IAC-20-A1.1.5 (x61085)

The Impact of Network Acuity on Information Sharing under Communication Delays in Space Multiteam Systems

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Abstract

Communication delays in long-distance space missions present a significant challenge for effective information sharing within multiteam system, including space crews and mission support. Crews and mission support need to leverage their indirect contacts (e.g., contacts' contacts) to route messages effectively. However, information-sharing failures lead to accidents on space missions. These failures result from an individual's lack of awareness of the networks of their contacts. We introduce the concept of *network acuity* to characterize an individual's perceptual accuracy of the networks of their contacts. We ask three research questions related to network acuity. What are the levels of network acuity among crews and mission support? How does communication delays impact individuals' network acuity? Which individual characteristics predict network acuity? We collected data from NASA's Human Exploration Research Analog (HERA), Campaign 3 and 4. We studied nine different, 4-member crews, each interacting on a simulated task with an 8-member mission support (MS) (N = 251). Data was collected using a web-based tool Project RED Relay where the crew and MS engage in a network routing task. Due to "bandwidth constraints," they were instructed to choose only two direct contacts (from 11 others) to relay messages sent by JPL to a final destination in order to implement a decision. They each receive messages that must be relayed to specific others in the crew-MS system in the fewest number of steps. In total, we conducted 53, 12-person relay sessions. Each session was assigned to either a 180-second communication delay, a 60-second communication delay, or no communication delay condition. We measured network acuity based on the extent to which each individual routed message through their contact who was on the shortest path to the destination. Our results show that network acuity among HERA crews was significantly higher than MS members in Campaign 4, but not Campaign 3. Additionally, we found communication delays did not impact network acuity among HERA crews, but reduced acuity among MS members. Further, crew members who scored lower on the personality characteristic of conscientiousness had higher network acuity in both Campaigns 3 and 4. Finally, crews' network acuity was associated with personality characteristics of openness to experience, agreeableness, and neuroticism in Campaign 4, but not Campaign 3. Overall, our findings suggest that selecting crews with high network acuity will play a key role in alleviating the risk of information-sharing failures within a multiteam system under conditions of communication delays.
Keywords: network acuity, information sharing, communication delay, isolation, team process

Acronyms/Abbreviations

Big Five Aspects Scale (BFAS)
Human Exploration Research Analog (HERA)
International Space Station (ISS)
Jet Propulsion Lab (JPL)
Long-Distance Space Mission (LDSM)
Mission Control Center (MCC)
Mission Support (MS)
National Aeronautics and Space Agency (NASA)
Red Planet Exploration and Development (RED)

1. Introduction

Communication delays involved in long-distance space missions (LDSMs) present a significant challenge for effective information sharing within a multiteam network, including space crews and mission support. As the distance between the astronaut crew and mission control center (MCC) gets farther, the communication delay between them becomes longer. For instance, there can be as much as a 22-minute one-way communication delay for all communication between space crews and ground support on earth during a Mars mission [1]. Because of this expected communication delay, crews are trained to operate autonomously as much as possible. However, they must coordinate with MCC since space missions often face unexpected events that affect crew performance. Prior research found that communication delays between crew and MCC indeed impact crew performance as well as well-being at the International Space Station (ISS) [2]. To avoid the negative impact of communication delays, both crews and ground support need to leverage not only their direct contacts but also their indirect contacts (e.g., contacts' contacts) to share information effectively.

However, information-sharing failures often occur and are linked to the success of space missions. For example, NASA experts pointed out that information withholding between teams, due to fear of negative repercussions, can be a risk to space missions [3]. Prior research shows ground-crew relations in multiteam systems comprising space crews and NASA's Mission Control Center (MCC) is critical to spaceflight mission performance [4] Similarly, members of MCC must interact efficiently to share information on current and upcoming states of the crew and their taskwork since ineffective information sharing led to crisis events in past missions [5].

To accomplish effective information sharing, each member needs to be aware of the communication network contacts of others in the multiteam systems. In other words, ineffective information sharing results from an individual's lack of awareness of the networks of their contacts [6]. For example, a past study found that employees who are female, lower tenure, or not well connected in an organization have limited awareness and consequently a lower ability to reach out to the right person who holds the information they need [7]. For information sharing, what matters is, "It's not who you know, it's who you know your network contacts know" [8]. For teams to effectively process information, each member must develop a mental model of "who knows whom" and "who knows who knows whom."

Here, we introduce the concept of *network acuity* to conceptualize an individual's ability to leverage their perceptions of the networks others in order to route information effectively. Research on social capital and cognitive social networks suggest that an individual's ability plays a role in accurately perceiving and mobilizing their social network [7,9,10]. Thus, we argue that network acuity plays a crucial role in information sharing because members need to activate their understanding of who is connected to whom to communicate with each other in multiteam systems effectively.

In this study, we ask three research questions related to network acuity. What are the levels of network acuity among space crew members and those in the mission support? To what extent do communication delays impact people's network acuity? Are there individual characteristics that predict network acuity?

2. Methods

2.1 Project RED Relay Task

To address our research questions, we collected data from NASA's Human Exploration Research Analog (HERA) at the Johnson Space Center in Houston. We conducted our study within HERA Campaigns 3 and 4, a 30- and 45-day simulated space mission where 4-person astronaut crews perform tasks in an environment that emulates isolated and confined conditions they will encounter on a mission to Mars. One task they conduct is called Project RED (Red Planet Exploration and Development), where the 4-person HERA crew works with an 8-person mission support (MS) on earth in a multiteam system that is tasked to decide where to construct a well to support a human colony on Mars. The multiteam system is set up of four teams: planetary geology, space human factors, extraterrestrial engineering, and space robotics (see Fig. 1). Each of these four units consists of one member from the 4-person HERA crew and two from the 8-person mission control.

Fig. 1. Space Multiteam System. The red icons indicate HERA crew members, while the rest of the icons are MS members.

After deciding on a location for the water well, they now have to coordinate information to implement their decision as a second activity via Project RED Relay (see Fig. 2). Project RED Relay is a network routing task requiring data from the Jet Propulsion Laboratory (JPL, in Pasadena, CA) to be routed to specific recipients in the 12-person multiteam system to help them execute plans for drilling the well. Due to "bandwidth limitations" in space communications, each of the 12 participants is instructed to select only two contacts from the 11 other individuals to whom they can directly route messages. They then attempt to route messages they receive directly from JPL (or indirectly from JPL via others who chose them as direct contacts in the activity) to the final recipient (see Fig. 3). They accomplish this task by choosing to relay the messages to one of their two contacts whom they believe will be most likely to get it efficiently to the final recipient. Everybody engages in two rounds of this activity, each lasting 10 minutes.

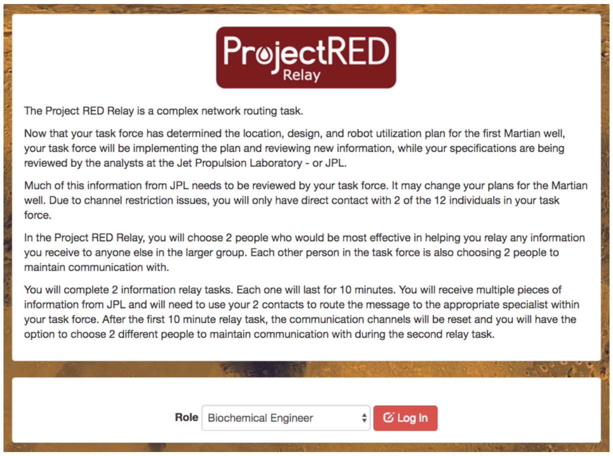

Fig. 2. Project RED Relay Log-in Interface

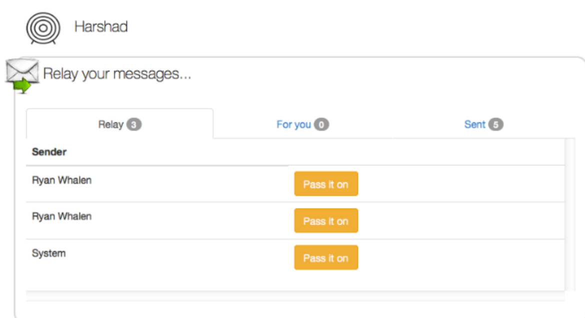

Fig. 3. Project RED Relay Task Interface.

2.2 Sample

Our sample included 9 different, 4-member crews (n = 36), each interacting on a simulated task with an 8-member MS (N = 251) on multiple occasions during their mission. Data were collected using a web-based portal linking the crew and MS to engage in a network routing task via Project RED Relay. They each receive messages that must be relayed to specific others in the crew-MS system in the fewest number of steps. In total, we conducted 53, 12-person multiteam network sessions.

2.3 Campaign

Our sample included crews from Campaign 3 and 4 for HERA. There were some differences between Campaign 3 and 4, which can impact network acuity. First, the mission duration was different. While Campaign 3 lasted for 30 days, Campaign 4 was for 45 days. During the time period, HERA crews were in an isolated, confined environment. This isolation can affect crews' performance. In addition, Campaign 4 crews experienced more severe sleep deprivation than Campaign 3 by design.

2.4 Communication Delays

Each network session was assigned to either a 180-second communication delay, a 60-second communication delay, or no communication delay condition. This assignment changed the duration of messages sent and received. In the no communication delay condition, messages are instantaneously sent and received. In the 60- and 180-second delay condition, they took 60 or 180 seconds to be received after they were sent. Note that only sessions in Campaign 4 on Mission Day 26 were assigned to the 180-second communication delay condition. None of the sessions in Campaign 3 experienced 180-second communication delays.

2.5 Network Acuity

From the Project RED Relay task, we measured *network acuity* based on the extent to which each individual routed messages through their contact who was on the shortest path to the final destination. We operationalize it as the accuracy rate per person at a session. To calculate network acuity, we took three steps. First, we calculated the observed accuracy rate in each round. Because individuals varied in overall activity (different total numbers of messages relayed per individual at a time point), we ensured that our measure controlled for the total number of routing events. To address this concern, we compute a null model of accuracy rates using 1,000 randomly shuffled versions of the observed routing decisions made by each individual. This generates the expected distribution of accuracy rate for an individual (i.e., expected rate) given the magnitude of their routing activity. Based on this null model, we then compute a z-score for each individual's observed network acuity rate.

2.6 Big Five Personality Traits

HERA crews responded to a series of surveys when they joined the HERA mission. We measured the Big Five personality traits using the Big Five Aspects Scale (BFAS) [11]. BFAS is a widely used personality scale to measure openness to experience (openness), conscientiousness, extraversion, agreeableness, and neuroticism. Openness is characterized by being imaginative and intellectually curious. A sample item includes "Love to reflect on things." Conscientiousness means that someone is disciplined and diligent. One of its items, for example, is "Keep things tidy." Extraversion is a trait showing an individual tendency to socialize with others. An example item for it is "Warm up quickly to others." Agreeableness is an individual characteristic of being sympathetic and cooperative. It is measured based on items, such as "Respect authority." Finally, neuroticism is related to moody characteristics. Its sample item includes "Change my mood a lot."

4. Results

Fig. 4 shows that the network acuity for HERA crews in Campaign 3 and 4 is, on average, -0.04 and 0.19, respectively. An individual's network acuity score of 0 indicates that the individual's ability to route a message to their contact who is on the shortest path to the final destination is exactly the same as on who is choosing randomly. Network acuity among MS members is -0.08 in Campaign 3 and -0.11 in Campaign 4. The difference between HERA and MS is not statistically significant in Campaign 3, $t(19) = 0.53$, $p = 0.60$. However, it is significant in Campaign 4, $t(31) = 7.62$, $p < 0.01$. This result suggests that HERA crews have higher network acuity than MS members in Campaign 4.

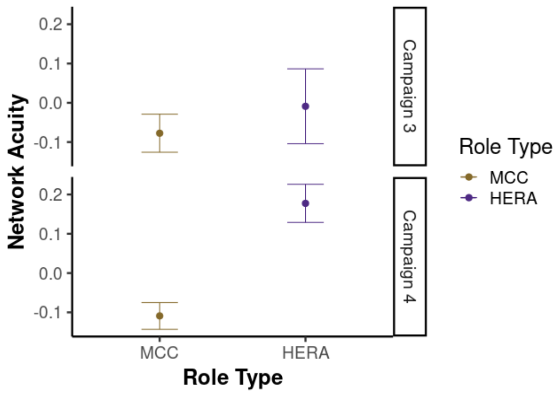

Fig. 4. Network Acuity for HERA crews and MS members by Campaign. The points indicate the average value, and the bars represent 95% confidence intervals.

Fig. 5 displays results on the impact of communication delays on network acuity. Network acuity among HERA crews stayed almost the same regardless of communication delays. In Campaign 3, we found no difference for HERA crews' network acuity between zero and 60-second communication delays, $t(67) = 0.02$, $p = 0.99$. Similarly, our results show that there are no statistically significant difference of network acuity among HERA crews in Campaign 4 between zero and 60-second ($t(98) = -1.92$, $p = 0.06$), and between zero and 180-second ($t(63) = 0.42$, $p = 0.68$), respectively. Yet, a 180-second communication delays significantly decreased network acuity among MS members in Campaign 4, compared to zero ($t(84) = 3.82$, $p < 0.01$) and 60-second communication delays ($t(89) = 3.66$, $p < 0.01$), respectively. However, there was no statistically significant difference in network acuity among MS members between zero and 60-second communication delays, $t(186) = 0.04$, $p = 0.96$. In Campaign 3, we also found no significant difference in network acuity among MS members between zero and 60-second communication delay conditions, $t(142) = 0.52$, $p = 0.61$.

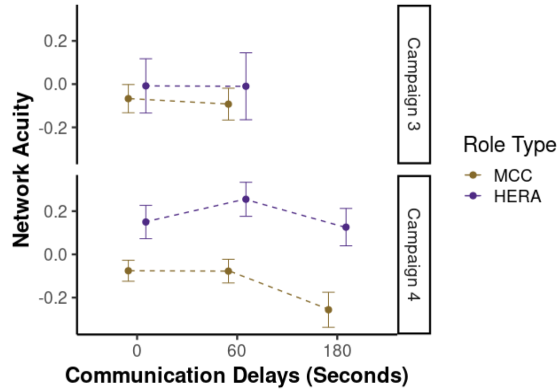

Fig. 5. Communication Delays and Network Acuity for HERA crews and MS members by Campaign. The points indicate the average value, and the bars represent 95% confidence intervals.

Fig. 6 shows how mission days impact network acuity. Each data point shows the average network acuity score in each session during the mission. For instance, the first Project RED Relay session was Mission Day 9 in Campaign 3, while it was Mission Day 11 in Campaign 4. The second session in both Campaigns was 60-second communication delays: namely, Mission Day 14 for Campaign 3 and Mission Day 17 for Campaign 4. Whereas the third session was the final one with no communication delays on Mission Day 29 for Campaign 3, it was 180-second communication delays on Mission Day 25 for Campaign 4. There was the fourth and last session without communication delays on Mission Day 39 in Campaign 4.

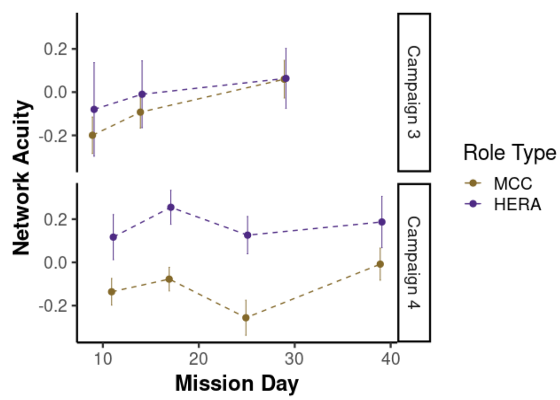

Fig. 6. Mission Days and Network Acuity for HERA crews and MS members by Campaign. The points indicate the average value, and the bars represent 95% confidence intervals.

In Fig. 7, we found a positive correlation between conscientiousness and network acuity in both Campaigns 3 ($r = -0.29$, $p < 0.01$) and 4 ($r = -0.25$, $p < 0.01$). These results suggest that high conscientious individuals have lower network acuity than moderately conscientious ones.

This suggests that individuals who are highly conscientious might "overthink" routing and end up making errors.

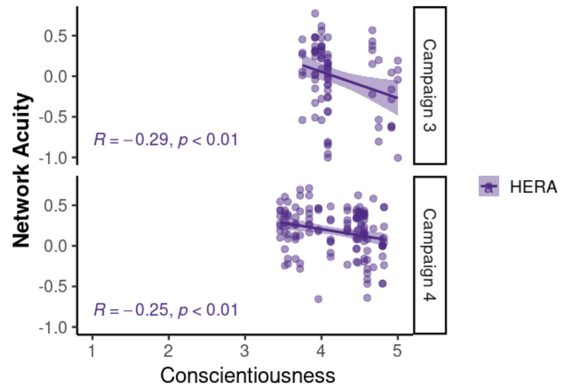

Fig. 7. Conscientiousness and Network Acuity for HERA crews by Campaign.

Fig. 8 indicates the relationships between agreeableness and network acuity. While there is no statistically significant correlation between agreeableness and network acuity in Campaign 3 (r = -0.02, p = 0.84), there is a negative and significant correlation in Campaign 4 (r = -0.23, p < 0.01). This means that HERA crew members with high agreeableness in Campaign 4 tend to have low network acuity than those with low agreeableness.

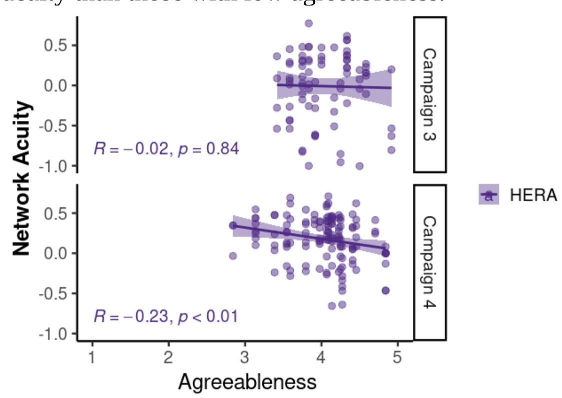

Fig. 8. Agreeableness and Network Acuity for HERA crews by Campaign.

In Fig. 9, we found a positive correlation between openness and network acuity in Campaign 4 (r = 0.27, p < 0.01), but not in Campaign 3 (r = 0.07, p = 0.52). This result suggests that HERA crew members with high openness have higher network acuity than those with low openness in Campaign 4.

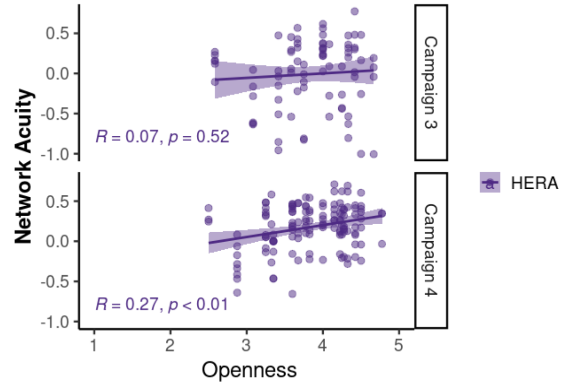

Fig. 9. Openness and Network Acuity for HERA crews by Campaign.

Fig. 10 presents the results of the correlation between neuroticism and network acuity. Our results show a positive correlation between them in Campaign 4 (r = 0.26, p < 0.01), indicating that those with high neuroticism are more likely to have high network acuity than those with low neuroticism. However, we did not find the same tendency in Campaign 3 (r = 0.05, p = 0.66).

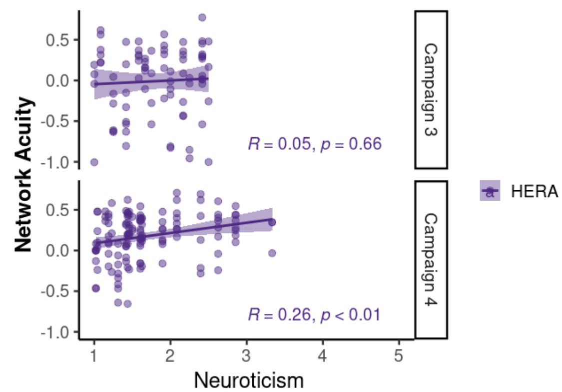

Fig. 10. Neuroticism and Network Acuity for HERA crews by Campaign.

Finally, Fig. 11 displays correlations between extraversion and network acuity in Campaigns 3 and 4, respectively. Our results indicate that neither Campaign 3 nor 4 had statistically significant correlations between them.

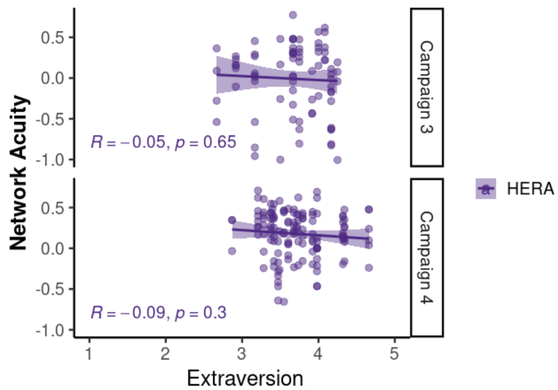

Fig. 11. Extraversion and Network Acuity for HERA crews by Campaign.

4. Discussion

This study advances our understanding of effective information sharing by introducing the concept of network acuity, which captures an individual's ability to leverage their perceptions of the network to route information effectively. Using Project RED Relay data from HERA Campaigns 3 and 4, we found that HERA crews had higher network acuity than MS members in Campaign 4, but not in Campaign 3. This difference was exacerbated among MS members when they faced 180-second communication delays. While network acuity among HERA crews was stable despite communication delays and isolation in both Campaigns, MS performance was significantly exacerbated by 180-second communication delays, compared to no communication delays and 60-second communication delays.

These results of communication delays show that impact on MS members can be problematic in terms of information sharing as the distance between a spaceship and the earth increases. Space crews can share their mental model among them, but for successful space missions, MS members also need to be aware of "who talks to whom" among space crews. This finding is particularly relevant to an ongoing discussion about how space agencies, such as NASA, will compose MS teams in LDSMs with communication delays [12]. It is possible that our findings of poor network acuity among MS might have been an artifact of the study design. MS participants each engaged in a one-time activity while HERA crews stayed the same for multiple sessions during their mission.

With respect to the isolation effect, our data did not indicate any significant impact of extended isolation on network acuity. Contrary to our expectation, HERA crews sustain their information-sharing ability throughout the mission regardless of having communication delays. This suggests that crews are able to engage in effective information sharing during the entire duration of isolation.

We found that individual characteristics (e.g., conscientiousness and openness) predict network acuity. Conscientiousness was negatively associated with network acuity. Traditionally, conscientiousness is regarded as a positive personal characteristic [13]. However, our results show that high conscientiousness can prevent crews from high network acuity. Note that our sample of HERA crews had a relatively high level of conscientiousness and no one was particularly low (M = 4.20 in Campaign 3; M = 4.18 in Campaign 4). In other words, being disciplined and diligent is essential for effective information sharing, but too much of it can negatively affect the information-sharing ability. Thus, our findings suggest that there might an optimal level of conscientiousness for network acuity.

Additionally, we found that most Big Five traits impact crew members' network acuity in Campaign 4, not Campaign 3. This is interesting because Campaign 3 and 4 had different setups in terms of the duration of missions and more communication delay sessions. Future research should explore how these differences impact the relationships between psychological traits and network acuity.

Overall, our findings suggest that selecting crew members with high network acuity will play a key role in alleviating the risk of information-sharing failures within a multiteam system under conditions of communication delays.

5. Conclusions

This study reported the pivotal role of network acuity in information sharing under communication delays in space multiteam systems. The current plans for LDSMs require multiteam systems where space crews have multiple roles and need to seek and route information using their contacts. Using a simulation tool Project RED Relay, our study illustrated network acuity is a useful measure to improve an individual's ability to work with each other effectively in future space missions. Based on our research, we believe network acuity should be seriously considered as a potentially useful screening characteristic in crew (and MCC) selection.

Acknowledgments

This research is based upon work supported by NASA under awards NNX15AM32G and 80NSSC18K0221. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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