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Think like a team: Shared mental models predict creativity and problem-solving in space analogs

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ABSTRACT

As long-distance space exploration missions move beyond low Earth orbit, and crews become more Earth-independent, it is essential to identify predictors of team performance - properties of teams that can be monitored during space flight to anticipate performance decrements. The most robust team state predicting performance in the team effectiveness literature is shared mental models. Shared mental models are properties of a group reflecting how members organize knowledge and understanding about the purpose of the team, the nature of the work, and how members work together. In this study we developed a measure of shared mental models for use in ground-based analogs. It was administered in the National Aeronautics and Space Agency (NASA)'s Human Exploration Research Analog (HERA) Campaign 4, Campaign 5, and the Nazemnyy Eksperimental'nyy Kompleks (NEK) SIRIUS-19 mission. HERA included eight 4-member crews in isolation for 45 days; NEK SIRIUS-19 included a 6-member crew in isolation for 120 days. To track performance variations, we administered two team tasks: a creative thinking task and a problem-solving task. We found substantial positive correlations between shared mental models and both dimensions of team performance in HERA and in NEK. Though shared mental models are a strong predictor of team performance across mission stages, we found some nuanced shifts. First, mental model sharedness in HERA is associated with crews generating fewer ideas in the third quarter than in other quarters, but also generating more novel, original ideas. Second, in the NEK mission we observed a third quarter effect with problem-solving, and the nature of the effect was that the effect of the shared mental model was most important in all quarters except the third. These results suggest that mission timing but also mission duration are important factors that condition relations between team process variables like shared mental models and team performance indicators.

1. Introduction

Space agencies endeavor to send teams on missions into deep space. The distance of interplanetary travel will require developing and supporting highly autonomous crews to work collaboratively on complex tasks. Previous research in ground-based analogs documents declining team performance as their time in isolation and confinement increased [1]. Thus, it is important to identify anticipatory factors that can be monitored to signal a potential decrement in team performance. Monitoring predictive conditions of team performance allows crews to anticipate potential challenges and to improve team states required for high performance.

1.1. Team performance in space crews

As crews venture further from Earth, they will have increased autonomy and also increased responsibility. They cannot rely on ground support in the same way as in past missions involving Apollo, Skylab, Shuttle, and the International Space Station. In all of these cases, ground support was in constant contact with the space crew. The space crews of future missions will consist of a small number of crew members, who are likely from different nations, and possessing widely different expertise

Abbreviations: National Aeronautics and Space Agency, NASA; Human Exploration Research Analog, HERA; Nazemnyy Eksperimental'nyy Kompleks, NEK; Shared Mental Model, SMM.

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and training [2]. Some of the critical expertise may lead to the formation of a crew composed of a pilot, engineer, natural scientist, and surgeon, for example. The crew may have some civilian and military members. The crew may include men and women. Despite this diversity, the crew will need to work together and cooperate on various conceptual tasks that require cooperation, reasoning, and sharing of information with teammates [3]. Two important performance domains are creative thinking and problem-solving. Creative thinking requires crew members to generate many possible and novel solutions when there may be more than one correct solution in response to some unanticipated situations. Problem-solving requires crew members to combine disparate expertise toward a correct solution.

The crew's ability to perform such conceptual tasks will likely be affected by prolonged isolation and confinement that characterize long distance space exploration missions. Isolation and confinement affect different aspects of crew dynamics, such as team conflict and mood, which in turn affect crew performance. In a review of analog research, Bell and colleagues [4] synthesized the results of 72 sources examining team dynamics over time, paying attention to the "third quarter phenomenon." The third quarter phenomenon refers to the expected tendency of increased team conflict and decreased positive mood levels during the third quarter of any isolated and confined mission [5]. Bell and colleagues [4] showed that while team conflict varied over time and all teams reported at least one conflict episode during the mission, there was no consistent trend across teams and, thus, no evidence of a third quarter phenomenon. Furthermore, there was inconsistent support for the third quarter phenomenon when examining team mood [4]. For example, Stuster [6] reported a decreased number of positive comments in the International Space Station crew members' journals in the third quarter of the mission. Steel [7] found a moderate increase in negative moods among members of a remote Antarctic base during the third quarter. Finally, Kanas and colleagues [8–10] found no changes in negative moods among crew members who participated in Shuttle/Mir space program or the International Space Station missions. The inconsistent results on the third quarter phenomenon could be attributed to the outcome measured [11], either as the content analysis of astronauts journal entries or self-report ratings on the positive and negative mood components of the Positive and Negative Affect Schedule [12] and Profile of Mood States [13] scales.

While some missions reported a third quarter phenomenon, and others did not, isolation and confinement lead to an increase in depressed mood [14] and team conflict [15–17] which in turn negatively affect crew performance. In a study of 4, 4-member crews who participated in one 30-day analog campaign, Larson and colleagues showed that while performance on execute tasks increases over time, the performance of creative and problem-solving tasks in space analogs decline over time [1]. These dimensions of knowledge-intensive conceptual tasks will be "critical as astronauts on future space missions become more reliant on one another to solve the inevitable and unanticipated challenges and opportunities of exploring deep space" [1] [p.114].

Given that prolonged isolation and confinement will be key characteristics of future missions, it is important to identify teamwork factors that can be monitored throughout a mission, as these conditions change, that may indicate or foretell a potential team performance decrement. This study examines shared mental models as a predictor of creative thinking and problem-solving in analog crews of 45- and 120-days experiencing prolonged isolation and confinement.

1.2. Shared mental models and performance in space crews

Previous research on teams finds shared mental models to be the most robust team state predicting performance [18]. Mental models characterize the degree to which members hold similar knowledge structures about their task and team interactions [19,20]. Team shared mental models represent knowledge and understanding about the purpose of the team commonly held by team members and the agreed-upon roles required of individual members. Shared mental models are established through common experience among team members regarding expected collective behavior patterns [21–23] and are robust predictors of team performance [24]. Researchers showed that effective team coordination depends upon the emergence of a mental model that is shared by team members [21,22,25]. When the strength of a team's shared mental model is high such that all team members share it, they may be better able to anticipate each other's actions and reduce the amount of processing and communication required during team performance. Conversely, when the strength of a team's shared mental model is low such that it is shared by some (but not all) all team members, coordination and information processing within the team will suffer since team members will not share the same purpose for the team actions.

The purpose of this study is to examine the relationship between crew shared mental models and crew performance in terms of creative and problem-solving tasks, i.e., to answer the question, how predictive are shared mental models of crew performance? Our second question probes the effect of mission phases: when in mission are shared mental models most predictive of crew performance, i.e., do shared mental models exhibit a third quarter effect?

2. Methods

The data used in this study were collected in two isolated, confinement, and controlled analogs as part of the National Aeronautics and Space Administration (NASA) Human Research Program: Human Exploration Research Analog (HERA) and Nazemnyy Eksperimental'nyy Kompleks (NEK).

2.1. HERA campaign 4 and campaign 5

HERA [26] represents an appropriate and fascinating context in which to examine how team shared mental models affect crew

Fig. 1. Photographs of the exterior (top) and interior (lower) of the Human Exploration Research Analog (HERA, Houston, TX); Image credits: NASA.

performance and is located at Johnson Space Center in Houston, Texas, USA. Fig. 1 presents photos of the interior and exterior views of the HERA research analog. HERA facilitates research on astronaut-like individuals and teams in a high-fidelity simulated space exploration mission environment. HERA mimics the context of a space mission in that crew members have structured daily tasks and live and work in an isolated and confined setting for an extended period of time. HERA participants are selected based on similarity in background to actual astronaut candidates. For example, HERA participants have advanced degrees in the science, technology, engineering, and mathematics field, have experience leading missions in extreme environments on Earth, or have military flight experience. HERA crew is composed of 4 members, and each crew member is assigned to a role: commander, flight engineer, and two mission specialists. Crew members are confined to the inside of the capsule during the entirety of the mission. Each crew member has a small bunk in close quarters with bunks of the other 3 crew members. The crew shares a single hygiene module. The crew completes scientific and maintenance activities as they would do on an actual space mission.

The data used in this study were collected from eight, 4-person crews, participating in two HERA campaigns: HERA campaigns 4 (HERA C4) and 5 (HERA C5) each including 4 crews living and working in the analog for 45 days. Due to Hurricane Harvey, a HERA C4 crew had to be prematurely aborted, and therefore there was a fifth crew added. In this study the incomplete mission was excluded. HERA C4 took place in 2017 and 2018. Crew members lived and worked in HERA for 45 days. The crews were on a hypothetical mission to land on an asteroid and collect soil samples, before returning home. As the crew traveled further from Earth, all communications in and out of the habitat, with mission control, experienced up to a 5-min delay each way. The delay gradually went away as the crew approached re-entry to Earth. The communication delay started on mission day 16 and ended on mission day 28. There was no communication delay among crew members within the habitat. Additionally, the crew was exposed to sleep deprivation: The crew members slept 5 h per night during the workweek and 8 h on Saturday and Sunday.

HERA C5 took place in 2019 and 2020. Crew members lived and worked in HERA for 45 days. The crews were on a simulated journey to Mars' moon Phobos. Similar to HERA C4, the crew experienced communication delay of up to a 5-min delay each way with the mission control. Unlike previous campaigns, crews in HERA C5 were not under a sleep deprivation condition. However, they had less privacy in their crew quarters and in the hygiene module: The sleep quarters had only cargo netting instead of a wall, and the hygiene module had a curtain rather than a door.

Table 1 includes the list with the HERA crews observed in the study.

Table 1
HERA teams observed in the study.

Campaign and Mission	Time Period
HERA Campaign 4 (45 days)	
Mission XIII (C4M1)	May 6 - June 18, 2017
Mission XIV (C4M2)	Aug 5. - 27 (Truncated due to Harvey)
Mission V (C4M3)	Oct. 28 - Dec. 11, 2017
Mission V1 (C4M4)	Feb. 3 - Mar. 19, 2018)
Mission XVII (C4M5)	May 4 - June 18, 2018 (This mission was added due to C4M2 ending early)
HERA Campaign 5 (45 days)	
Mission XVIII (C5M1)	Feb. 15 - Apr. 1, 2019
Mission XIX (C5M2)	May 24 - July 8, 2019
Mission XX (C5M3)	Aug. 1 - Oct. 7, 2019
Mission XXI (C5M4)	Jan. 25 - Mar. 9, 2020

2.2. NEK SIRIUS-19

NEK is a unique, multi-compartment facility used as an analog for isolation, confinement, and remote conditions in exploration scenarios located in the Institute of Biomedical Problems at the Russian Academy of Sciences in Moscow, Russia. Similar to a spaceflight environment, the crew members are physically isolated from the outside world and have limited communication beyond NEK's walls. Fig. 2 presents a photo of the exterior views of the NEK research analog facility.

Data were collected from the SIRIUS-19 mission. SIRIUS-19 was a joint United States - Russian mission to study the effects of an isolated, confined, and controlled environment similar to what astronauts might experience on spaceflight missions. The SIRIUS-19 mission took place in 2019 and had a 6-person crew composed of four Russian and two U.S. crew members. The international crew included three women and three men: crew commander, flight engineer, flight surgeon, and three mission specialists. During their time in isolation, the crew worked a normal work week, performing a variety of tasks that were part of more than 80 experiments required for understanding the human factors important to the eventual exploration of deep space. The SIRIUS-19 mission scenario involved a simulated journey to the moon. The crew entered the moon's orbit, and midway through the mission, a subset of the crew landed on the lunar surface to carry out several moonwalks and gather samples, while being monitored by the two crew members who remained in orbit. The crew then reunited, orbited the lunar gateway, and returned to Moscow. The crew experienced a 5-min communication delay one-way with the mission control for nearly the entire mission starting on mission day 11 through mission day 110.

2.3. Tasks assessing team performance

Team performance was tracked across two dimensions: creative thinking and problem-solving. First, we used creative thinking tasks that require the group to engage in divergent thinking to generate ideas that do not yet exist. Second, we used intellective tasks that require the group to solve a problem that has a correct answer.

2.3.1. Creativity thinking tasks

Creative thinking tasks require the group to engage in divergent thinking to generate ideas that do not yet exist [27] and was assessed using an alternative use task approach and brainstorming solutions to space challenges tasks [28]. First, for the alternative uses tasks, crew members received instructions to generate as many alternative uses for a specified object. Four parallel versions of the task were created by varying the object named in the task (i.e., brick, paperclip, rubber band, and spoon). Crew members were instructed to spend 5 min individually generating alternative uses, and then came together as a crew to discuss additional uses.

Second, for the brainstorming solutions tasks, crew members received instructions to generate as many ideas as possible for specific challenges possible in a space context. Thirteen parallel versions of the task were created by varying the type of space challenge (e.g., basic housekeeping issues, high workload, maintaining cohesion within the crew, boredom with food, understanding the science studies, boredom, sleep, working with mission control, and getting used to being in a confined space). Crew members were instructed to spend 5 min individually brainstorming solutions, and then came together as a crew to discuss additional uses.

Following the procedure used by Larson et al. [1], both the alternative uses tasks and the brainstorming solutions tasks were completed utilizing the Qualtrics Survey Platform. The crews received instructions and timing guidelines, and typed responses from tablets. All tasks were scored using three dimensions: fluency, flexibility, and novelty [29–31]. Fluency was measured as the number of unique ideas the crew came up with. Flexibility was measured as the number of categories of ideas generated by each crew. Lastly, novelty was computed based on how

Fig. 2. Photograph of the exterior of the NEK Analog (Moscow, Russia); Image credits: NASA.

infrequently the ideas the crew came up with were listed across the other crews. Flexibility and novelty [29,31] are based on qualitative coding of all the ideas. Specifically, the number of categories for each item was determined by three raters categorizing all the items generated by the crews. If two of the three raters agreed on the overarching category, the item was classified as that category [31]. If two raters did not agree, the item was discussed, and a consensus reached. It is important to mention that novelty was not computed for NEK because the measure requires multiple crews to perform the same tasks; there is only one NEK mission included in this study.

2.3.2. *Problem-solving tasks*

Problem-solving tasks require the group to solve a problem that has a correct answer [32,33] and were assessed using survival tasks [34] and estimation tasks [35]. For the survival tasks, the crew members were provided with an explanation of the situation and a list of 15 available items, which they were to rank in order of their importance 1 (most important) to 15 (least important) to crew survival. Four parallel versions of the task were created by varying the survival scenario and objects ranked by the crew. The first scenario was the NASA moon survival task with validation provided by NASA experts. The second scenario was a desert survival task with validation provided by the Chief of the Desert Branch, Tropic Information Center of the Air Force University at Maxwell Air Force Base. The third scenario was a winter survival task validated by a US Army survival trainer. Finally, the fourth scenario was a lost at sea consensus-seeking survival task [36], a task commonly used to assess group decision quality. Similar to Larson et al. [1], the survival tasks were completed utilizing Qualtrics, and it was through Qualtrics the crew members received the instructions. The instructions were to spend 10 min independently to review the scenario and rank the items. Next, the crew members were instructed to spend 15 min discussing their rankings and arrive at a final crew ranking that represents their best assessment of the importance of the items. The survival tasks were scored using one dimension: problem-solving. The problem-solving was measured by computing the absolute difference between the crew ranking of the item and the respective expert ranking for the survival tasks, and then summing the deviations. Because greater deviation reflects lower performance, the score was reversed for this measure.

For the estimation tasks, the crew received a list with 10 estimation questions and were instructed to spend 10 min independently to consider their answer, and then came together as a crew to discuss their estimates for an additional 15 min. Thirteen parallel versions of the task were created by varying questions. Table 2 contains an example of such a task containing 10 estimation questions. The estimation tasks were completed utilizing Qualtrics, and it was through Qualtrics that crews received instructions and timing guidelines, and typed responses from tablets. The estimation tasks were scored using one dimension: problem-

Table 2
Estimation task example.

Question	Units
How deep is the Mariana Trench, one of the deepest parts of the Pacific Ocean?	Meters
As of 2018, what was the total number of movie theater screens in the United States?	Number
How many iPhones were sold by Apple in 2018?	Number
What percentage of Chinese exports are shipped to the United States?	Percentage
How many words are there in the King James Authorized Bible?	Number
How many taste buds does an average person have?	Number
As of February 8, 2019, how many days has the International Space Station been in orbit?	Days
How many questions does a kid ask every day on average?	Number
What is the record for the longest a human has gone without sleeping?	Hours
How many times would an average person's heartbeat in the course of a year?	Number

solving. Different from the survival tasks scoring, the problem-solving score for estimation tasks was measured as the percentile relative to the most expected estimation. The percentile measure was necessary because it is not possible to aggregate the absolute differences between the crews' answer to the estimation items and the correct answer because all items are on different scales (e.g., fractions, millions, meters, Celsius, etc.) The most expected estimation for each item was based on data collected on survey participants.

First, the survey participants were recruited using CloudResearch Prime Panels, a survey research platform. Inclusion criteria were currently residing in the U.S., having a bachelor's degree of higher education, having completed 500+ Human Intelligence Tasks on the Amazon Mechanical Turk (MTurk) crowdsourcing website, and with an approval rate of 95 % or higher. The survey participants received a total of 151 estimation questions. The questions were presented in a random order. Each survey participant was asked to complete all questions. Evenly interspersed in the items were six attention check questions (e.g., "what does 2 + 2 = ?"). A total of 94 responses from the survey participants were used in the reference distribution, after removing respondents who failed to complete the survey or failed attention checks.

Next, for each survey participant and for each SIRIUS-19 crew member, an item-level score was computed as the absolute difference between the participant estimation to the question and the correct value. Then, for each item estimated by crew members, researchers counted how many survey participants had an item-level score greater than the crew member's score. A lower value of the item-level score represents a better estimation. For example, a score of 0.50 would indicate the crew member's estimation was closer to the correct value than 50 % of survey participants. A score of 0.75 would indicate the crew member's estimation was closer to the correct value than 75 % of survey participants, etc. Finally, the problem-solving score for the estimation task was computed as the average across the 10 estimation questions.

Table 3 contains a summary of the tasks administered in HERA and NEK and the mission days.

Table 3
Tasks used to assess crew performance in HERA and NEK.

Specific task	Assessed on Quarter (Mission Day)	
	HERA	NEK
Creative tasks		
Alternative uses	Quarter 1 (no tasks performed)	Quarter 1 (MD 30)
	Quarter 2 (MD13, MD18*)	Quarter 2 (MD 56)
	Quarter 3 (MD 26*)	Quarter 3 (MD 92)
	Quarter 4 (MD 41**)	Quarter 4 (MD 113)
Brainstorming solutions	n/a	Quarter 1 (MD 6, MD 16, MD 20)
		Quarter 2 (MD 35, MD 42, MD 50)
		Quarter 3 (MD 70, MD 78, MD 85)
		Quarter 4 (MD 99, MD 104, MD 108, MD 118)
Problem-solving tasks		
Survival	Quarter 1 (no tasks performed)	Quarter 1 (MD 30)
	Quarter 2 (MD13, MD18*)	Quarter 2 (MD 56)
	Quarter 3 (MD 26*)	Quarter 3 (MD 92)
	Quarter 4 (MD 41**)	Quarter 4 (MD 113)
Estimation	n/a	Quarter 1 (MD 6, MD 16, MD 20)
		Quarter 2 (MD 35, MD 42, MD 50)
		Quarter 3 (MD 70, MD 78, MD 85)
		Quarter 4 (MD 99, MD 104, MD 108, MD 118)

Note: * ± 1 day ** ± 3 days across the 8 HERA crews.

2.4. Shared mental models

We developed a measure of shared mental models, based on subject-matter expert input, for use in ground-based analogs [37]. First, each individual's task mental model was collected using the elicitation method. A task mental model represents the relationship among task procedures or strategies, and equipment needed to accomplish team goals [22,38,39] and is critical for team success especially for teams that have a pre-assigned task schedule such as NASA crews [40]. Crew members were asked, on a scale of 1 (totally unrelated) to 7 (very strongly related), to report their perceptions of the relationships between a list of 8 task elements [41], which produced 28 dyadic values for each crew member for each day. The list of task elements included: (1) *Completing our individual work tasks*; (2) *Completing our crew responsibilities*; (3) *Communicating with mission control*; (4) *Performing extravehicular activities*; (5) *Ensuring crew health and safety*; (6) *Performing maintenance activities*; (7) *Participating in scientific studies*; and (8) *Managing our time and staying on task*.

Next, the Euclidean Distance measure between each pair of crew members was used to represent the degree to which their mental models were dissimilar. Then, the distance was divided by the maximum possible difference (i.e., if one person entered all '1s' and the other person entered all '7s'). This gave a number between 0 and 1 for a proportion of possible differences between two crew members. Finally, the number was inverted by subtracting it from 1 in order to get a proportion of possible similarity as opposed to distance. The result was a dyadic relational measure where ties are weighted indicators of shared cognition between each pair of crew members. The crews' task shared mental models were assessed 38 times in each HERA mission and 35 times in SIRIUS-19. Given that team tasks were performed four times in each HERA mission and thirteen times in SIRIUS-19, we used the shared mental models collected immediately before the team task was performed during analyses.

3. Results

3.1. HERA results

Table 4 presents the descriptive statistics on crew performance dimensions and shared mental model for the eight HERA crews. Examining the performance for creative thinking tasks, there was wide variation in creativity, with the high score of 93 ideas more than double the low score of 25 ideas (i.e., fluency). Similar variation was observed with the number of categories of ideas (i.e., flexibility). The novelty score does not show variation in Table 4; however, this is due to the way the measure is computed. Examining the performance for problem-solving tasks, there was a wide variation in the problem-solving score; the best performance was a deviation of 20 points from the expert model across 15 items, whereas the worst observation was 72 points. Finally, the shared mental model varied from 0.55 (least similar mental model) to 0.80 (most similar mental model).

For interpretability across different measurement scales, the raw

Table 4
Descriptive statistics for HERA.

Variable	Mean	SD	Min	Max
Alternative uses				
Fluency	52.19	15.14	25	93
Flexibility	23.81	4.54	15	33
Novelty	0.99	0.00	1	1
Survival				
Problem-solving	−44.94	12.63	−72	−20
Predictor				
Shared mental model	0.71	0.07	0.55	0.80

Note: N = 32; Reported means and standard deviations are calculated from the raw score values for each dimension.

scores were converted to z-scores using the distributions of scores for the eight crews at the four time points. This process was done for each of the creative thinking and problem-solving dimensions. The statistical analyses include z-scores.

Fig. 3 displays the crews' performance over time in HERA C4 and C5. Fig. 3 depicts that the crew performance decreases in the third quarter of the mission for all crews, except for the crew C5M4.

Fig. 4 presents the shared mental model over time for HERA C4 and C5. Fig. 4 depicts that there is a slight increase in shared mental model over time in HERA C4. However, the shared mental model varies in HERA C5 with a decrease in the last quarter of the mission.

Next, we used Hierarchical Linear Modeling (HLM) to detect statistically significant differences in the tasks assessing team performance. HLM is appropriate because of the nesting of task performance activities which were collected during different time periods, and during different missions for HERA. Table 5 presents the HLM results for creative thinking tasks and problem-solving. Models 1, 3, 5, and 7 present the effect of shared mental model and third quarter effect of performance. Furthermore, we examined the interaction effect between shared mental models and the mission phase on team performance. Thus,

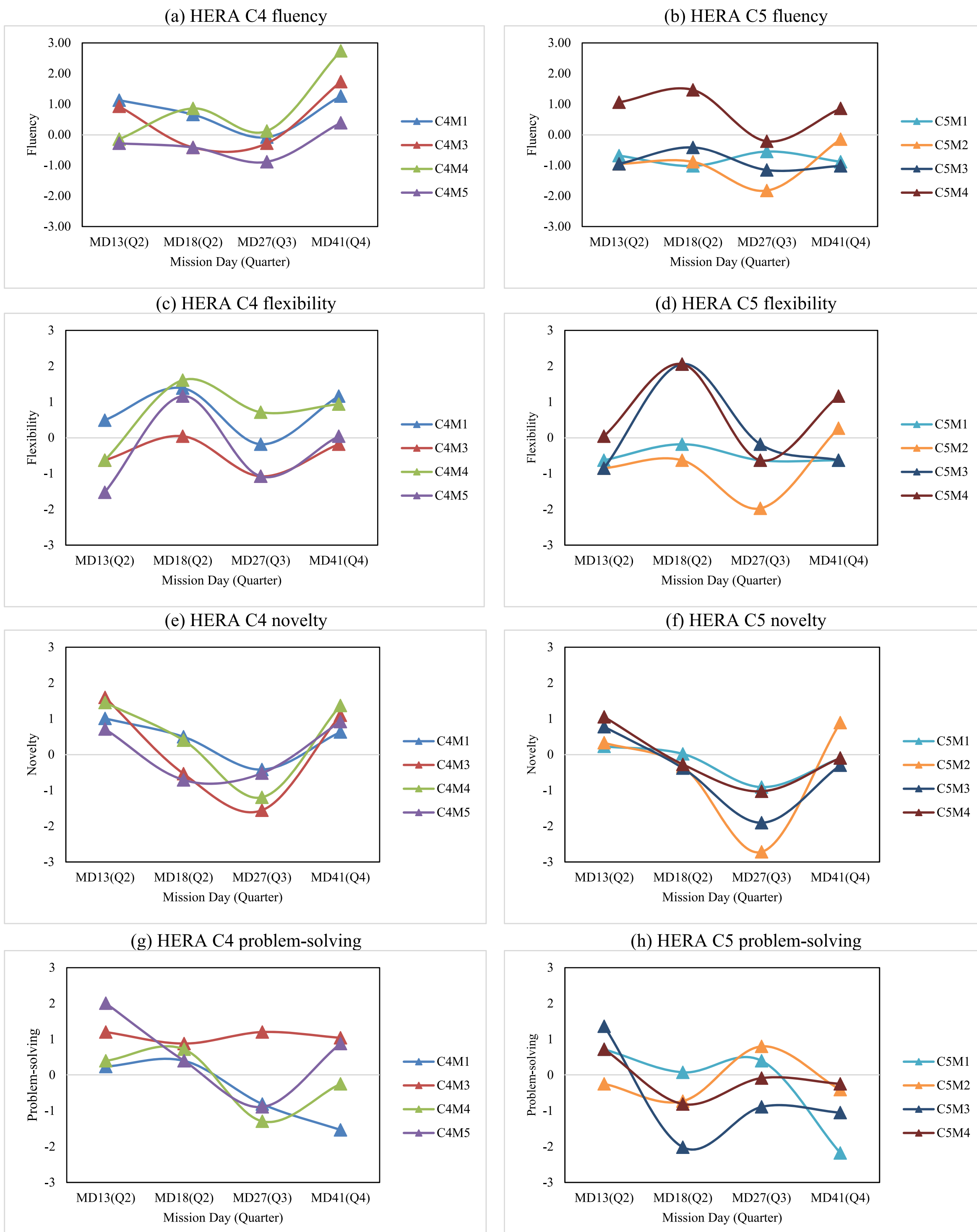

Fig. 3. Performance over time in HERA.

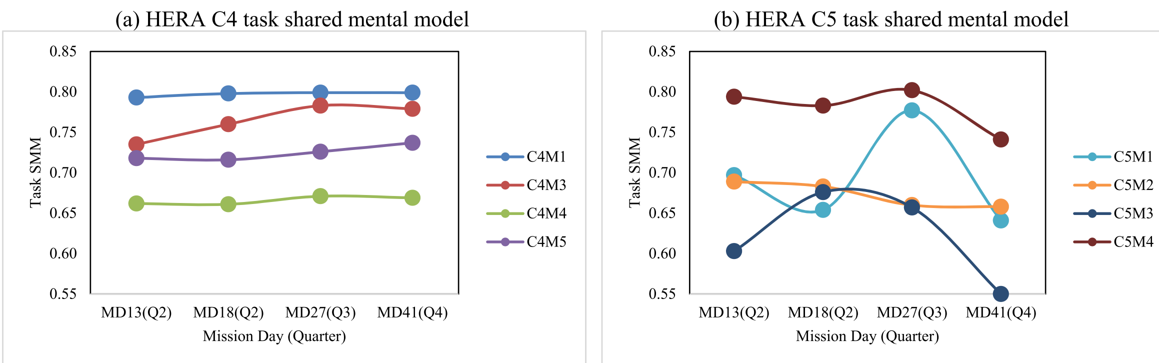

Fig. 4. Task shared mental model over time in HERA.

Table 5
HLM results predicting the effect of task shared mental model on team performance on creative thinking tasks in HERA.

	Fluency (z-score)		Flexibility (z-score)		Novelty (z-score)		Problem-solving (z-score)	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Fixed effects								
Intercept	−5.689*** (1.209)	−6.023*** (1.233)	−3.344* (1.482)	−4.215*** (1.144)	−1.709 (1.044)	−0.791 (1.002)	−2.382 (1.840)	−2.259 (1.856)
Predictors								
Task SMM	8.321*** (1.448)	8.793*** (1.508)	5.019* (2.075)	6.250*** (1.665)	3.017* (1.369)	1.721 (1.302)	3.457 (2.778)	3.284 (2.751)
Quarter 3	−1.030*** (0.112)	0.652 (0.944)	−0.972*** (0.242)	3.110 (2.969)	−1.787*** (0.264)	−6.118** (2.258)	−0.353 (0.384)	−0.932 (3.975)
Interaction effects								
Task SMM x Quarter 3		−2.308+ (1.335)		−5.602 (3.874)		5.943* (2.991)		0.796 (5.071)
Random effects								
Variance Components								
Residual	0.341* (0.168)	0.338* (0.168)	0.648 (0.192)	0.622+ (0.170)	0.416*** (0.084)	0.391*** (0.090)	0.934 (0.244)	0.932 (0.245)
Mission	0.244* (0.169)	0.240* (0.164)	0.152** (0.100)	0.154** (0.095)	0.000 (0.000)	0.000 (0.000)	0.004 (0.142)	0.005 (0.143)
Additional information								
Observations	32	32	32	32	32	32	32	32
Wald Chi2	94.053	161.245	17.000	53.679	47.588	74.722	2.075	2.856
AIC	77.181	78.849	92.205	93.139	72.734	72.780	98.772	100.757
BIC	84.510	87.643	99.534	101.934	80.062	81.574	106.101	109.552

Note: Robust standard errors in parentheses; + $p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Models 2, 4, 6, and 8 add the interaction term between shared mental model and the third quarter to compare the relationship during the third quarter to that observed in the other mission quarters.

Examining Table 5 shows shared mental model positively predicts fluency (Model 1, β = 8.321, $p < 0.001$), flexibility (Model 3, β = 5.019, $p < 0.05$), and novelty (Model 5, β = 3.017, $p < 0.05$). While the third quarter negatively predicts fluency (Model 1, β = −1.030, $p < 0.001$), flexibility (Model 3, β = −0.972, $p < 0.05$), and novelty (Model 5, β = −1.787, $p < 0.05$). Neither shared mental model nor the third quarter influence problem-solving.

Next, the coefficient estimate of the interaction term of the shared mental model and third quarter is negative and marginally significant in Model 2 (β = −2.308, $p < 0.1$) and positive and significant in Model 6 (β = 5.943, $p < 0.05$). Figs. 5 and 6 present the graphical representation of the interaction effects. These results indicate that, based on Model 2, the relation between shared mental models and fluency is less pronounced in the third quarter as compared to the other quarters. However, based on Model 6, shared mental models are more strongly related to novelty during the third quarter than during the other quarters. Taken together, we observed a third quarter effect with shared mental models whereby

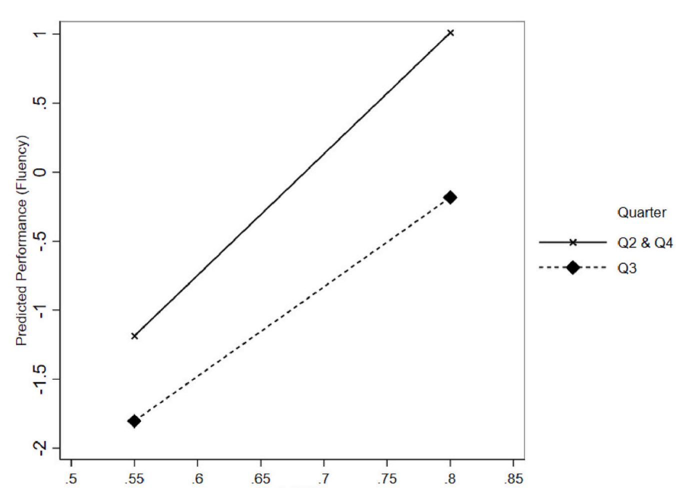

Fig. 5. Interaction effect of task shared mental model and third quarter on fluency in HERA.

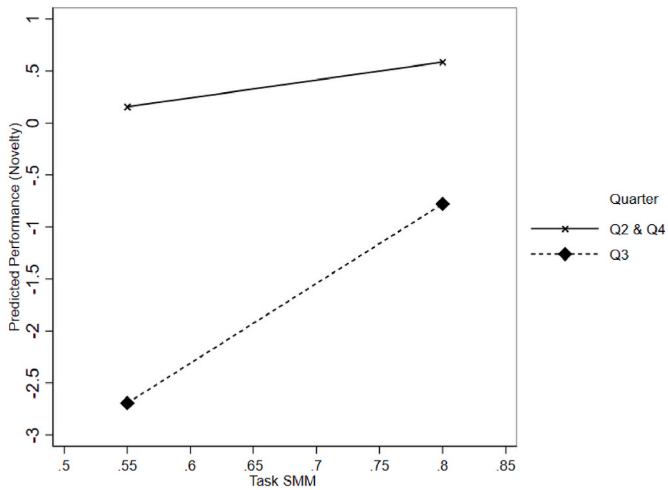

Fig. 6. Interaction effect of task shared mental model and third quarter on novelty in HERA.

the degree of sharedness of mental models is associated with crews generating fewer ideas than in other quarters, but also generating more novel, original ideas than in other quarters.

3.2. NEK results

Table 6 presents the descriptive statistics on crew performance dimensions and shared mental model for the NEK SIRIUS-19 crew. Given that the scores were coded differently for each task administered in NEK, we present the statistics separately for each type of task. Examining the performance for alternative uses tasks, there was lower variation in creativity than in HERA, with a high score of 37 ideas and a low score of 21 ideas (i.e., fluency). It is important to note that in HERA there were 16 crews for a total of 64 individuals, while in NEK there was only one crew with 6 members. Similar variation was observed with the number of categories of ideas (i.e., flexibility). Examining the performance for brainstorming solutions tasks, there was a wide variation of solutions to space challenges from a low score of 5 to a high score of 26. Similar variation was observed with the number of categories of solutions (i.e., flexibility).

Next, examining the performance for survival tasks, there was a wide variation in the problem-solving score; the best performance was a deviation of 22 points from the expert model across 15 items, whereas the worst observation was 82 points, which is worse than what was observed in HERA. Examining the performance for estimation tasks, the problem-solving score ranged from 0 to 1, with a mean of 0.45. In other words, on average, the crew was closer to the correct value than 45 % of survey participants. Finally, the shared mental model varied from 0.69 (least similar mental model) to 0.82 (most similar mental model).

Similar to the HERA analysis, for interpretability across different measurement scales, the raw scores were converted to z-scores using the distributions of scores for the SIRIUS-19 mission at the 17 time points. This process was done for each of the creative thinking and problem-solving performance task dimensions. The statistical analyses include z-scores.

Fig. 7 displays the SIRIUS-9 crew shared mental model and fluency. Fig. 7 depicts that both shared mental model and fluency decrease as the mission progresses, with a slight increase during the last days of the mission.

Fig. 8 displays the SIRIUS-9 crew shared mental model and flexibility. Fig. 8 depicts that flexibility varies across the mission with a declining trend as the mission progresses.

Finally, Fig. 9 displays the SIRIUS-9 crew shared mental model and problem-solving. Fig. 9 presents that problem-solving varies as the mission progresses.

Next, we used HLM to detect statistically significant differences in the tasks assessing team performance. HLM is appropriate because of the nesting of task performance activities that were collected during different mission phases in NEK. Table 7 presents the HLM results for NEK for creative thinking and problem-solving tasks. Models 1, 3, and 5, present the effect of shared mental models and the third quarter on crew performance. Furthermore, we examined the interaction effect between shared mental models and the mission quarter on team performance. Thus, Models 2, 4, and 6 add the interaction term between shared mental models and the third quarter to compare the relationship during the third quarter to that observed in the other mission quarters.

Examining Table 7 shows shared mental models positively predict fluency (Model 1, $\beta = 11.540, p < 0.05$), flexibility (Model 3, $\beta = 14.249$, $p < 0.001$), and problem-solving (Model 5, $\beta = 15.545, p < 0.05$). A third quarter main effect was not observed in the SIRIUS-19 mission. However, we did observe an interaction effect with the third quarter when it comes to problem-solving. The coefficient estimate of the interaction term of shared mental models and the third quarter is negative and significant in Model 6 ($\beta = -23.102$, $p < 0.01$). Fig. 10 presents the interaction effect graphically. The form of the interaction indicates that shared mental models are positively related to problem-solving performance in all quarters except the third quarter, when the relation is weakly negative. This pattern contrasts with what was observed in the shorter duration HERA analog where there was a third quarter effect with creativity, and not problem-solving, and where the nature of the effect was to render shared mental models more predictive of performance, rather than less, as was observed in the NEK.

Table 6
Descriptive statistics for NEK.

Variable	Mean	SD	Min	Max
Alternative use tasks				
Fluency	31.25	7.04	21	37
Flexibility	19.75	4.27	15	25
Brainstorming solution tasks				
Fluency	13.85	6.44	5	26
Flexibility	10.08	5.56	5	17
Survival tasks				
Problem-solving	−57.50	25.63	−82	−22
Estimation tasks				
Problem-solving	0.45	0.104	0	1
Predictor				
Shared mental model	0.75	0.04	0.69	0.82

Note: N = 17; Reported means and standard deviations are calculated from the raw score values for each dimension.

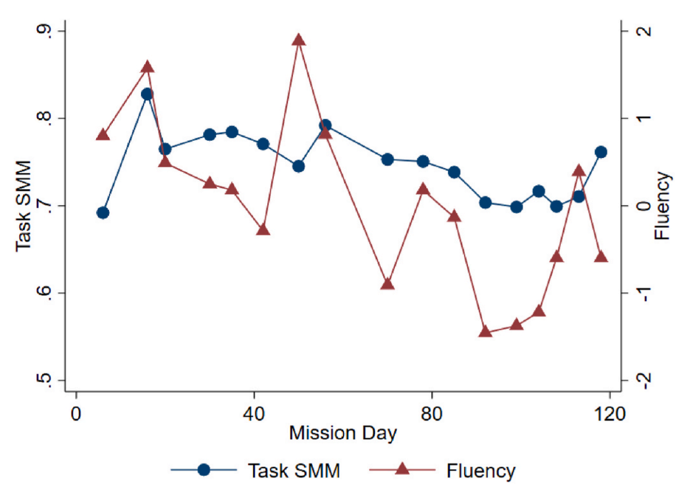

Fig. 7. Fluency performance and task shared mental model over time in NEK.

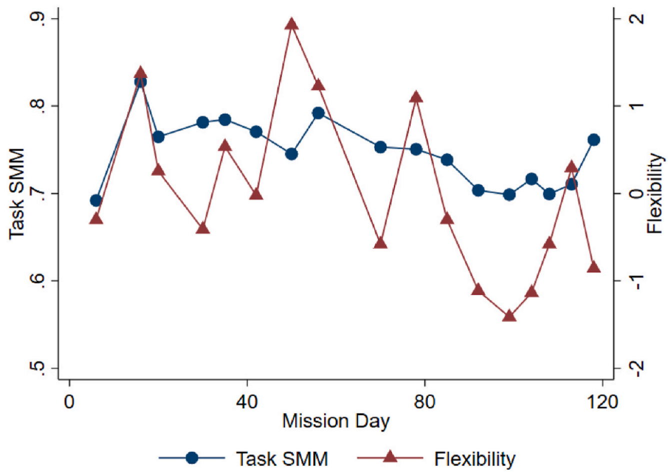

Fig. 8. Flexibility performance and task shared mental model over time in NEK.

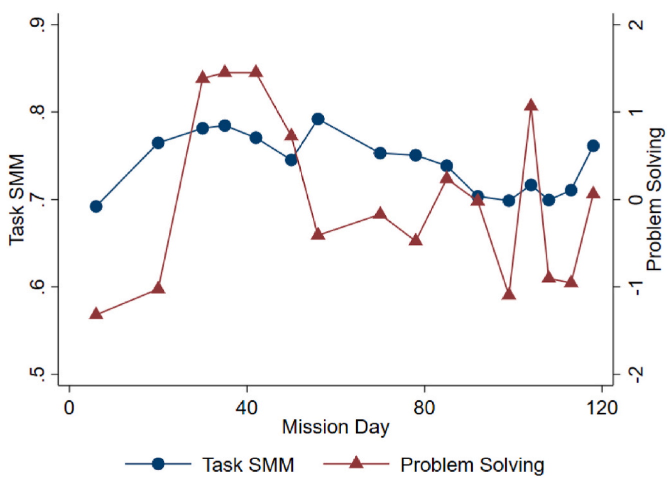

Fig. 9. Problem-solving performance and task shared mental model over time in NEK.

4. Discussion

Space agencies endeavor to send expert teams on missions into deep space. The unprecedented level of autonomy necessitated by deep space exploration requires that we understand the factors most predictive of crew performance, and that can be measured in missions to preempt performance decrements. This study developed a measure of the strongest known predictive of team performance, shared mental models, and implemented it within 9 ground-based analog missions. Additionally, we examined how the mission phases influence team performance.

We found substantial positive correlations of shared mental models team performance in HERA and in SIRIUS-19. Shared mental models positively predict performance on creative thinking tasks in HERA and in SIRIUS-19. However, shared mental models positively predict performance on problem-solving tasks only in SIRIUS-19. Furthermore, we noticed a third quarter effect in the 45-day HERA analog, but not in the 4-month NEK SIRIUS-19 mission.

Though shared mental models are a strong predictor of team performance across mission stages, we found some nuanced shifts. Examining the interactions, we find evidence of a third quarter effect with crew shared mental models and creative thinking. Mental model sharedness is associated with crews generating fewer ideas than in other quarters, but also generating more novel, original ideas. Shared mental models are therefore quite important to crew creative thinking during the third quarter. Importantly, we did not observe the same relation with creativity in the longer duration NEK SIRIUS-19 mission. In that mission, we observed only a third quarter effect with problem-solving, and the nature of the effect was that the effect of the shared mental model was most important in all quarters except the third.

This difference in findings suggests mission timing but also mission duration are important factors that condition relations between team process variables like shared mental models and team performance indicators. We add the important caveat that the findings in HERA replicate across 8 crews, whereas those of NEK SIRIUS-19 were observed in a single crew. The challenge of studying multiple crews in long duration analogs precludes rapid replication of these findings.

The first contribution of this research is to establish that crew mental models predict team performance on tasks that require creative thinking (i.e., thinking outward to generate many possible and novel solutions when there may be more than one correct solution) and those that require problem-solving thinking (i.e., combining disparate expertise toward a correct solution). In the 45-day HERA analog, mental model similarity predicts crew performance on creative thinking tasks. In the 4-month NEK SIRIUS-19 mission, variations in crew mental model similarity tracked performance variations on repeated administrations of both creative and problem-solving tasks. Though shared mental models are assessed via a survey, they are not based on subjective perceptions of the crew's functioning. They elicit mental schema about the work and compute geometric-based distance measures. Their ability to track performance variations is therefore of great potential utility in space missions.

The second contribution of this study is the demonstration of the predictive utility of shared mental models within the same crew over time. Though shared mental models have been found through multiple meta-analyses [18,42,43] to predict performance, the current studies do not examine this relationship within crews, rather validity coefficients are based on between-crew comparisons. The extension of this relation to the within-crew case has immediate value to space agencies where a single team will need to maintain high performance for three years, and in addition, this finding is notable for any setting where the same team works together over repeat performances.

Furthermore, these findings contribute to the teamwork literature by highlighting the importance of developmental and temporal cycles. Much work on teams examines relationships between mental models and performance at one point in time or once per team. These findings demonstrate that within the same team, there is meaningful variation in how well shared mental models predict performance. The context of the group can condition the strength of these relations. These findings invite teams' researchers to consider the degree to which other needed processes and states are differently predictive depending on context and timing.

The third contribution of this study is the finding that shared mental models have different degrees of prediction during different phases of the mission. In short duration analogs, we observe heightened importance of shared mental models on crew creativity during the third quarter as compared to other periods. In the long duration analog, we found an opposite third quarter effect where the effect of shared mental models on problem-solving was diminished during the third quarter. Taken together, these findings suggest the third quarter is especially interesting in terms of team dynamics, if not as straightforward as previously thought.

Previous studies of individual adaptation to harsh environments document a third quarter effect suggesting decrements in morale and well-being during this period [7,44,45]. In contrast, research on teams in ground-based space analogs documents a decline in crew performance just before the end of the mission, a so-called fourth quarter effect [1,46].

The current and prior findings together underscore the importance of understanding the developmental cycles of teams over time, and how these cycles affect different aspects of performance over time. Future

Table 7
HLM results predicting the effect of task shared mental model on team performance on creative tasks and problem-solving tasks in NEK.

	Fluency (z-score)		Flexibility (z-score)		Problem-solving (z-score)	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Fixed effects						
Intercept	−8.473*	−7.892*	−10.613***	−9.944***	−11.516*	−13.092**
	(3.774)	(4.000)	(2.622)	(2.727)	(4.576)	(4.854)
Predictors						
Task SMM	11.540*	10.766*	14.249***	13.357***	15.545*	17.666**
	(4.875)	(5.180)	(3.434)	(3.575)	(6.260)	(6.652)
Quarter 3	−0.605	−9.262	−0.106	−10.072	−0.039	16.988**
	(0.382)	(7.730)	(0.424)	(9.234)	(0.347)	(5.446)
Interaction effects						
Task SMM x Quarter 3		11.741		13.517		−23.102**
		(10.597)		(12.913)		(7.486)
Random effects						
Variance Components						
Residual	0.595	0.583+	0.585	0.570	0.615+	0.568+
	(0.190)	(0.190)	(0.217)	(0.214)	(0.164)	(0.190)
Additional information						
Observations	17	17	17	17	16	16
Wald Chi2	15.124	43.807	20.221	43.089	6.238	10.186
AIC	47.406	49.066	47.140	48.681	45.636	46.362
BIC	50.739	53.232	50.473	52.847	48.727	50.225

Note: Robust standard errors in parentheses; + $p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

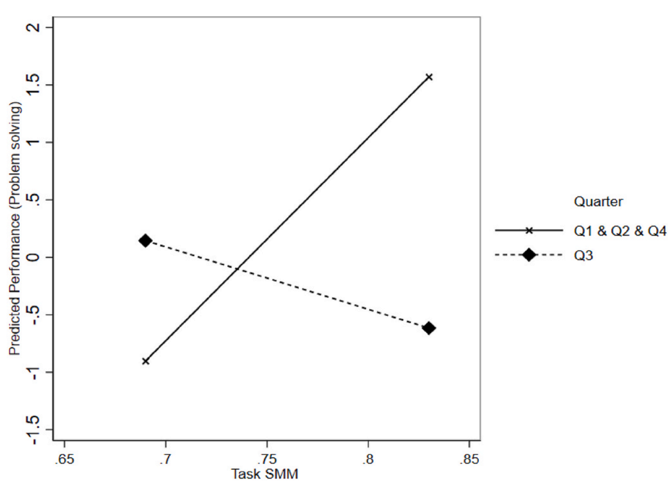

Fig. 10. Interaction effect of task shared mental model and third quarter on problem-solving in NEK.

research is needed to further unpack these effects and will be useful in knowing how best to support space crews at different points in time.

4.1. Limitations and future directions

This study has several limitations. An important limitation of the current findings is the use of a realistic but simulated context. These teams were not in fact on a life-or-death space mission, and thus some of the extremity of such a mission would certainly exert a strong effect on these relations.

A second limitation of this study is that we did not consider other typologies of shared mental models. Mathieu and colleagues [39] highlighted the effect of task- and team-based mental models on team process and performance. We have implemented both measures of team and task mental models in HERA and NEK. However, there was no variance in the team mental model measure, and consequently we did not retain it.

Another limitation of this study is that we examined the effect of mental model similarity (i.e., shared mental model) on performance, but we were not able to explore the effect of mental model accuracy, which has also been found to predict team performance [18]. The shared mental model measure used in this study was developed with input from NASA subject matter experts and it was designed to capture mental models on elements of taskwork during the mission that do not have a right or wrong answer. However, the convergence of the model does not capture the accuracy of it.

Finally, future research should examine the effect of transactive memory systems [47] on crew performance. Expertise is very important in space missions, especially since the crew is carefully assembled to have all of the expertise needed with as little redundancy as possible. However, in the analog missions the crew expertise is not a factor in selection or in assignment of roles. The crew members do the same work tasks and are essentially interchangeable. Thus, when we designed the current study, we chose to focus more on shared mental models than on transactive memory.

5. Conclusion

In conclusion, results from this study suggest crew mental models are a useful team-level property to actively monitor during long-distance space missions. These results demonstrate that crew shared mental models predict crew performance on creative and problem-solving tasks in two space analogs of different durations. Furthermore, we observe these predictions within crews, that is, variations over time within a crew track observed fluctuations in creative thinking and problem-solving. This suggests mental models may be used to trigger the need for crew refresher training or other countermeasures that support space crews on autonomous, long-distance missions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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