Lessons from a Space Analog on Adaptation for Long-Duration Exploration Missions

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BACKGROUND: Exploration missions to asteroids and Mars will bring new challenges associated with communication delays and more autonomy for crews. Mission safety and success will rely on how well the entire system, from technology to the human elements, is adaptable and resilient to disruptive, novel, or potentially catastrophic events. The recent NASA Extreme Environment Missions Operations (NEEMO) 20 mission highlighted this need and produced valuable "lessons learned" that will inform future research on team adaptation and resilience.

METHODS: A team of NASA, industry, and academic members used an iterative process to design a tripod shaped structure, called the CORAL Tower, for two astronauts to assemble underwater with minimal tools. The team also developed assembly procedures, administered training to the crew, and provided support during the mission.

RESULTS: During the design, training, and assembly of the Tower, the team learned first-hand how adaptation in extreme environments depends on incremental testing, thorough procedures and contingency plans that predict possible failure scenarios, and effective team adaptation and resiliency for the crew and support personnel.

DISCUSSION: Findings from NEEMO 20 provide direction on the design and testing process for future space systems and crews to maximize adaptation. This experience also underscored the need for more research on team adaptation, particularly how input and process factors affect adaption outcomes, the team adaptation iterative process, and new ways to measure the adaptation process.

KEYWORDS: NEEMO, iterative design, extreme environments, astronauts, human factors.

Anglin KM, Kring JP. *Lessons from a space analog on adaptation for long-duration exploration missions.* Aerosp Med Hum Perform. 2016; 87(4):406–410.

Longer and more complex space missions to asteroids, the Moon, Martian moons, and the surface of Mars, will present astronaut crews and Mission Control teams with new challenges.[9] With communication delays between Earth and Mars ranging from 8 to 24 min, and minimal opportunities for resupply if a tool, component, or entire system fails, crews will have to function more autonomously, and creatively, than ever before.[7] The safety and success of these long-duration exploration missions (LDEMs) will rely on how well the entire system, from the vehicle to the crew, is adaptable and resilient to disruptive, novel, or potentially catastrophic events.[2] Flexibility must be built into vehicle and habitat components so that system failures can be overcome.[8] Most importantly, the overall team, which includes the crew in space and personnel at Mission Control, must possess team adaptability: the capacity to respond to disruptive events, or "triggers," by adjusting team strategies, roles, and behaviors.[6] Teams with this ability to adapt also develop resilience; a team state referring to their belief they can respond to disruptive events and their capacity to thrive and perform under such conditions.[6]

The importance of adaptation and resilience was highlighted during the NASA Extreme Environment Mission Operations (NEEMO) 20 mission in July 2015 when assembly of a tower-shaped structure did not go as planned. NEEMO missions take place at the Aquarius facility—a small habitat operated by Florida International University and located approximately 19 m underwater off the coast near Key Largo, FL. During missions typically lasting between 7 and 14 d, crews of four astronauts, supported by two habitat technicians, simulate exploration

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This manuscript was received for review in September 2015. It was accepted for publication in December 2015.

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DOI: 10.3357/AMHP.4489.2016

space missions complete with extravehicular activities (EVAs), multiple experimental tasks, and interaction with the NEEMO Mission Support Team. For NEEMO 20, four aquanauts spent 2 wk underwater evaluating tools and techniques for future EVAs on different surfaces and gravity levels, from asteroids to Mars moons and the Martian surface. Specifically, the NEEMO 20 crew assembled a tripod shaped structure called the Collaborative Oceanic Reliability Analysis Laboratory (CORAL) Tower. The present paper describes how development of the CORAL Tower, related procedures and training, and difficulties during assembly, produced several key "lessons learned" that highlight the need for adaptation and resiliency during LDEMs, both for technology design and the personnel involved in the mission.

METHODS

Students at Embry-Riddle Aeronautical University (ERAU) and engineers at Teledyne Oil & Gas designed the CORAL Tower based on two key criteria. The first was to design a structure two astronauts could assemble during underwater EVAs, with minimal tools, to demonstrate potential construction techniques and materials for Mars habitats. Expanding on the design of the first CORAL structure—deployed fully assembled during the NEEMO 19 mission—the larger CORAL Tower utilized cam-lock bolts and hinge-able brackets to facilitate assembly. The second objective was to employ an iterative design process to design, test, then redesign the structure in order to develop the most robust and simplified structure possible. In addition, an ERAU graduate student was tasked with developing assembly procedures, administering training to the crew, and providing support during the mission.

Design and Testing of the CORAL Tower

In the months leading up to the NEEMO 20 mission, the ERAU and Teledyne team employed an iterative design process that involved prototyping, testing, analyzing, and refining the structure. The first iteration of the CORAL Tower involved 3 main legs held together by 24 crossbars of 4 different lengths which were attached to fiberglass brackets on the legs by cam-lock bolts. Using a single-lever cam action, the cam-lock bolts were the only fasteners and did not require additional tools. During initial assembly tests, conducted in a hangar, it was found constructing the Tower was too difficult for just two individuals. In addition, given that buoyancy and visibility for the assembly process would be much different underwater during the NEEMO mission, the team conducted the next assembly test in the university swimming pool.

The pool test proved to be vital to the evolution of the Tower design. As two student scuba divers attempted the assembly, initial flaws in the design became apparent. Most critical was the difficulty of properly aligning the three main legs, and keeping them upright, while the crossbars were maneuvered into place. As shown in **Fig. 1**, the main legs tended to spread apart and tilt out of the proper orientation. Without the proper distance and orientation, the divers had to force the structure into position. Because the fiberglass brackets on the main legs for the crossbars were not flexible or durable, many snapped. Furthermore, the main legs would shift to the point of nearly collapsing, which was prohibiting assembly and a potential safety issue for crewmembers during the NEEMO mission.

Fig. 1. Original CORAL Tower design during pool testing.

In addition to vividly illustrating the need for stronger, metal brackets on the main legs that could rotate and accept crossbars at different angles, the pool test revealed the need for a way to hold the three main legs in place, in the proper orientation, while crossbars were attached. As a result, the team designed a "cap" for the top of the Tower with sockets for the main legs, as well as a "support structure;" three extendable poles that would hold the cap in place, at the proper height, while the crew maneuvered the main legs into place.

Training and Assembly of the CORAL Tower

With the Tower design finalized, the next major step was developing written assembly procedures for the crew and a training approach. Like the Tower design, the procedures also went through many iterations based on feedback from the NEEMO 20 crew and Mission Support team. With each version, the goal was to increase clarity, brevity, and highlight any potential obstacles to assembly and safety considerations. Training then occurred during a 1-h session the week before the start of NEEMO 20 and was designed to include visual, auditory and tactile elements to maximize understanding and accommodate different learning styles. As the trainer read the procedures aloud, two students, involved in the Tower design, demonstrated each step. During this phase, questions from the crew were addressed and clarified. Finally, the crew was given the opportunity to practice assembly with guidance from the trainer. With feedback from the crew and the NEEMO Mission Support team, including highly skilled divers, this training process proved extremely beneficial in identifying problems that could develop during assembly. Thus, precautions along with other procedural clarifications were incorporated into the final assembly procedures document provided to the crew and Mission Support team.

Assembly of the Tower began on Day 9 of the mission with two EVA crewmembers working at the construction location with support from a third crewmember reading aloud the procedures over the radio from inside Aquarius. The crew were also working under a 10-min communication delay with the Mission Support team. The crew started with erecting the support structure with the top cap in preparation of then orienting and installing the three main legs. However, to train the crew to be adaptable and flexible in response to disruptive events, the Mission Support team purposely had a key piece of equipment go "missing." This equipment, an alignment tool used to line up holes in the brackets prior to installing the main legs, was designated as necessary for assembly to continue in the mission "flight rules." Although the EVA crewmembers used their creativity and found a suitable alternative for this tool, it was not an approved replacement. Thus, the crew followed the rules and ceased assembly.

On Day 10, two different EVA crewmembers again attempted to complete assembly of the Tower, having procured a 3-D printed replacement alignment tool. Unfortunately, while one crewmember attempted to equalize their weight by holding on to the support structure, this component, which was critical to the assembly process, fell over and broke apart. Had communication with Mission Control not been delayed by 10 min, the Mission Support team could have alerted the crewmember to this error; however, this was not possible. It is important to note similar delays will occur during exploration missions, altering how directly involved Mission Control can be with crew activities.

This event highlighted two detrimental oversights on the part of the CORAL Tower development team. First, the procedures should have included clear warnings against leaning on or using the support structure for balance. Labeling on the structure should also have indicated fragile areas on the support structure and that specific parts were not "handles." Second, the team had not developed sufficient contingency plans prior to the mission for potential failures of key components, like the support structure. Had the procedures document contained a series of alternatives or solutions, the crew could have overcome the failure with minimal input from the Mission Support team and likely completed assembly during the same EVA.

Instead, the EVA was cancelled and the crew and Mission Support team brainstormed and developed several alternative assembly approaches that did not require using the failed support structure. On the Mission Support side, engineers from multiple fields of expertise also came together and used hastily made cardboard prototypes of the CORAL Tower structure in order to envision the new assembly process. Through a creative and invigorating discussion, the team compared many alternatives and, ultimately, developed two feasible solutions with the highest level of safety for the crew and success. The first choice was to break simulation and use "lift bags" and additional support divers to steady the structure during assembly. The second choice, deemed more problematic, involved partially building the Tower on its side and then righting the structure with ropes. On the crew side, they developed a "build on its side" approach as their first choice so as not to break simulation and maintain the original plan of two crewmembers performing the assembly with no additional support (i.e., no lift bags or support diver assistance). When the crew and Mission Support teams compared solutions, Mission Support ultimately sided with the crew's plan. On Day 11, the crew implemented the new plan and, as shown in **Fig. 2**, assembly was a success.

RESULTS

During the design, training, and assembly of the CORAL Tower, the entire team learned many valuable lessons, from design considerations for extreme settings to the importance of contingency plans. In essence, all of these lessons learned fall under the heading, or "umbrella," of adaptation in extreme environments.

First, incremental human factors testing during the design process is critical and should be done outside the lab and in settings analogous to the ultimate environment. In addition to practice assembly sessions in a hangar setting, the ERAU team tested in the campus pool to approximate the conditions expected for NEEMO 20. This test highlighted design flaws and led to upgrades to bracket strength and flexibility as well as the development of an additional "support structure" to facilitate assembly. Coincidentally, it was this support structure that ultimately failed during the mission. Although the failure could have been prevented with further testing, other changes resulting from the pool test analogous to the mission environment provided the adaptability required. The alternative assembly approach implemented would not have been feasible had the main leg brackets not been redesigned to be more durable and "hinge-able" based on the previously noted pool test.

Second, the team learned that procedures must be thorough and provide one or more contingency, or "Delta," plans for each potential failure. When the support structure failed, a key component in the assembly, the ERAU team involved in developing the assembly procedures should already have devised a plan to

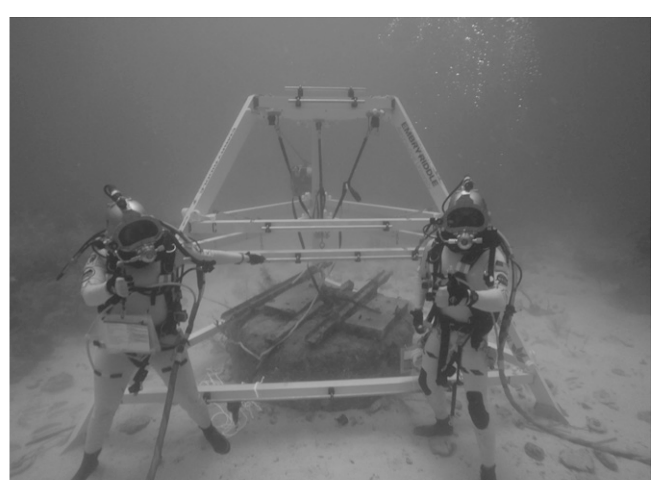

Fig. 2. Fully assembled Tower with NEEMO 20 astronauts.

continue assembly without that component. The team did not envision or imagine the support structure would collapse as it did, and, therefore, did not have a preplanned Delta. During a real space mission, such failure of imagination could have disastrous consequences. Implementing a systems engineering perspective when developing procedures and employing a fault-tree analysis, which is a top-down process that identifies pathways with the potential to lead to failures, will decrease chances of a major failure threatening task completion or mission success. This analysis could then be represented in a more dynamic procedures document that provides a trouble-shooting and solution-generation functionality. For example, the document could provide a list of possible failures, such as "If the main bracket fails, then consider this procedure" with hyper-linked alternatives. This dynamic procedures document could supplement the crew's solution-generation process, particularly when communication delays prevent direct support from Mission Control.

Third, the entire team, from the crew to Mission Support, must be adaptable. When problems occur, the team must work together efficiently to develop viable alternatives. The NEEMO 20 crew was a prime example of successful adaptation when they developed their own contingency plan to complete the Tower after the initial component failure. Likewise, the iterative testing of the Tower uncovered the need for more flexibility in the structure design; flexibility that was critical in allowing the crew to develop their contingency plan. When failures arise in extreme settings like space or planetary operations, the design, the crew, and the Mission Support team all need to be adaptable and resilient. This is particularly crucial during LDEMs when the crew's level of autonomy will vary due to communication delays and less direct support from Mission Control.

DISCUSSION

As NASA's vision is "to reach for new heights and reveal the unknown so that what we do and learn will benefit humankind," adaptation of both human and technological elements will be vital to the success of each exploration mission. Our experience during the NEEMO 20 mission highlighted the importance of adaptation and demonstrated the value of incremental testing and need for thorough procedures with predesigned contingency plans. This experience also underscored the need for more research on the team adaptation process. As noted in a recent review of the team literature, Maynard, Kennedy, and Sommer[6] express that research on team adaptation has been hindered by "both the lack of an integrated perspective and the absence of agreed upon operational definitions for adaptation-related concepts" (p. 654). To address this weakness, and improve understanding of team adaptation for the LDEM context, we argue researchers should focus on three key goals.

First, researchers should conduct laboratory- and field-based studies to test the validity of a nomological network of team adaptation developed by Maynard, Kennedy, and Sommer.[6] Based on an input-mediator outcome framework, this model categorizes a team's capacity to adapt (an input focus), the result of teams that adapt (an outcome focus), and the actual process of adaptation within teams (mediator or process focus). Although this team adaptation model is solidly grounded in prior team performance literature, significant gaps remain in our knowledge of the specific relationships between input, mediator, and outcome variables, particularly for small teams in settings analogous to LDEMs.

Second, research is needed on the cycle of adaptation, specifically how trigger type and severity alter the number of iterations teams undergo before finding an optimal response or solution.[1,6] Similar to the view of team learning as a dynamic process, team adaption has the potential to have multiple cycles and iterates.[3] Burke and colleagues[4] suggests team adaptation is a recursive cycle of process-oriented phases (i.e., situation assessment, plan formulation, plan execution, and team learning).

Building on this model, we suggest successful adaptation involves a team adaptation iterative process and recognize teams may require more iterations when trigger severity increases before finding the best solution. Our Team Adaptation Iterative Process (TAIP) model incorporates Burke et al.'s[4] recursive cycle of process-oriented phases previously described with a dynamic team learning perspective and describes five stages. First, preparation is when the team identifies the change in environment, assesses the situation by gathering task-relevant cues from the environment to allocate meaning to the perceived cues, and defines a set of rules and practices to start problem solving. Second, in the development stage, the team uses the assessed information to internalize the problem and create/encode the possibilities. Third, formation involves communication of the members to identify or combine ideas that provide the pieces of solution or the solution itself. The fourth stage, verification, occurs when the team carries out the developed solution and demonstrates whether or not it satisfies the assessment and criteria defined in the preparation stage. If the developed solution does not succeed, teams engage in the fifth stage, iteration, in which the four previous stages are repeated until the problem is overcome successfully.

The third recommendation for research on team adaptation is to develop a valid and reliable measure of the adaptation process, or mediator segment, of the Maynard, Kennedy, and Sommer[6] model. We argue such a measure can be developed by focusing on the behavioral changes that occur during team adaptation specific to three types of processes or phases (transition, action, and interpersonal) identified by Marks, Mathieu, and Zaccaro.[5] During transition phases, the team participates in mission analysis, planning, goal specification, and formulating strategies. During action phases, members identify task accomplishment, monitor progress and systems, coordinate with team members, and monitor and back up their teammates. Lastly, interpersonal phases, which are salient throughout a team's lifecycle, relate to activities such as conflict management, motivation and confidence building, and affect management. Using a behaviorally anchored rating scale approach, we have developed and are currently validating a Small Team Adaptation Rating Scale (STARS) which captures the frequency of behaviors associated with transition, action, and interpersonal phases or processes. With repeated testing with multiple teams, we expect to refine the scale with more detailed behavioral descriptions and the addition of behaviors in each category.

To conclude, research on the team adaptation model, the iterative process, and development of an adaptation process measure are viable next steps in understanding how small teams of astronauts will adapt and succeed on long-duration missions over the next 15–20 yr to destinations like Mars. As our experience during NEEMO 20 emphasized, success on these missions will require extensive testing of technologies and related human factors issues, dynamic procedures documents that provide immediate access to multiple contingency plans, and, most of all, a high degree of adaptability and resilience, both for the technological components and the human elements.

ACKNOWLEDGMENTS

We would like to thank the reviewers for their constructive feedback. We also thank the NEEMO team, Teledyne Oil & Gas, and Embry-Riddle Aeronautical University's Department of Human Factors and Office of Undergraduate Research.

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