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Designing for the edge: Invisible systems as behavioral amplifiers and friction points in analog missions

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Abstract

Space is difficult—humans who live and work in space experience life in isolated, confined, and extreme (ICE) conditions. To understand the impact on humans in this type of environment and the challenges faced by individuals in these conditions, analog missions have played a significant role in problem-solving for spaceflight research. Analogs offer a chance to closely examine these risks and test strategies to mitigate the challenges. To adjust to these conditions, individuals and teams have received training and support that mitigates the adverse and challenging effects of the environment. Historical research has focused on issues of behavior, social, environmental, and cognitive performance as mechanisms of linear performance outcomes. While that research provides a solid foundation for understanding the challenges of living in ICE conditions, we argue that the social systems in which those conditions exist create aberrant behaviors by individual team members—utilizing an interdisciplinary theoretical approach to analyze aberrant crew behavior. The examination of behavioral vignettes through complex adaptive systems acknowledges that behavioral situations are dynamic and adaptive and do not occur in a vacuum but rather through dynamic changes throughout the mission. It is these systems that create an emergent behavioral environment, which we will explore through behavioral vignettes. We conclude that hierarchical systems are neither inherently good nor inherently bad but rather part of the dynamic nature of space and analog missions. This paper provides insights that may help teams and support team members recognize and address these situations.

Keywords: psychology, organizational behavior, hierarchy, conflict, scenarios, complex adaptive systems, interdisciplinary methods

Introduction

Humans living and working in space experience isolated, confined, and extreme (ICE) conditions. To adjust to these conditions, individuals and teams must engage in activities that mitigate the adverse and challenging effects of the environment. NASA has identified isolation and confinement as the #2 hazard of long-duration space exploration, as it can lead to behavioral and cognitive degradation [1]. Long-duration missions are defined as a long-term stay in which an astronaut crew remains in a stationary location, such as the International Space Station, or on a long-duration mission to travel to a destination, like the proposed Mars mission, which is estimated to last approximately 1,000 days or about 2.7 years [2].

Isolated, confined, and extreme (ICE) conditions

ICE conditions are present on Earth in many forms, providing important insights into human behavior in environments generally unsuited to humans. Military submarines, Antarctic research stations, and prisons are three illustrative examples of Earth-based ICE conditions, each one providing insights into how humans perform and interact in these situations. The extended periods of isolation in submarines (the "hatch-to-hatch" phenomenon in which crews do not see the outside world until a mission is over), the long duration of mission times, and the intense physical confinement all provide a great comparison to crews working and living in space. Prisons, by contrast, present a socially and psychologically rich analog. Incarcerated individuals endure involuntary confinement, hierarchical structures, restricted autonomy, and prolonged adversity [3-5], conditions comparable to those of high-risk or prolonged space missions, where emergencies, resource shortages, or punitive regimes can arise. Finally, Antarctic research stations have been a source of high-fidelity research for ICE environments for decades, providing a natural laboratory for social and behavioral science research [6,7]. Antarctic research stations, such as Concordia and McMurdo Station, have housed hundreds of international researchers

who work and live together in extreme Antarctic weather conditions. These case studies provide an extensive research archive on psychological conditions, including loneliness, cognitive performance, and interpersonal team dynamics [5,6,8].

Why analogs for space research

Analog missions are field tests in locations that have physical similarities to the extreme space environments [9]. To understand human space exploration, high-fidelity analogs have been explicitly designed to closely mimic space conditions. Cromwell and Neigut (2020) have made a distinction between isolated, confined, and extreme environments and isolated, confined, and controlled environments, which are labeled as ICEEs and ICCEs, respectively. ICEEs are space analogs that take place in an extreme environment, have primary mission goals other than research, have limited or no experimental control of conditions, and have variable crew sizes selected for field work or training purposes [10]. ICCEs often take place in an environment designed to simulate a space mission, where research is the primary goal, conditions are partially experimentally controlled, crew size is regulated, and selection is made to meet astronaut criteria [5]. The analog types that will be discussed here fall under the ICCE category – Hawai'i Space Exploration Analog and Simulation (HI-SEAS), Mars Desert Research Station (MDRS), or MARS 520, a long-duration analog simulating a Mars Mission, whereas the Earth analogs discussed earlier – prisons, submarines, and Antarctica fall under the ICEE category.

Team dynamics and social systems

Team dynamics and group behavior have been studied extensively in the context of long-duration space travel [11-13]. Kanas (2023) states that analogs offer the opportunity to study potential risks as well as to test appropriate countermeasures to mitigate those risks [5]. It offers the opportunity to provide insights into the human condition as an individual and their interactions with and within teams' ICCE conditions. The team dynamics offer insight into how multiple individuals interact with each other during a mission. Behavioral health research in analog environments creates an opportunity to understand human and team dynamics. De La Torre et al. (2012, 2024) provide an extensive review of the psychosocial and neurological aspects of human spaceflight [7,8].

Hierarchy as a social system

Hierarchical culture has been the default organizational culture within analogs [14]. This culture enables effective and efficient coordination between crew members. However, it can also create the social conditions to initiate conflict and maladaptive behaviors [14]. Within this dynamic interpersonal environment, social systems are at work, enabling situations that influence decision-making and behavior, which may belie the assumed nature of individuals and teams. It is these systems that create an emergent behavioral environment, which we will explore through behavioral vignettes. This paper provides insights that may help teams and support team members recognize and address these situations.

Theoretical framework for analysis

Team dynamics and group behavior have been studied extensively in the context of long-duration space travel [11-13]. First, we explore the interdisciplinary methodology for situational analysis. Hierarchy, defined as vertical differences in the possession of socially valued resources among group members, is a fundamental concept in the study of groups and teams [15]. This paper employs an interdisciplinary approach to examine the invisible systems that emerge from the adaptive behaviors of individuals and teams.

The research of analogs is rich in lessons and can help forge necessary models for studying adaptation processes in all their cognitive, affective, occupational, social, and physical dimensions. This paper examines the psychosocial challenges faced by humans in space-induced isolation, as well as potential countermeasures that could be developed to mitigate them. We will utilize an interdisciplinary framework based on complex systems theory and organizational behavior to explore how a hierarchical culture can engender aberrant behavior in individuals and teams.

Hierarchical team structures offer both a benefit and harm to team effectiveness [5,8,15]. This structure provides direction for communications, processes, and procedures in a team environment. This type of clarity is essential for maintaining team effectiveness. Analog crews do not operate in a vacuum – support teams surround them to ensure guidance, direction, and support during a mission.

Complex adaptive systems

The application of complex adaptive systems (CAS) theory enables the dynamics of group interaction to be studied as a system rather than as a series of individual linear transactions that aggregate to an outcome. Preiser et al. (2018) guide the utilization of complex systems [16]. In particular, they utilize complex socio-ecological systems (SES) as theoretical and methodological approaches for research. The authors suggest that six organizing principles indicate CAS, which are 1) constitutional relationships, 2) adaptiveness, 3) dynamic, 4) radically open, 5) contextual, and 6) complex causality. In this paper, we will focus on the features of adaptiveness and dynamics as it applies to a hierarchical system. Adaptiveness: CAS adapts over time in response to feedback from interactions between system elements and between elements and their environment. The dynamic interactions that constitute CAS and their relationships with the environment are nonlinear, meaning that the magnitude of a system's outputs cannot be measured in direct proportion to the magnitude of its causes [16]. The dynamic nature of analog missions means that interpersonal interactions are not the result of a linear cause-and-effect relationship. We illustrate this through the following example: Crew Member A interacts with Crew Member B, and the outcome is direct between the two individuals, resulting in a causal relationship between

them. Dynamic interactions suggest that other factors may be at play, potentially altering the causality, and these factors themselves are not static.

Organizational behavior and team conflict

Organizational behavior and team conflict models provide another lens for assessing crew behavior from a systems perspective. Greer et al. (2018) posit that there are two pathways to team effectiveness within a hierarchal culture [15]. One is based on coordination-enabling processes, and the other on conflict-enabling states. Coordination-enabling processes yield a more positive outcome within a hierarchical environment, suggesting that they can provide guidance and role stabilization for effective team outcomes. The conflict-enabling states, which are brought about by external stressors, are not forgiving within a hierarchical environment. They often enable stressful and conflict-enabling behavior in individuals. The emergent behavior of conflict is the focal point of this paper, outlining how a conflict-inducing environment precipitates aberrant behavior in teams and crews. Preiser et al. (2018) provide a guide utilizing complex systems, particularly complex socio-ecological systems (SES), for theoretical and methodological approaches in research [16].

Together, these frameworks provide a unique lens with which to assess behavioral situations that occur in analog or space environments. Through CAS, it is recognized that behavioral situations are dynamic and adaptive and do not occur in a vacuum but rather through dynamic changes throughout the mission.

Behavior vignettes

Analog missions, while typically not sponsored by a formal military organization, often involve the influence of a hierarchical structure with pseudo-military expectations as part of the experience. For example, when assigning crew roles, the terminology often includes Commander, Co-Commander, Officer, etc. The terminology not only expresses the role but also the behavioral expectations surrounding it.

To examine how hierarchical structures enable and influence aberrant behavior, this study presents behavioral scenarios — fictionalized examples of real-analog situations from the empirical literature. These familiar vignettes serve as tools for illustrating how systems impact psychological behaviors under isolated, confined, and extreme conditions, as mimicked by analog missions. Each vignette will be described and analyzed for maladaptive behavior patterns.

Behavior scenario 1: Will work for silence

In a long-duration analog mission simulating a journey to Mars, crew members have been increasingly agitated and impatient in their communication with mission control. The crew is on day 300 of a 500-day simulation. They feel like they do not have control of their own time, nor are they trusted to make simple decisions about their work. Mission Control, the support team for the simulation, has scheduled the crew's time down to the minute. At the beginning of the mission, the schedule was a relief. Crew members needed to learn their roles and understand how tasks would be completed, as well as the success measures for their work. As time passed, they became more proficient at completing tasks and understanding the workflow of their work, as well as how they functioned as a team. However, as time has passed, one crew member has become increasingly hostile and frequently experiences conflicts not only with Mission Control but also with other crew members. As a result, crew member #5 has instigated a cease communication rule with Mission Control for the crew. The crew members have reluctantly supported the cessation of communication because they have enjoyed the freedom to complete their work on their terms, despite the behavior of crew member #5.

Analysis: This is a familiar scenario. It has been the subject of many articles and has become a part of space industry mythology about crews "misbehaving." What if it were not the crew's fault for misbehaving, nor Mission Control's fault for being over-demanding? When crew member behaviors are addressed as an individual problem, in this case, Crew Member #5 was feeling frustrated due to a lack of acknowledgment of their on-the-ground expertise. Mission Control was employing a tried-and-true method of task management as an effective management tool. The breakdown in this situation is due to a conflict of control and a failure to recognize the crew's growth and capability to be effective.

Behavior scenario 2: Silent withdrawal

Four months into a year-long space simulation, a crew member, "Pat," who is the second youngest person on the crew, has been noticeably absent from certain crew activities. They have dutifully attended team meetings and completed their work tasks on time. However, team members have noticed that Pat has not attended any of their crew team gatherings, which are meant to foster team cohesion and camaraderie. When the Commander sought out Pat for a one-on-one conversation, as she does with all the crew, Pat confided that they had stopped speaking up since their ideas had been dismissed when it came to solving problems during the mission. All other crew members have noticed Pat's behavior, and they have begun to ignore Pat, thereby reinforcing their passive withdrawal from the crew. As the mission continued, Pat withdrew to the point that the only communication the other crew members received from Pat was through work logs and basic greetings.

Analysis: In this case, the individual's decision to withdraw from their fellow crew members was due to a perceived dismissal of value. The hierarchical system in place engaged Pat enough to ensure their tasks were done and completed; however, their interpersonal relationships suffered, and their behavioral health deteriorated to minimal standards. Greer et al. (2018) would classify this situation as a conflict-inducing [15]. When hierarchies are perceived as more illegitimate and political, such as those with steep or highly centralized structures, they are more likely to foster harmful team conflicts and negatively impact team

performance. In this case, Pat, as a junior member of the crew, was not seen as an equal contributor to the team, and therefore, their ideas were not well regarded. Pat chooses to withdraw enough to minimize engagement with others. Not all conflict is exemplified by hostile behavior. At times, individuals may cease to engage with their fellow crew members, leaving the other crew members bewildered and or frustrated. However, the Commander, in her legitimate efforts to support every team member, failed to address the interpersonal impact of Pat's behavior on the other crew members. In this case, the Commander needed to understand the dynamics of the hierarchical system to engage situational leadership. They would need to make an effort to allow each crew member to contribute while maintaining situational task leadership as needed for effective and efficient operations.

Discussion

Analog research is rich in lessons and can help forge necessary models for studying adaptation processes in cognitive, affective, occupational, social, and physical dimensions. This paper explored the challenges and countermeasures related to the psychosocial issues that challenge humans in space-related conditions. The goal of this paper is not to argue that hierarchy is inherently good or bad but rather to recognize it as a dynamic system that supports or rewards behaviors that fit a particular situation. These vignettes highlight how aberrant team dynamics are symptoms of when a part of the system is not appropriately applied. It is not determined that these environments are causal; instead, they provide a different lens through which to assess certain crew situations and behaviors. Individual crew members are selected for their ability to function within a system and be effective team members. In a hierarchical system, that well-adjusted individual may exhibit maladaptive behavior because the hierarchal constraints were not appropriate for the dynamics of the situation.

Utilizing a lens of complex adaptive systems, the exploration of these systems allows for the ebb and flow of effectiveness. The overall mission is dynamic, and individuals adapt their behaviors to the dynamics of the situation. The dynamic situations explored in the paper exemplify how a system impacts individual behaviors within a hierarchal system. Individuals adapt to their environment, regardless of what their behavioral profile may suggest. When a situation requires coordination and quick decision-making, it has a more positive impact on team effectiveness. While hierarchy may provide structure in stable settings, in conflict-enabled environments it is more likely to amplify a negative effect [15].

Limitations and future directions

Throughout this case study, the goal was to identify situations in which a hierarchical environment can facilitate the emergence of aberrant behaviors. As a retrospective analysis, the details of the situation can only be speculated. Hierarchy is not typically addressed directly as a causal factor for behavioral outcomes. Extrapolating the assumption of hierarchy can be seen as a leap. However, explanations of behaviors, especially in a top-down environment, can be an anchor point for systemic analysis.

Complex adaptive systems (CAS) methods can be used as a tool to enable a more nuanced understanding of the exhibited behavior. The emergence is not necessarily due to individual behavior, although there is always a seed of possibility; however, the systems created by the hierarchy support these behaviors, leading to the emergence of these behaviors. Research on human psychological and existential factors that enable the prediction and explanation of human performance under extreme conditions is necessary for successful space exploration and survival, alongside the more well-studied technological and safety aspects [8]. The use of interdisciplinary research methods and frameworks can help research move beyond traditional frameworks to gain a better understanding of crew behavior.

Conflicts of interest

The authors declare that they have no conflicts of interest with the contents of this article.

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AI use disclosure

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