we provide some explicit propositions that predict the relationship between decrements in individual cognition due to conditions inherent to spaceflight and how they could affect certain team cognitive processes. In Part IV, we detail the results of our operational assessment. In Part V, we review the literature on team training to enhance team cognitive processes, which may be of use in long-distance spaceflight missions. In Part VI, we systematically reiterate and discuss each of the critical team cognitive processes we have identified and then provide operational (e.g., training, selection, monitoring) as well as research recommendations. Lastly, in Part VII, we provide a brief conclusion summarizing our report.

Part I: Individual Cognition in Space and Spaceflight Analogues Research Overview

While the goal of the overall report is to provide insights regarding team cognitive processes critical to long-duration and long-distance spaceflights, the current section provides the foundation for such a discussion by reviewing the current state of the science on individual cognition in space and analog environments. To elaborate, during the early stages of our review of the extant literature, it was evident that the vast majority of the literature examining cognition during spaceflight or analogues was conducted at the individual level. Therefore, an examination of this literature was needed to assess what the current state of cognition research is, and from here, inferences could by articulated regarding the relation between individual- and team-level cognitive processes based on those findings. Because the focus of the current report was not on individual cognition, the intention was not to create an exhaustive list of every space and cognition paper in existence, but rather to be able to discern what data trends exist in the space literature.

The articles included in our review were selected through a variety of methods, relying primarily on google scholar, NASA's technical reports database, and through the reference lists of articles cited in the space literature papers. Articles were initially selected if they examined cognition in space or analog environments, thereby excluding laboratory studies conducted on student and civilian populations to maintain a level of consistency within the database. As the article coding continued, a few laboratory studies and review papers were included in the database if they were cited in the space literature that was reviewed. The final database of articles examining individual cognition consisted of 82 articles; however, due to the fact that many articles examined multiple cognitive constructs within the same article (e.g., memory, executive function, reasoning, etc.), the final sample consisted of 168 entries/observations. All references that were included in this review are included in their own reference section at the end of the report titled, "Individual Cognition Lit Review References."

To simplify the process of analyzing the different cognitive constructs, individual cognitive constructs were hierarchically categorized into groups based on similarities in function (see Figure 1). For example, articles that examined constructs or activities such as problem solving, arithmetic, and verbal reasoning were all categorized as *reasoning*. Fine motor control, body orientation, and tracking ability were all categorized as *psychomotor functioning*. It is important to note that these categories reflected here are for the purposes of organizing our literature review and findings and do not necessarily represent the structure or function of individual cognitive processes. For example, visuo-spatial ability would technically be considered part of the visuo-spatial sketchpad within working memory; however, due to the different activities and different patterns of findings within these two constructs, working memory (within central executive functioning) and visuo-spatial ability, were considered separate categories. These categories allowed us to reduce the overall number of constructs when viewing the patterns of outcomes. The findings were further categorized based on the environment in which it was examined (e.g., cold, microgravity, isolation, etc.). The most commonly used metrics in these studies were the Cognitive Assessment Tool for Windows (WinSCAT), Standardized Tests for Research with Environmental Stressors (NATO-STRES), NASA Task Load Index (TLX), or components used in those tests, such as the Stroop test or a digit symbol substitution task. Although the findings of this review are approximations based upon multiple studies conducted in multiple settings, distinct trends emerged that can be used to guide team cognition research. Table 1 provides an overview of these findings. Following Table 1, we systematically review the findings for each of the major individual cognitive processes.

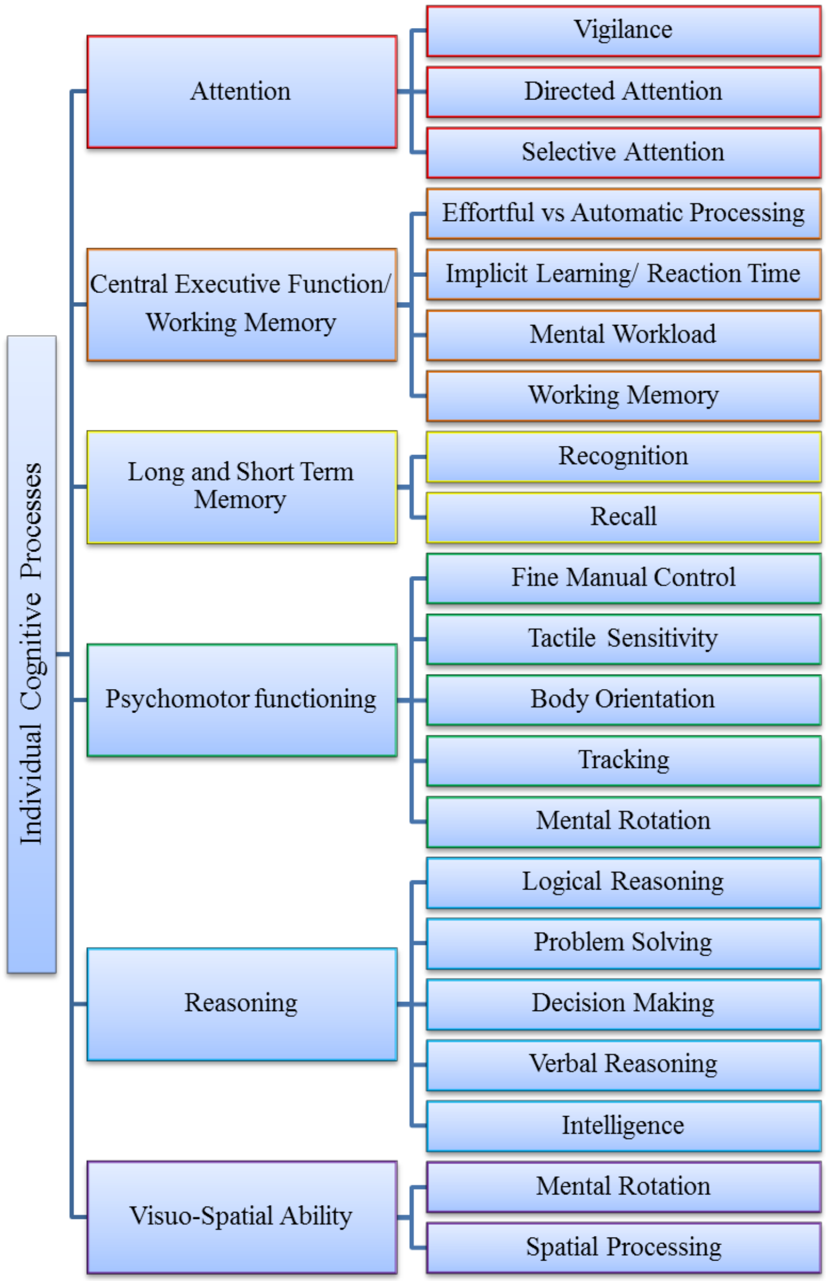

Figure 1. Summary of individual cognitive processes extant in spaceflight and analog research.

Table 1. Overview of Effects of Extreme Environmental Factors on Individual-level Cognition

Individual Cognition Category	*Extreme Environment Characteristics*	*Number of Entries*	*Findings*		
			Not Impaired	↓ *Impaired*	↑ *Improve*
Attention	Cold	6	2	4	-
	Isolation/Extreme Env.	4	1	3	-
	Microgravity	3	2	1	-
	Sleep	3	-	3	-
		Total: 16	**Overall: Impaired**		
Central Executive Functioning	Cold	17	5	10	2
	Isolation/Extreme Env.	8	4	1	3
	Microgravity	25	9	14	2
	Radiation	6	-	6	-
	Sleep	5	-	5	-
		Total: 61	**Overall: Impaired**		
Long Term and Short Term Memory	Cold	9	1	6	2
	Isolation/Extreme Env.	8	1	6	1
	Microgravity	10	6	3	-
		Total: 27	**Overall: Mixed**		
Psychomotor Functioning	Cold	7	2	5	-
	Isolation/Extreme Env.	1	-	-	1
	Microgravity	19	2	16	1
	Radiation	1	-	1	-
	Sleep	2	-	2	-
		Total: 30	**Overall: Impaired**		
Reasoning Ability	Cold	11	3	7	1
	Isolation/Extreme Env.	4	-	4	-
	Microgravity	4	2	2	-
	Sleep	2	-	2	
		Total: 21	**Overall: Impaired**		
Visuo-Spatial Ability	Microgravity	12	8	3	1
	Radiation	1	-	1	-
		Total: 13	**Overall: Not Impaired**		

Attention

Sixteen observations were found examining extreme environmental effects on attention. Of these, only three were conducted in space and specifically examined the effects of microgravity on attentional processes. The majority of the remaining articles used analog environments such as crews in Antarctica, the Arctic, or divers. Further, the samples consisted almost exclusively of males. Cognitive constructs included in the "attention" category included vigilance, directed attention, sustained attention, and concentration. Many methods were used to assess the attention constructs, including the visual detection of stimuli, the NASA Performance Assessment Workstation (PAWS), and NASA Task-Load-Index, among others. Overall, there appears to be impairment of attentional abilities, specifically with regards to decreased accuracy and increased response time, and particularly in extreme environments such as cold, isolation, and when experiencing sleep deprivation (e.g., Cabon, Coblentz, Mollard, & Fouillot, 1993; Palinkas et al., 2005). Conversely, attention did not appear to be as severely impacted in spaceflight even though it possesses some of the aforementioned characteristics (e.g., Benke, Koserenko, Watson, & Gerstenbrand, 1993).

Central Executive Functioning

Central executive functioning was a broad category used to describe cognitive constructs such as working memory, dual-task performance, inhibition function (e.g., using a Stroop test), implicit learning (e.g., using choice reaction time or digit-symbol substitution tasks), etc. Sixty-one observations were made examining central executive functioning. Of these, 23 observations were made in analog environments such as Arctic crews or simulations in high-fidelity situations such as the Russian Mars 500 or Mars Research Desert Station, 19 observations were made in spaceflight, 14 were from laboratory studies, and five were taken from review papers. Most of the participants were male, which should be noted as it may relate to generalizability to female participants.

Mixed results were found for the impact of cold on central executive functioning. Although a majority of the studies found impairment in some form, overall the impairment was attributed to distraction and oftentimes the impairment was with regards to reaction time and not accuracy (Mäkinen, Palinkas, Reeves, Pääkkönen, Rintamäki, Leppäluoto, & Hassi, 2006; Palinkas, Mäkinen, Pääkkönen, Rintamäki, Leppäluoto, & Hassi, 2005). Isolation did not appear to impair executive functioning beyond a decreased ability to sustain mental effort. Mixed results were found with regards to the impact of microgravity. The studies that found impairment as a result of microgravity often found an increase in reaction times during the cognitive tests (e.g., digit-symbol substitution and number recognition; Kelly, Heinz, Zarcone, Wurster, & Brady, 2005) or found only initial impairments and subsequent return to normal functioning after a few days in space (e.g., Lorenz, Manzey, Schiewe, & Finell, 1995). Often, these decrements were attributed to space sickness or high workload (Pattyn, Migeotte, Morais, Soetens, Cluydts, & Kolinsky, 2009; Ratino, Repperger, Goodyear, & Potor, 1988). The observations made regarding radiation were from a single study examining the long-term effects of radiation in residents (from various distances) surrounding the Chernobyl area (Gamache, Levinson, Reeves, Bidyuk, & Brantley, 2005). These preliminary results indicate that even lower levels of long-term radiation exposure cause impairments in various cognitive areas, possibly as a result of diffuse axonal injury. Lastly, lack of sleep was found to negatively impact cognitive performance. Researchers found that even a two-hour loss of sleep per night "causes decrements comparable to decrements after 24 hours of continuous deprivation" (Barger, Wright Jr., Burke, Chinoy, Ronda, Lockley, & Czeisler, 2014, p. 238). Three of the sleep studies were conducted in space, and all three showed decrements in performance (Dijik et al., 2001a; Dijik et al., 2001b; Schiflett et al., 1996). Given the issues surrounding sleep in a space environment, these findings have significant potential impact on individual cognition.

Long-Term and Short-Term Memory

Twenty-seven observations were made regarding long- or short-term memory. Most of the studies examining the effects of isolation were conducted in a laboratory, whereas all of the studies examining the effects of microgravity were conducted during spaceflights. This means that there are notable differences in the studies, not only based on the sample and environment studied, but also the number of participants in the studies examining the impact of microgravity on memory ranged from one to five men, whereas the findings from the laboratory (isolation studies) were based upon larger samples of often 10-15 men. Again, most of the studies examined almost exclusively men. Overall, both cold and isolation/extreme environments were found to impair cognitive functioning, often through reduced accuracy and increased reaction times (e.g., Palinkas, 1992; Reed et al., 2001); however, microgravity was not found to be impactful on memory (e.g., Eddy, Schiflett, Schlegel, & Shehab, 1998; Manzey, Lorenz, Schiewe, Finell, & Thiele, 1993; Newman & Lathan, 1999).

Psychomotor Functioning

Thirty observations were reviewed, in which the effect of cold, radiation, lack of sleep, microgravity or isolation on psychomotor abilities was assessed. Nineteen of these observations were conducted in space, with the remaining observations originating from laboratory study (five studies), extreme environment, and two in simulated space environments. Often, psychomotor functioning was examined using some form of an unstable tracking exercise (e.g., Bock, Fowler, & Comfort, 2001; Manzey, Lorenz, Poljakov, 1998; Manzey, Lorenz, Schiewe, Finell, & Thiele, 1993), but other exercises were also used such as tapping of a rhythm (e.g., Semjen, Leone, & Lipshits, 1998) or observations of movements (e.g., Tafforin & Lambin, 1993). Experiments in which the participants were subjected to cold for brief or extended periods revealed impairments in psychomotor skills including manual dexterity and hand grip strength. Likewise, individuals exposed to radiation (i.e., Chernobyl residents) or lack of sleep also exhibited impairments in psychomotor abilities. Microgravity had more varied effects, often with some form of impairment such as decrements in speed or changes in kinematics of movements (e.g., Berger et al., 1997; Bock, Fowler, & Comfort, 2001).

Reasoning Ability

Twenty-one observations examined the impact of environmental factors on reasoning abilities, such as mathematical processing, verbal reasoning, and logic. Half were conducted in a laboratory setting, often examining the effects of cold on reasoning using divers or climactic or hypobaric chambers to simulate cold conditions. Five observations were conducted during spaceflight, and five were made during analog conditions (i.e., examining military training teams or South Pole explorers). The strongest impairments were a result of cold conditions, followed by isolation/extreme environments, and sleep. Mixed results were found with regards to the impacts of microgravity on reasoning. Two studies found impairments; one with regards to impaired weight discrimination of objects in space when handling them, and the other with regards to time estimation (i.e., estimations of how much time had elapsed). Casler and Cook (1999) noted in their review paper that cognitive constructs such as reasoning are not well documented in space; however, from the limited studies conducted in space, it appears that there is no impairment in reasoning ability in space.

Visuo-Spatial Ability

Thirteen observations were found regarding the effects of environmental stressors on visuo-spatial abilities such as mental rotation and visuo-motor tracking. All of the studies examining the effects of microgravity on visuo-spatial abilities were conducted during spaceflights (with variable spaceflight durations), with the exception of one head-tilt laboratory study. Most of the examinations consisted of very small sample sizes, ranging from one to four astronauts, with the exception of two examinations, which had eight astronauts. Eight of the 11 observations looking at microgravity effects found no impairments; however, three did find impairments. Several of the studies attributed decrements in performance to fatigue; however, in some studies, the effects of microgravity, for example, on tracking performance lasted for several days after return to Earth (e.g., Manzey & Lorenz, 1999).

Effects of Long-Term Radiation Exposure

While the studies of the effects of extended exposure to radiation on human cognition in space is limited, especially over long durations, some recent ground-based research using animals does provide some insights that are relevant to consider for long-duration spaceflights (LDSF). For example, a recent radiation study demonstrated that prolonged exposure to radiation is related to neurobehavioral changes in rodents (Hienz et al., 2010). Specifically, given exposure to radiation, performance on the rat Psychomotor Vigilance Task, the findings showed decreases in sustained attention and slower performance. More recently, Parihar et al. (2015) demonstrated in more detail the neurobiological changes that occurred in mice following 6 weeks of exposure to charged particles similar to those astronauts would be exposed to under spaceflight conditions. The changes were correlated with decreased performance on a rodent cognitive task required attention to novel objects. Indeed, many studies over the past decade have shown decrements to cognition in rodents due to radiation exposure (e.g., Shukitt-Hale, Casadesus, Cantuti-Castelvetri, Rabin, & Joseph, 2003). Therefore, while research in space has not yet been conducted that has examined the effects of space radiation on human cognition, animal models suggest there will be decrements under LDSF conditions (e.g., Parihar et al., 2015).

Summary

From our review of the literature, it seems as if many of the characteristics of space (e.g., microgravity, cold, isolation) may impair certain cognitive abilities, while having relatively little effect on others. Of course, given the small amount of research that has actually been conducted in space, the mixed findings for certain characteristics on cognition, and the relative sample bias towards males, this interpretation is tenuous pending the accumulation of further research. Further, ground-based research with animal models suggests that radiation exposure will negatively affect individual cognition. Nonetheless, the pattern of results that exists at an individual cognitive level, can easily be seen by examining Table 1. With this as our foundation, we next discuss theory and research related to team cognition and how findings from individual cognition might have a cascading effect on team-level cognitive processes.

Part II: Bridging the Gap from Individual- to Team-Level Cognition in Spaceflight

Team Cognition Overview

During LDSF, a range of environmental, technological, and social factors are experienced. Typically, dealing with events in the LDSF context requires routine responses from the team. Other times, though, there are potentially life-threatening and unforeseen events requiring adaptive responses. The teams comprising the spaceflight crew and ground control must be capable of performing effectively across a wide range of cases for the duration of their missions. This brief summary of team cognition is meant to ground the context of our efforts in understanding team cognition and team performance in LDSF.

At the core of effective team performance, whether for routine or non-routine events, is the concept of coordination. Fiore and Salas (2004) argued that coordination was at the core of team cognition. The critical aspect of teamwork, that is, the synchronization and coupling of teamwork behaviors, is driven by shared and complementary knowledge across the team, as well as team member awareness of this distribution. They suggested that team cognition can be conceptualized as the mechanism that "fuses the multiple inputs of a team into its own functional entity" (p. 237). Essentially, they argued that the affective, behavioral, and cognitive processes within the team must effectively bind to produce coordinated teamwork.

In later writing, Fiore and Salas (2006) argued for a more foundational understanding of team coordination. They noted that the etymological origins of coordination suggest it was derived from three distinct concepts – "arrange," "order," and "together" – and that the term addresses a more complex construct than just working together. This interpretation fits with many key definitions of teamwork in the literature. Specifically, Marks, Mathieu, and Zaccaro (2001) defined *team coordination* as "orchestrating the sequence and timing of interdependent actions" (p. 363). Most recently, when discussing the relation between team cognition and team coordination, Elias and Fiore (2012) noted that team cognition helps to both manage social dynamics and effectively scaffold team interaction. Theoretically, coordination acts as a set of constraints that "endows behavior with meaning and purpose, with directedness and aim, and allows for anticipation precisely by narrowing the range of action" (p. 585). In short, team research studies coordination as it encompasses the ways in which a team sequences and times their behaviors to achieve effective performance (e.g., Elias & Fiore, 2012; Fiore, Salas, Cuevas, & Bowers, 2003; Rosen, Fiore, Salas, Letsky, & Warner, 2008).

The above theoretical distinctions are provided as a foundation for our report. Further, to provide conceptual clarity to some of the team cognition literature, we need to provide some categorical distinctions between team types and their relationship to coordination. First, one important distinction within the team literature is between "action teams" and "project teams." *Action teams* are composed of team members with highly specialized expertise and well-defined roles. They must collaborate in short-duration events that often require adaptation to unpredictable situations (Sundstrom, De Meuse, & Futrell, 1990). *Project teams* are brought together to produce what is typically a one-time output that requires they apply not only expert and specialized knowledge, but also judgment and decision making. Project teams are typically from different disciplines or organizational functions and they may be brought together for incremental product improvement, or they may be expected to produce radical innovation (Cohen & Bailey, 1997).

Another important distinction within the team cognition literature is between behavioral coordination and knowledge coordination. *Behavioral coordination* is the type most often associated with the timing and sequencing of actions in service of team goals and tasks. This typically manifests itself in time-stressed situations when a team's procedure needs to be executed safely and effectively (e.g., emergency response teams). By contrast, *knowledge coordination* more generally describes the awareness and use of team member expertise. That is, in situations where team member knowledge is distributed, for a given team to effectively execute its tasks, it needs to know where to find critical information and knowledge as well as how and when to apply that knowledge.

A majority of the team performance literature studied action teams and this work led to the development of concepts under the general notion of shared cognition (e.g., Shared Mental Models and Transactive Memory Systems; see DeChurch & Mesmer-Magnus, 2010; Rico, Sanchez-Mansanares, Gil, & Gibson, 2009). Performance in action teams (e.g., aviation crews, emergency response teams, etc.) typically relies on behavioral and knowledge coordination; the former to sequence their actions in time-stressed settings and the latter to know whom to go to when modifying their actions. But an important subset of team research has focused more on knowledge coordination and its role in knowledge building. This occurs more in project teams that have been assembled, for example, to solve a problem or develop a new product. We bring these distinctions to the forefront because LDSF has teams associated with it that cut across these definitions. A given spaceflight team might be like an action team (e.g., to deal with a short-duration event such as a crew changeover), or like a project team (e.g., to deal with a particular problem that has arisen). Further, these teams might require behavioral coordination (e.g., coordinating their efforts during an extravehicular activity [EVA]), knowledge coordination (e.g., diagnosing why a solar panel array is non-functional), or a combination of both. And, in many cases, it is highly likely that LDSF teams will require the ability to deal with both routine and non-routine events.

In Table 2 we present a conceptual overview of the team process types, to which we have just referred, in juxtaposition with the type of task (e.g., whether it is a routine task versus a non-routine task). Further, inherent and essential to each of these is the nature of the coordination within the team. Again, our point here is to provide a differentiation between these important dimensions so as to highlight their distinct and interdependent role in supporting effective team performance. This serves to guide how we are conceptualizing the nature of the team cognition required for LDSF.

Table 2. Team Performance as a Function of Task and Process Type

		TEAM PROCESS TYPE	
		Behavioral Coordination	***Knowledge Coordination***
TEAM TASK TYPE	***Routine Event like Crew Changeover***	Behavioral coordination in this task type involves, for example, monitoring and backup behaviors.	Knowledge coordination in this task type involves, for example, drawing on role knowledge of a team member for task specific assistance.
	Non-Routine Event like EVA for Main Bus Switching Unit Repair	Behavioral coordination in this task type involves, for example, reactive strategy adjustment to alter plans in response to unanticipated events.	Knowledge coordination in this task type involves, for example, leveraging complementary expertise about a given technology for trouble-shooting a problem.

Team Cognition Literature Review

As noted in Part 1, research conducted in space has only studied individual-level cognition (e.g., Manzey, Lorenz, & Poljakov, 1998). However, the study of team cognition is advantageous and complementary to the study of individual cognition because with a team comes a suite of collective cognitive resources including knowledge, skills, and abilities, all of which are necessary for accomplishing complex tasks, especially in high-stakes situations (e.g., Sikorski, Johnson, & Ruscher, 2012). For the purposes of our review, we define *team cognition* as an emergent phenomenon that arises in the dynamic interdependency of inter-individual and intra-individual factors as team members interact with their environment, their technology, and each other (e.g., Cooke, Gorman, Myers, & Duran, 2012; Fiore & Schooler, 2004; Rosen, Fiore, Salas, Letsky, & Warner, 2008). Much like individual cognition, team cognition, occurring at the level of the team, extends beyond more than just the teams' internal knowledge. It also includes team cognitive processes such as collaborative problem solving, decision making, and planning (e.g., Cooke et al., 2012).

A recent meta-analysis of team cognition research showed that team cognition positively predicts the task-related processes of the team, the teams' motivational states, as well as the performance of the team (DeChurch & Mesmer-Magnus, 2010). This meta-analysis focused on what we introduced as the knowledge coordination component of team cognition including shared mental models and transactive memory systems. Accordingly, in the subsections that follow we first review the shared mental models and transactive memory systems constructs prior to our review of collaborative problem solving, team decision making, and team planning, respectively. Our goal here is to provide a brief overview of each of these team cognitive processes. In doing so, this helps to frame the constructs of interest that are critical for supporting in LDSF missions. Further, throughout discussion of each critical team cognitive process, we expand and elaborate upon the findings from spaceflight and space analogue research regarding individual-level cognition and provide our best interpretation in terms of how these findings would scale up to team-level cognition. At a general level, this scaling is represented by Figure 2 in which individual-level cognitive processes, specific to each member of the crew, are nested in, and constituting, the collective team-level cognitive processes.

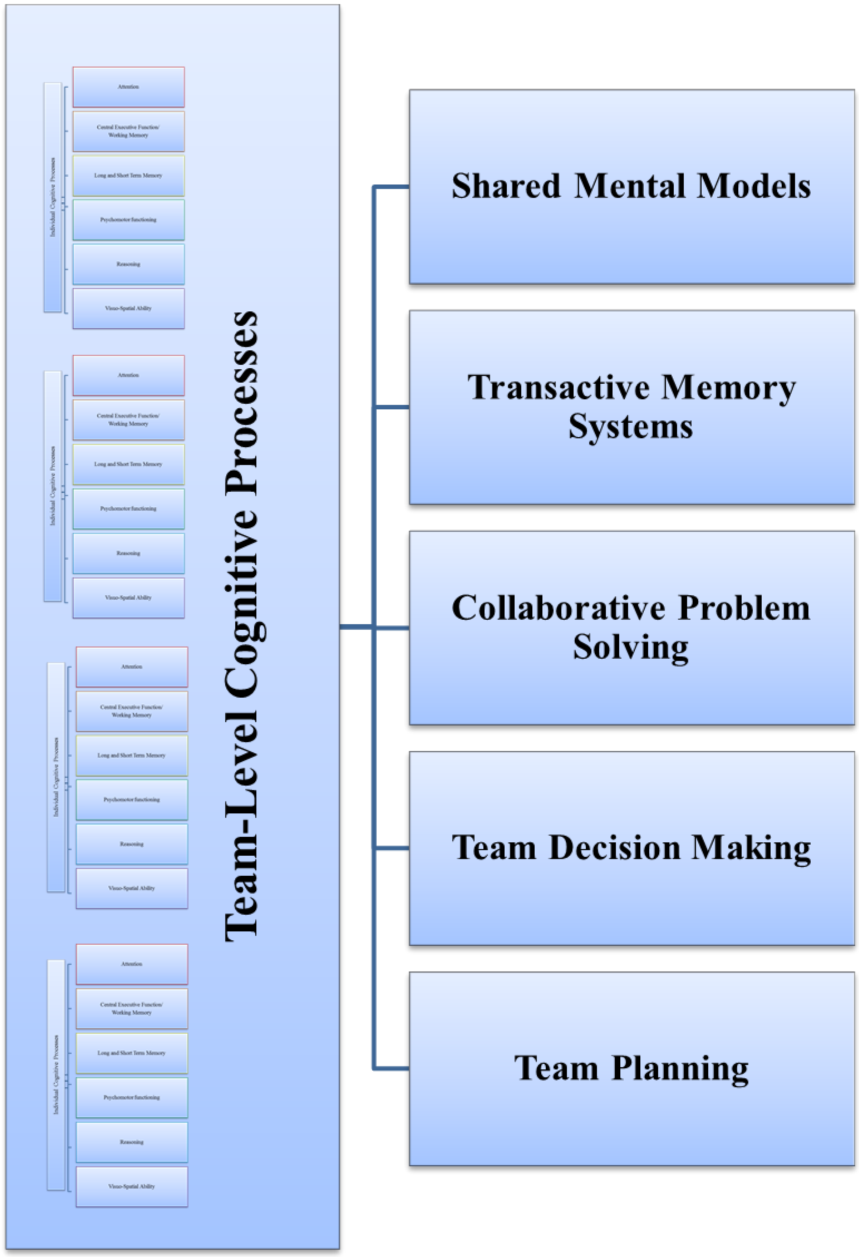

Figure 2. Illustrative schematic highlighting the import of individual cognition in constituting team-level cognitive processes.

Shared Mental Models

Teams who have a shared knowledge of their interdependencies, the problem to be solved, and the terminology used across their representative disciplines, are better able to coordinate activities. Often times in the literature, this knowledge is referred to as a mental model. At a general level, *mental models* are internal representations we hold of various task and/or social situations (Stevens & Gentner, 1983) that are formed through a mix of prior experience and current observations (Wilson & Rutherford, 1989). *Shared mental models* (SMMs) are essential to understanding team cognition as these are the "knowledge structure(s) held by each member of a team that enables them to form accurate explanation and expectations for the [team and task], and in turn, to coordinate their actions and adapt their behavior to demands of the task and other team members" (Cannon-Bowers, Salas, & Converse, 1993, p. 228). Shared mental models have been found to affect critical mission processes and outcomes such as team adaptation, implicit coordination, team performance, and shared leadership (Burke, Stagle, Salas, Pierce, & Kendall, 2006; DeChurch & Mesmer-Magnus, 2010; Rico, Sanchez-Manzanares, Gil, & Gibson, 2008; Salas, Sims, & Burke, 2005). Therefore, due to the widespread implications of successful mental model formation for successful team planning, team decision making, coordination, leadership and performance, more attention will be provided in the current study's literature review regarding the details of shared mental models.

Often the literature discusses mental models in teams in terms of their sharedness or similarity among team members, thus the ubiquity of the term *shared* mental model; however, there are two aspects of shared mental models that are necessary to consider. Firstly, mental models are most effective when they are shared or similar among members (i.e., do team members hold the same mental models as their teammates). *Similarity* is considered the most important aspect of mental models, as similarity in shared mental models has shown to be a good predictor of team performance (e.g., Stout, Cannon-Bowers, Tannenbaum, & Salas, 1999). Secondly, the *accuracy* of the shared mental model needs to be considered. Smith-Jentsch, Cannon-Bowers, Tannenbaum, and Salas (2008) discussed the importance of developing both a shared and accurate mental model to facilitate effective teamwork and performance. Indeed, a propensity of the extant literature states that when team members hold similar (i.e., shared) and accurate (i.e., reflecting the true state of the event) mental models, it allows them to better understand complex phenomena, as well as form more accurate predictions of future states/events (Cannon-Bowers, Salas, & Converse, 1993; Johnson-Laird, 1983; Rouse & Morris, 1986). In fact, the concept of one (i.e., sharedness) going hand in hand with the other (i.e., accuracy) is so prevalent in the literature, that many researchers either disregard the accuracy component or explicitly merge the two criteria such that the terms shared mental model and accurate mental model are used interchangeably (Mohammed, Ferzandi, & Hamilton, 2010).

Relatedly, a recent study examined quality and similarity of team mental models. In looking at adaptive team performance, the findings suggest that higher quality mental models were most important when similarity was low. But, when teams showed higher similarity, quality did not matter (see Resick et al. 2010). As such, for the purposes of understanding team cognition in LDSF, we distinguish between accuracy/quality of the mental model and the sharedness/overlap of the mental model. Based upon the theorizing of Smith-Jentsch (2009) and Hoeft (2006), Table 3 illustrates this distinction.

Table 3. Accuracy and Sharedness of Team Mental Models

		Accuracy	
		Low-Quality Mental Model	***High-Quality Mental Model***
Sharedness	***Low Agreement***	Worst performance	Accurate but different (e.g., in situations with differing functional roles the team members may have accurate mental models of their own task but not their teammates)
	High Agreement	Inaccurate but agreed upon mental models – they may be able to coordinate but it would be down the wrong solution paths (e.g., they will get to an incorrect solution rapidly)	Best coordination

Another important distinction is that raised by Huber and Lewis (2010) who propose that it is not the sharedness of group member's mental models that drives success in team performance, but rather how accurately they understand the *different* mental models each teammate holds. Huber and Lewis use the term "*cross-understanding*" to refer to the accuracy of one's knowledge of another teammate's mental model. Teammates that hold dissimilar mental models may still be able to perform well if they are able to fully understand the differences to best shape the ways in which they interact and approach problems that arise. Thus, individuals who hold different mental models, but have a high cross-understanding of these differences are able to better cope or compensate for team members' different views. For example, if one team member believes that communication within teams should be succinct and direct to the point, other team members who have a high understanding of this mental model regarding communication norms will be less likely to be offended by short responses, and also may tailor the way they interact with that particular team member to match. Thus, although team members may hold different views, they can still interact efficiently as a team because they understand their differences.

Based upon this line of theorizing, Huber and Lewis (2010) propose that cross-understanding may explain some discrepancies that have been found in the literature regarding phenomenon such as when diversity helps or hiders group performance. This understanding is particularly important in environments in which team members may have different disciplinary and educational backgrounds, research preferences, ideological preferences, and vastly different areas of specialty that may make communicating among members difficult and thus hinder the advancement of knowledge and research in these teams. This is especially impactful in multi-disciplinary teams, such as spaceflight teams, where team members may have different mental models regarding different aspects of the task or team. What this suggests, though, is that as long as they are knowledgeable as to the content differences between their mental models and are able to either address the issues or adjust their actions, then performance will not be hindered by the *lack of similarity* in team members' mental models.

Additionally, although the similarity and accuracy of mental models are important features of this form of cognition, the content or focus of a mental model are also important. Teams can form mental models regarding the rules/protocols of team functioning and interaction (i.e., shared interaction models, or teamwork mental models), the task being performed (i.e., shared task models, or taskwork mental models), or even the equipment used in the task/job (i.e., shared technology models; Cannon-Bowers, Salas, & Converse, 1993; Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Salas, Burke, & Cannon-Bowers, 2000; Smith-Jentsch, Cannon-Bowers, Tannenbaum, & Salas, 2008). Of the three, most researchers have focused on taskwork and teamwork mental models. For example, Mathieu, Heffner, Goodwin, Salas, and Cannon-Bowers (2000) found that both teamwork and taskwork mental models positively impacted team processes, and thus team performance; and that both training (e.g., Marks, Sabella, Burke, & Zaccaro, 2002) and the beliefs of leadership (Marks, Zaccaro, & Mathieu, 2000) can impact the development of shared mental models.

Teams are said to have a *shared task model* when they have a similar conceptualization of the goals, strategies, and procedures regarding the successful completion of a task. Thus, teams that do not have a shared task model may not coordinate effectively because they are working towards different goals, they may not address critical events that impact the success of the task (because those aspects are mistakenly ignored as non-critical), or the strategies individual members use in completion of the task may conflict with the strategies employed by other members. Shared task models are critical in space missions in particular because the effective coordination of both mission control and space crews relies on the shared understanding of the problem. If one team does not understand the task requirements in a similar manner as the other, then each team will be in conflict with regards to the goals, priorities assigned to tasks, and the strategies used to problem solve issues that arise during mission.

Another type of mental model that has received a great deal of empirical support is shared teamwork model, or *team interaction model*. Team interaction mental models are similar when team members hold the same conceptualization as to the interaction norms for the team, role interdependencies, knowledge of communication channels, as well as knowledge of what factors impact effective teamwork (Cannon-Bowers et al., 1993; Smith-Jentsch et al., 2008). When teams hold similar team interaction models, they are able to coordinate more effectively because they know what actions are appropriate in the team setting and how the team usually works together. Teams with dissimilar team interaction models may have trouble coordinating because some members may behave contrary to what the team norms are (or contrary to what individuals expect from team interactions), thus causing friction and disagreements among members which in turn may decrease the likelihood that teams will be able to coordinate their actions and engage in adaptive behaviors effectively (Gurtner, Tschan, Semmer,& Nägele, 2007).

Having a shared task model is necessary for mission success, but many researchers have found that shared team interaction models may be even more impactful on effective team performance. Cooke, Gorman, Duran, and Taylor (2007) found that experienced teams outperformed the notice teams on a novel task because they were able to learn the rules for effective communication better than the novices; reportedly, this difference was attributed to the fact that experienced team members understood the importance of communication and were able to allocate their communication time more effectively. Thus, experienced teams were able to spend less time coordinating and more time in other tasks. Although this study did not measure shared mental models, the findings are indicative of the impact that team members with similar team interaction models have on communication and coordination activities. Team interaction models are of particular interest to long-duration, or long-distance, spaceflight because of their impact on communication, coordination, and team interaction.

A third category of mental models for consideration is the *shared technology model*. Shared technology models, also known as equipment mental models, consist of knowledge regarding the proper use of equipment, their purposes, and their limitations (Mathieu et al., 2000). This type of mental model would be the easiest to impact through training for a job, in which individuals learn about their task and the equipment associated with the task. As such, it is not as impactful in the study of long-duration spaceflight because team members would already be highly familiar with the equipment and their uses through mission training. However, both taskwork and teamwork mental models are likely to change depending on events that arise during the mission, and the evolution of the group dynamics on board. Therefore, both team interaction models and shared task models are of particular interest to understanding team cognitive processes in LDSF.

Some more recent work on shared mental models provides interesting findings. In one example, Dong, Kleinsmann, and Deken (2013) investigated task-related team mental models in the context of design teams. In particular, they integrated two established methods to allow for an unobtrusive and objective examination of team mental models: latent semantic analysis (LSA) and reflective practice analysis (RPA). The authors demonstrated that the combined use of these methods allows for determining whether each individual team member's mental model is similar to the team level mental model (using LSA) and whether the team mental model actually influences the teams' behavior as they work to accomplish their goal (using RPA). In short, Dong et al. (2013) developed a novel way to examine team mental models and determine the relationship between those mental models and the behaviors. While this was employed in a design context, because the authors employed these techniques on communications transcripts of the team' task, they could easily be adopted for investigation of spaceflight or mission control crews.

A study conducted my Lee, Johnson, and Jin (2012) examined the effects of changes in team and task-shared mental models on team performance in completing an engineering project across a semester in time. Contrary to other research, Lee et al. (2012) did not find that team or task-shared mental model structure had an effect on overall team performance. However, at later measurement times in the semester, individual performance increased as a function of increased similarity of team-shared mental model structures. Further, the degree to which team members perceived they had similar team and task-shared mental models was important for performance. In particular, teams that perceived they had highly shared task models had better performance over time; whereas, highly shared perceptions of the team-shared mental model improved individual performance. In general, Lee et al. (2012) provided evidence that team and task mental models, whether structural or the perceptions of those models by team members, had effects on individual and team performance.

A novel aspect of shared mental models was investigated by Resick, Murase, Randall, and DeChurch (2014). They specifically sought to examine the strategy team mental model, which was argued to represent a team's understanding of the relationships between decision alternatives for a task. Importantly, the authors used a similarity statistic to determine the degree to which team members held shared mental models and were particularly interested in the degree to which this would be related to the degree to which team members would elaborate upon information and ultimately, perform on a strategic decision-making game. In general, Resick et al. (2014) found that similarity in strategy team mental models was positively related, albeit weakly, to participants' tendency to elaborate on information. This information elaboration was, in turn, predictive of team performance, particularly under conditions in which teams encountered environmental disturbances. In short, these researchers concluded that team mental models are emergent properties of the team that affects the degree to which team member elaborate on information when each member has unique knowledge. Under some conditions, such as those where unexpected events arise, as should be prepared for in spaceflight, similarity in team mental models may help motivate team members to elaborate on information. This, in turn, may lead to better performance.

A survey study conducted during a strategy and management competition investigated the degree to which similar team and task-shared mental models during the early period of time that a team works together affects the level of conflict in the team as well as their effectiveness at later points in time (Santos & Passos, 2013). Results of this research indeed showed that higher similarity of team-shared mental models reduced the level of conflict within the team and, in turn, led to better performance. However, similarity of task-shared mental models did not have any effect on conflict but did improve performance. The researchers concluded that both task- and team-shared mental models contribute to effective team performance, albeit in different ways. These results are relevant to LDSF given that increased similarity in team-shared mental models has the ability to reduce conflict in the team. Ensuring minimal conflict will likely be essential for spaceflight crews on missions with long periods of isolation and confinement.

Lastly, Turner, Chen, and Danks (2014) conducted a meta-analysis to investigate the relationships between team cognition constructs and team performance, including shared mental models, team mental models, information sharing, transactive memory systems, cognitive congruence, and group learning. Second only to information sharing, the shared mental model construct had a strong association with team performance. The explanation provided by the researchers for this finding was that teams need to exchange information that is not shared by all team members to perform effectively, yet it is still important for team members to have shared knowledge particularly regarding their task.

In completing our review of the shared mental model literature we can conclude that shared mental models serve three purposes. Shared mental models provide a shared understanding (description) of what is happening in a given situation; a shared expectation (prediction) of what is likely to occur in the future as a result of the teams actions; and a shared understanding (explanation) as to what led to team outcomes (Mohammed, Ferzandi, & Hamilton, 2010; Rouse, Cannon-Bowers, & Salas, 1992). The implication for spaceflight crews is that teams that develop this form of shared cognition will be able to better identify problems, predict how their actions will impact outcomes, explain why things are occurring, and ultimately perform better on their tasks.

Individual Cognition in Space and Shared Mental Models

Although shared mental models have not been examined during spaceflight, the individual cognitive processes that impact the development of shared mental models have been examined, to varying extents. Although the specifics of the situations that arise will directly impact the degree to which different individual- and team-level cognitive processes are utilized, shared mental models are likely dependent upon several of the individual cognitive processes represented in Figure 1 (i.e., attention, central executive functioning, short- and long-term memory, and reasoning).

During off-nominal situations, the ability to attend to multiple sources of information and select which ones are most impactful for the current situation is a critical skill that would directly impact the shared understanding of the problem to be solved. Indeed, given the extreme environment of spaceflight, even nominal situations can necessitate attentive vigilance. Attention has traditionally been examined using tasks such as sustained attention tasks where participants are asked to divide their attention between two tasks (on a computer screen) and the two tasks alternate as to which one is active at any given time. Attention has also been tested by having participants attend to a faint light in their peripheral vision while performing another task. This capability would allow individuals to notice changes in the environment that may change the shared state of the problem to be addressed by the team. Therefore, impairment on attentional capabilities will negatively impact the updating and utilization of shared mental models, which are heavily reliant upon the communication of critical information between teammates. Thus, individual attentional processes are critical to ensure that the information that is shared between teammates is current and accurate to develop and maintain accurate and shared mental models.

Likewise, several aspects of the central executive functions, including working memory, are needed to create and update the shared mental models of team members regarding the problem at hand. Central executive functions, such as working memory, have been tested in many ways; for example, using dual-task tests in which individuals must simultaneously engage in two tasks that utilize different cognitive abilities (e.g., such as a critical tracking test and a memory search test), or using activities which rely on inhibitory responses (such as the Stroop test in which individuals must inhibit the impulse to read text written the color written rather than name the color of the ink that the word is written in). Thus, impairment in the ability of individuals to effectively manage two tasks simultaneously, or switching between two tasks that utilize different types of mental processes (e.g., spatial processing and arithmetic), may critically affect the team's ability to adapt to changing situations. Specifically, if individuals are unable to process the large amount of information and perceived stimuli, then they may not view problems in the same way and may focus their actions on disparate aspects of the situation, thus reducing the effectiveness of teamwork and jeopardizing the safety of the crew.

Additionally, the individual's memory may be impactful on shared mental models. In previous research, memory has been traditionally measured using tests where participants are asked to remember lists of names or numbers and recall them at a later time in the experiment. If individuals are not able to correctly recall new information they received in the midst of a new problem (i.e., short-term memory) or are unable to correctly recall information they learned previously, perhaps earlier during training (i.e., long-term memory) or during the event itself (e.g., short-term memory), then the mental model that the individual has may differ from the mental model that his/her teammates have of the situation, task, or technology; thus, the sharedness of the mental model would be low and performance would be impaired.

Finally, the individual cognition construct of reasoning ability can be seen to impact the development and maintenance of shared mental models by impacting the individual's ability to logically decide what information is relevant in the given situation. Reasoning has been examined in the literature using problem-solving tasks, logical and grammatical reasoning tests, and arithmetic tests. Impairments of reasoning ability would negatively impact the development and implementation of shared mental models by causing individuals to arrive at different conclusions when analyzing the situation in their own minds, thus leading to the development of less-accurate or less-shared mental models (which will decrease team performance).

Given that many of the individual cognition constructs that impact the development of shared mental models are negatively impaired in extreme environments (including spaceflight), the examination of shared mental models in space is important for mission success. Even if the impairment is only reaction time (versus accuracy of knowledge), during off-nominal situations reaction times and mental processing speeds will negatively impact the effectiveness of all team processes, including shared mental model development. Traditionally shared mental models are measured using various techniques that force the individual to rate or describe how related two concepts are, such as in as paired-comparisons, similarity ratings, questionnaires, card-sorts, and concept mapping. The mental models of individual members are then compared to the mental models of the team to examine the degree of sharedness of the mental model, or compared to an expertly derived model (i.e., the mental model of an expert) to examine the accuracy of the mental model. Through these pairings, researchers can examine how individuals structure their knowledge and which concepts are more closely related to other concepts, thus providing insight into why certain decisions are made within the team.

To move forward with the literature, the individual level cognitive constructs that have been examined during space missions, for which there is existing data, should be integrated into mission-relevant exercises rather than as separate and artificial tests. Thus, researchers will be better able to make intuitive connections between the individual-level cognitive constructs and team-level cognition constructs, such as shared mental models. Research examining shared mental models will likely need to be conducted using monitoring techniques (i.e., record performance episodes of a space crew) in a training exercise or simulation in which information regarding the situation dramatically changes, such that it necessitates the adaptation of the team's mental model regarding the problem, task, or equipment (depending on the exercise and situation). Thus, researchers can then examine how effectively teams were attending to new information (i.e., attention), how effectively they were able to process multiple sources of information/stimuli during the exercise (i.e., central executive function), their memory as to what occurred or what information was relevant (i.e., memory), and their reasoning ability in deciding what actions should be taken to achieve the altered mission goals (i.e., reasoning).

Transactive Memory

Transactive memory systems (TMSs) theory arose out of social psychology research in couples (Wegner, 1987). In teams research, a transactive memory system has been "defined as the shared division of cognitive labor with respect to encoding, storing, and retrieving knowledge from different but complementary areas of expertise" (Huber & Lewis, 2010, p.8). It is also often described as an individual's knowledge of who in the team possesses certain knowledge, skills, or expertise. Whereas the shared mental model construct focuses on the overlapping of knowledge structures as the beneficial aspect to performance, transactive memory focuses on how the distribution of knowledge can benefit performance. This understanding enables team members to attend more closely to information that pertains to their area of expertise, thus allowing members to become more specialized (TMS; Austin, 2003; Lewis, 2003, Wegner, 1987). This specialization of team members is one of the defining characteristics of a TMS (Austin, 2003). Early research in TMS (Moreland & Myaskovsky, 2000; Hollingshead, 2001) noted that these can be characterized by three components: *specialization* (team members having different knowledge depending on their position or role), *credibility* (beliefs of the accuracy of other members' knowledge), and *coordination* (the ability to effectively coordinate information exchange between members). High levels of TMS have been related to successful team performance in a variety of settings (Zhang, Hempel, Han, & Tjosvold, 2007). Both TMSs and cross-understanding are similar in that they are both involving knowledge of other team members' understanding; but, they are different in that TMSs depend on, and often lead to, team members developing more differentiated knowledge structures among team members, whereas cross-understanding does not.

Empirical studies have supported the necessity of strong TMSs in teams, demonstrating that it increases implicit coordination among team members (Kozlowski & Ilgen, 2006; Liang, Moreland, & Argote, 1995; Marques-Quinteiro, Curral, Passo, & Lewis, 2013). Liang, Moreland, and Argote, (1995) likened TMSs to having access to an external storage system, such as a library, from which team members are able to draw information. The differentiation of knowledge means that individuals may specialize in different aspects of the task, which allows individual members to free up cognitive resources for other aspects, while having confidence that someone else in the team already has this knowledge stored and available for use at a later time. TMSs may be more critical than SMMs in interdependent tasks, where team members may have specialized roles, but SMMs may be more critical in pooled tasks where the individual contributions of members is surmised in a linear fashion such that team members can work more independently and pool together the outcomes of their work to create a whole final product (Kozlowski & Ilgen, 2006). Additionally, studies have shown that there are barriers to the development of TMSs in virtual teams, and that face-to-face interactions are better for the development of TMS (Hollingshead, 1998).

Given the nature of space missions, and the virtual interactions with mission control, this has the potential to be problematic. However, because a majority of the task-related interactions will occur onboard the spacecraft, TMS may be more impactful for the spaceflight crews, while having a similar SMM may be more impactful for interactions between the spaceflight crew and mission control. Researchers also have investigated how teams form a TMS. Team training appears to be a strong predictor of TMS formation. Teams trained together, rather than individually, develop a TMS and make fewer mistakes, remember more details regarding the procedure for tasks, exhibit greater specialization in task knowledge, and coordinate their actions better than teams composed of members who trained individually (Liang, Moreland, & Argote, 1995). Thus, a TMS may be developed prior to the mission during joint training with mission control personnel and spaceflight crews.

Recent work on TMSs has helped to elucidate additional factors that contribute to team cognition. This is particularly relevant to LDSF because this research shows how the structure of the distributed knowledge may play a role in mission success. Recent studies have examined the structure of TMSs, examining features such as when it is beneficial to have a centralized TMS structure (i.e., teams with one member who has an overall understanding of the team, and who possesses the necessary skills, knowledge, or abilities) or distributed/decentralized TMS structure (i.e., such knowledge is more evenly distributed among team members (Mell, van Knippenberg, & van Ginkel, 2013). This study found that, in groups with members who are highly specialized and possess differentiated knowledge, may benefit from a centralized TMS structure. This was argued to be due to the fact that such team members may find it more difficult to create an accurate TMS regarding the knowledge, skills, and abilities of their team members. The authors suggest that in such specialized environments where group membership is changing frequently, it would be beneficial to have a person whose role is dedicated to developing an up-to-date and accurate understanding of the TMS of the group members, and act as a central point of knowledge for the group rather than rely on group member updating their TMS.

In a recent study, Gockel and Brauner (2013) investigated perspective taking versus egocentrism in terms of whether transactive memory benefited from one or the other when team members possessed different or similar knowledge. Teammates were more agreeable in assessments concerning one another's knowledge on a given topic and retained transactive memory that was more accurate when perspective taking played a role in team dynamics. There was no interaction between the team members' knowledge type (differentiated vs. integrated) and perspective taking versus egocentrism. However, there was an effect when knowledge was similar. Gockel and Brauner provided three rationales behind such findings: (1) participants' awareness, in the integrated or similar knowledge condition, of each other's background knowledge when completing the knowledge assessments, (2) participants not knowing which expertise domain a particularly detailed question might fit into, thus yielding low transactive scores from the differentiation or different knowledge condition, and (3) the fact that team members with similar backgrounds are capable of communicating with one another more efficiently. Ultimately, Gockel and Brauner concluded that perspective taking was more beneficial for transactive memory than egocentrism, despite the absence of a neutral "control" condition that could be examined simultaneously. Furthermore, such positive effects on "team-level outcomes," as perspective taking produces, only require a short intervention to generate.

Hsu, Shih, Chiang, and Liu (2012) examined TMSs, through the use of surveys, in the context of teamwork processes and performance, confirming that enhanced team performance was a result of more effective communication and more efficient coordination achieved through a "mature" transactive memory system. Utilizing structural equation modeling, the results demonstrated that TMS directly and indirectly influenced team performance. Directly, the stronger a team's TMS, the better a team performed. Indirectly, the presence of a positive coefficient between TMS and team performance indicated that such an effect was partially mediated and further analyses concluded that both communication and coordination possessed strong mediating effects, with coordination demonstrating a stronger effect. Hsu et al. (2012) suggested that TMS could be improved through several means, by utilizing interventions when team members have no previous history with one another to allow for more frequent interactions between members in the form of group training, decision making, job rotation, and feedback sharing. Additionally, they recommended that purposely pairing members with some level of familiarity working together would also improve team TMS.

Another recent study explored the predictive ability of communication quality in team TMS (Liao, O'Brien, Jimmieson, & Restubog, 2014). Among the factors examined were the mediating role of team identification (i.e., a shared common identity for team members) and the moderating role of professional identification (i.e., an unshared identity of a given team member). Data were collected from healthcare personnel working in hospital teams. Communication quality was predictive of the team's TMS structure. Liao et al. (2014) also found that TMS could be predicted if team identification was low or high and professional identification was high. Similarly, TMS was only positively affected by team identification if there was a low amount of professional identification. Thus, Liao et al. (2014) concluded that professional identification supported the integration of knowledge in teams through acknowledgment of distinct expertise domains and identities.

Recent research examined TMS in extreme, dangerous, and stressful situations (Marques-Quinteiro, Curral, Passos, & Lewis, 2013). This study used an approach known as a referent-shift consensus model to assess higher-level team dynamic constructs using data that were derived from lower-level team members. The results demonstrated that implicit coordination among team members during novel tasks positively affected team performance through the prediction of adaptive behavior. Furthermore, transactive memory systems strengthened the relationship between team coordination and adaptive behaviors. Marques-Quinteiro et al.

(2013) concluded that a more developed TMS enabled adaptability by better utilizing coordination mechanisms and, in turn, freeing up cognitive resources for communication or attention processes.

Another recent study examined TMSs in teams through theory of team compilation and adaptation in the context of unplanned member loss (Siegel Christian, Pearsall, Christian, & Ellis, 2014). Hierarchal regression analyses were used to assess team performance on a 40-minute developmental task that involved a command-and-control simulation in which team members were each assigned a role and had to work on a cooperative basis to launch vehicles, and identify and engage enemy targets. This task allowed teams to develop a TMS through interaction in completing the simulation and under a condition where a team member was "lost" and their criticality to the task varied. The results revealed that TMS was positively related to team performance as long as the team member lost was of low criticality, thus those teams with a strong and well-developed TMS actually outperformed teams with a poorly developed TMS. However, the criticality of the lost team member moderated the relationship between TMS and performance in that any benefits gained from a well-developed TMS vanished when a more significant team member was absent, leading the researchers to conclude that increased difficulty in team plan formation was the underlying factor in this interaction. Ultimately, Siegel et al. (2014) concluded that it is essential for managers to identify the criticality of each team member as early as possible in the team formation process, make teams aware of the loss of a member, and provide a meeting in which the team can regroup and formulate a new plan.

Given the inherent relationship between TMS and team performance on a variety of tasks in the extant literature, TMS research has implications for spaceflight crews as well as mission control teams. One aspect of this research is that not all members of mission control need to have an accurate TMS with the spaceflight crew. Rather, key mission control personnel (who are not likely, or not contractually allowed to leave the job) could be trained with the spaceflight crews so that there are a minimum number of members on ground teams who possess this knowledge structure (cf. Kanas et al, 2006; 2007). Another aspect is that the quality of communications affect the development of TMSs and thus certain types of communication should be facilitated both in and between spaceflight and ground crews. Further, the ability to form a TMS is related to one's ability to take the perspective of other teammates, which may be crucial for crew well-being during LDSFs.

Individual Cognition in Space and Transactive Memory Systems

TMSs are impacted by several individual cognitive processes that have been examined in the literature thus far. Similar to shared mental models, transactive memory is likely most strongly influenced by attention, central executive functions, memory, and TMSs through the individual team members' ability to monitor the environment, which is especially important during emergency situations or rapidly changing events. For teammates to effectively coordinate their actions, individual team members need to be able to attend to the environment in a quick and accurate manner to know what the other team members are doing at any given time. As discussed earlier, attention has been commonly measured in the literature reviewed using tests such as a sustained attention task. Attentional capabilities impact whether individuals realize that another team member needs backup behaviors, if he/she can provide certain information relevant to another team member's task, which can impact the realization that another team member may be more qualified to work on a particular aspect of a problem or task (i.e., core aspects of TMSs). Therefore, problems related to attentional capabilities can have a substantial negative impact on transative memory utilization.

Likewise, central executive functions such as working memory, the ability to shift between multiple activities and sources of information, monitoring one's (and others') activities, implicit learning of new information, and others are all likely to directly impact the ability of individuals to manage multiple stimuli to determine how best to utilize the team's resources (i.e., team members). As discussed earlier, central executive functioning is often measured in the literature using dual task tests or other working memory tasks. If an individual's central executive functioning is impaired, then this would negatively impact the ability of individual team members to accurately discern relevant and irrelevant stimuli, thus overwhelming or over-utilizing the cognitive resources available for individual members to perform their duties at their highest ability.

Transactive memory will also rely on the memory of individuals to recognize the key elements of a situation that may change how the team functions and recall which team members possess the skills to deal with these rapidly changing situations. As discussed earlier, memory is often tested using recognition or recall tests. Individuals who are unable to recall previously shared information will slow down the team functioning by repeatedly asking for information or engaging in unnecessary behaviors that will impair team functioning. Lastly, the individual's reasoning ability will also impact how effectively the nominal and off-nominal situations are processed, and assist in determining which actions are needed and are most appropriate in a given situation. Reasoning has often been tested using tests such as logical reasoning tasks.

While the links between individual cognition constructs and team level TMSs is based upon theoretically informed cognitive inferences between concepts, it is unknown exactly how spaceflight may impact the development and implication of a TMS. Therefore, an examination of TMSs in a space environment is needed to see how certain unique environmental factors, such as the long-term effects of cosmic radiation and microgravity effect cognition both at the individual level and consequently at the team level. To integrate both individual level cognition research and TMSs research, the methods of measuring the different constructs must also be integrated such that the impact of individual cognitive processes can be more readily discerned within the team-level cognitive processes of interest. Thus, researchers will be better able to make intuitive connections between the two seemingly disparate fields of research.

For example, transactive memory systems have traditionally been tested using tasks in which knowledge is distributed among team members, and actions and information must be coordinated for successful completion of the task. A classic example of a transactive memory test is the construction of the AM portion of an AM/FM radio, such as in Liang, Moreland, and Argote (1995) where study individuals were trained on how to assemble the radio either as an intact team or individually, and then assigned into teams to perform the task. They found that when trained as a team, performance increased (i.e., more steps were recalled and a more complete product was created) as contrasted to when individuals were trained separately. They also found that transactive memory mediated the impact of training on performance outcomes (Liang, et al., 1995). Individual cognitive constructs could be examined in an exercise, such as the AM radio construction, if certain activities needed to complete the task were related to the constructs of interest (e.g., memory could be measured by how many details of the training are recalled, attention could be measured by testing if they picked up on a specific non-essential cue, etc.).

Collaborative Problem Solving

The spaceflight domain is inherently complex and often characterized by novel and ill-structured problems, often with no known solution, which require collaboration across multiple distributed teams of diverse disciplinary expertise (Orasanu, 2005). From a theoretical perspective, a problem is said to arise when there is a situation to be addressed, but which has no known solution. In the context of LDSF, solving problems involves the integration of knowledge across a large number of interconnected factors distributed across socio-technological systems (Fischer, Greiff, & Funke, 2012); that is, the problem factors exist across the technology, the environment, and the team members. Many of these problems are characterized as *complex* given that the tasks in which these arise are dynamic, varying as a function of temporal demand; additionally, many of the variables involved do not display a one-to-one relationship (Quesada, Kintsch, & Gomez, 2005). Thus, complex problems, by necessity, require teams to collaboratively solve them. This requires the team be able to fluidly adapt and develop a robust and well-organized knowledge repertoire, taking into consideration the teams' shared mental models and transactive memory systems.

Recent qualitative evidence of team problem solving in complex work environments has shown that teams may face difficulties associated with problem detection such as lack of recognition of important cues, decreased alertness, use of inexperienced team members to monitor for problems, and sometimes a resistance across team members to accept that a problem even exists (Klein, 2006). Relatedly, a study of problem solving in space shuttle mission control showed that once an anomaly was detected, teams self-organize through their interactions into functionally distinct teams that ultimately creates a more robust problem-solving team (Watts-Perotti, 2007). Therefore, in service of team problem solving, team members must engage in *knowledge building* whereby individual team member's internalized knowledge is transformed to externalized knowledge by both individual and team-level cognitive processes (Fiore et al., 2010a; 2010b). In this way, teams collaboratively build knowledge, drawing upon their own expertise, through the transformation of data to information to knowledge in service of team problem solving (Fiore et al., 2010a). This process ultimately contributes to effective team problem solving outcomes (Fiore et al., 2010a).

Indeed, given the detailed account of collaborative problem solving provided by the *macrocognition in teams framework* (Fiore et al., 2010a; 2010b), significant strides in understanding the collaborative problem-solving processes of teams has been accomplished (see Table 4 for descriptions of each of the major components and sub processes of this framework). For example, Rosen (2010) examined team knowledge-building processes specified by the macrocognition in teams framework in a simulated collaborative problem-solving experiment by examining team communications data. The results showed that each of the processes associated with team knowledge building were evident and related to team outcomes with a differential sequencing of processes in high-performing teams as compared to low-performing teams. Further support was found for the utility of the macrocognition in teams framework given the identification of many of the associated processes in communication logs from experienced teams performing simulated tasks in command- and control-related domains (Hutchins & Kendall, 2010). More recently, evidence was found for many of the collaborative problem-solving processes predicted by the macrocognition in teams framework when examining retrospective accounts of a complex problem with the International Space Station that was solved by experts in NASA's Mission Control Center (Fiore, Wiltshire, Oglesby, O'Keefe, & Salas, 2014). Additionally, recent research found support for team knowledge-building processes during a collaborative problem-solving activity where teams were required to analyze and write a report regarding a fictitious information systems company (Seeber, Maier, & Weber, 2013).

The work of Seeber et al. (2013) also provides a tool for understanding the interaction of the team during collaborative problem solving given their development of the Collaboration Process Analysis (CoPrA) tool, which captures temporal and phasic aspects of team process. Our introduction of collaborative problem solving prior to decision making and planning is strategic given that most instances of problem solving involve team decision making and planning, while the inverse may not always hold true (see for discussion Mosier & Fischer, 2010; Orasanu & Salas, 1993). We view collaborative problem solving as a form of team cognition including many team cognitive processes and of significant importance to better understand for LDSF.

Individual Cognition in Space and Collaborative Problem Solving

The link between individual cognitive constructs and team-level collaborative problem solving is more intuitive than some of the previously discussed constructs such as shared mental models or transactive memory. Therefore, it may be easier to make the inferential leap between individual-level cognition findings in the literature and the team-level construct of team problem solving. However, team problem solving often relies heavily on other cognitive constructs such as shared mental models and transactive memory systems such that it is not an additive (compositional) process of scaling from the individual to a team level. Depending on the task, it is often a compilational process such that the overall process is different in nature than the individual cognitive processes. Thus, experimentation is needed specifically examining team problem solving in space, rather than assuming the effects of spaceflight on individual problem solving affect team-level problem solving in the same way.

Team Decision Making

Studies of decision making have traditionally focused on individual decision making in laboratory settings, but have more recently included studies of decision making in real-world environments (i.e., naturalistic decision making research; see Klein, 2008). From this research came the need to understand how it is that teams make decisions. Team decision making can be defined as "the process of reaching a decision undertaken by interdependent individuals to achieve a common goal" (Orasanu & Salas, 1993, p. 328). Team decision making can, in part, be distinguished from individual decision making by the fact that the collective decision-making processes of a team are able to draw upon a richer repertoire of strategies that support adaptive performance than does an individual decision maker (Entin & Serfaty, 1999). Of course, the basic premise remains the same for team decision making as individual decision making in that team members are typically presented with a situation where they must gather information, make a judgment about it, and select an appropriate response (e.g., Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995; Mosier & Fischer, 2010). In many situations, teams face time pressure, uncertainty, ill-structured problems, shifting goals, and organizational contexts (e.g., Mosier & Fischer, 2010; Orasanu, 2005). Therefore, team decision making requires the integration of more sources of information and varying task perspectives than individual decision making (Orasanu & Salas, 1993).

In line with the account of team performance we provided in Table 2, team decision making is also characterized along these dimensions. That is, it includes aspects of both behavioral and knowledge coordination. For example, while the ultimate outcome of team decision making is a response or selection of a course of action (e.g., Sukthankar & Sycara, 2010), the effectiveness of team decision making is often determined by the degree to which they have shared team member and problem mental models as well as good implicit and explicit communication and coordination strategies (e.g., Orasanu & Salas, 1993; Rico et al., 2008). Further, Hollenbeck et al. (1995) developed a multilevel model of team decision making and found that three core team-level constructs accounted for a significant amount of the variance in team decision making accuracy. These constructs included *team informity*, which was defined as the degree to which all members of the team are kept informed with regard to all relevant cues associated with the factors needed to make the decision. Next was *staff validity*, defined as the degree to which the team is composed of members who are able to make accurate interpretations of the information required for the decision. Last, was *hierarchical sensitivity*, defined as the degree to which the leader of the team is able to effectively weight each team member's decision to arrive at an accurate team-level decision (Hollenbeck et al., 1995). This model was further supported and refined in Hollenbeck et al.'s (1998) later work where they found that not only did these constructs account for more than half of the variance in team decision making accuracy, but that interventions providing feedback on these core construct improved team performance.

More recently, Smith, Johnston, and Paris (2004) recognized the importance of interface design when supporting Naval team decision making and developed the Tactical Decision-Making Under Stress (TADMUS) Decision Support System (DSS). This work modeled the decision-making support system based upon an analysis of the way experts make decisions. This helped develop an interface that minimizes load on short-term memory, manages attention, mitigates confirmation biases, and provides diagnostic feedback in such a way that team decision-making performance of Naval Officers was more accurate.

At a general level, what is critical to understand about team decision making is that fact that decision-making processes become distributed across the individuals in a team and sometimes even across teams of teams. This may be further complicated when teams of teams, or multi-team systems, are composed of teams that have different priorities or immediate goals that do not perfectly coincide (e.g., the overarching goal may be the same; however, the timing of when certain goals are achieved may be different between teams). Leveraging Rasmussen's (1986) Decision Ladder, Stanton and Bessell (2013) conducted a study of how experienced submarine crews return to periscope depth, a complex and safety-critical task. While this was a simulated study, submarine crews are close analogues of spaceflight crews (Orasanu & Lieberman, 2011). Just as Hollenbeck (1995) provided a number of key constructs to examine team decision making, the Decision Ladder provide a useful representation for tracing the decision processes of individuals to constitute the team-level decisions (see Figure 3.)

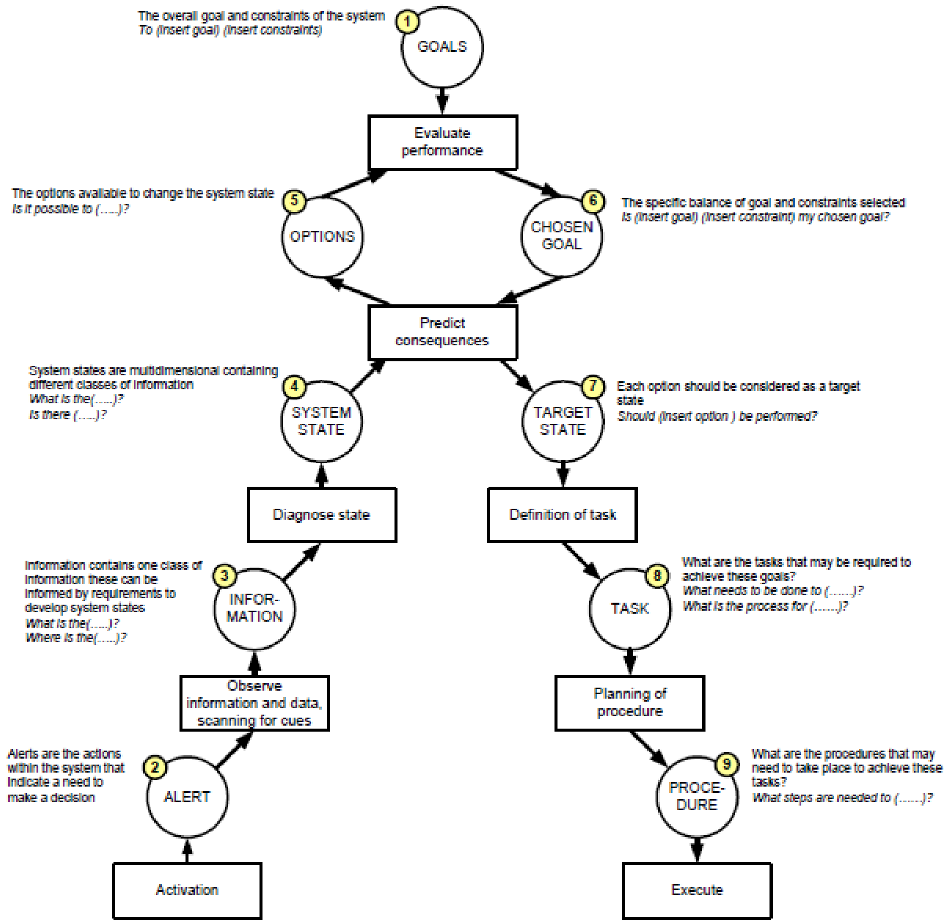

Figure 3. Rasmussen's (1986) Decision Ladder (from Stanton and Bessell, 2013).

While a thorough discussion of the decision ladder applied to teams can be found elsewhere (Jenkins, Stanton, Salmon, Walker, & Rafferty, 2010), we provide a brief overview here. The boxes and nodes constituting the ladder represent information processing activities and states of knowledge resulting from those activities, respectively. Generally, the left side of the ladder represents information-gathering activities of the team; whereas, the right side represents the planning and executing of tasks (Stanton & Bressell, 2013). The decision ladder is often constructed based on retrospective or observation accounts of decision making in the real-world (Jenkins et al., 2010). This model is insightful in that it explicates an overall goal for a certain task, what information team members were alerted to that necessitated the need for a decision to be made, what information is used as the basis for that decision, the evaluation of system or situational states, the generation of options and potential consequences for a given decision as well as the planning and executing of tasks to reach a desired target state (Jenkin et al., 2010).

More practically, Stanton and Bessell (2013) were able to use this model to construct an exhaustive set of informational constraints, goals, tasks, procedures, etc. involved in returning to periscope depth in a submarine crew. Not only were they able to collate and explicate all of these important elements of the team decision-making process, but they were also able to specify team members to the associated nodes and boxes for which they contributed to the team decision-making process. In short, the decision ladder model of team decision making is very informative, but it is currently limited by the time-intensive process of constructing it after the decision making occurs.

During the process of decision making, Bonner and Bolinger (2013) determined that individuals were less confident and were outperformed by groups. In this study, the researchers took a novel approach to decision-making interventions. Where most interventions rely on externally provided data, Bonner and Bolinger focused group members on their individual knowledge or on the integrated team knowledge. Their decision-making approach entailed a series of estimations or "educated guesses" regarding such topics as world knowledge and topics of local interest to ensure the knowledge was accessible to the study participants. For example, some of the questions asked participants to estimate the freeway driving distance from Salt Lake City to New York City or the population of Utah. The group that received the intervention, in which associated knowledge was generated, demonstrated that accuracy was the most important factor in group estimates. Conversely, member influence carried the most weight in terms of confidence during group estimates. When associated knowledge was generated before participants entered the group, they were less likely to apply this knowledge when planning group strategies as opposed to those who generated associated knowledge interactively within the group. Bonner and Bolinger concluded that associated knowledge was more likely to be used when generated in an interactive group setting due to the coordination of members' inputs to better understand the task and its accompanying concepts. Additionally, generating associated knowledge on an individual basis may have also predisposed individuals to preemptive judgments. Ultimately, accuracy was increased in an interactive group setting when interventions focused participants on the knowledge to be used in the decision-making process.

The types of team decision making outlined briefly in this section are important considerations for spaceflight given the nature of performance in this domain. Specifically, NASA team decision making is certainly hierarchically structured both within the spaceflight crew and for those working on the ground. Of course, the work of NASA is also heavily technology-based so considerations for how team cognitive processes can be enhanced through interface design are of great import. Further, the ways in which teams build their knowledge, whether independently or collectively, and the effects this has on both forming TMSs and making appropriate decisions is a significant consideration for LDSF.

Individual Cognition in Space and Team Decision Making

As discussed earlier, the effectiveness of team decision making is heavily influenced by the degree to which team members have shared team member and problem mental models; therefore, many of the individual team cognitive processes discussed in the mental models section (i.e., attention, central executive functioning, short- and long-term memory, and reasoning) will impact team decision making as well.

Additionally, team decision making will be strongly impacted by an individual's attentional capabilities. According to Hollenbeck et al.'s (1995) multilevel model of team decision making, team informity (i.e., the degree to which members are informed of the relevant cues needed for decision making) is one of the core constructs in the model and relies heavily on individual's ability to detect changes in the environment. Thus, team decision making will be negatively impacted by a deficit in an individual's attentional capabilities. In spaceflight, these changes may be more difficult to detect due to deficits in visuo-spatial abilities (e.g., the rotation and location of equipment or debris during an emergency). Thus, visuo-spatial abilities of individual members may negatively impact the ability to detect changes, separate from the attentional capacities of the individuals.

The other two constructs in Hollenbeck et al.'s (1995) multilevel model are staff validity (i.e., members' ability to make accurate interpretations of the information) and hierarchical sensitivity (i.e., the leader's ability to effectively weight each team member's decision to arrive at an accurate team-level decision), both of which may require multiple individual cognitive processes such as central executive functioning to keep track of and monitor information, and reasoning abilities to integrate such information in a useful manner. A deficit in either central executive functioning will make team decision making more difficult. Also, teams in space have the additional mental burden of having to mentally account for the changes in kinematic movement, which may impact how effectively and quickly individuals are able to carry out the solutions to problems. Therefore, team decision making relies on all aspects of individual cognition to some extent; however, research can move forward by examining how these individual cognitive abilities impact team-level cognitive processes. As is known from the teams' literature, team-level processes are often compilational in nature and are not merely the aggregate of individual-level processes (e.g., DeChurch & Mesmer-Magnus, 2010). Thus, it is important to examine the unique ways that spaceflight impacts team decision making, which may be different from how spaceflight impacts individual decision making. Given the overlap in the cognitive processes involved in team decision making and the previous team-level cognitive constructs above, an example of how individual cognitive processes can be measured in a team setting will be reserved for the end of this section.

Team Planning

Team planning is a team cognitive process that can improve team performance when conducted before or during a given mission. Team planning typically includes setting goals, clarification of team member roles, prioritization of tasks, assessment of what types of information all team members require access to and those only required by specific team members, and also, how team members intend to back each other up in the event of errors (Stout, Cannon-Bowers, Salas, & Milanovich, 1999). In early research with a four-person team (two participants, two confederates) simulated aviation navigation and defense experiment with an undergraduate population showed that teams with better planning quality had more similar shared mental models of the informational requirements of the task; communicated necessary information under high workload situations without it being requested, which in turn led to better performance; and lastly, displayed fewer errors during task performance (Stout et al., 1999).

More recent theorizing in this area has differentiated team planning into three sub-dimensions (Marks, Mathieu, & Zacarro, 2001). *Deliberate planning* can be defined as development and transmission of the primary course of action for the team prior to engaging in the task. *Contingency planning*, also occurring prior to engaging in a task, can be defined as the development and transmission of backup or alternative plans in the event that anticipated issues arise that detract from the primary plan. Lastly, *reactive strategy adjustment* is the modification of the team's current plan as a function of unanticipated occurrences in the performance environment (Marks et al., 2001). Recently, DeChurch and Haas (2008) sought to investigate the relationship between these three types of team planning processes and team performance in the context of a team scavenger hunt task. Results showed that reactive strategy adjustment planning had the strongest relationship with team performance. Contingency planning also had a strong effect on performance albeit less so than reactive strategy adjustment. Overall, the three types of planning all were related to improved team coordination.

Using the model set forth by Marks et al. (2001), Mathieu and Schulze (2006) focused on the deliberate type of team planning by examining the effect of formal plans on transition processes and performance outcomes. Business students using The Capstone business simulation worked in groups of three or four to act as an executive committee overseeing an electronic sensor device manufacturer. Plan formality was assessed by the course instructor and transition processes were assessed through group member surveys. A composite score was calculated for performance using data from the simulator, such as total profits, return on assets, stock price, and market share. Formal plans were shown to have a significant positive effect on performance outcomes, as well as a positive relationship with transition processes (Mathieu & Schulze, 2006).

In 2013, a series of studies conducted by Fisher suggested a two-factor structure of team planning in which taskwork and teamwork are distinct factors that comprise the larger activity of team planning. All three studies involved teams comprised of two to eight individuals working on either a psychology- or business-related project. Teams were surveyed upon completion of the project and used a 5- or 7-point Likert scale to respond to questions regarding team planning (e.g., “My team set goals for completing the task”). Data were also collected to assess team performance on the projects. Taskwork planning was found to show a strong positive relationship with coordination and had an indirect effect on team performance through the mediating role of coordination. Teamwork planning was found to have a similar relationship with interpersonal processes and also showed an indirect effect on team performance through the mediating role of interpersonal processes (Fisher, 2013).

More recently, across three research studies, Fisher (2014) examined several factors of team planning in terms of whether a distinction could be made between taskwork and teamwork-related planning. Study 1 and 2 focused on the development of a novel measure to identify indicators of team planning so that any relationships between task-focused and team-focused planning factors could be distinguished. The results indicated that taskwork planning was characterized by items that covered the planning process for the actual task itself, whereas items concerning the team members and their abilities distinguished teamwork planning. Thus, Fisher concluded that task-focused and team-focused planning were markedly different forms of planning. Study 3 explored the relationships between team processes, such as coordination and interpersonal processes, and the two forms of planning. Task-focused planning demonstrated the propensity to predict coordination whereas team-focused planning was more predictive of interpersonal processes. Further analyses indicated that team processes mediated the relationships between task- and team-focused planning in an indirect manner. Recommendations to increase accuracy and team functioning effectiveness included interventions that emphasize both the taskwork and teamwork components of planning to improve team performance.

Individual Cognition in Space and Team Planning

Team planning in space will likely require both reasoning abilities and consideration of the ways in which psychomotor functioning (i.e., how bodily movement is slowed or less accurate) impacts plan timelines for completion. Thus, the greater the individual’s impairment in psychomotor functioning, the greater the difficulty individuals will have in planning how long certain activities will take, which will then impact how the team interacts as a result of coordinating different levels of impairment. Memory will also likely impact the success of planning ability, as individuals will need to have successfully encoded outcome information from previous experiences and be able to recall relevant actions that were successful or unsuccessful in achieving various goals. As noted in the review, shared mental models impact the effectiveness of team planning (e.g., teams with better planning quality had more similar shared mental models), and therefore many of the factors that impacted successful mental model formation will also impact successful planning.

Team planning can be examined within the context of other team activities (e.g., emergency planning tasks). Just as in experiments that examine shared team mental models, team planning will likely be best examined using observational methods that rely on think-aloud procedures or observing behaviors to gauge the processes through which teams engage in planning activities. The aspects that would be examined are likely similar to the other cognitive constructs that have already been discussed in previous sections (e.g., attentional processes may be examined by measuring whether key events or information are attended to); thus, the example of how individual constructs can be examined in a team setting will be discussed in the next section to avoid repetition of ideas.

Summary

In Part II of this report, we have provided a background on team cognition and specifically overviewed those team cognitive processes that are most salient and critical for LDSF. Following our overview of each of these constructs, we related each team-level cognitive process to individual-level cognitive processes that have been studied in space or close analogues that were reviewed in Part I. In Table 4, we summarize each of these critical team cognitive processes for LDSF, describe the important aspects of them, and include authoritative references. In the next section, we provide more concrete speculations and predictions on the relationship between individual and team cognition during LDSF.

Table 4. Summary of Team Cognitive Processes

Component	Definition	Source
Team Knowledge Structures		
Shared mental models	Organized knowledge structures which are held by more than one team member and involve the integration of information and the comprehension of a given phenomenon.	Johnson-Laird (1983), Cannon-Bowers, Salas, & Converse (1993).
• Shared task models	Shared or complementary knowledge among team members pertaining to basic task attributes (e.g., task goals, strategies, procedures) and how to accomplish the task.	Salas, Burke, & Bowers (2000).
• Shared technology model	Shared knowledge on equipment function, operating procedures, system limitations, and likely failures. This has also been referred to as an equipment shared mental model (Rouse, Cannon-Bowers, & Salas, 1992).	Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers (2000).
• Shared team interaction models	Shared or compatible knowledge pertaining to the roles and responsibilities of team members, information sources, interaction patterns, communication channels, and role interdependencies. This is similar to the concept of knowledge of the co-functioning of team members (see Rouse, Cannon-Bowers, & Salas, 1992) and also seems to encompass the notion of knowledge pertaining to the concept of 'temporal patterns of team performance' as argued for by Rouse et al., 1992 (e.g., when in time team behaviors occur, or how long a team requires for task performance).	Cannon-Bowers, Salas, & Converse (1993).
Transactive memory systems	Wegner (1986) "defined the transactive memory system as a combination of the knowledge possessed by each individual and a collective awareness of who knows what" (Austin, 2003, p. 866). It has also been argued that team members' meta-knowledge, consensus/agreement, and accuracy are necessary components.	Wegner (1986), Yoo & Kanawattanachai (2001), Austin (2003).
• Specialization	Team members having different knowledge depending on their position or role	Austin, 2003
• Credibility	Beliefs of the accuracy of other members' knowledge	Austin, 2003
• Coordination	The ability to effectively coordinate information exchange between members	Austin, 2003

Component	Definition	Source
Collaborative Problem Solving Processes		
Individual Knowledge Building	Any actions taken by an individual team member to build their own knowledge. This may include actions like reading task-relevant content, asking questions, and accessing displays. This refers to information that the individual has access to and does not require integration, analysis, and evaluation.	Fiore et al., 2010a, b; 2014
• Individual Information Gathering	Any action taken by an individual team member to seek and the add information to their own existing knowledge.	Fiore et al., 2010a, b; 2014
• Individual Information Synthesis	Any action taken by an individual team member where he or she compares relationships among information, context, and artefacts to develop actionable knowledge.	Fiore et al., 2010a, b; 2014
• Knowledge Object Development	An individual team member creates cognitive artefacts that support the creation of actionable knowledge for the task. Cognitive artefacts can include but are not limited to: Notes, diagrams, tables, and sketches.	Fiore et al., 2010a, b; 2014
Team Knowledge Building	Any actions taken by team members to disseminate information and to transform that information into actionable knowledge for team members.	Fiore et al., 2010a, b; 2014
• Team Information Exchange	Any actions taken to pass relevant information to team members. These may include statements or questions pertaining to or containing facts about the task environment or situation, including requests and provision of information.	Fiore et al., 2010a, b; 2014
• Team Knowledge Sharing	Team member provide explanations or interpretations to each other that become shared between team members or with the team as a whole.	Fiore et al., 2010a, b; 2014
• Team Solution Option Generation	Development or offering of potential solutions to a problem. These are statements that provide a partial or complete solution--a sequence of actions intended to meet a given operation objective--or ask for further refinement and clarification of a solution.	Fiore et al., 2010a, b; 2014
• Team Evaluation and Negotiation of Alternatives	Attempts by team members to clarify or identify the pros and cons of potential solution options. These may include statements that (1) compare different potential solutions on the basis of speed, cost, or ease of execution, (2) provide support or criticism of a single potential solution, or (3) ask for an evaluation of a potential solution.	Fiore et al., 2010a, b; 2014

Component	Definition	Source
• Team Process and Plan Regulation	Team discussions or critiques of the team's knowledge building process or plan, or talks about the processes that the team members exhibit during the development of plans and solutions. This refers to processes and reactions to feedback or assessments of plans that the team has already executed, and assessments of the teamwork processes that the individual describes. These statements may include references to directing the group's process or helping it do its work by proposing questioning, or commenting on goals for the group or specific actions team member's need to take to address a goal.	Fiore et al., 2010a, b; 2014
Internalized Team Knowledge	Knowledge held by individual members of the team that only an individual or some individuals have access to but not all the other team members.	Fiore et al., 2010a, b; 2014
• Team Knowledge Similarity	Degree to which differing roles understand one another and hold a shared awareness of the situation including how much they understand one another each team members' critical goals.	Fiore et al., 2010a, b; 2014
• Team Knowledge Resources	Degree to which differing roles share an understanding of the locations of important resources. That is, the team members' collective understanding of resources/responsibilities associated with the task.	Fiore et al., 2010a, b; 2014
Externalized Team Knowledge	Facts, relationships, and concepts that have been explicitly agreed upon or not openly challenged or disagreed upon by factions of the team. This refers to knowledge that the entire team has access to, like a situation that all team members are aware of.	Fiore et al., 2010a, b; 2014
• Externalised Cue-strategy Association/Goal Orientation	Team's collective agreement (consensus) as to their task strategies and the situational cues that modify those strategies and how. This refers to plans or strategies that are altered due to a situation occurring or new information/knowledge is presented to team members.	Fiore et al., 2010a, b; 2014
• Pattern Recognition and Trend Analysis	Accuracy of the patterns or trends explicitly noted by members of the team that is either agreed upon or unchallenged by other members. These refer to knowledge about a situation that is occurring over time where individual notice a pattern or trend. Pattern recognition involves perceptual processes one uses in the identification of individual cues and groups of cues that may be indicative of an important event. Trend analysis is a form of pattern recognition that requires the integration of cues across time in order for recognition to occur.	Fiore et al., 2010a, b; 2014

Component	Definition	Source
• Uncertainty Resolution	Degree to which the team has collectively agreed upon the status of problem variables. This may refer to whether the team members are unaware of the situation, all team members agree there is a situation they don't understand, or the team understands the problem at hand.	Fiore et al., 2010a, b; 2014
Team Problem Solving Outcomes	Assessments of quality relating to a team's problem solutions or plan.	Fiore et al., 2010a, b; 2014
• Quality of Plan (problem-solving solution)	Degree to which the problem-solving solution developed by the team achieve an appropriate resolution. Refers to the success/failure of the plan executed.	Fiore et al., 2010a, b; 2014
• Efficiency in Planning Process	Amount of time it took for the problem solving team to arrive at a successful resolution to the problem.	Fiore et al., 2010a, b; 2014
• Efficiency of Plan Execution	Quality of the plan in terms of the amount of resources and time required to execute the plan.	Fiore et al., 2010a, b; 2014
Team Decision Making		
Team Decision Making	"the process of reaching a decision undertaken by interdependent individuals to achieve a common goal" includes "the ability to gather and integrate information, use sound judgment, identify alternatives, select the best solution, and evaluate the consequences"	Cannon-Bowers et al., 1995, p. 346; Orasanu & Salas, 1993, p. 328
• Team Informity	Degree to which all members of the team are kept informed with regard to all relevant cues associated with factors needed to make the decision	Hollenbeck et al., 1995
• Staff Validity	Degree to which the team is composed of members each of which is able to make accurate interpretations regarding the information required for the decision	Hollenbeck et al., 1995
• Hierarchical Sensitivity	Degree to which the leader of the team is able to effectively weight each team member's decision to arrive at an accurate team-level decision	Hollenbeck et al., 1995

Component	Definition	Source
Team Planning		
Team planning	"The development of alternative courses of action for mission accomplishment. This involves decision making about how team members will go about achieving their missions, discussion of expectations, relay of task-related information, prioritization, role assignment, and the communication of plans to all team members".	Hackman & Oldham, 1980; Marks, Mathieu, & Zaccaro (2001). Stout, Cannon-Bowers, Salas, & Milanovich, 1999
• Deliberate planning	"The formulation and transmission of a principal course of action for mission accomplishment" (p. 366).	Marks, Mathieu, & Zaccaro (2001).
• Contingency planning	Refers to the a priori formulation and transmission of alternative plans and strategy adjustments in response to anticipated changes in the performance environment.	Marks, Mathieu, & Zaccaro (2001).
• Reactive strategy adjustment	Reactive strategy adjustment is the alteration of existing strategy or plans in response to unanticipated changes in the performance environment and/or performance feedback. (p.365-366)	Marks, Mathieu, & Zaccaro (2001).

Part III: Predicting the Relationship between Decrements in Individual Cognition to Team Cognition during LDSF

In Part II, we reviewed the pertinent forms if team cognitive knowledge and types of team cognitive processes that are foundational for understanding effective flight and ground crew performance for LDSF. We provided speculations regarding the relationship between individual and team cognition. In the current Part III, we focus on findings of individual cognition for both space- and ground-based research to provide more concrete prediction regarding the relationship between detriments to individual cognition and how such detriments could affect team cognition. Only example relevant studies are mentioned here as these were more extensively detailed in prior sections.

Detriments to Individual Attention in Space and Ground Research

Attention Relevant Space Research. As previously discussed in Part I, during spaceflight, some research suggests individual attention may be negatively affected (e.g., Eddy, Schiflett, Schlegel, & Shebab, 1998). Specifically, in this research, which was conducted during inflight testing, astronauts performed worse on the Directed Attention Task. This suggests that during spaceflight, astronauts' divided attention, or trying to attend to multiple tasks at once, suffers a performance decrement when compared to performance on this task during pre-flight conditions.

Attention Relevant Ground Research. Prior ground-based research on the effects of ***chronic sleep loss*** shows disruption on Psychomotor Vigilance Task (e.g., Cohen et al., 2010), which requires individuals to maintain sustained attention. While this research was not conducted in space, it is well documented that the conditions characterizing extreme environments can lead to sleep loss (e.g., Lieberman et al., 2005). Thus, a warranted conclusion is that if astronauts are suffering from sleep loss during LDSF, their attention will be negatively affected.

Further, ground-based radiation studies have demonstrated that prolonged exposure to radiation-induced neurobehavioral changes in rodents (Hienz et al., 2010). Specifically, given exposure to radiation performance on the rat Psychomotor Vigilance Task, the animal analog to the human task mentioned previously, the findings showed decreases in sustained attention and slower performance. More recently, Parihar et al. (2015) demonstrated in more detail the neurobiological changes that occurred in mice following 6 weeks of exposure to charged particles similar to those astronauts would be exposed to under spaceflight conditions. The changes were correlated with decreased performance on a rodent cognitive task required attention to novel objects.

Predicted Effects of Individual Attentional Decrements on Team Decision Making

Based on the research highlighted in this part of the report as well as in Part I, we predict that decrements to individual attention under conditions of LDSF, whether due to radiation, sleep loss, or other factors, will negatively affect team decision-making processes. We expect there to be a cascading effect on team decision making based on the following propositions:

- ***Proposition 1***: Decrements to individual attention in LDSF may lead the individual to failure **to update** their **task knowledge** during a mission operation, especially during tasks required vigilance or sustained attention.

- ***Proposition 2***: Failure to update task knowledge as a function of impaired attention will in turn negative affect emergent team cognitive states such as development of the team's **shared mental model**.
- ***Proposition 3***: Negatively affected team-shared mental models, whether inaccurate or non-overlapping, will lead to negative effects on **team decision outcomes** (i.e., poor or non-optimal decisions).

Detriments to Individual Working Memory in Space and Ground Research

Memory Relevant Space Research. During spaceflight, the research findings on memory tasks are largely equivocal. For example, some tasks that draw on working memory and executive control show some decrements under spaceflight conditions (e.g., Manzey & Lorenz, 1998; Manzey, Lorenz & Polyakov, 1998). Contrarily, in other research, pre-flight to in-flight comparisons show no differences on short-term memory tasks (e.g., Eddy et al., 1998). While the research conducted in space evidencing memory decrements are equivocal, the findings from ground-based analogs suggest that some of the conditions of LDSF may negatively affect individual memory.

Memory Relevant Ground Research. In a spaceflight analog (i.e., Antarctic missions), memory problems have been found (e.g., Reed et al., 2001). Specifically, this is relevant to LDSF because it was a study conducted over a duration of 11 months in which short-term memory performance decreased over time. This generally suggests that being in an extreme environment under conditions of isolation and stress, problems with individual memory may occur across long exposure to these conditions. Relatedly, ground-based sleep research has shown problems with memory tasks, often as a function of chronic sleep loss or sleep debt (e.g., Van Dongen et al., 2003; Banks and Dinges, 2007). Lastly, ground-based radiation studies using an animal analog demonstrated that prolonged exposure to particle radiation (analogous to that astronauts would be exposed to), leads to memory impairments in rodents (Hienz et al., 2010). Taken together these space- and ground-based research findings suggest that there may be some detriments to individual memory as a function of some of the conditions of LDSF.

Predicted Effects of Individual Memory Decrements on Team Problem Solving

Based on the research highlighted in this part of the report as well as in Part I, we predict that decrements to individual memory under conditions of LDSF, whether due to radiation, sleep loss, or other factors, will negatively affect team problem-solving processes. Specifically, we predict the following relationships between individual memory and team problem-solving abilities:

- ***Proposition 4:*** Decrements to individual memory under conditions of LDSF may hinder the team's development of a **transactive memory system** and, in turn, compromise the awareness of team members' specific expertise.

- ***Proposition 5:*** Decrements to individual memory under conditions of LDSF may alter **information sharing** (e.g., inaccurate push/pull) and impair **knowledge building** and solution generation.

Detriments to Individual Reasoning and Psychomotor Functioning in Space and Ground Research

Reasoning and Psychomotor Relevant Space Research. Long-duration spaceflight shows research has shown an impact of condition of spaceflight on individual reasoning. For example, during early phases of a long-duration missions, impairments on a reasoning task were found (Manzey et al., 1998). Likewise, research has also shown decrements to psychomotor functioning during spaceflight. One example showed that performance on a fine-motor control task was impaired during spaceflight and, in particular, during conditions of isolation (e.g., Newman & Lathan, 1999). This evidence suggests that at least during early phases of spaceflight individual reasoning abilities could be impaired. Further, more generally, psychomotor functions could be impaired during conditions of spaceflight. Of course, these issues have not been studied in space over very long durations.

Reasoning and Psychomotor Relevant Ground Research. Similarly, in ground-based analogs, decrements to individual reasoning, particularly under high stress and sleep-deprived scenarios has been found (e.g., Lieberman et al., 2005). In addition, ground-based sleep research has shown decrements in psychomotor performance as a function of sleep loss (e.g., Dinges et al., 1997). Further, ground-based radiation studies have demonstrated that prolonged exposure to radioactive particles can lead to psychomotor impairments in rodents (Heinz et al., 2010). Taken together, findings from space- and ground-based research suggests there may be impairments to individual reasoning and psychomotor capabilities during LDSF conditions.

Predicted Effects of Individual Memory Decrements on Team Planning

Based on the research highlighted in this part of the report as well as in Part I, we predict that decrements to individual reasoning, memory, and psychomotor functioning under conditions of LDSF, whether due to radiation, sleep loss, or other factors, will negatively affect team planning processes. Specifically, we predict the following that detriments in individual reasoning, memory, and/or psychomotor functioning will negatively affect team planning in the following ways:

- ***Proposition 6:*** Decrements to individual **reasoning** (e.g., logical thinking) and **memory** (e.g., recalling critical information), due to conditions of LDSF, will negatively affect the construction of a **team plan**.
- ***Proposition 7:*** Decrements to individual **psychomotor functioning** (i.e., bodily movement that may be slowed or less accurate), may negatively affect the ability of team members to successfully meet **plan completion timelines**.

Calling out Concerns on Radiation

Although some of the material here has been discussed in prior sections, the general findings on radiation exposure represent one of the most problematic areas of concern. Although initial research focused on understand cancer risks, a consistent and robust body of studies shows that cognitive impairment results from long-term exposure to hazardous radiation. To call this out, we reiterate some of the key findings.

First, there is the overarching concern of galactic cosmic rays and the potential to damage the central nervous, potentially putting astronauts at risk for significant ailments such as Alzheimer's disease (Cucinotta et al. 2014). In addition to similarly arguing that exposure to charged particles may cause long-term neurocognitive problems, others have documented how this may cause cognitive impairment in areas of mission critical importance (Tseng et al., 2014). In more specific research, others have shown how whole body exposure to harmful radiation can cause impairments on attentional set shifting tasks (Britten et al., 2014).

Most concerning, though, are the recent studies about the effects of radiation from a longer-term perspective (Parihar et al, 2015). Although this and current studies are only on rodent populations, there is a high likelihood of some form of brain damage due to space radiation. Parihar et al. found that "structural parameters revealed marked and significant reductions in the number of dendritic branches, branch points, and overall dendritic length" in the population exposed to radiation." Using tests of "novel object recognition" and "object in place." the findings showed marked impairment following expected dosage of hazardous radiation. Importantly, the variability in this damage was then correlated with performance. Specifically, findings suggest that there are substantial individual differences associated with exposure to radiation. Parihar et al. noted that it is important to correlate "radiation-induced changes in neuronal morphometry to behavioral performance and demonstrate that certain structural changes in neurons correspond to select deficits in cognition." Finally, performance decrements were beginning to appear even only weeks into the study. This suggests that problems in crew functioning may occur even earlier than anticipated.

We call these findings out because they are particularly relevant to our report. Putting such findings into the context of team cognition, these findings make teamwork all the more critical to success. Specifically, unlike fatigue, there is yet any countermeasure for impairments caused by radiation. As such, this could influence cognitive functioning, which, in turn, may jeopardize, or at least compromise, the ability of the crew to deal with any problems that emerge. Thus, these findings make teamwork all the more critical to success. In particular, given the likelihood of variability in harm, and variability in the form of cognitive impairment, teamwork processes such as backup behavior, mutual performance monitoring, are of the utmost importance. In addition to training on cognitive and collaborative processes, research absolutely must attend to the consequences of radiation on astronaut populations. That is, it is not enough to just understand the consequences of sleep deprivation or confinement on long-duration missions. Radiation seems to be the most consequential of the risks that must be understood and mitigated to the degree possible. As such, the aforementioned propositions need to be pursued in the context of the variety of risks for missions with an increased attention to radiation exposure consequences for humans and how these can be mitigated.

Summary

In this section, we have drawn from our literature review findings regarding factors associated with LDSF and their associated effects on individual cognition. Based on these findings, we have provided specific hypotheses, in the form of propositions, about what the relationship may be between detriments to individual cognitive abilities and team cognitive processes. Here we only briefly reiterated some of the findings that provide the basis for these predictions, although more details can be found in Part I as well as the respective references. Future work is necessary to evaluation these predictions. In Part IV of this report, we provide details of our Operational Assessment.

Part IV: Operational Assessment of Team Cognitive Processes

Ten NASA individuals from a variety of backgrounds including astronauts, mission controllers, operations researchers, and training managers participated in our Operational Assessment.

Broadly, the findings of the operational assessments serve to highlight how current NASA operations support or involve certain team cognitive processes. For the purposes of this report, we aim to highlight some key examples related to the critical team cognitive processes we identified. In addition, we also include a brief summary of other key issues that were thematically raised across multiple interviews. To make sense of the notes and summaries of the interviews, we categorized many interview segments into a table with sections corresponding to critical team cognitive knowledge and processes. This table served as a distillation of our interview summaries presented in our operational assessment report. What we present in text are key excerpts from the interviews that exemplify the team cognitive processes that are central LDSF missions.

One example from that, in particular, highlights the role of mission control and the flight director as an example of *team decision making* and *team planning*.

> *"The [team member] asks what each entity is doing during the day and they decide on their plan based on how these conversations go."*

Other findings described the nature of team cognitive processes in spaceflight and what is necessary for it to be effective. In particular, the following excerpt highlights what is important for *team problem solving* in spaceflight crews.

> *"Problem solving is constant and has to be a natural thing that everyone does and the team is good at… need to know when to incorporate ground and when not to… need to be autonomous in solving own problems and better at expressing what they are seeing, the ramifications, priorities/urgencies, etc. to the ground..."*

Not only did our interviewees describe critical team cognitive processes, they also emphasized the important of team knowledge structures. In the following quote, one individual mentioned the importance of shared mental models for all individuals involved in spaceflight.

> *"Shared mental models among ground, crew, and family is very important, including schedule and expectations of the mission docking of spacecraft."*

In addition to shared mental models, the importance of transactive memory systems is highlighted in the following quote. Specifically, the emphasis here is on a member of the ground crew's ability to not only understand the various roles and knowledge of the flight crew and the ground crew, but also have the ability to take their perspective.

> *"as the [team member] you are the interface with the crew doing the verbal communication with them. That role is partly communicator and telling them what the team wants to tell them and partly translator because the [team member] understands what is happening by crew perspective better than anyone else in the room"*

An important aspect of our operational assessment is that we not only found that the interviewees discussed aspects of team cognition, which was of importance for our project, but that there were several recurrent themes in the interviews worth noting that related to team performance. One theme was the importance of *managing social and emotional relationships* onboard with the flight crew, between the ground crew, and with the crew's families. Another was a concern about the amount of *technical knowledge* crewmembers will require with increasing independence from ground during long-duration exploration missions (LDEMs) and the *design of the hardware/vehicle* to minimize this issue. That is, due to the long-distance nature of exploration missions, there will be significant time lags. This will require the crew a vehicle that is designed simple enough so the crew is able to maintain and repair it, provided they are given the appropriate technical knowledge. Several interviewees also noted the importance of allowing crews to *train together* and work together for long durations, which is sometimes very difficult with international alliances. Lastly, we also saw an emphasis on the need to select crewmembers who are *emotionally independent* and able to maintain a high degree of self-motivation over long periods of time.

In short, our operational assessment allowed us to better understand the way that critical team cognitive knowledge and processes occurs in mission operations as well as some important issues salient to operations personnel. With this as a foundation, we next turn to discussion of team training strategies that have been shown to enhance various team cognitive processes. Throughout, we emphasize which team cognitive process certain training strategies are applicable to and also refer back to the other important themes identified by operations personnel as appropriate.

Part V: Training to Enhance Team Cognitive Processes

Given the impact of team cognition on team performance through its influence on the ability of teams to anticipate, coordinate, and adapt to task and team demands, the focus of the next section is on how team training can improve team cognition (Fiore, Ross, Jentsch, 2012). Specifically, we draw from team training research related to the team cognitive processes specified above and make salient how certain types of training may be applicable to the context of long-duration spaceflight.

Defining Team Training

Generally, *team training* is defined as an intervention or effort to improve team performance by teaching the competencies (knowledge, skills, or abilities) to individuals that are necessary for effective performance as a team (Cannon-Bowers et al., 1995; Delise et al., 2010). Team training can take many forms. Team training interventions can focus on either taskwork or teamwork competencies (or both). *Taskwork* training targets the improvement of task-specific skills. For example, cross-training is a taskwork training intervention in which individuals learn about the skills and duties of their teammates; ranging either from a superficial level (e.g., positional clarification) in which individuals learn about the different positions within the team, to a deeper level (e.g., positional rotation) in which individuals are trained to be able to actually perform the tasks duties of other positions within the team (Delise et al., 2010; Salas et al., 2008; Klein et al., 2009). In contrast, *teamwork* training often develops more transferable skills that may be used in multiple settings (rather than being applicable to a specific task). Teamwork training may include skills such as mutual performance monitoring, feedback, leadership, management, coordination, communication, and decision making (Salas et al., 2008, p.909).

Team building is another intervention that is used in teams to improve overall team performance. Whereas team training focuses on either taskwork or teamwork skills, and usually includes a practice component within the context of the intended transfer setting, team building does not focus on skill-based competencies and is often conducted out of the transfer environment context. Team building interventions often aim to improve goal-setting, interpersonal relations, problem solving, or role clarification (or any combination of the above; Klein et al., 2009). However, despite the different approaches to improving team performance, the targeted outcomes from both team training and team building interventions can include affective (e.g., socialization, trust, team potency), cognitive (e.g., declarative knowledge, transactive memory systems, shared mental models), process (e.g., coordination, cooperation, strategy development, self-correction, assertiveness, decision making, situational assessment), or performance outcomes (Klein et al., 2009; Salas, Rozell, Mullen, & Driskell, 1999). It is also worth noting that in much of the extant team literature, team problem solving and decision making are considered behavioral processes, and, as such, this review will include information on both cognitive outcomes and process outcomes. Therefore, both team training and team building interventions will be examined in the current review, as both offer opportunities to examine the effect of team interventions on both cognitive and process outcomes of interest, which may impact the success of long-duration space exploration missions.

General Effectiveness of Team Training and Team Building

Several recent meta-analyses attest to the effectiveness of team training and team building interventions in improving cognitive, affective, process, and performance outcomes (Delise et al., 2010; Klein et al., 2009; Salas et al., 1999; Salas et al., 2008;). For example, a recent team training meta-analysis by Salas and colleagues (2008) examined the impact of specific training contents on various outcome measures (i.e., affective, cognitive, process, and performance) and found that, in general, team training has a moderate, positive impact on team functioning (effect size = .34). Furthermore, the positive effects were found to be greater depending on the type of training administered and types of outcomes examined (Salas et al., 2008). When looking at the specific team training strategies used, team knowledge training was the most effective (effect size =.81) followed by tactical training (effect size =.67), critical thinking (effect size =.60), team adaption and coordination (effect size =.56), coordination/crew resource management (effect size =.47), cross-training (effect size =.44), self-guided training (effect size =.36), and self-correction training (effect size =.27).

Coordination and cross-training were found to be the two most commonly used training strategies employed. Most team training interventions focus on either taskwork or teamwork (or mixed), and all three foci appeared to be equally effective in improving performance outcomes. Overall, teamwork and mixed methods were the most effective in improving cognitive, affective, process, and performance outcomes. The size of the team appeared to influence the impact of team training on various outcomes. Specifically, medium-sized teams experienced greater improvements in cognitive outcomes (effect size = .46), whereas small teams benefited the most in terms of improvements in affective (effect size = .39) and process (effect size =.59) outcomes.

These findings were further supported by another team training meta-analysis that found that, in general, team training had positive effects (Delise et al., 2010). Of particular interest, team training had the greatest positive impact on team cognition (mean sample-weighted effect size = 1.37), both within training and in transfer environments. Furthermore, the effects of training on cognition was larger in the transfer environments (mean sample-weighted effect size = 2.40) than in the training environments (mean sample-weighted effect size = 1.21); thus, showing that training may be more effective in changing cognition when individuals have the opportunity to use these skills in the transfer environment. This is particularly promising for training in long-term spaceflight missions, as these findings may indicate that training during long-duration missions will be especially impactful given the space crew's ability to integrate the target skills into their daily activities immediately, thus furthering improvements in cognitive processes and performance.

Team building, on the other hand, has not produced the same level of effectiveness as team training studies have found. A meta-analysis on team building found that, overall, only subjective measures of performance indicated that team building was successful in increasing performance; however, this was not supported by objective measures of performance (Salas, Rozell, Mullen, Driskell, 1999). However, it is important to examine the different types of team building interventions before drawing conclusions as to the effectiveness of team building in general. When examining the specific components of the team building intervention, role clarification was found to be impactful on both subjective and objective measures of performance (correlation = .75 and .71, respectively); however, goal setting, interpersonal relations, and problem solving focused team building interventions all failed to demonstrate performance improvements in both subjective and objective measures of performance studies (Salas, et al., 1999). Furthermore, the longer the duration of the team building intervention, the less effective the (subjective) performance outcomes.

A more recent meta-analysis (Klein el al., 2009) found that team building was effective for only process and affective outcomes. However, and perhaps due to only three effect sizes on which to rely, improvements in cognitive outcomes (effect size = .13) were non-significant, thus implying that team building may not be useful in improving cognitive outcomes. When examining the content of the intervention on overall team performance, goal-setting (effect size = .37) and role clarification (effect size = .35) were the most impactful, but both interpersonal relations (effect size = .26) and problem solving (effect size = .24) demonstrated moderate effects on performance (Klein et al., 2009).

Given that one of the areas of interest to NASA is the improvement of problem-solving abilities of teams, and the fact that affective (e.g., trust and team potency) and process (e.g., coordination and cooperation) outcomes are impactful in team performance, the usefulness of team building should not be completely disregarded (particularly in light of the small sample size of cognition studies). We also note that NASA programs, such as the National Outdoor Leadership program (NOLS), encourage the kind of team building experiences that may be subjectively beneficial. However, many of the functions that are achieved in team building can be simultaneously achieved in other training exercises (e.g., role-clarification can be achieved in cross-training interventions). Therefore, while team building may be beneficial prior to a mission, its utility "during" a mission may be less so.

Specific Training Interventions to Enhance Team Cognitive Processes in LDSF

Several different types of interventions have been traditionally used in team training that we suggest have utility in improving team cognitive processes in support of long-duration spaceflight missions. These include cross-training, team reflexivity training or self-correction training, knowledge building training, knowledge sharing training, emergency response training, and adaptive team coordination training (Salas et al., 2008). Some of these have been detailed in a recent NASA technical report on Team Training (Noe, Dachner, Saxton, & Keeton, 2011), while other have not. Depending on the desired outcome (i.e., which team cognitive process should be developed), different team training interventions may be more appropriate. These different types of interventions will be described in the next section below, in addition to the types of outcomes they impact.

Cross-Training

What is it? Cross-training is a type of team training in which members of the team gain some form of training on the positions of other team members (e.g., Marks, Sabella, Burke, & Zaccaro, 2002). Three types of cross-training methods that are commonly used. These methods are *positional clarification* (in which individuals are told about the other positions on their team), *positional modeling* (in which individuals are both told about the position and have the opportunity to observe or shadow the position, thus gaining a deeper understanding of the duties of the position), and *positional rotation* (in which individuals are given hands-on training in the other positions such that they are able to perform the role if needed).

What do the findings show? Cross-training was shown to improve the development of team interaction shared mental models. This led to improved coordination and backup behaviors, and, consequently, improved performance (Marks et al., 2002) and team decision making (McCann, Baranski, Thompson, & Pigeau, 2000). Positional rotation provides individuals with the deepest level of understanding and experience with the other roles in their team. However, Marks et al. (2002) found no statistical differences between positional modeling and positional rotation with regards to shared mental models. This indicates that individuals do not necessarily need to be given hands-on experience in the other roles on the team to see improvements in shared mental models (and consequently improved performance). Rather, they can observe the roles of other members of the team, which is a less time-consuming training intervention. Obviously, there are benefits to the positional rotation method; however, when under time constraints, the less time-consuming positional modeling training may be implemented to significant effect. More recently, cross-training, in its full form (including all types specified above) was shown to improve teamwork knowledge and overall team performance in a simulated unmanned vehicle team experiment (Gorman, Cooke, & Amazeen, 2010).

What need does it fill? On the one hand, cross-training provides an empirically evaluated training technique that has been shown to contribute to the development of team-shared mental models and, in turn, improve team performance. However, despite the focus on SMMs in the research on cross-training, this form of training is also likely to be beneficial in the development of transactive memory systems in which individuals develop knowledge of the specializations of team members to facilitate coordination. Cross-training is therefore likely an effective method of training for space missions, not only among members of the spaceflight crew, but also between mission control and the spaceflight crew. In addition, cross-training may help to address one of the recurrent themes from our operational assessments. Specifically, this form of training could be used to increase the technical knowledge regarding hardware/vehicle design for those individuals requiring such knowledge.

What do we recommend? Kanas et al. (2006; 2007) suggested training both spaceflight crew and mission control together on certain aspects of the other's jobs in order for each group to gain a better understanding of what stressors the other team must contend with while on the job and to gain a deeper appreciation for the role of the other team in mission success. In accord with Kanas et al, we recommend that spaceflight and ground crews should receive some form of cross-training. By training space crews and mission control personnel together, prior to the missions, we expect this would help them gain a better understanding of both the nature of each other's tasks and associated interdependencies as well as the stressors to which particular positions are prone. Further, the will also help teams gain a better and deeper appreciation for the other team and the ways in which they support the successful accomplishment of the mission.

Team Reflexivity Training

What is it? Team reflexivity training is an intervention that guides either individuals or groups in reflecting upon the objectives, strategies, and processes of the group, and encourages individuals or groups to adapt objectives, strategies, and processes to both current and possible changes in the environment (Gurtner, Tschan, Semmer, & Nägele, 2007). Although individual methods of reflexivity interventions may differ, the general procedure would include the following steps after a team performance episode: 1) reviewing the task performance of the group (e.g., ''How did you ask for information? How did you pass on information? How was the team organized?''; Gurtner et al., p. 132), 2) thinking about potential improvements in the processes and methods used to complete the task (e.g., ''Are there alternatives to your chosen task performance procedures, and if so, what are they?''; p. 132), and 3) creating suggestions for future work such that the next time the task is done the processes and outcomes are improved.

What do findings show? Gurtner et al. found that team interaction mental models were more similar after individuals or teams engaged in reflexivity exercises (as compared to a control), as guided by the three steps described above. Furthermore, the reflexivity intervention had both a direct effect on SMMs and was also partially mediated by the commander's communication of strategies. Additionally, SMMs influenced strategy implementation, which then impacted performance. The study demonstrated that shared mental models can be improved by reflecting on what work has been accomplished so far and reflecting on how performance could be improved in the future. Further, van Ginkel, Tindale and van Knippenberg (2009) found that reflexivity training also improved team-shared task understanding and decision quality.

What need does it fill? Given the benefits of team reflexivity training, it provides an empirically evaluated training technique that contributes both to the development of shared mental models as well as to improved team decision-making quality. Therefore, this strategy provides not only a way to enhance two types of team cognition, but it also improves overall performance.

What do we recommend? Spaceflight and mission control teams should receive instruction in how to implement team reflexivity processes. Team reflexivity training, is a technique that is easily instantiated as an ongoing training strategy for long-duration missions given the lack of need for outside personnel during the process and because it can be performed either at the individual or at the team level.

Self-Correction Training

What is it? Similar to reflexivity training, self-correction training is a method whereby participants are empowered to improve their performance by reflecting on past performance episodes and self-diagnosing areas for improvement. Whereas reflexivity training is generally applicable to any setting due to its non-specific nature, and can be facilitated by a series of questions (i.e., without the use of a facilitator or trainer), self-correction training requires more initial training for proper use. Because self-correction is more focused and specific, it has the potential for greater benefits (Gurtner et al., 2007). Guided team self-correction, or Team Dimensional Training (TDT), is a specific type of self-correction that was derived from an expert model of teamwork, and which has been found to improve both taskwork and teamwork performance (Smith-Jentsch, Cannon-Bowers, Tannenbaum, & Salas, 2008).

The expert model of teamwork consists of team behaviors that fall into four dimensions. The first dimension, information exchange, consists of behaviors such as providing situational updates and seeking and providing information at appropriate times. Communication delivery, the second dimension, includes behaviors such as adhering to communication norms, avoiding excess or unnecessary discussions, using the correct terminology, speaking clearly, etc. The third dimension, supporting behavior, encompassed behaviors that support the flow of work among team members such as offering and accepting assistance when needed, providing feedback on errors, and correcting errors that are brought to the team’s attention. Lastly, initiative and leadership, included behaviors such as providing guidance and direction to the team and stating priorities.

What do findings show? TDT has been found to improve teamwork mental models in teams, as well as increase performance and decrease errors in complex task simulations (Smith-Jentsch, Milanovich, & Merket, 2001; Smith-Jentsch et al., 2008; Smith-Jentsch, Zeisig, McPherson, & Acton, 1998). Current work is examining TDT in the context of mission control teams.

What need does it fill? In sum, TDT is a structured debriefing method of training that focuses on the debriefing sessions as an opportunity to have team members reflect upon both the positive and negative instances of the four dimensions of teamwork that occurred during a given occurrence (such as a training session, or a mission). Through this guided self-correction exercise, teams are able to identify both what they did right, what they did wrong, why these occurred, and the outcomes these actions elicited. Thus, teams are able to, on their own, correct problems that arise and take ownership for mistakes. The need, therefore, filled by this strategy, is that it allows for general improvements in teamwork mental models and overall performance.

What do we recommend? The use of a self-correction training method is a candidate for long-duration space missions due to the fact that it has been shown to be effective in increasing both task and teamwork SMM, increases performance, and is self-contained within the team (i.e., can be performed independently of mission control). Current practices are investigating this method in the NASA context, but should recognized that it particularly focuses on improving the teamwork dimensions and does not explicitly address and enhance critical other team cognitive processes.

Knowledge Building Training

What it is? Problem-solving teams are often composed of individuals with distinct sets of knowledge and expertise that require integration to effectively perform. This can be problematic as a number of barriers such as differential mental models of the task and a tendency for team members to discuss commonly held information, as opposed to unique information, are pervasive. Renstch, Delise, Salas, and Letsky (2010) conducted the only studies to explicitly focus on team training for knowledge building. Knowledge building training consists of a schema-enriched communication (SEC) component as well as a knowledge object component. For the SEC component, team members were trained to engage in communicative processes that elicit the structure and organization of their knowledge, as well as the assumptions, meaning, rationale, and interpretations associated with each member's knowledge. The knowledge object component consisted of utilizing an external representation (i.e., an information board) that allowed for team members to post and organize their knowledge in a common space from which they can visually manipulate that knowledge, more easily remember it, as well as draw attention to specific information as appropriate.

What do findings show? The effectiveness of the knowledge building training was tested on a three-person team task designed by Navy SEALs and examined in an undergraduate population. The results showed that the knowledge building training led to improved knowledge transfer (i.e., the exchange of knowledge from one team member to another), knowledge interoperability (i.e., knowledge that multiple team members are able to recall and use), cognitive congruence (i.e., an alignment or matching of team member cognitions), and higher overall team performance on the task (Rentsch et al., 2010). In a follow-on study, Rentsch, Delise, Mello, and Staniewicz (2014) found the same improvements to team cognition, but under conditions in which team members were distributed (i.e., in different locations).

What need does it fill? While there have only been two experiments evaluating this type of training, the results show promise for the need to improving team cognitive processes in LDSF. In particular, given that this training improves the knowledge building processes of teams, we expect it would be suitable for improving collaborative problem solving and team decision making. Further, this type of training seems like it would be equally applicable to both space and ground crews. That is, due to the specialized nature of NASA teams and the specific roles of members within teams, knowledge building is a critical team cognitive process.

What do we recommend? This is a promising training technique that should be investigated further. In particular, although the training was examined in the context of a complex Naval task, it was studied with undergraduate populations. A first step would be investigating this with real-world professionals and also adopting/adapting this for NASA contexts. In addition, because the results show this as a beneficial form of training, whether the team are co-located or distributed, it should be investigated as a type of training that applies to spaceflight and ground crews and the ways in which they work together.

Knowledge Sharing Training

What is it? Sikorski, Johnson, and Ruscher (2012) conducted an experiment to investigate the effects of a team knowledge sharing (TKS) training intervention to improve team performance in science classroom setting. This intervention is designed to improve the sharing of both team- and task-related knowledge by prompting teams to engage in reflective processes, certain types of communication, as well as planning to improve performance. In turn, this improves the teams' SMMs and leads to better performance outcomes. The intervention specifically focused on five SMM components identified by Johnson et al. (2007): general task and team knowledge, communication skills, attitude toward teammates and task, team dynamics and interactions, and team resources and working environment.

What do findings show? Overall, the results showed that the TKS training interventions were able to improve similarity in teams' SMMs as well as lead to improvements in performance when compared to a control condition. This training technique has only been examined in the context of a science classroom with undergraduates.

What need does it fill? While this training leads to improvements in SMMs and performance, it appears that many of the components of knowledge sharing training are included in other forms of training, such as TDT. Compared to some of the other forms of training reviewed here, this training provides fewer unique benefits to team cognition that are not positively affected by other methods.

What do we recommend? Given this research has only been studied in a classroom learning context, it is likely the same benefits and more would be achieved by adopting the knowledge building training discussed previously. Another limitation of this method is that it is difficult to conduct without the assistance of outside member (e.g., to administer and analyze survey responses).

Emergency Response Training

What is it? Emergency response training can help to prepare individuals for unforeseen events that require adaptive responses (Ford & Schmidt, 2000).

What are the findings? Emergency response training typically improves performance under laboratory or simulated conditions; however, it fails to transfer to the real world (Ford & Schmidt, 2000). A number of reasons for this have been offered. First, it is difficult for the knowledge to be retained when there are limited opportunities to perform (and practice) emergency response scenarios. Second, it is challenging to train for all of the skills needed for emergencies as these will vary as a function of the demands of a given emergency. Further, and related, the acquired skills do not generalize well. Finally, it is particularly challenging to design training that can develop the capacity for individuals to assimilate into the larger teams conducting the emergency response.

What need does it fill? Ford and Schmidt (2000) outline a set of guidelines for improving emergency response training effectiveness. While there is not a clear "emergency response training" program with consistent results, this work does provide some very useful ideas that may be worth incorporating into other training techniques that contribute specifically to improving teams' ability to solve novel and complex problems. A subset of the guidelines for emergency response training focus specifically on ways to enhance teamwork by focusing on the development of specific teamwork skills including adaptability, situation awareness, performance monitoring, interpersonal skills, coordination skills, assertiveness, and decision-making skills. Given that emergency response teams often face high workloads and levels of stress, circumstances, which tend to cause a team to neglect teamwork in favor of taskwork, such teamwork skills are essential to effective performance. Another focus is on the development of shared mental models because such overlapping knowledge structures contribute to fluent team performance in times where explicit coordination is difficult.

What do we recommend? Given the needs that emergency response training can address, it might be particularly relevant to training for LDSF as it can prepare teams for performance episodes that are non-routine and situations where explicit coordination is problematic. In particular, given its ability to address team cognitive processes such as collaborative problem solving, planning, decision making, and SMMs, we recommend this as an area that should be further explored; in particular, it should be evaluated to see how guidelines and techniques from this training could be incorporated into extant training operations.

Adaptive Team Coordination Training

What is it? Team adaptation and coordination training (TACT) is a type of training that teaches teams to recognize changes in the situations they experience and modify accordingly. As part of this, teams are taught to recognize how their stress levels change dependent on the situation; coordination strategies that allow the team to adapt to high-workload situations such as pre-planning, using idle periods, favoring information transmission, anticipating information needs, and redistribution of workload; and, lastly, the ideal conditions for which each strategy should be adopted (Entin & Serfaty, 1999). During the training, teams are provided with a series of vignettes where they can see the difference between effective and ineffective teams when they employ adaptive strategies under high-stress situations. Following this, teams are able to experience a set of practice scenarios to apply what they have learned while receiving performance feedback during and after their interaction. In turn, this training is meant to improve teams' coordinative and communicative mechanisms during periods of high workload or stress. The developers argue that this can occur when formerly explicit processes become more implicit. This training can be enhanced through inclusion of periodic situation briefs, conducted by the team leader, with the goal of improving team situation models (TACT+). To test this training approach, a simulated anti-air warfare experiment with 30 experienced naval officers in five-person teams was conducted (Entin & Serfaty, 1999).

While not the same type of training per se, Gorman et al. (2010) conducted an experiment to assess the effectiveness of training to improve the adaptability of teams. Specifically, perturbation training was given to participants who were preparing to perform in a simulated unmanned aerial vehicle command and control task. The training consisted of exposing team members to perturbations (i.e., disruptions) of critical coordination mechanisms. This was operationalized as disruption of communication modalities during the acquisition of skill for the task.

What do findings show? Results showed performance was significantly improved for both the TACT and the TACT+ training conditions when compared to a pre-training assessment. Also, teams with TACT or TACT+ training were more resilient to stress. Likewise, teams who received the TACT or TACT+ training also demonstrated significantly higher teamwork and communication quality. Lastly, the TACT+ training, which included methods for providing periodic situation updates, improved performance and teamwork above that of just the TACT.

With respect to the Gorman et al.'s (2010) perturbation paradigm, results showed that teams given this type of training, in contrast with cross-training and procedural training, performed better on the majority of the missions that were assessed. This technique provided a mechanism through which teams were able to be more adaptive to unexpected task constraints.

What need does it fill? In sum, with respect to training team cognitive processes, team adaptability and coordination training, as well as perturbation training, are likely candidates to support the needs of personnel involved in long-duration spaceflight missions. Specifically, as outlined above, teams require the ability to perform effectively in both routine and non-routine tasks. Therefore, the types of training detailed here would contribute to team effectiveness particularly for non-routine tasks, but this may also generalize to performance in routine tasks as well, which will be essential for spaceflight crews. Not only this, but the additional benefits of enhanced communication quality as well as resilience to stress are likely indicators of the potential for this training technique.

What do we recommend? Given that these tasks were examined in Department of Defense related tasks, we recommend they be adopted/adapted for NASA contexts. In particular, given the evidence, these strategies show potential as a means for improving team cognition in spaceflight crews, particularly as they gain more autonomy for long-duration missions in which they must adapt to off-nominal events on their own.

Stress Inoculation Training

What is it? Given the impact of stress on performance in long-duration spaceflight missions (e.g., Palinkas, 2007), it is important to examine training strategies shown to help ameliorate the negative effects of stress. In the broadest sense, this form of training teaches individuals and teams how to both identify and ameliorate the negative effects of stress. Stress reduction research has occurred in domains such as emergency response, military, and sports training. Across these domains, we find some results that are relevant to training for LDSF.

What do findings show? First, much research shows positive effects of stress reduction training; however, these strategies appear to be moderated by individual differences in how stress is perceived. For example, individual differences in how arousal is perceived (i.e., as a challenge or as a threat) can impact the types of reactions individuals have in stressful environments, and influence their ability to optimally perform (Kerr, 1997). Furthermore, the impact of affect on performance in competitive environments (which may be similar to other stressful environments) is idiosyncratic and, therefore, difficult to generalize findings from one individual to another (Johnson, Edmonds, Tenenbaum, & Kamata, 2007). Such findings are problematic given that much of the individual-level research examining stress on cognition in space has relied on a very small sample size (sometimes as small as one to three spaceflight crewmembers). Therefore, findings that stressors in a space environment did not result in negative performance for one individual does not necessarily mean that such factors will not negatively impact others (e.g., Casler & Cook, 1999; Eddy, Schiflett, Schlegel, & Shehab, 1998; Kanas et al., 2006; Kanas et al., 2007; Manzey, Lorenz, & Poljakov, 1998).

Second, research in sport psychology has studied how expert athletes respond to stress. For example, experienced performers have been shown to engage in self-regulatory processes that can diminish the negative effects of stress. These strategies are also more elaborate and are applied more frequently and more consistently with experienced performers than by individuals who have little or no experience with the activity (Hardy, Gammage, & Hall, 2001; Hardy, Hall, & Hardy, 2004; Tenenbaum et al., 2008). This implies that as individuals gain experience, they also develop more elaborate methods to cope with the stress, and are able to utilize these resources more often. Some examples of such processes include self-talk, emotional control, imagery, relaxation, and attentional control, which experienced athletes have been shown to use to cope with stress (Hardy, Jones, & Gould, 1996; Cohen, Tenenbaum, & English, 2006). This line of research suggests that stress can be managed by individuals through the use of psychological and emotional self-regulation strategies, which thus allows for optimal affective states and improved performance.

Self-talk has also been shown to influence how individuals cope with environmental stressors, such as loud traffic noises. Vera, Vila, and Godoy (1994) exposed individuals to loud traffic noises and had them read statements aloud that were either negative (e.g., stating that they could not tolerate the noise) or positive (e.g., stating that the noise was tolerable). Participants who read negative statements aloud experienced more anxiety, as measured by physiological responses such as rapid heartbeat and constriction of blood vessels (similar to a flight-or-fight response). Therefore, self-talk can influence reactions in either a negative manner, such that it exacerbates the problem, or in a positive manner, such that it actually improves the situation for participants and thus performance increases (e.g., Hatzigeorgiadis, Theodorakis, & Zourbanos, 2004; Van Raalte et al., 1995).

The use of such self-regulatory techniques has been most recently applied to military members prior to their deployment to Iraq as a prevention for Post-Traumatic Stress (e.g., Stanley, Schaldach, Kivonaga, & Jha, 2013; Wolfsdorf & Zlotnick, 2001). The specific technique, Mindfulness-based Mind Fitness Training (MMFT), is similar to meditation in that it requires participants to focus their attention on an object for a given period of time, focusing on the contact of their body with the floor and chair, and awareness of their own body sensations (Stanley et al., 2013). The impact of MMFT on stress reduction was not clear; however, participants reported improved communication, unit cohesion, self-knowledge, awareness of strengths and weaknesses, and openness to feedback. Additionally, they showed an improved ability to recognize emotions in both themselves and other team members.

What need does it fill? The various forms of stress inoculation and reduction provided empirically evaluated training techniques that can be used to help address the recurrent theme of socio-emotional aspects of LDSF identified in our operational assessment. In particular, given these training techniques can improve the ability of individuals to regulate their own emotions and better recognize the emotions of others in stressful situations, this will likely impact team cognition and performance.

What do we recommend? Given this brief review, and more recent studies looking at stress reduction and inoculation training in a team context, this is an area worthy of further research for LDSF. For example, team members who are unable to cope with stress may begin to displace their frustration on other team members, and lead to a cycle of negativity between team members, as was seen in the team interactions between spaceflight crew (ISS and Mir) and mission control (Kanas et al., 2006; 2007). As such, the implementation of stress training in long-duration spaceflights is likely to improve both psychological health and team interactions, which, in turn, may improve team cognitive processes. Therefore, we suggest that it be adopted/adapted for NASA context given this would support an important theme highlighted by NASA operations personnel. Further, this should not just be considered for the flight crews and ground crews but also for the extended groups involved (e.g., families dealing with stress of members on a long-duration mission).

Training Delivery Methods

The proliferation of technology into every sector of life has changed the delivery modes available in administering training. Whereas 50 years ago the options were limited to the traditional face-to-face lectures in a classroom setting, reading manuals, or watching videotapes, today training modes have expanded to include more technologically advanced and interactive modes of instruction. Beyond the traditional classroom style, where the instructor is in close proximity (visual distance) to the trainee and which can include both lecture and/or discussion, there are now many other modes of training (Arthur, Bennett, Edens, & Bell, 2003). These additional training delivery modes include, but are not limited to, print-based training (using reading material and workbooks), audio-based training (in which training is delivered through audio files with no visual component), video-based training (where trainees are instructed through television, videotapes, or videoconferencing), computer-based training, and simulation-based training. We briefly review a subset of these and discuss their relevance for team cognition training.

Computer-based training (CBT) is particularly useful because of its flexibility in delivery of content. CBT can be customizable to the trainee’s needs as well as adaptive based upon learning progress. This latter development is particularly important and relevant for LDSF in that the training programs, themselves, adapt to the learner, such that the program measures what material is most needed and then adjusts the content of the training to fit the needs of the trainee at any given stage of learning (Buch & Barley, 2002). The benefit of these varied modes of training is that they can be administered at varied locations. However, what must be examined is how much interaction the training affords the learner (i.e., passive versus active) as well as the degree to which it provides opportunities for practice and feedback. These factors will influence the effectiveness of the training. For example, video-based training may provide visual training for how to do a task, but not the opportunity to engage in the trained activity or receive feedback on performance. Conversely, a computer-based training mode can include a simulation of the task for multiple practice opportunities and feedback on performance.

Simulation-based training (SBT), in use for many training initiatives at NASA, may also be tailored specifically for team cognitive processes. SBT typically is able to provide context and situation-specific training that can help individuals develop higher-order cognitive skills (Fowlkes, Norman, Schatz, & Stagl, 2009). Many of the training studies reviewed above rely on SBT for these reasons as well as because they are able to support teams performing complex tasks in ways other training strategies cannot (e.g., Moorthy, Vincent, & Darzi, 2005). Overall, SBT can be used for training a number of team cognitive processes. These include adaptability, shared mental models and transactive memory systems, decision-making skills, as well as a number of macrocognitive skills that contribute to effective team performance (e.g., Fiore et al., 2012; Salas, Rosen, Held, & Weissmuller, 2009; Ward et al., 2008).

Regardless of the mode of training individuals receive, practice and feedback are considered critical in the acquisition of effective performance strategies; and it is generally accepted that the quantity of practice directly relates to performance improvement (Stout, Salas, & Kraiger, 1997). At issue is the opportunity to practice skills. Due to the monotony that will be experienced during LDSF, it is critical that maintenance training of team cognitive skills be built into the mission. Specifically, the ability to continuously practice skills and receive feedback is critical for the maintenance of team cognitive skills. The importance for practice and feedback is particularly evident in non-routine events such as the non-fatal collision with Mir in the 1990s. In this incident, one of the contributing factors for the collision was the lack of simulation training in space (Ellis, 2000). The last training the cosmonaut received was 4 months prior to the collision, while still on Earth. The lack of ability to practice critical skills, or the opportunity to learn to adapt to unforeseen circumstances while in a simulated setting, led to what could have been a fatal mistake. This example underscores the importance of choosing delivery methods that are as adaptive and accessible as possible to the needs of the spaceflight crews and those supporting them on the ground.

To conclude Part IV of our report, we have included Table 5 as an overview of the training strategies we have summarized. In this table, we list methods that can be used for implementing training strategies along with the associated knowledge, skills, and attitudes that the training has been shown to improve. Further, we also include subscripts by each entry to indicate the range of possible methods for evaluating a given training component. Notably, the information in Table 5 contains more than just the specific team cognitive processes we have covered in our report. But, the point here is to demonstrate the widespread utility of some of these strategies for not only improving team cognitive processes, but also the knowledge, skills, and abilities that contribute to team effectiveness.

Table 5. Summary of Training Strategies, Delivery Methods and Associated Knowledge, Skills, and Attitudes

Training Strategy	Method	Knowledge	Skills	Attitudes
Event-Based Training / Scenario-Based training	• Simulation • Paper-and-Pencil Vignettes • Role Play • Embedded Instructional Agent	• Task Knowledge[1,2,3,5,6,7] • Equipment Knowledge/ Technology Model[1,2,3,5,6,7] • Characteristics[1,2,3,5,6,7] • Situation Awareness[4, 5,7,8] • Team Interaction Knowledge[1,3,5,6,7] • Transactive Memory Systems[2,3,5,6,7] • Larger Mission[2,5,7] • Constraints[5,6]	• Mission Analysis[9,10,11] • Goal Specification[9,10,11] • Planning[9,10,11] • Mutual Performance Monitoring[9,10,11] • Monitoring Goal Progress[9,10,11] • Systems Monitoring[9,10,11] • Task Structuring[9,10,11] • Adaptability[9,10,11] • Conflict Resolution[9,10,11] • Assertiveness[9,10,11] • Boundary Spanning[9,10,11] • Team Leadership[9,10,11] • Stress Management[9,10,11] • Decision Making[9,10,11] • Affect Management[9,10,11] • Compensatory Behavior[9,10,11] • Information Exchange[9,10,11] • Motivating[9,10,11] • Intra-team Feedback[9,10,11] • Coordination[9,10,11] • Cooperation[9,10,11] • Flight Skill[9,10,11] • Navigation[9,10,11] • Risk Assessment[9,10,11] • Visual Scanning[9,10,11] • Handoffs[9,10,11] • Teamwork[9,10,11]	• Risk Perception[12, 13]

Training Strategy	Method	Knowledge	Skills	Attitudes
Self-Correction Training / Guided Self-Correction Training	• Lectures • Behavioral Modeling • Use of structured after action reviews • Simulation	• Task Knowledge[1,2,3,5,6,7] • Equipment Knowledge/ Technology Model[1,2,3,5,6,7] • • Teammate Characteristics[1,2,3,5,6,7] • Situation Awareness[4, 5,7,8] • Team Interaction Knowledge[1,3,5,6,7] • Transactive Memory Systems[2,3,5,6,7] • Larger Mission[2,5,7] • Constraints[5,6]	• Mission Analysis[9,10,11] • Goal Specification[9,10,11] • Strategy Formulation[9,10,11] • Mutual Performance Monitoring[9,10,11] • Monitoring Goal Progress[9,10,11] • Systems Monitoring[9,10,11] • Task Structuring[9,10,11] • Adaptability[9,10,11] • Conflict Resolution[9,10,11] • Assertiveness[9,10,11] • Boundary Spanning[9,10,11] • Team Leadership[9,10,11] • Stress Management[9,10,11] • Decision Making[9,10,11] • Affect Management[9,10,11] • Compensatory Behavior[9,10,11] • Information Exchange[9,10,11] • Motivating[9,10,11] • Intra-team Feedback[9,10,11] • Coordination[9,10,11] • Cooperation[9,10,11] • Flight Skill[9,10,11] • Navigation[9,10,11] • Risk Assessment[9,10,11] • Visual Scanning[9,10,11] • Handoffs[9,10,11] • Teamwork[9,10,11]	• Risk Perception[12, 13,14] • Motivation[12, 13] • Trust[12, 13] • Loyalty[12, 13] • Team Satisfaction[12] • Cohesion[12, 13] • Team Psychological Safety[12, 13] • Affect[12, 13, 14] • Collective Efficacy[12, 13] • Team Commitment[12, 13] • Trust in Automation[12, 13]

Training Strategy	Method	Knowledge	Skills	Attitudes
Cross-Training	• Lectures • Role Play • Behavioral Modeling • Paper-based vignettes • Simulation based vignettes • Embedded Instructional Agents	• Task Knowledge[1,2,3,5,6,7] • Equipment Knowledge/ Technology Model[1,2,3,5,6,7] • Teammate Characteristics[1,2,3,5,6,7] • Team Interaction Knowledge[1,3,5,6,7] • Transactive Memory Systems[2,3,5,6,7]	• Adaptability[9,10,11] • Cooperation[9,10,11] • Coordination[9,10,11] • Decision Making[9,10,11]	
Stress Training	• Lectures • Behavioral Modeling • Simulation • Vignettes • Embedded Agents	• Mental Models[1,2,3,4,5,6]	• Stress Management[9,10,11] • Affect Management[9,10,11]	• Risk Perception[12, 13]
Team Adaptation and Coordination Training	• Lectures • Behavioral Modeling • Simulation	• Team Interaction Knowledge[1,3,5,6,7] • Team Knowledge/ Team Characteristics [1,2,3,5,6,7]	• Monitoring[9,10,11] • Adaptability[9,10,11] • Compensatory Behavior[9,10,11] • Cooperation[9,10,11] • Coordination[9,10,11] • Teamwork skills[9,10,11] • Temporal patterns of team performance[9,10,11] • Collaboration[9,10,11] • Inter-team Communication[9,10,11] • Dynamic Reallocation of Functions[9,10,11] • Information Exchange[9,10,11] • Workload Distribution[9,10,11]	• Collective Efficacy[12, 13] • Perceived Support[12, 13]

Training Strategy	Method	Knowledge	Skills	Attitudes
Team Building	• Role Play • Behavioral Modeling • Ropes Courses • Interactive Collaborative Exercises • Trust Games • Ice Breakers	• N/A	• Motivational Skill[9,10,11]	• Motivation[12, 13] • Trust[12, 13] • Perceived Support[12, 13] • Loyalty[12, 13] • Team Satisfaction[12] • Cohesion[12, 13] • Team Psychological Safety[12, 13]
Superscript Key Detailing Methods for Evaluating Listed KSAs		1=Concept Map 2=Card Sorts 3=Pairwise Ratings 4=Queries 5=Questionnaires 6=Verbal Protocols 7=Communication Analysis 8=Eye Trackers	9=Questionnaires 10=Communication Analysis 11=Observation Scales	12=Questionnaires 13=Communication Analysis 14=Physiological

Part VI: Operational and Research Recommendations

In Part VI of this report, we present our operational and research recommendations based on our literature review and our operational assessments. We categorize our recommendations according the each of the critical team cognitive processes detailed in our report (e.g., shared mental models, transactive memory systems, collaborative problem solving, team decision making, and team planning). Further, our operational recommendations are typically grouped into recommendations for training, selection, and monitoring; however, as appropriate, additional content was added based on areas of importance identified in our operational assessments.

Shared Mental Models

Training: The extant literature has provided overwhelming support for the notion of shared mental models and evidence of its impact on team processes by allowing all team members to metaphorically be "on the same page" with regards to having a common conceptualization of the problem or task, teamwork, roles, equipment, etc. Therefore, training operations that support the development of SMMs should be a priority. Training methods such as *team planning* (Stout et al., 1999), *self-correction training* (Blickensderfer et al., 1997), *knowledge sharing training* (Sikorski et al., 2012), *team-correction training* (Smith-Jentsch et al., 2008), and *cross-training* (Marks et al., 2002) have been shown to improve similarity in teams' SMMs as well as lead to improvements in performance. The decision of which methods are most beneficial to be utilized in LDSF will be impacted by which training methods are capable of being flexible enough to be administered with minimal reliance on external variables (e.g., communication delays with Earth), as well as consideration as to which types of training rely on cognitive processes may be less negatively impacted by spaceflight variables such as microgravity or radiation.

Additionally, another area of research that will need to be conducted is how the replacement of a team member relatively close to launch impacts the reestablishment of shared mental models. It is possible that the new member will simply develop their shared mental model to match that of his/her teammates; however, because the team has already trained together and formed both cognitive and emotional bonds with each other, it may be wise to either re-select the entire team again. Re-training the entire team with the one additional member may create feelings of resentment for the repetition of training; however, if the team was re-selected again to account for the new changes in the team's composition and dynamics as a result of the new configuration of personalities, knowledge, skills and abilities, then the resulting team may be superior to the modified (new member) team.

Selection: Individuals can be selected based on assessment of their ability to take others' perspectives and whether they are open to new ideas that may help foster improved shared mental models. Personality variables that contribute to the successful development of shared mental models should be considered as well. Recent research has shown that an individual's agreeableness is significantly related to the development of shared mental models, which leads to team effectiveness (Yang, Kang, & Mason, 2008). However, teams composed of individuals who are all high on the trait of agreeableness may risk creating teams that engage in group-think, or lack the ability to generate creative solutions to problems due to the lack of divergent thinking. Thus, the proper balance of different characteristics is needed to ensure that any given personality type does not dominate the group. Other personality variables that are influential in communication skills are also likely to be critical in selecting team members that are more likely to develop shared mental models. Given the international nature of the future teams, cultural training will be essential for all space crew, and a common language will be an important factor in developing an integrated crew for facilitated communication and to prevent the isolation of team members.

Monitoring: Several methods for measuring shared mental models exist in the literature. Paired-comparisons, card-sorts, concept mapping, importance ratings (similarity), priority rankings, questionnaires, communications analyses are all techniques that are commonly used for assessing and monitoring shared mental models. However, many of these methods are time consuming due to the numerous connections that are explicitly measured between concepts (e.g., paired comparisons), and often, the task of making these comparisons is contrived – both which are drawbacks of the measurement of shared mental models, particularly in demanding situations such as during spaceflight or operations. However, the type of metric selected has implications for the predictive capabilities of the measure; therefore, the selection of a measurement method must not be made solely on ease and speed of administration. For example, mental models measured using structural networks metrics, such as paired-comparisons, have been found to be better predictors of team adaptation and performance than other (quicker) methods such as ranking priorities or rating importance of variables/information/etc. (Resick, Murase, Bedwell, Sanz, Jimenez, & DeChurch, 2010). Therefore, researchers must be mindful of the benefits and consequences of measurement techniques utilized.

Composition: Previous research has suggested that some types of mental model formations are more impactful on team performance than others. For example, teamwork-based mental models are more impactful on mission success and performance than taskwork models (Cooke et al., 2007). This also underscores the importance of selecting individuals who are more likely to engage in teamwork activities, which may foster shared mental models. Additionally, the sharedness and accuracy of shared mental models are not interchangeable. A team may have a shared, but inaccurate representation of a situation. This is further complicated by the fact that there may be multiple correct mental models to choose from, in which sharing the same (accurate) mental model is important (Smith-Jentsch, 2009). When multiple correct mental models exist, the ability of the team to discuss and agree upon a shared understanding of how to interact (i.e., teamwork mental model) will be important.

Research: Current measurement methods for shared mental models are often long and time consuming, particularly when using more predictive methods such as paired-comparisons. Therefore, either new methods of shared mental model measurement need to be developed for use in real-world settings where there are severe time constraints preventing the use of very long and time consuming paper measures, or current methodologies that have proven effective in predicting important team processes (such as team adaptation) need to be modified such that they can be administered in a less time-consuming manner. The development of such methods would allow long-duration spaceflight teams to be able to routinely evaluate their shared mental models to assess where discrepancies exist that may impact mission success. This would also allow researchers to examine the impact of various variables of spaceflight on the process of development of shared mental models. Additionally, more research is needed to examine the types of individual traits, such as personality, that are most conducive to the development of shared mental models. The training for shift handovers would be an ideal setting for examining the development of shared mental models on Earth. Also, in a spaceflight setting, examining shared mental model formation during synch points (similar to debriefing exercises) during training exercises would be a good opportunity for shared mental model research.

Transactive Memory Systems

Training: Previous research has demonstrated that training as a unit (rather than individually) improves the development of transactive memory systems (Moreland & Myaskovsky, 2000). This allows individuals to learn about the skills, knowledge, and abilities (KSAs) of their teammates, which is incorporated into their transactive memory system. Training often focuses on how to perform a specific task. Through the training, individuals learn the strengths and weaknesses of their teammates; however, training to develop a strong TMS should include more than just proficiency on a task, but also interaction techniques that will not only aide in the development of a shared mental model of teamwork processes and communication norms, but also provide individuals with ways in which they can update and develop their TMS regarding the qualifications (i.e., KSAs) of the individuals or units with which they interact. This may be particularly relevant during long-duration spaceflight when crewmembers are involved with continuous training, or learning of system maintenance for example, in efforts to make the crew less reliant on ground support as the distance between Earth and the space destination increases. The continuous learning of new techniques regarding the shuttle and emergency tactics means that the knowledge of team members may change over the course of the mission (especially on a long mission to Mars, for example). Therefore, the continuous updating of the transactive memory system of the space crew will ensure efficient team processes during a high-intensity, off-nominal event.

Selection: The method of communication between mission control and the spaceflight crews creates a centralized communication structure (i.e., only one individual from mission control verbally communicates to the spaceflight crew, thus there is a centralized individual who must have a strong transactive memory system of both the mission control personnel and the spaceflight crew; Mell et al., 2013). Selecting individuals who are able to effectively communicate, have strong teamwork skills, and are able to mentally process large amounts of information regarding the knowledge, skills, and abilities of both crews to best direct questions or information will be important. The importance of selecting based on this cognitive process is significant given the delays that ground crews will face in communicating with the flight crew during LDSF missions.

Monitoring: Questionnaires regarding the distribution of knowledge in the team, communication analyses, and paired-comparison matrixes are commonly used to assess TMS. As previously discussed in the shared mental model section, paired-comparisons often take a long time to administer and may not be appropriate for use in spaceflight due to the amount of time it takes away from other functions (as well as the negative testing effects it causes for astronauts to engage in activities). Therefore, communication analyses (at least in training) may be best suited for spaceflight. However, when the spaceflight crews are further away from Earth (and thus the communication delay is greater), other paper-and-pencil methods may be more feasible. Ideally in long-duration spaceflight the crew will be able to facilitate the exchange of information such that they are able to discuss the strengths and weaknesses of crewmembers in a constructive, learning-focused way that allows for both the development and maintenance of TMS and the ability to self-diagnose areas for individual improvement. Techniques such as the Guided Team Self-Correction (Smith-Jentsch, Cannon-Bowers, Tannenbaum, & Salas, 2008) in which a well-structured debriefing session is conducted by the team members and which promotes error-management training (i.e., mistakes are good opportunities for learning). This would provide a setting where crewmembers are able to follow a structured method for discussing events that have occurred, which may lead to improved TMS of crewmembers in addition to improving skills, shared mental models, and communication among crewmembers.

Research: Assessments of TMS in spaceflight and ground crew operations are needed, particularly when using virtual communication under conditions of communication lags. Additionally, research needs to examine the impact of changing key personnel mid-mission, such as the flight director or the CAPCOM, as unforeseen events (e.g., accidental death) may change the team functioning; especially with regards to members who interact primarily with the space crew, such as the CAPCOM. Previous studies have demonstrated the difficulties of developing TMS in virtual teams, research has shown that face-to-face interactions are better for the development of TMS (Hollingshead, 1998). Given that LDSF crews are stable once the mission has begun, the difficulties will lay in the TMS development for mission control, and between mission control and the space crew. Research into how TMS can be measured in a more natural manner that is appropriate for repeat measurement over the course of a long-duration space mission is needed. The current methods for measuring TMS (e.g., Lewis, 2003) are not likely to be used repeatedly during space missions due to the repetitive nature of answering the same questions; however, if a TMS measure was integrated into a more useful technique, such as a debriefing method (e.g., Smith-Jentsch et al., 2008), then space crews would be able to assess TMS while achieving other goals that may be more embraced by space crews such as improving team performance on a specific task.

Collaborative Problem Solving

Training: Instructional strategies should be incorporated into current training operations that *measure* and *enhance* collaborative problem-solving processes such as team knowledge building and others. In particular, *knowledge building training* can improve the transfer of knowledge from one team member to another, knowledge interoperability (i.e., knowledge that multiple team members are able to recall and use), cognitive congruence (i.e., an alignment or matching of team member cognitions), and higher overall team performance on the task (Rentsch et al., 2010). Because the exchange of knowledge is critical to collaborative problem solving, providing this type of training will improve teams' ability to solve problem. An important consideration would be cross-team knowledge building training that incorporates the organizational structure of Mission Control and the spaceflight crew.

Another way to improve team abilities to collaborative problem solving would be through *perturbation training,* which has been shown to improve team performance in responding to routine scenarios and adapting to novel problems (Gorman et al., 2010). Specifically, by using training scenarios that already require teams to work together to solve problems, and then introducing a perturbation (i.e., disrupting) to some critical communication modality, teams will develop the ability to be more adaptive and resilient when complex problems arise.

Selection: The relationship between collaborative problem solving processes and performance should be established. Such information can serve as an indicator that can inform the selection and composition of teams. It is possible that the current selection criteria for teams may be inadequate for LDSF due to the increased likelihood for interpersonal conflict, boredom and/or loneliness effects, impacts of psychological stress or environmental factors, etc. All of these factors can impact both interpersonal processes, which will consequently impact collaboration and collaborative problem solving. This may also impact mood, which consequently impacts mental flexibility in problem solving (Gasper, 2003). Thus, it is not enough to pick the most expert individuals in their fields, one must also consider the underlying processes that may foster better outcomes (such as collaborative problem solving).

Monitoring: Given that the crew and ground will likely be out of synch with regards to their stage of planning during an off-nominal event that occurs during LDSF, research needs to examine methods to ensure that both parties are in synch and how to adapt to changes in situations where one team (e.g., mission control) is out of synch with what is happening onboard the space vehicle. It may be useful to utilize and expand current tools such as the Collaboration Process Analysis tool (Seeber, Maier, & Weber, 2013) to monitor collaboration as it is occurring during training and during actual performance. Automating such methods would be an extremely useful means of monitoring collaborative problem-solving ability.

Research: Both the processes and phasic aspects of collaborative problem solving need to be examined across the boundaries of mission control teams and spaceflight crews in both actual and simulated spaceflight scenarios. Right now, ground support is able to diagnose and begin solving problems in real time with the space missions; however, this will not always be the case. More research is needed on how to train teams to solve problems in asynchronous situations. Time-stamped communications data are needed for such research to be conducted.

Additionally, research is needed as to how mission control can better support space crews in anticipation of off-nominal events when they are significantly time delayed from information and communication with the crew. Mission control has access to multiple experts in various fields to diagnose, problem solve, and provide recommendations to issues that arise on the space station or in shuttle missions; however, during long-duration spaceflight missions, the crew will not have the benefit of immediate access to such teams of experts. Solutions to both worst-case scenarios (as well as more likely problems that may arise) should be continuously developed and tested on the ground, and then uploaded to the crew's onboard library for them to review while on a long-duration mission. This would keep both the ground engaged in the mission and provide a useful service to the crew that can be referenced during emergencies, as well as provide continuous learning material to the crew to prevent boredom while in transit. Research into the optimal methods of conveying complex information to the crew that can be easily comprehended and used in an emergency will be essential (e.g., "space cliff-notes"). These quick guides would be supplemental to the more detailed, technical guides that can be used for training while in space, while still providing a quick reference guide to use during emergency situations with potentially severe time pressures.

Team Decision Making

Training: Current training operations need to provide the opportunity for teams to make decisions in varying hierarchies under high-stakes, ambiguous, and time-constrained scenarios that may include shifting goals (Orasanu, 2011). Involving the space crews in some of the meetings for the development of the generic flight rules and mission flight rules will allow them to gain insights into the process by which the experts in mission control use to make the decisions regarding the course of actions for off-nominal events. This may aide the space crews in their own decision-making processes when they are out of communication range and need to make decisions independently of ground support for a situation that is novel. Further, during *simulated long-duration missions,* such as the Mars 500, training team decision-making processes would be ideal in that it is analogous to actual missions.

Selection: Measuring staff validity and hierarchical sensitivity during simulated training scenarios can be used as metrics for selecting and composing a team as well as team leaders, respectively. That is, by having the team perform simulated missions, the quality of the decisions and the metrics can be examined and used to determine the idea individuals for certain positions.

Monitoring: The decisions made by mission control and spaceflight teams should be monitored and documented both as a means to assess decision quality as well as to provide feedback and training for future missions to examine how team decision making will be impacted by the lessened role of mission control in long-duration space exploration missions. Data logs and communications reports and analysis provide a means of monitoring team decision making.

Research: Team decision-making research is required in the context of mission control teams and spaceflight crews in both actual and simulated spaceflight scenarios; particularly, when space crews are forced to face off-nominal problems that are traditionally supported and directed by mission control in real time (versus during delayed communication with the space crew). Research into how mission control will be able to most effectively address problems when they have less contact and feedback from the space crew will be needed. The development of detailed written or video protocols that the crew can access in emergencies, which are easy to understand when under pressure, will be necessary, especially when the crew is faced with diagnosing issues that are typically handled by the multiple experts on the ground.

Team Planning

Training: Training should support team planning by providing opportunities for development of the three main types of plans, measuring the quality of the plans, and providing feedback (Stout et al., 1999). Pre-flight training should include simulations in which team members utilize deliberate, contingency, and reactive-strategy planning independent of outside assistance from mission control. Teams should provide feedback by employing debrief meetings (similar to synch points) in which members discuss recent experiences, identify areas needing improvement, and set goals. Debrief meetings have been shown to increase team effectiveness by up to 20% (Tannenbaum & Cerasoli, 2013). Specifically, team-led guided debriefs throughout the planning process have been shown to result in superior team processes (Eddy, Tannenbaum, & Mathieu, 2013). Demonstrating the incremental benefits of structured debriefing activities while in spaceflight may be essential to get the buy-in of participants who may not fully realize the benefits of such activities, and thus may not actually use it in practice when not under supervision of ground support.

Selection: Teams can be selected and composed based on evaluations of their collective team planning. Team dynamics can be tested during simulations to determine which iterations of group members display highest-quality team planning and performance outcomes.

Monitoring: Extensive planning occurs in current operations that can be assessed for quality based on team planning quality detailed in Stout et al. (1999). *Team Planning Quality* can be assessed by ratings of team planning dimensions of goal setting, clarification of team member roles, prioritization of tasks, assessment of what types of information all team members require access to and those only required by specific team members, and also, how team members intend to back each other up in the event of errors Additionally, *plan formality* can be assessed to determine the extent to which teams utilize deliberate planning in their meetings. Greater plan formality is linked with greater performance outcomes (Mathieu & Schulze, 2006). To identify areas of strength and weakness, monitoring can differentiate between taskwork and teamwork planning using the model set forth by Fisher (2013). Feedback in these areas can be addressed during team-led guided debriefs in which performance deficits are directly linked planning strategies that were not successful. Teams can then implement changes in strategy and planning.

Research: Team planning research is required in the context of mission control teams and spaceflight crews in both actual and simulated spaceflight scenarios, particularly in long-duration missions. Future research should focus on identifying which of the two proposed models of team planning (three-sub-dimensions vs two-factor) more closely relates to team planning in simulated and actual spaceflight. Additionally, the flight control processes are currently predicated on the fact that the crew has rapid ground support, which has access to both trend (long-term) data as well as the support of multiple teams of experts weighing in on the decisions. Crews will need to make decisions and plans using limited information and resources, which will require greater research on how to provide more information to crews such that the information can be quickly and easily comprehended in an emergency, and how mission control can assist in this new dynamic. Furthermore, the space vehicle itself may need to be redesigned to allow the crew to be able to diagnose and repair the vehicle with less direct assistance from ground support.

Part VII: Conclusion

In short, the challenges facing astronauts on long-distance missions arise from a complex combination of physiological, psychological, and technological factors. NASA has detailed, for many years, the problems of sleep disruption on health and well-being. NASA has also studied the challenges arising from confinement. Similarly, in various ways, NASA has attended to the problems of hazardous radiation exposure to crew health. NASA is now studying more closely the psychosocial factors that can contribute to crew well-being.

To conclude, the objective of this report was to provide a detailed summary of the many aspects of the project we pursued when investigating team cognition in the context of LDSF. First, we provided a summary of our review of research conducted in space or close analogs examining individual cognition. Next, we provided an overview of team cognition and described the foundation from which the project was conducted. We focused specifically on a set of critical team cognitive processes including shared mental models, transactive memory systems, collaborative problem solving, team decision making, and team planning. We connected each of these critical team cognitive processes back to individual cognition and provided an account for how individual cognitive processes would scale up to the team level in the context of LDSF. From this foundation, in the next section, we made specific predictions regarding how decrements to individual cognitive processes due to LDSF conditions would affect team cognitive processes. Following this, we provided a high-level overview of the major themes we discovered in our operational assessment. Then, we described and evaluated methods used to train and improve team cognition and, to the extent possible, related this to training for long-duration spaceflight missions. Following our detailed review of team training to improve team cognition, we provided a systematic set of recommendations and consideration for the operation and research contexts based upon both our literature review as well as our operational assessments with NASA experts. In short, team cognition is an underexplored area in the context of LDSF. It has been our aim to redress this gap by higlighting a detailed path forward both for NASA research and operations.

We end this report with a recommendation. This recommendation looks to the past for guidance on the future. Over half a century ago, in one of the first articles on human spaceflight, Clynes and Kline (1960) evaluated the varied possibilities and needs for successful missions in space. This article is noteworthy for its visionary stance and the creation of the concept of a cyborg. This was their prescient recognition of the need to consider the very real possibility of combining cybernetics with biological organisms. The stated that the term “cyborg” be used to describe an "exogenously extended organizational complex functioning as an integrated [unconscious] homeostatic system” (p. 27). What they meant was that machine and astronaut realistically become a hybrid system. Although one could argue that NASA spent the next several decades, through the creation of the space suit etc., doing just that, the larger point they were making was lost. In particular, Clynes and Kline noted: “The environment with which man is now concerned is that of space. Biologically, what are the changes necessary to allow man to live adequately in the space environment? Artificial atmospheres encapsulated in some sort of enclosure constitute only temporizing, and dangerous temporizing at that, since we place ourselves in the same position as a fish taking a small quantity of water along with him to live on land. The bubble all too easily bursts” (p. 27).

Stated most simply, what they were suggesting was not that we should work to change the environment of space to suit the needs of humanity. They were not arguing that we build spacesuits and capsules that will keep us safe from the hazards of space by recreating the environment in which we live. Rather, they were pushing us in a more visionary way. Specifically, they suggested that humanity evolve itself to be suited for space. Their concept of a cyborg was the first step in that direction. If we are able to partially adapt our biology, rather than trying to create an artificial environment in space, we open up a range of possibilities for long-duration and long-distance missions. Considering this, now in light of decades of findings about human physiology and cognition changing because of spaceflight, microgravity, and radiation, this call for evolving our physiology is now more warranted than ever. Furthermore, thanks to advances in genetics, neuroscience, and general medicine, identifying physiological differences that make one more resilient to space environments is now possible. Considering how that can be leveraged to change human physiology more generally, should also be part of any research program on long-distance space missions. Coupling this idea with advances in neurotechnology and biotechnology makes their vision all the more realizable. In this way, the concept of astronaut as cyborg, and the crew as a team cognitive cyborg, can be used to help us imagine what is not only necessary, but what could be possible to advance humanity, and help us to reach the stars.

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13. ABSTRACT *(Maximum 200 words)*

To date, most spaceflight research has examined only individual cognitive factors, when it is often the team cognitive processes of space and ground crews that lead to successful missions. Toward this end, our research took a multidisciplinary literature review and operational assessment approach to form the foundation for understanding the issues surrounding team cognition for future long-duration space exploration missions. On the one hand, we conducted an extensive review of research examining individual cognition in space. With this firm grounding in empirical research on cognition in space, we integrated this with research done on team cognition in complex, albeit, non-space environment. Such comparisons allowed us to identify key individual cognitive factors that potentially contribute to team-level cognitive processes critical for the maintenance of effective and adaptive team performance and overall, crew well-being. As such, we discuss issues related to, or supporting, team cognitive processes, and current methods used to address these in other relevant domains. In turn, the results of our literature review and operational assessment take the form of recommendations for future research related to training, selection, composition, and monitoring critical team cognitive processes that are consistent with operational needs.

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