Organizing for Mars: A Task Management Perspective on Work within Spaceflight Multiteam Systems

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Objective: The aim of this study was to examine how task, social, and situational factors shape work patterns, information networks, and performance in spaceflight multiteam systems (MTSs).

Background: Human factors research has explored the task and individual characteristics that affect decisions regarding when and in what order people complete tasks. We extend this work to understand how the social and situational factors that arise when working in MTSs affect individual work patterns.

Methods: We conducted a complex multi-site space analog simulation with NASA over the course of 3 years. The MTS task required participants from four teams (Geology, Robotics, Engineering, and Human Factors) to collaborate to design a well on Mars. We manipulated the one-way communication delay between the crew and mission support: no time lag, 60-second lag, and 180-second lag.

Results: The study revealed that team and situational factors exert strong effects: members whose teams have less similar mental models, those whose teams prioritize their team goal over the MTS goal, and those working in social isolation and/or under communication delay engage longer on tasks. Time-on-task positively predicts MTS information networks, which in turn positively predict MTS performance when communication occurs with a delay, but not when it occurs in real-time.

Conclusion: Our findings contribute to research on task management in the context of working in teams and multiteam systems. Team and situational factors, along with task factors, shape task management behavior.

Application: Social and situational factors are important predictors of task management in team contexts such as spaceflight MTSs.

Keywords: dual task, time sharing, task switching, shared/team mental models, team collaboration, team coordination, team cognition

INTRODUCTION

Sometime in the 2030s, space agencies around the world plan to embark on an interplanetary mission to Mars. Among the scientific puzzles that must be solved prior to launch is how to best organize the crew and its support teams for success. Space missions require an extreme form of teamwork such that specialized experts working in small teams must coordinate their expertise with other teams. Such work units have been formally defined and investigated as multiteam systems (MTSs; Mathieu et al., 2002; Zaccaro et al., 2012). In the space exploration context, the crew and mission support teams collectively comprise a spaceflight multiteam system (SFMTS; Pendergraft et al., 2019). Work on a Mission to Mars will require alternating between tasks focused on individual, team, and multiteam goals. At each foci, the degree of interdependence of the work increases. Existing work on MTSs document greater challenges in coordinating work *between* teams as compared to *within* teams (Davison et al., 2012; DeChurch & Marks, 2006; Marks et al., 2005). On a Mission to Mars, component teams will be separated by millions of miles and subject to one-way communication lags of up to 22-minutes.

NASA-affiliated scientists are actively investigating the many performance challenges inherent in deep space exploration (Landon et al., 2018; NASA, 2017; Salas et al., 2015), including high-workload, high-tempo, long periods of boredom, and extended isolation (Salvucci, 2013; Wickens et al., 2016; Wickens & McCarley, 2008). Given the multiteam nature of space exploration, we consider factors that

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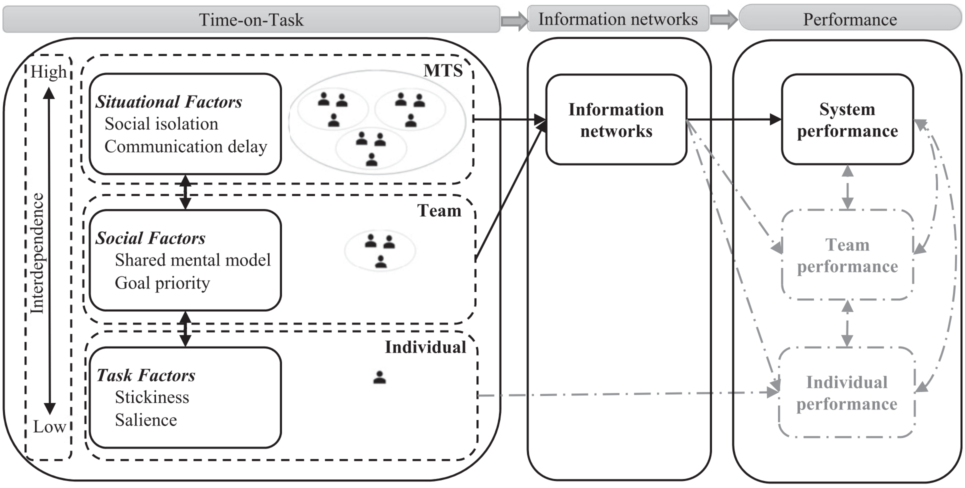

Figure 1. Conceptual framework linking task management to multiteam performance. *Note.* The dotted lines highlight additional relationships and constructs that, though not studied in this paper, connect the current research with previous work in human factors on task management.

shape the task management behaviors of crew members alternating between individual, team, and between-team tasks. Previous work identifies task and individual characteristics that shape when and in what order people complete tasks (cf. Salvucci, 2013; Wickens et al., 2016; Wickens & McCarley, 2008). We extend this work to understand the role of team and situational factors in task management. Figure 1 provides a visual of our conceptual model, which integrates the role of task (e.g., stickiness, salience), social (e.g., shared cognition, level of goal priority), and situational factors (e.g., communication delay, social isolation) in determining how long individuals spend on tasks. We investigate this model using data collected in a NASA space analog.

Task Management in Spaceflight Multiteam Systems

Spaceflight MTS performance is the result of the combination of individuals' performance on tasks directed at individual, team, and system (DeChurch & Zaccaro, 2010; Mathieu et al., 2018; Salas et al., 2008). Effective performance relies on the extent to which people appropriately prioritize, organize, and accomplish work. Given the multiple goal foci—and tasks required of each—individuals working in MTSs engage in a form of multitasking. Research suggests multitasking can result in "switch costs" in the form of process loss associated with inefficient task switching and inopportune (e.g., working memory loss, lengthened time to complete tasks, interference from strategies appropriate to prior task sets; Salvucci & Taatgen, 2008). Therefore, individuals who (1) spend more time on task, and those who work on tasks (2) continuously rather than iteratively, and (3) sequentially rather than concurrently, are likely to outperform those who switch tasks frequently or attempt to attend to more than one task at a time (Koch et al., 2018; Wickens & Gutzwiller, 2017). Interestingly, task performance (Payne et al., 2007) and objective task priority (Wickens et al., 2016) are not consistently associated with efficient task-switching decisions.

Working in a spaceflight MTS exponentially increases the cognitive load needed to prioritize, manage, and accomplish work (Fox et al., 2020; Gutzwiller et al., 2019; McDonald et al., 2015; Wickens et al., 2015). Prior research suggests that time-on-task affects performance due to the allocation of finite cognitive resources. We extend this logic to the spaceflight MTS work context (Mesmer-Magnus et al., 2020), and test the idea that time-on-task affects MTS performance through the mechanism of information networks.

Task-Related Predictors of Time-on-Task

Prior research identifies task-related impetuses steering individuals to continue attending to an ongoing task versus switching to an alternative task. Wickens and colleagues' (2015) strategic task overload management (STOM) model organizes task-related factors that together predict the "stickiness" of an ongoing task versus the "attractiveness" of an alternative task. Stickiness is predicted by (1) *difficulty* (the degree to which a task is effortful and requires a high cognitive load), (2) *interest* (the degree to which the task is engaging), and (3) *importance* (the degree to which a task is comparatively more important to goal attainment than alternate tasks). Together, these factors should predict lengthier time-on-task (task stickiness) for several reasons. First, people are ultimately guided by the principle of inertia, so they are more likely to continue with an ongoing task rather than switch to an alternate (Csikszentmihalyi & Kleiber, 1991). Second, difficult ongoing tasks have likely required a significant investment of cognitive resources which prompt workers to remain on the task until completion in order to ensure a return on resource investment (Wickens et al., 2016). Third, although objective task priority is not consistently associated with task management behavior, subjective assessments of task priority/importance logically interact with perceptions of task interest prompting inertia rather than switching.

The *salience* of a task can also affect the degree of inertia to remain on the task. Salient tasks are those that are accompanied by reminders or explicit instructions and have auditory or visual cues that attract attention. Though the STOM model typically includes salience of an alternative task as an attribute that affects switch likelihood (Wickens et al., 2016), given our emphasis on sustained attention, or time-on-task, we include it as an attribute of ongoing tasks. Like difficulty, interest, and importance, we expect the salience of an ongoing task would positively affect time-on-task.

Thus, as articulated in prior work by Wickens and colleagues, task factors affect task behavior. Given that individuals are the building blocks of SFMTSs and their thoughts and actions contribute to task accomplishment, it is logical to expect that individuals' task behaviors ultimately affect system functioning. In the next section, we will consider how the embedding context of the individual—the team and situation—also affect task behavior beyond the role of task factors. According to Wickens' research, we expect that at the task level (i.e., within-person):

H1: Task stickiness (H1a) and task salience (H1b) are positively related to time-on-task.

Social-Related Predictors of Time-on-Task

In order to extend the task management concept to the MTS context, we next consider the role of social factors in teams as teams represent the most immediate social context of work for an individual. Extensive prior research on teams finds that cognitive emergent states affect behavioral processes. Two such properties found to shape behavior are (1) shared mental models (Cannon-Bowers & Salas, 2001) and (2) team goal motivations (Courtright et al., 2015). Shared mental models refer to commonly held knowledge about the task and team that allows members to anticipate and execute actions effectively (DeChurch & Mesmer-Magnus, 2010b; Kozlowski & Ilgen, 2006). When team members exhibit a shared understanding of their environment, roles, and responsibilities, individuals can work effectively without the need for explicit coordination/communication (DeChurch & Mesmer-Magnus, 2010a; Mesmer-Magnus et al., 2017). Conversely, less similar mental models may require more frequent communication and/or interdependent work time.

H2a: Team mental model similarity is negatively related to time-on-task.

Team goal priority is defined as the relative value a team places on individual, team, or multiteam goals. Individual goals involve less interdependence, and they are not mutually reliant on the actions of others, whereas team goals are more interdependent, relying on at least one other individual. Multiteam goals are even more interdependent, relying on the combined actions of at least one individual on a different team. Team goal priority, reflecting the motivational intention to focus on goals at the individual, team, or system level is a second aspect of the team social context affecting behavior within SFMTSs. Prior research finds goal priorities are an emergent property that regularize into a shared belief within the team about which foci is the most important (Carter, 2016). When teams prioritize the MTS goal, members will prioritize tasks that contribute to the goal attainment of the larger system. Conversely, teams who prioritize team or individual goals may have members who contribute less to tasks leading to system goals in favor of goals at lower levels.

The level of goal a team prioritizes shapes tendencies toward time-on-task due to differences in interdependence and coordination (Courtright et al., 2015). Pursuing individual goals enables members to work more independently than when pursuing team goals and allows them to switch tasks less frequently because they require less input from others. Team goals, in contrast, prompt interdependence, requiring input from other team members and thus prompting more frequent switching (and less time-on-task) to collaborate with one's teammates. The coordination required by an interdependent task necessitates more shifts in attention than do fewer independent tasks. Prioritizing a multiteam goal amplifies the required degree of coordination, and thus task switching. Teams whose members prioritize MTS goals need to shift attention from individual work to conferring with teammates, and also to providing input to and seeking feedback from members of other teams.

H2b: The interdependence of team goal priorities inversely predicts time-on-task.

Situational-Related Predictors of Time-on-Task

Continuing to extend the task management concept to the MTS context, we now consider the role of situational factors that affect behavior within multiteam systems. Two particularly important factors in SFMTSs are social isolation and communication delays. Social isolation in MTSs may occur due to "the absence of relationships, ties, or contact with others" (Valtorta et al., 2016, p. 1010), and occurs frequently between members of the crew and ground. Social isolation is a situational and dynamic element of context. So, while the pattern of isolation remains fixed among members of the crew and ground, social isolation within the crew shifts as the mission progresses. The same can be said of the social isolation patterns present within ground members. This shifting isolation occurred in the Apollo 11 mission when Michael Collins remained in orbit on the *Columbia* while Neil Armstrong and Edwin "Buzz" Aldrin entered the *Eagle* lunar module for their historic lunar landing.

The more distributed MTS component teams are in time and/or physical location, the more socially isolated members of constituent teams become. Social isolation results in team members spending more time on tasks before switching to another task.

H3a: Social isolation is positively related to time-on-task.

Communication delay is another important situational factor affecting task behavior in space missions. Communication delay refers to the degree to which there is lag time in the sending/receiving of information among individuals. This affects the speed with which members can coordinate their work, sharing information, and integrating their interdependent actions. Though it is possible to have real-time communication without a delay even in the presence of physical and spatial distance, deep space exploration will involve considerable and dynamic communication delays among subsets of MTSs. We expect that, similar to the effects of social isolation, communication latency encourages extended work on tasks.

H3b: Communication delay is positively related to time-on-task.

Implications of Time-on-Task for Multiteam Work

Having considered how factors present at the individual, social, and situational levels affect behavior in multiteam systems, we now consider the consequences of time-on-task for MTS functioning. Prior research has demonstrated that time-on-task is a consistent predictor of task performance, such that the longer people spend completing a task before switching, the better their performance (Wickens & Gutzwiller, 2017). This rationale makes sense when thinking about the performance of independent tasks, wherein the efficient allocation of cognitive resources is maximized by greater time investment (Kiesel et al., 2010; Monsell, 2003). In the context of spaceflight MTS work, however, cognitive resource allocation is less likely to fully explain the link between time-on-task and performance on interdependent tasks. Here, system performance is maximized when members can efficiently communicate during task completion. Delays in communication caused by poorly developed or incomplete information network structures affect both time-on-task and the ultimate performance of the system.

Time-on-task and information networks. The longer people spend on tasks, the more expertise they develop, and the more likely they are to be seen as a valuable source of information by others. In this way, time-on-task plays an important role in developing information networks in MTS. When individuals spend more time on tasks, independent or interdependent, they are developing a greater understanding of tasks and how different tasks relate to each other. Greater time on independent tasks builds expertise, a necessary but not sufficient condition for the formation of information network ties. Greater time on interdependent tasks supports information network tie formation in two ways. First, by providing opportunities for individuals to learn one another's expertise, and second, providing additional opportunities to coordinate with and learn from other MTS members (Kozlowski & Ilgen, 2006; Moreland & Thompson, 2006). This time together promotes the development of meta-knowledge about one another's expertise, value to the collaboration, and so forth (Zhang et al., 2007). At the MTS level, the density of information networks reflects the degree to which members see one another as valuable and instrumental to the work. We posit that when working in MTSs, time on task promotes the formation of dense information networks within the MTS.

H4: Time-on-task is positively related to information network density in multiteam systems.

Though team members develop denser information networks, the more time they spend coordinating work (Kozlowski & Ilgen, 2006; Moreland & Thompson, 2006), this relationship is likely to be moderated by communication delay. Working under a communication delay allows individuals more time to process information gained through their interactions. This delay creates time for reflection that would render the effect of time-on-task on information networks denser than without a delay. Support for this idea comes from research on communication delays incurred by virtual teams which suggest that working asynchronously can promote information processing due to enhanced affordances (Leonardi & Treem, 2012). For example, regardless of communication delay, remote collaboration entails the use of digital technologies. These technologies provide visibility of contributions, persistence of knowledge, editability of information, and association of ideas with contributors (Leonardi & Treem, 2012). When remote collaboration also entails delay, these affordances enable members to process these associations more deeply, ultimately benefiting the development of information networks.

H5: Communication delay and time-on-task interact to predict information network density, such that the relationship between time-on-task and information network density is stronger for those experiencing communication lags than for those who are not experiencing lags.

Information networks and system performance. Meta-analytic research demonstrates team information network density is an important predictor of team effectiveness and performance (Balkundi & Harrison, 2006). Densely configured networks indicate a high level of information sharing which enhances coordination and performance (Balkundi & Harrison, 2006; Hansen, 1999; Reagans & Zuckerman, 2001).

H6: Information network density is positively related to system performance.

As strong information ties enable members to more easily adapt processes and tools to work around the constraints imposed by latency, denser, more sophisticated information networks logically buffer the implications of communication delay on MTS performance (Poole & Contractor, 2011).

H7: Communication delay and information network density interact to predict system performance, such that the relationship between information network density and system performance is stronger for those experiencing communication lags than for those who are not.

METHOD

We observed 26 twelve-member space analog MTSs performing a complex and realistic multiteam task simulating a Mars mission as part of NASA's HERA (Human Exploration Research Analog; Cromwell & Neigut, 2020), located at Johnson Space Center in Houston, Texas. HERA mimics the context of a space mission in that crew members have highly structured daily tasks and live and work in an isolated and confined setting for an extended period of time. HERA hosts a series of 4-person crews embarking on 30- or 45-day missions. Crew members experience similar levels of isolation, confinement, and communication delay to the levels that would be expected in a space exploration mission. Crew members are subjected to a rigorous selection process and are screened according to the same criteria used to select astronauts (e.g., advanced STEM degree, military flight experience).

In order to study spaceflight MTSs, we developed a task requiring the crew to work with an 8-member Martian analysis group (MAG) located at one of two university laboratories. MAG members had at least some college education and no previous experience working together. Together each 4-person HERA and 8-person MAG comprised a 12-person MTS was divided into four disciplinary teams of three members (one HERA crew member and two MAG members) for the purpose of the task. Table 1 provides an overview of roles. In total, the sample included 36 HERA crew members across 9 crews along with 208 MAG members. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at Northwestern University. Informed consent was obtained from each participant.

The Multiteam System Task: Project RED. Project RED is a computer-based task requiring a 12-person MTS to collaborate to design a well on Mars capable of producing the highest volume of clean water within the 30–45-minute task window. Successful performance requires effective information sharing within and across the four SFMTs component teams. Although the Project RED platform provides a variety of communication tools, to be consistent with the constraints of communication delay and social isolation, the entire system cannot communicate simultaneously. The MTS was structured similarly to the rotation of MAG members in real space missions, so although the crew remained the same over the course of the mission, new MAG members were recruited for each administration of the task. Each HERA crew engaged in Project RED a total of 3 or 4 times over

TABLE 1: Summary of Project RED Roles

Individual Role	Area of Expertise
Planetary geology team goal: Find a location for the well that has the most water available for a future colony (i.e., MTS system goal).	
Sedimentologist 	Understands properties of the ground layers; these determine the presence of different soil types & water. *Goal*: Find an abundant water source.
Hydrogeologist 	Understands the properties of the water table at different locations; can determine types and amounts of contamination at each water source. *Goal*: Find a water source with minimal contaminants.
Structural geologist 	Understands the properties of the aquifer and recharge rate of different locations; affects the capacity and sustainability of the water source; affect the required depth to reach water. *Goal*: Find an accessible and sustainable water source.
Extraterrestrial engineering team goal: Design a well that maximizes total clean water output, determined by the total water output and the number of contaminants in the water.	
Biochemical engineer 	Can design a filtration system for wells given the various types and amounts of contaminants in a water source. *Goal*: Design a filtration system to remove contaminants.
Fluid engineer 	Can design an appropriate piping system given the various environmental and pump design considerations. *Goal*: Design a piping system to minimize water restriction.
Mechanical engineer 	Can design a pump to generate the maximum possible amount of water given the characteristics of different water source locations. *Goal*: Design a pump with sufficient energy & force.
Space human factors team goal: Minimize the terrain cost, the amount of money that will need to be spent constructing and utilizing the well.	
Meteorology specialist 	Expert on the microclimates of Mars, which affect the frequency and severity of dust storms, which affect the costs associated with using and maintaining the well. *Goal*: Minimize the meteorology costs associated with using the well.
Terrain specialist 	Expert on Martian terrain and how nearby terrain will affect the accessibility and usability of the well by a human colony. *Goal*: Minimize costs of accessing and using well.
Maintenance specialist 	Expert on the repair and maintenance costs required to keep the well in good working order. *Goal*: Minimize maintenance costs.
Space robotics team goal: Develop a well construction plan that minimizes the total direct cost, the amount of money required to build the well using robots and rovers.	
Drilling specialist 	Expert in alternative drilling methods that can be used to construct the well. *Goal*: Minimize drilling time.
Materials specialist 	Expert in the parts needed to maintain the robots and rovers that will be used to construct the well. *Goal*: Minimize cost of robot and rover parts.
Operations specialist 	Expert in minimizing the upkeep and maintenance costs associated with different types of robots and rovers that could be used to construct the well. *Goal*: Minimize equipment costs during construction.

Note: HERA members are denoted with black role icons; all other roles are Martian analysis group (MAG).

the course of their mission, but each MAG member was "on console" only once. Appendix A provides additional information.

Manipulations. *Team goal priority.* Team goal priority (Courtright et al., 2015) reflects each team's primary goal, which was manipulated through training instructions and reinforced during participants' use of the decision calculator (see Table 1). The primary goal of each component team was Geology (MTS), Engineering and Human Factors (Team), and Robotics (Individual). Team goal priority was operationalized as a nominal variable with three categories MTS, Team, and Individual.

Social isolation. Members of the HERA crew were confined to the analog with extremely limited communication with those outside the analog and were considered socially isolated. On the other hand, members of the MAG maintained their typical levels of social interaction outside of the task and as a result, were not considered to be socially isolated. Social isolation was operationalized with two levels: present = 1 or absent = 0.

Communication delay. Additionally, we manipulated the level of members' ability to communicate with one another, as is the case in real aeronautical missions, such that the crew experienced delays when communicating with MAG members on Earth as they traveled farther away. Therefore, sessions performed in the middle of the HERA missions had the longest communication delay: 60-second delays for the 30-minute tasks, and 60-second and 180-second delays for the 45-minute tasks. When applied, the delay lagged communication across component teams, but within-crew and within-MAG communication always occurred without a delay. Communication delay was operationalized with three levels: no delay = 0 seconds, 60-second delay, and 180-second delay.

Measures. Measures were obtained from a combination of server logs, survey measures, and subject-matter expert ratings. Table 2 provides a detailed explanation of each measure.

Time-on-task was measured using digital traces from the server logs. The server log for each individual was unitized based on the task they were working on, and then the time-on-task was calculated as the number of seconds that an individual remained on an ongoing task before switching to an alternative task. There were 7, 171 task episodes included in the task-level analyses. Each task episode corresponds to one of the 15 tasks (6 individual tasks, 6 team tasks, and 3 MTS tasks). Table 3 summarizes Project RED tasks.

Information network density was measured using sociometric network surveys. During each Project RED task, we administered a network survey every 10 minutes. Each MTS completed the network survey either 2 or 3 times. Participants read the stem, "Who was a valuable source of information?" Participants saw a roster of all MTS members and were instructed to select all who apply. Information network density is represented as the number of ties in the entire MTS's network. Usually, network density is operationalized as the number of observed ties divided by the number of possible ties. Given that all MTSs in this study had 12 members and therefore the same number of possible ties, for ease of interpretation we operationalized density using the numerator. Figure 2 depicts what the information networks might look like in such an MTS. There were 93 information networks included in the network-level analyses.

MTS performance reflected the degree to which the MTS achieved the collective goal of creating a well on Mars and was operationalized as the number of people who would gain access to clean, sustainable water (standardized value). There were 26 MTSs included in MTS-level analyses.

Analytical Approach. Given the nesting of task episodes as collected across participants in 26 sessions across nine missions (i.e., four levels), we selected Hierarchical Linear Modeling (HLM) to test our hypotheses. We performed HLM analyses at three focal levels of analysis: task, network, and MTS. Analyses predicting time-on-task were conducted at the task level (within person over time). Analyses predicting information networks were conducted at the network level (within MTS over time). Analyses predicting performance were conducted at the MTS level. We estimated

TABLE 2: Summary of Focal Variables

Variable	Source	Description
Task-related predictors		Task dimensions (i.e., difficulty, interest, importance, salience, Wickens et al., 2015) were rated on a scale from 1 (low) to 5 (high) by two subject-matter experts (SMEs). SMEs independently rated each task attribute. SMEs resolved rating differences by discussing their rationale and reached an agreement through that discussion. The interrater agreement was 92% within 1 point.
Task stickiness	SME	Task stickiness dimensions (Cronbach's α = .79): • Task difficulty: The degree to which a task is effortful and requires a high cognitive load • Task interest: The degree to which the task is engaging • Task importance: The degree to which a task is more versus less important to goal attainment
Task salience	SME	Task salience: The degree to which the task is accompanied by reminders or explicit instructions to perform the task that are audible and visible to individuals
Social-related predictors		
Shared mental model	Survey	Mental model was collected using the elicitation method (Klimoski & Mohammed, 1994): *Rate the extent to which each pair of items are related in achieving the goals of Project RED (from 1 = Totally Unrelated to 7 = Very strongly related). Teamwork items:* • motivating one another and coordinating our work; • motivating one another and managing conflict; • motivating one another and monitoring our progress; • motivating one another and sharing information; • coordinating our work and managing conflict; • coordinating our work and monitoring our progress; • coordinating our work and sharing information; • managing conflict and monitoring our progress; • managing conflict and sharing information; • monitoring our progress and sharing information Shared mental model was calculated by computing the Euclidean distance in scores on the mental model measure between each pair of MTS members, and then averaging these distances at the team level. A higher score represents more distance and thus a less similar mental model; a lower score represents a more similar mental model.
Team goal priority	Manipulation	Team goal priority (Courtright et al., 2015) was operationalized as a categorical variable based on each team's primary goal, reinforced through training and decision calculator (see Table 1). The primary goal of each component team was, Geology (MTS), Engineering and Human Factors (Team), and Robotics (Individual).
Situational-related predictors		
Social isolation	Manipulation	Two levels, operationalized as a binary variable: *0* (isolation is absent) and *1* (isolation is present; Landon et al., 2018).
Communication delay	Manipulation	Three levels, 14 sessions with no delay (0-second delay), 9 with a 60-second delay, and 3 with a 180-second delay.

TABLE 3: Project RED Tasks

Task Description	Digital Trace Task Examples
Individual tasks	
Task 1: Building an understanding of drivers of performance/expertise for my role.	Click: Searching through the information database.
Task 2: Advocating for outcomes important to my role.	Chat: "I really think we should use PVC material for the pipe."
Task 3: Investigating personal performance in new locations.	Click: Clicking on a map cell that has been unprompted by others.
Task 4: Revisiting/updating personal outcomes in old locations.	Click: Updating a map cell that has been previously saved.
Task 5: Sharing role-specific expertise.	Chat: "The PVC pipe would cost $1,000 which is within budget."
Task 6: Providing feedback on task force members.	Click: Answering the pop-up survey questions.
Team tasks	
Task 7: Understanding team variable associations with different land characteristics/locations.	Two clicks: Two teammates concurrently working with the same location in their respective decision calculators.
Task 8: Investigating team outcomes in new locations.	Chat & click: Clicking on a map cell that has been prompted by teammates.
Task 9: Revisiting/updating team outcomes in old locations.	Chat & click: Updating a map cell that has been prompted by teammates.
Task 10: Exchanging information with my teammates.	Chat: The exchange of any information between two individuals on the same team.
Task 11: Advocating for the importance of team outcomes to other teams in the task force.	Chat: "Geology has agreed that location 34.37 will have the most abundant and clean water output, we should choose this location."
Task 12: Negotiating with each other about team decisions.	Chat: "[from Structural Geologist to Sedimentologist] I prefer 64.32 to 37.45 because the water there is easier to extract than at 37.45."
MTS tasks	
Task 13: Exchanging information about team constraints to other teams (request, provide, elaborate)	Chat: Exchanging information across team boundaries.
Task 14: Reaching a final decision about the well location.	Chat: Members of at least two teams agreeing on a map location.
Task 15: Submitting decision about well location.	Twelve clicks: Members submitting their final decision by selecting their name in the signoff window.

statistically significant differences in the resulting task episode durations and detected statistically significant differences in the resulting information networks for each of the 26 sessions as well as in the nested MTS performance for each of the nine missions. Figure 3 summarizes our hypotheses.

RESULTS

Table 4 reports descriptive statistics for focal constructs depicting the effects of communication delay and social isolation on focal outcome variables. On average, participants spent 82 seconds per task before switching to

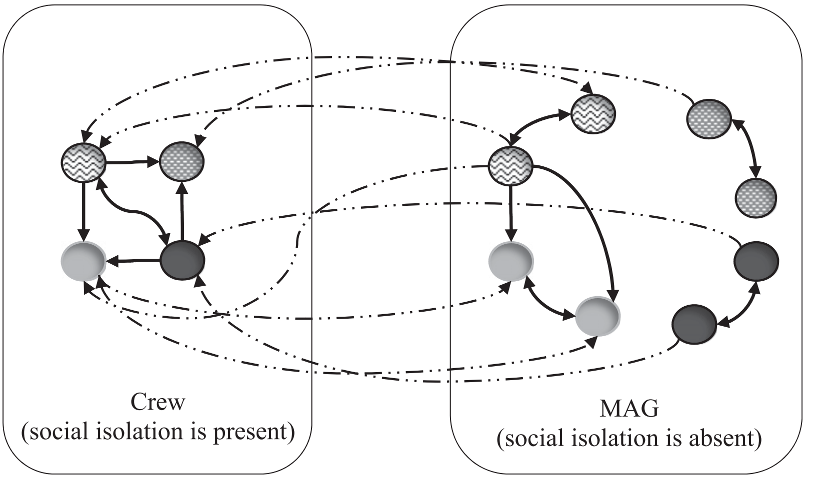

Figure 2. Information network density in MTS. *Note:* Nodes represent people and the node color/pattern denotes the component team they belong to. Links represent information relations among MTS members (i.e., MTS information networks). Dash lines denote crew-MAG information relations.

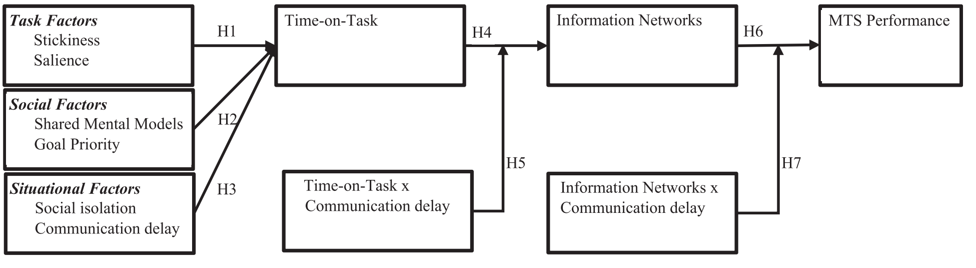

Figure 3. Summary of proposed hypotheses.

an alternative task. Social isolation and communication delay played a considerable role in task episode duration, such that participants spent approximately 13 more seconds on a task when in isolation than not, and 17 more seconds on a task while in communication delay than when communicating in real time. Overall, performance was higher when there was no communication delay than when there was a delay.

Time-on-task. We examined task, social, and situational factors that determine time-on-task. Table 5 presents variable intercorrelations at the task level, and this corresponds to the HLM analysis presented in Table 6. The first step in multilevel analysis is to construct a null model without any explanatory variables to see if/how the variance is distributed over different levels. The model defines the amount of variance that exists around the mean of the dependent variable, time-on-task, at the mission level, the session level, and the participant level and is calculated as an ICC. Model 1 represents the Null model and results show that 17% of the variance in the task episode duration could be explained at the mission, session, and participant level. The ICC is significant, and confirming multilevel analysis using HLM is an appropriate strategy. Models 2, 3, and 4 sequentially introduced the task, social, and situational predictors.

Results in Model 4 (the full model) indicate that task stickiness has a positive effect on time-on-task (H1a; $\gamma = 3.92$, $p < .05$). H1a was

TABLE 4: Descriptive Statistics of Focal Study Variables, by Social Isolation and Communication Delay

	Time-On-Task (seconds)	Information Network Density	Performance (Z-Score)
Observations	7171	93	26
Overall	82.16 (101.75)	25.31 (7.7)	-
Social isolation			
Absent (MAG)	78.32 (98.33)	10.77 (5.07)	-
Present (crew)	91.37 (109.02)	3.68 (3.12)	-
Communication delay			
Absent	75.61 (93.46)	24.14 (7.93)	0.09 (1.05)
Present	91.16 (111.54)	26.61 (7.31)	−0.18 (0.97)

Note: Information network density is computed as the number of ties. Network density is operationalized as the number of observed ties divided by the number of possible ties. Given that all MTSs in this study had 12 members and therefore the same number of possible ties, for ease of interpretation we operationalized density using the numerator. The performance is at MTS level; therefore, we cannot separate between Crew and MAG.

TABLE 5: Intercorrelations at the Task Level

Variable	Mean	SD	1	2	3	4	5	6
1 Time-on-Task	82.16	101.75						
2 Task stickiness (alpha)	−0.01	0.84	0.03***					
3 Task salience	3.14	0.81	−0.01***	0.43***				
4 Shared mental model (distance)	6.00	2.05	0.04***	0.00***	−0.03***			
5 Goal priority	2.08	0.72	−0.08***	0.03***	0.02***	0.03***		
6 Social isolation	0.29	0.46	0.06***	0.01***	0.09***	−0.03***	−0.02	
7 Communication delay (sec)	36.47	53.63	0.10***	−0.02***	−0.05***	−0.06***	0.00	0.01

Note: N = 7,171 task episodes, $^{***}p < 0.001$, $^{**}\ p < .01$, $^{*}\ p < .05$.

supported. H1b was not supported, as task salience has a negative and non-significant effect. Next, teams whose shared mental models are dissimilar had longer time-on-task (H2a; $\gamma = 2.95$, $p < .05$) and teams that prioritize proximate goals had longer time-on-task than those who prioritize more distal goals. Indeed, team Robotics (which focused on achieving individual goals) spent more time on tasks than team Geology (which focused on achieving the MTS goal), and Engineering and Human Factors teams (which were team goal oriented) spent more time on task than team Geology (H2b; $\gamma = 24.67$, $p < .001$ and $\gamma = 18.52$, $p < .001$). Thus, H2 was supported.

Finally, results suggest participants in social isolation spent more time on task than participants not in isolation (H3a; $\gamma = 12.35$, $p < .01$) and that participants who worked on the task in a session that experienced communication delay between crew and MAG spent more time on task than did those who worked in sessions without a delay (H3b; $\gamma = 0.24$, $p < .01$). As such, H3 was supported.

Time-on-task affects information network density. Next, we examined how time-on-task shapes system information networks, positing that spending more time on tasks increases the number of ties in the information network, an effect which will be stronger when communication delay is present than absent. Table 7 presents results supporting H4 and H5. These analyses were conducted at information networks level; correlations among key variables were as follows: 0.19 (communication delay present/absent with time-on-task), 0.16 (communication delay with

TABLE 6: Hierarchical Linear Model Results Predicting Time-on-Task

	Model 1	Model 2	Model 3	Model 4
Fixed-effects				
Intercept	96.08***	104.56***	71.69***	57.85***
	(6.24)	(8.28)	(11.61)	(11.58)
Task factors				
Task stickiness (alpha)		3.77*	3.81*	3.92*
		(1.59)	(1.59)	(1.58)
Task salience		−2.76+	−2.57	−2.79+
		(1.62)	(1.62)	(1.62)
Social factors				
Shared mental model (distance)			2.80*	2.95*
			(1.19)	(1.17)
Goal priority (ref. Geology)				
Engineering & human factors			18.48***	18.52***
			(5.36)	(5.28)
Robotics			24.80***	24.67***
			(6.26)	(6.17)
Situational factors				
Social isolation				12.35**
				(4.70)
Communication delay (sec)				0.24**
				(0.08)
Random effects				
Variance components				
Residual	9096.64***	9089.39***	9089.39***	9092.05***
	(156.18)	(156.07)	(156.07)	(156.16)
Mission	77.96*	112.50**	98.37**	37.77
	(165.06)	(187.20)	(172.90)	(129.09)
Session	629.63***	620.35***	584.94***	449.27***
	(258.84)	(256.91)	(242.01)	(202.12)
Person	1143.34***	1153.38***	1057.84***	1016.58***
	(150.27)	(151.18)	(143.20)	(140.07)
Additional information				
ICC: Mission & session & person	0.17			
Observations	7171	7171	7171	7171
Wald Chi2		6.24*	28.52***	44.98***
AIC	86178	86165	86136	86124

Standard errors in parentheses; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, + $p < 0.1$.

information network), and 0.20 (time-on-task with information network). Model 2 in Table 7 indicates a positive link between time-on-task and number of ties in MTS information networks (H4; $\gamma = 0.05$, $p < .01$). Models 3 and 4 indicate that time-on-task does not influence the number of ties in the MTS information networks in the absence of communication delay, but increases the number of ties in the presence of communication delay (H5; $\gamma = 0.08$, $p < .001$). These results are also illustrated in Figure 4.

TABLE 7: Hierarchical Linear Model Results Predicting Information Network Density

	Model 1	Model 2	Model 3	Model 4
	Null	Overall	Communication Delay: Absent	Communication Delay: Present
Fixed-effects				
Intercept	25.29***	20.64***	22.99***	19.17***
	(1.16)	(2.12)	(3.53)	(2.53)
Time-on-task		0.05**	0.02	0.08***
		(0.02)	(0.04)	(0.02)
Random effects				
Variance components				
Residual	35.25***	31.76***	36.05***	25.75***
	(6.09)	(5.49)	(8.66)	(6.13)
Mission	0.56	1.43	0.00	19.87***
	(6.57)	(6.75)	(0.00)	(12.13)
Session	22.89***	23.53***	25.94***	0.00***
	(11.01)	(10.85)	(14.25)	(0.00)
Additional information				
ICC: Mission & session	.40			
Observations	93	93	49	44
Wald Chi2		7.03***	0.15	13.05***
AIC	635	630	342	291

Standard errors in parentheses; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, + $p < 0.1$.

Information network density predicts MTS performance. Finally, we examined how information networks shape MTS performance. Table 8 presents results supporting H6 and H7. These analyses were conducted at the MTS level. MTS-level correlations among key variables were as follows: 0.18 (communication delay present/absent with information networks), −0.14 (communication delay with MTS performance), and 0.35 (information networks with MTS performance). Examining Model 2 in Table 8 shows that having a high number of ties in MTS information networks is associated with higher performance (H6; $\gamma = 0.06$, $p < .05$). Model 3 shows that MTS information networks do not predict performance in the absence of communication delay. Model 4 shows that the number of ties in MTS information networks positively influence MTS performance when there is a communication delay (H7a; $\gamma = 0.10$, $p < .05$). These results are also illustrated in Figure 5.

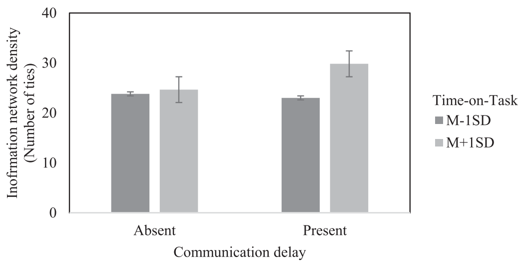

Figure 4. Interaction of communication delay and time-on-task for information networks.

DISCUSSION

Sometime in the next decade teams of extreme teams will embark on a mission to Mars. We advance a multilevel perspective of task management in order to understand how individual, task, team, and situational factors jointly explain time-on-task at the within-individual level (i.e., individual behavior over time). We then explain how aggregate

TABLE 8: Hierarchical Linear Model Results Predicting Multiteam System Performance

	Model 1	Model 2	Model 3	Model 4
	Null	Overall	Communication Delay: Absent	Communication Delay: Present
Fixed-effects				
Intercept	−0.07	−1.69*	−1.19	−2.88*
	(0.22)	(0.81)	(0.95)	(1.16)
Information network density		0.06*	0.05	0.10*
		(0.03)	(0.04)	(0.04)
Random effects				
Variance components				
Residual	0.85	0.69	0.48	0.59
	(0.28)	(0.24)	(0.26)	(0.24)
Mission	0.12	0.16	0.44	0.00***
	(0.21)	(0.21)	(0.36)	(0.00)
Additional information				
ICC: Mission	.13			
Observations	26	26	14	12
Wald Chi2		4.24	2.10	5.64
AIC	78.60	76.74	45.00	35.78

Standard errors in parentheses; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, + $p < 0.1$.

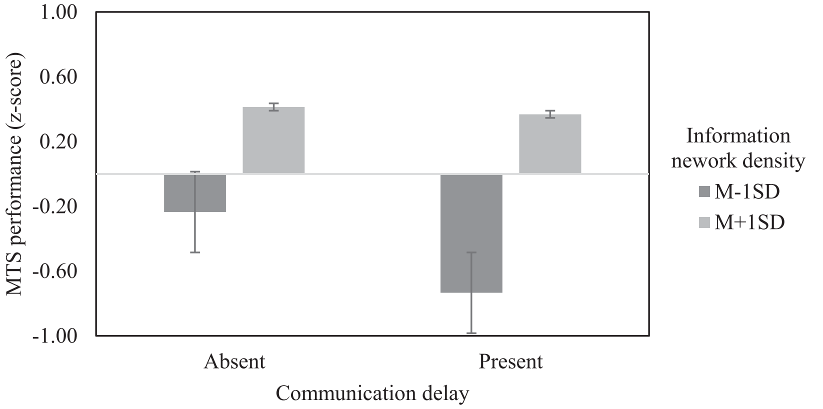

Figure 5. Interaction of communication delay and information network for MTS performance.

time-on-task in an MTS shapes the formation of information networks and multiteam performance.

Using MTSs performing an engaging task based on a realistic space exploration scenario, we explore the role of task, team, and situational factors in task management behavior. We operationalize task management as time-on-task, a useful way to consider individuals' level of investment in their various independent versus interdependent tasks (Gorman et al., 2010), and understand the impact of task management behavior on MTSs performance. The length of time individuals spend on a task is known to positively predict task performance (Wickens & Gutzwiller, 2017).

Human factors psychologists argue the link between time-on-task and performance in independent work can be explained as a function of the effectiveness and efficiency with which individuals allocate their finite cognitive resources (Huestegge et al., 2014). The mechanism underlying this relationship is more complex within collaborative work. The ultimate performance of an MTS is not only determined by the effectiveness/efficiency with which individuals complete their discrete tasks, but also how well the work is coordinated throughout the system. Thus, we add to prior research on the time-on-task—performance link (Koch et al., 2018), by assessing the role of information network sophistication in mediating the link between time-on-task and system performance. Whereas prior research has tended to focus more narrowly on communication as the precursor to team/MTS performance, our broader focus on information networks incorporates a motivational dimension important to collaborative work (Balkundi & Harrison, 2006).

Further, whereas prior research has tended to study task management in relatively decontextualized lab settings (raising generalizability concerns; Gutzwiller et al., 2016), we test these ideas in a space analog setting that allows a high degree of control over the nature of tasks while providing a compelling context for the MTS, four members of which are isolated and confined in the analog. Moreover, we study these ideas in the context of MTSs that have been the subject of major failures in the past (Lifshitz-Assaf, 2018; Vaughan, 1990), further magnifying the importance of research on SFMTs.

Practical Implications. Our findings suggest aspects of social isolation and communication delay affect task duration, information network development, and MTS performance. Communication delay is especially important, having both direct and indirect effects on MTSs. Of particular interest is the notion that isolation and delay interact such that constituent teams in isolation may be less affected by communication delay than non-isolated constituent teams. During significant MTS task episodes, the focal team (the crew) may be heavily entrained on a task while their counterpart teams (MAG) may be in "standby," "spinning their wheels" waiting for feedback/questions from the crew. The essence of this idea was foreshadowed in interviews with NASA personnel about the experience of collaborating under communication latency "... working under a communication delay, we could communicate only very basic things....for example, as you would tend to not ask ground control for small details, you will just try to figure them out yourselves because communicating with a time delay of 10 minutes would be less efficient…there would be fewer communications going on with the ground" (DeChurch & Mesmer-Magnus, 2015, p. 81).

Another implication of these findings is the importance of information networks to MTS performance under communication delay. We found time-on-task promotes the development of more dense information networks, which predict system performance under communication delay. When component teams are anticipating a period of communication delay, it may bolster their performance to develop these networks through additional mechanisms such as MTS planning and briefing.

This study also highlights the importance of examining cross-level effects in multiteam systems. The current results find team shared mental models, by reducing time-on-task, ultimately hinder MTS performance. This finding should be juxtaposed with extensive prior research demonstrating that team mental models positively predict team performance (DeChurch & Mesmer-Magnus, 2010a). The differential effect of team mental models in promoting team performance, but indirectly undermining system performance, underscores the complexity involved in MTSs. Processes and states beneficial at one level may undermine another (DeChurch & Zaccaro, 2010).

Lastly, these findings have implications for MTSs and virtual/global organizations. Our findings regarding communication delay suggest care should be taken when structuring tasks for those collaborating at a distance where coordination/scheduling tends to be a pain-point (Cramton, 2001; Montoya-Weiss et al., 2001). These findings suggest virtual work be structured such that members have longer stretches of uninterrupted time to work on their tasks. A consulting team working virtually while being dispersed across continents may benefit from carving out a longer meeting time where they can work simultaneously as a team or system to improve their output on a discrete task, rather than trying to multitask. Not only does communication delay increase the need for longer stretches of time-on-task, it also impacts the development of social ties within the collaborative system, particularly between isolated and non-isolated members. This effect is further magnified in systems with a greater proportion of isolated members.

Limitations and Future Research. A key limitation of this research relates to the relatively small number of MTSs included in our database. Although we measured 244 individuals within 84 teams and 26 MTSs, firm conclusions regarding the role of individual task management for team and MTS performance remain tentative until more data within a variety of MTSs can be collected. Future research is needed to investigate other contextual features of MTSs which may interact to affect task management behavior and performance. How might communication medium affect behavior and performance? We explored interactions that occurred across a blend of in-person and virtual interactions, though these interactions were confounded with the nature of the team/task, such that crew and mission control interactions tended to occur in real-time and in-person, but cross-team interactions tended to occur virtually. Future research is needed to tease apart the implications of modality and level of interaction.

A second limitation of our study is the nature of the experimental task. The MTS convened for either 30 or 45 minutes. Future research on longer timeframe tasks is needed to understand the degree to which findings generalize. The current findings are best understood in MTSs who come together in intensive periods of interaction with a meaningful beginning and end of the MTS task. There are many variations of MTS tasks, and future research is needed to understand the effect of the timeframe and the degree of overlap in team member contributions to their performance.

Also related to the issue of timeframe is the need for future research that explores potential "sweet spots" in the duration of time-on-task. This study finds working for a longer time on tasks benefits information networks and subsequent performance, though due to the intensive, synchronous collaboration involved in the task, the continuous intervals were relatively short. Future studies of task management in MTSs are needed to explore these relations in asynchronous MTSs where task durations can be far longer, measured in hours rather than seconds.

A third limitation relates to the findings regarding social isolation. The NASA analog participants were isolated whereas the MAG members were not. However, there are also other differences between these participants in addition to social isolation which may account for observed differences. The MAG participants were participating in a research study lasting 5 hours in total, whereas the crew members invested weeks in pre-mission training, 30 or 45 days living in isolation, and then weeks in post-mission testing. This would likely create differences in the crew and MAG in terms of commitment to the mission and task fatigue. We cannot rule out that commitment differences affect the finding that social isolation affects time on task. Another potential difference was task fatigue, since the crew was performing this MTS task multiple times in the context of the larger mission, whereas the MAG participants were performing the task only once. Hence, the social isolation effect may have been driven instead by commitment or fatigue. We note that these three constructs are highly intertwined in applied settings.

CONCLUSION

Task management in MTS requires individuals to shift back and forth among individual, team, and inter-team activities. Extending the task management literature to the MTS level enables us to understand the following three sets of contributing factors: task, team, and situational. As MTS performance failures tend to result in salient, costly outcomes, identifying its precursors is paramount. Our findings contribute to research on task management from the human factors literature, while also extending these principles to research on teams and MTSs. Furthermore, these findings have practical application in the design of work during long-distance space exploration missions.

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KEY POINTS

- We extend human factors research on task management to incorporate team and situational factors.
- Team factors are important predictors of task management behavior: members of teams with less shared mental models and those whose teams prioritize their team goal over the MTS goal engage longer on tasks.
- Situational factors also exert strong effects on task management: members whose teams are in social isolation and under communication delay engage longer on tasks.
- Time-on-task positively predicts MTS information network density, which in turn positively predicts MTS performance when communication occurs with a delay, but not when it occurs in real-time.

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APPENDIX A: EQUIPMENT, MATERIALS, AND PROCEDURE

Equipment and Materials

This experiment was coordinated across two geographic locations: the HERA crew operated out of the Johnson Space Center in Houston, Texas, and the Martian analysis group (MAG) was located at a large university. Participants in both stations worked with one another —some virtually and some in-person—to build a hypothetical well that would sustain a population on of Mars. All participants used the Project RED platform, a custom software that the research team had constructed for the purpose of studying multiteam systems, to communicate and coordinate with one another toward the construction of the well. Regardless of location, each participant was equipped with a laptop computer that allowed them to complete their training and the multiteam task. The HERA crew was collocated and worked from the confines of the analog, but the MAG was structured a bit differently. Within the lab where MAG was stationed, there were four rooms—two individuals would be assigned to a room, based on their disciplinary team. Thus, the two MAG members of Planetary Geology both worked from the Geology Room, the two MAG member of Extraterrestrial Engineering both worked from the Engineering room next to Geology, and so on. Members not collocated could use the chat function in the Project RED interface to communicate with one another.

For the duration of the task, several experimenters (at least 2, and as many as 5) monitored the participants in a separate adjoining room. This experimenter control station consisted of a feed of each of the four MAG rooms, and each room displayed three screens as follows: (1) Participant X's laptop screen, (2) Participant Y's laptop screen, and (3) a video recording of both Participant X and Y. One experimenter was responsible for capturing the recording of the screens and videos in each room, and one experimenter manually administered the Project RED session. This included starting a new session before participants arrived at the lab and allowing the final sign-off to become available when the session was about to end. In total, the data collected included audio and video recordings of each room (NASA also records HERA during these sessions), chat communication between dispersed individuals, performance measures created from a distribution of parameters embedded in the game, and surveys participants respond to after the task has been completed.

Procedure

All participants received the same 1.5-hour training. Participants begin by watching videos that explain the circumstances of the mission, as well as the information associated with their specific roles. The first video outlines the overall task, which is water infrastructure development in the Argrye Quadrangle region of Mars aimed at providing clean sustainable water to future inhabitants of Mars. Additionally, this video introduces the disciplinary teams that make up the multiteam system. The second video focuses on the individual's role, providing information about the role within the larger context of the system, as well as more detailed information about the role. After watching these training videos, participants completed a training survey that helped them acclimate to the Project RED interface and the types of tasks that they would be required to engage in while acting in their roles.

Once training is completed, a member of the research team would instruct the Hydrogeologist, who acted as the 'Mars COMM' point of contact between the HERA crew and MAG, to make contact with HERA. Once HERA and MAG confirmed contact with one another, the research team started the timer for the study. Participants then had 30 or 45 minutes to work individually, with teammates, and across teams in the system to decide where to build their well and what specifications to submit for each role. Once the task was finished, members of the system submitted their final specifications, which helped determine performance, and completed a survey regarding their task

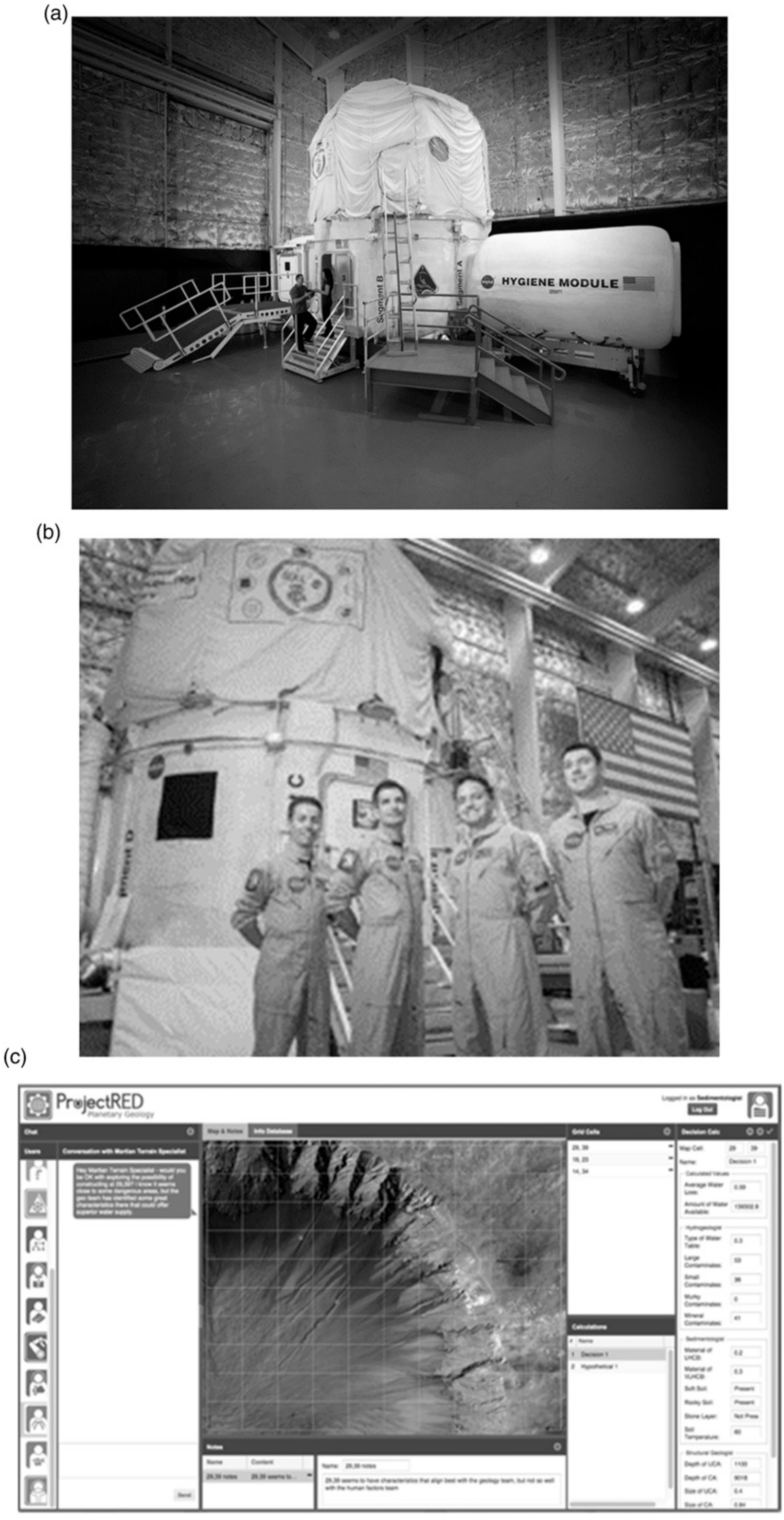

Figure A1. NASA space multiteam system simulation. (a) Space Crew Habitat at JSC in Houston; HERA: Human Exploration Research Analog; Image credits: NASA. (b) Space Crew (4 members); Image credits: NASA. (c) Project RED Task Interface.

switching preferences and behaviors throughout the duration of the task. Figure A1 includes photographs depicting (a) the crew habitat, (b) the crew members, and (c) the task interface.

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