Communication Delays Impact Behavior and Performance Aboard the International Space Station

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INTRODUCTION: Long-duration space explorations will involve significant communication delays that will likely impact individual and team outcomes. However, the extent of these impacts and the appropriate countermeasures for their mitigation remain largely unknown. This study examined the feasibility and acceptability of utilizing the International Space Station (ISS) as a research platform to assess the impacts of communication delays on individual and team behavior and performance.

METHODS: For this study, 3 ISS crewmembers and 18 mission support personnel performed 10 tasks identified by subject matter experts as meeting study criteria, 6 tasks without a delay in communication and 4 tasks with a 50-s one-way delay. Assessments of individual and team performance and behavior were obtained after each task. The completion rate of posttask assessments and postmission interviews with astronauts were used to assess feasibility and acceptability.

RESULTS: Posttask assessments were completed in 100% of the instances where a crewmember was assigned to a task and in 83% where mission support personnel were involved. Qualitative analysis of postmission interviews found the study to be important and acceptable to the three astronauts. However, they also reported the study was limited in the number and type of tasks included, limitations in survey questions, and preference for open-ended to scaled items.

DISCUSSION: Although the ISS is considered a high fidelity analog for long-duration space missions, future studies of communication delays on the ISS must take into considerations the constraints imposed by mission operations and subject preferences and priorities.

KEYWORDS: behavioral health, International Space Station, long duration spaceflight, distributed teams, research-operational collaboration.

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Long-duration space explorations will involve significant delays in communication between astronaut crews in space and mission support personnel on Earth. Such delays will make it difficult for mission control to provide support to the crew, and could negatively impact individual and team performance, behavior, and mood, unless teams are provided with the tools and training to overcome or prevent these communication-related challenges.[10,13] Concerns about the adverse impacts of communication delays across distributed teams are not new, and are not unique to spaceflight operations.[2,12,16] Briefly, research suggests communication delays may negatively impact teamwork processes (i.e., coordination and cohesion), individual well-being (i.e., perceptions of stress and psycho-physiological indicators of strain such as burnout and turnover), and organizational outcomes (i.e., team performance).[5,16,21] However, the extent of these impacts on distributed space teams and the appropriate countermeasures for their mitigation remain largely unknown.

To date, very few studies have observed teams in remote environments that operate and perform tasks without communication with management teams (i.e., mission control). Some studies have explored issues related to delayed voice communication within the larger topic of crew autonomy.[7,14] These studies suggest crewmembers will need to be more autonomous from mission control during deep space explorations. In addition, research from analog environments on Earth indicate communication delays are associated with behavioral

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and performance-related challenges such as decreased task efficiency, reduced situational awareness, and weakened rapport between crewmembers and mission support personnel.[6,17] While these studies provide important insights into the potential impacts of communication delays between astronauts and mission control personnel, they are limited in number and fidelity. Importantly, the reported impacts of communication delays in low fidelity environments may be underestimated, particularly for tasks involving highly complex, dangerous, and/or off-nominal situations.[7] Given these limitations, there remains an urgent need to further explore the impacts of communication delays between astronauts and mission control personnel, preferably in high fidelity environments.

The current study, conducted by the Behavioral Health and Performance Element of the NASA Human Research Program, examined the impacts of communication delays in the analog environment most comparable to deep space: the International Space Station (ISS).[15] However, conducting a research study in an active operational environment such as the ISS is likely to pose certain challenges and risks, especially since the experimental factor being manipulated (communication delays) could jeopardize ISS operations and exert negative impacts on the health and well-being of the study subjects.[10,20] Accordingly, conducting such a study will likely involve tradeoffs between operational requirements to insure optimal performance and safety and research requirements for addressing potential threats to performance and safety.[11,19,22] Given these concerns, the current study examined whether or not the ISS represents a feasible and acceptable research platform to assess the impacts of communication delays on individual and team performance and well-being. Specifically, the study explored whether: 1) there were technical restrictions to implementing communication delays to-and-from the ISS; 2) the study procedures were acceptable, valid and relevant to long-duration missions; 3) crewmembers aboard the ISS were interested and engaged in participating in such a study, especially given the high demand for their time; and most importantly, 4) there were any adverse impacts to ISS operations or to the safety of the study subjects. Results from the assessment of specific impacts of communication delays on individual and team performance and well-being are reported in a separate paper. Lessons learned may guide future research efforts involving communication delays in active operational environments such as the ISS.

METHODS

Subjects

The study included 3 astronauts on the ISS and 18 participating mission control personnel such as the CAPCOM (the individual who communicates with the crew from mission control) and Mission Director. All subjects were fluent English speakers. Additional details on mission increment and demographic characteristics were withheld to preserve subject confidentiality and anonymity. All procedures for data collection were reviewed and approved by the Institutional Review Boards of NASA's Johnson Space Center and the University of Southern California. Prior to the start of the study, all subjects signed written informed consent.

Procedure

ISS crewmembers and mission support personnel were asked to perform tasks with and without communication delays to and from the ISS. Three subject matter experts (SMEs) were asked to identify a set of tasks representing variation on two dimensions of task complexity, criticality (low or high), and novelty (low or high), and meeting the following requirements: 1) task duration was at least 60 min (to ensure sufficient time to capture behavioral assessments and complete ratings); 2) tasks involved communication between crew and ground (more than four transmitted messages); 3) at least two crewmembers were involved in the task (team-level task); 4) delays in communication involved all communication mediums (i.e., voice/text/video) but did not include telemetry or other hardware and/or system communications; 5) a different task was completed each day over a 4-d period early in the mission and late in the mission, and two additional tasks were completed at the midpoint of the mission (to control for team effects over time); and 6) tasks for this particular study targeted a specific ISS increment consisting of three ISS crewmembers, as well as participating mission support personnel.

The SMEs identified 10 tasks that met the study criteria and were acceptable to the Mission Operations Directorate (MOD) at Johnson Space Center. Six of the tasks were completed under control conditions (no delay in communications) and four were completed under a 50-s one-way delay in communications. This delay was suggested by the MOD as adequate for conducting the study without jeopardizing operations on the ISS. A description of study tasks is provided in **Table I**.

Table I. Study Tasks.

TASK	DELAY	CRITICAL	NOVEL	DESCRIPTION
1	No	High	High	Crew replaced broken equipment used to support ISS habitability
2	No	Low	Low	Crew performed weekly cleaning activities
3	No	Low	High	Crew conducted scientific experiment
4	Yes	Low	Low	Crew performed weekly cleaning activities
5	Yes	High	High	Crew performed extravehicular mobility unit maintenance
6	Yes	High	Low	Crew began loading disposal items into the Cygnus spacecraft
7	No	High	Low	Crew transferred cargo from the automated transfer vehicle to ISS
8	No	High	Low	Crew conducted scientific experiment
9	No	High	Low	Crew conducted scientific experiment
10	Yes	Low	High	Crew replaced broken equipment used in human physiology research

After each task, participating ISS crewmembers and mission support personnel were asked to complete posttask questionnaires that were developed in collaboration with the Astronaut Office (AO) and included questions about individual and team behavior, performance, and mood. The posttask questionnaire took approximately 10 min to complete and included the following items:

Individual, crew and team performance. All subjects were asked to rate their performance (Individual), the performance of the crewmembers (Crew), and the performance of the entire team including both ISS crewmembers and mission control personnel (Team). Each item was rated on a 9-point scale ranging from 1 (poor) to 9 (excellent).

Crew well-being (team mood). ISS crewmembers were asked to complete a short instrument containing three items from the Moos Group Environment Scale:[18] 1) "Each of the participating crewmembers was given the freedom to cope with the demands of completing the task in his or her own way"; 2) "The crew had no difficulty getting along with one another while completing the task;" 3) "Participating crewmembers were able to focus on getting the job done without distractions." Each item was rated on a 5-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). Team Mood represents the sum of the three items. The interitem reliability (Cronbach's alpha) for the 3-item measure was 0.74.

Individual well-being (stress/frustration). All subjects were asked: "Please comment on how you felt at the end of each task (e.g. more or less frustrated than usual, more or less stressed than usual)."

Perceived support. All subjects were asked to comment on the support provided during the task. Crewmembers were asked: "Please comment on the support you felt you had from the flight control team when completing the study task today (e.g. how much support, satisfaction with the support, type of support)." Mission control personnel were asked: "Please comment on the support you felt you were able to provide to the crew today (e.g. how much support, satisfaction with the support, type of support)."

Communication quality. All subjects were asked to indicate their level of agreement with the following statements: 1) "I understood what was being communicated;" and 2) "I felt the other person understood what I was trying to communicate." Each item was rated on a 5-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). Communication quality represents the sum of the two items. The interitem reliability of the 2-item measure was 0.83.

Task Autonomy. ISS crewmembers were asked to complete a short instrument containing three items adapted from Hackman and Oldman:[9] 1) "We had significant autonomy in determining how we do this job;" 2) "We could decide on our own how to go about doing this task;" and 3) "We had considerable independence and freedom in how we did this task." ISS crewmembers were also asked if they required autonomy in completing the task: 4) "We required significant autonomy in determining how we do this job;" 5) "We had to decide on our own how to go about doing this task;" and 6) "We required considerable independence and freedom in how we did this task." Each item was rated on a 5-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). Task autonomy represents the sum of the six items. The inter-item reliability of the 6-item measure was 0.89.

Posttask assessments were returned by participating astronauts 100% (22/22) of the time, and by participating mission control personnel 83.3% of the time (15/18). The completion rates of specific items on the posttask questionnaire are described in **Table II**.

Individual semistructured interviews were conducted with the participating astronauts less than 21 d postmission to obtain their opinions about their experience with the study, including: the feasibility and acceptability of data collection schedules, the validity, reliability, and acceptability of study tasks and survey items, and to elicit recommendations for changes in protocol or data collection instruments for future studies. The principal investigator and two behavioral research scientist coinvestigators conducted the interview. Postmission interviews lasted approximately 45 min and were digitally recorded for analysis.

The feasibility and acceptability of utilizing the ISS as a research platform to study the impacts of communication delays was evaluated in terms of the number and type of tasks studied, completion rate of posttask assessments, and astronaut assessment of the feasibility and relevance of the study itself and of specific survey items to operational conditions. Qualitative data from postmission interviews with the three astronauts were analyzed using an inductive coding approach based on "Consensus, Co-Occurrence, and Comparison."[25] This qualitative coding methodology allows researchers to analyze both a priori and emergent themes in the data. The coding scheme was developed in an iterative process. Briefly, audio transcriptions of the postmission interviews were transcribed by the lead author, and then reviewed by the principal investigator. The raw data from the audio transcriptions was condensed into analyzable units based on their underlying theme(s), and a comprehensive set of codes was developed based upon these themes. After the initial coding scheme was developed, the interview transcriptions were coded by the lead author and then reviewed by the principal investigator. Differences in assigned codes for particular segments of text were resolved through consensus among research team members. When a particular phrase contained multiple units of meaning, all relevant codes were assigned. The data was then inspected to ensure the comprehensiveness of the coding scheme. Codes that did not represent substantially different units of meaning were combined. Low frequency codes were

Table II. Survey Items.

PRIMARY OUTCOME MEASURES	VALID (MISSING)
1. Performance: 3 items (9 point scale)	36 (1)
2. Crew Well-being*: 3 items (5 point scale)	21 (1)
3. Individual Well-being: 1 item (open-ended)	23 (14)
SECONDARY OUTCOME MEASURES	
1. Communication Quality: 2 items (5 point scale)	35 (2)
2. Task Autonomy*: 3 items (5 point scale)	22 (0)
3. Perceived support: 1 item (open-ended)	29 (8)

* Astronauts only.

reviewed to determine whether they represented a truly unique meaning or if they could be effectively subsumed under a more frequently assigned code. After the code list was finalized, base-level codes were grouped into different themes using the principle of constant comparison.[8] These themes were compared to each other in order to develop higher order organization of the data. The final structure consisted of three levels: themes, subcategories, and categories. The frequency of each theme was calculated by summing the number of times the coded theme appeared in the transcripts.

RESULTS

Qualitative analysis of the postmission interviews identified 19 themes, which were grouped into two categories and seven subcategories. Frequencies and percentages of total comments for the 19 themes are presented in **Table III**.

The first category, 'Experience with current study' included 40 comments (50.6% of comments). These comments were grouped into eight themes, which were further grouped into three subcategories: 1) 'general experience' (15.2% of comments); 2) 'study tasks' (17.7% of comments); and 3) 'survey instruments' (17.7% of comments).

The first subcategory included two themes related to the astronauts experience with the study. The first theme, 'enjoyed study,' included comments from all three astronauts indicating they enjoyed the study. For example, one astronaut stated, "And really, I didn't want to like this research project, but I did like it. I learned a lot." The second theme, 'valid/important,' included comments from the astronauts suggesting the study captured important information and reflected the kinds of challenges crewmembers are likely to face on long-duration missions. For example, one astronaut stated, "I think it is useful that we think about this because this is going to be a future problem and it's good to develop the tools that allow us to deal with those situations."

The second subcategory included three themes related to the number and type of tasks included in the study. Within this subcategory, astronauts most frequently reported they felt the study should have gone further and assessed more tasks under situations of communication delays ('limited number of tasks'). For example, one astronaut reported, "I think it is difficult to talk about all these really interesting questions, and interesting experiment, and I think it's really important that we do it, but I feel like I didn't participate enough to really bring in useful data." In addition, the astronauts expressed concerns about the types of tasks involved in the study ('certain tasks not suitable'). For example, they indicated tasks that involved a low level of communications were not suitable to study the impacts of communication delays. Despite these concerns, the astronauts reported they felt the communication delay filter was realistic and they liked how it was inserted into the study tasks ('Realistic comm. delay filter').

The third subcategory included three themes related to the data collection methods used in the study. The first theme, 'certain questions need better explanations,' included comments indicating the astronauts did not understand the rationale for asking certain questions. For example, one astronaut stated "They (the questions) were very similar, and I didn't really understand the background of the questions. What they had in mind. I felt like I couldn't really answer them, and there was a very wide scale." The second theme, 'prefer open-ended questions', included comments related to the format of the survey items. The astronauts indicated they used the open-ended items to highlight relevant information that was not being captured with the scaled items. For example, one astronaut reported "Maybe I felt this way; the 1-to-7 questions are good once we really understand the right questions to ask. I'm happy to answer the 1-to-7s, but I was also using the fill in the blank areas to kind of highlight some things that I saw throughout the things… I just don't want you to miss stuff that is useful." The last theme, 'Survey items did not capture all relevant information,' included comments related to limitations of the posttask questionnaires. For example, one astronaut suggested "It (the questionnaire) didn't box us in a corner enough. It almost didn't feel to me like the right questions were being asked."

The second category, 'Recommendations for future studies' included 39 comments (49.4% of comments). These comments were grouped into 11 themes,

Table III. Qualitative Analysis of Post-Mission Interviews.

CATEGORY	SUBCATEGORY	THEME	FREQUENCY (%)
I. Current Study	A. General Experience	i. Enjoyed study	6 (7.6%)
		ii. Valid/important	6 (7.6%)
	B. Study Tasks	i. Limited number of tasks	6 (7.6%)
		ii. Realistic comm. delay filter*	5 (6.3%)
		iii. Certain tasks not suitable	3 (3.8%)
	C. Survey Instruments	i. Better descriptions needed	5 (6.3%)
		ii. Prefer open-ended formats	5 (6.3%)
		iii. Not all relevant information captured	4 (5.1%)
II. Future studies	A. Additional tasks	i. High comm. tasks	8 (10.1%)
		ii. Complex tasks	5 (6.3%)
		iii. Time-critical tasks	4 (5.1%)
	B. Study Location	i. SIMS†	8 (10.1%)
		ii. ISS	3 (3.8%)
	C. Additional questions	i. Performance	3 (3.8%)
		ii. Mood	2 (2.5%)
		iii. Comm. quality	1(1.3%)
	D. Additional scenarios	i. Personal comms.	2 (2.5%)
		ii. Video comms.	2 (2.5%)
		iii. All day comm. delay	1 (1.3%)

Abbreviations: *Comm(s).= Communication(s); †SIMS = Simulators (i.e., analog environment on Earth).

which were further grouped into 4 subcategories: 1) 'additional communication delay tasks' (21.5% of comments); 2) 'study location' (13.9% of comments); 3) 'additional questions' (7.6% of comments); and 4) 'additional communication delay scenarios' (6.3% of comments).

The first subcategory included three themes related to the type of tasks future studies should include. The astronauts most frequently reported future studies should include 'high communication tasks' (i.e., tasks that require high levels of back and forth communications between ISS crewmembers and mission support personnel). For example, one astronaut stated, "I wish there were more situations for me, maybe I even do like a maintenance task where there is frequent comm. with ground involved or required, knowing this will make it frustrating in a way." In addition, they suggested including more 'complex tasks,' like payload science tasks, and 'time-critical tasks,' like emergency scenarios.

The second subcategory included two themes related to where future research studies should be conducted: SIMS (simulated missions conducted on Earth) and ISS. Even though the astronauts suggested SIMS represent useful research platforms to study the impacts of communication delays, they claimed studies on the ISS will better reflect the challenges space crews will likely face during deep space missions. For example, one astronaut reported "Definitely can benefit from analogs, but you will get the best data on the ISS. The ISS reflects real training, the real situation. It shows the amount of collaboration they will be doing. In SIMS, not all of that stuff will be reflected."

The third subcategory included three themes related to the types of questions future studies should include with regards to 'performance,' 'mood,' and 'communication quality.' For example, the astronauts suggested asking whether task efficiency was compromised, and/or whether the delays changed the way tasks were performed. Furthermore, they suggested asking whether the delays changed the way the crew communicated with the ground support team, and if it altered the rapport between the crew and the ground (i.e., feelings of connectedness and camaraderie).

The fourth subcategory included three themes related to additional scenarios future studies should assess. The astronauts most frequently suggested including delays in 'personal communications' (i.e., communications with family and friends). Such communications were not included as part of the study protocol in response to concerns expressed by both the MOD and the AO. In addition, the astronauts recommended incorporating communication delays in 'video communications,' and/or including an 'all day communication delay' (i.e., implement communication delay filters in ISS communications for an entire day). For example, one astronaut reported: "I would love to see a communication delay day…you got a good amount of data on individual tasks, but a lot of times for us on this heavily impacted timeline up there, we are test, test, test, test. We never got to see how in this, how it trickles through the day. And how does it feel when the crew gets behind, and more behind. And that's where I think you will start to add stress, and you will start to see some really neat little bubbles and outliers in the data."

DISCUSSION

Research on the behavioral and performance-related challenges associated with communication delays likely to occur during deep space missions has relied extensively on Earth-based analog environments.[10,19,22] Although the ISS has long been viewed as a high fidelity analog to such missions in comparison, the feasibility and acceptability of utilizing the ISS to study the impacts of experimental communication delays has been questioned given issues of cost, insufficient subjects to achieve statistical power, limited facilities, logistics, and limited regard for the importance of behavioral issues.[10,11,19] The results of this study suggest that such research is both feasible and acceptable to potential study subjects within certain constraints.

As expected, completion of this study required the close collaboration of several stakeholders, including the researchers, the operational support staff, project administrators, funding and regulatory agencies, and the astronauts themselves. Even though the different stakeholders were united by a desire to promote the health and well-being of astronauts and prevent performance decrements of distributed space teams under conditions of communication delays, the success of research-operational collaborations relies heavily on negotiations and compromise.[21] The current study involved tradeoffs between operational requirements to insure optimal performance and safety on the ISS, administrative requirements and astronaut preferences for certain data collection methods, and research requirements for conducting a scientifically sound study to assess potential threats to performance and well-being.

Overall, it was technically feasible to implement communication delays to-and-from the ISS, and to obtain posttask information on mood and performance from the subjects. The astronauts were in agreement as to the importance of the study, and there was little difficulty with recruitment. However, prior to conducting the study there were a number of concerns expressed by the MOD and the AO that resulted in significant challenges to utilizing the ISS as a research platform.

To start, the MOD expressed concerns about the potential impact of communication delays when performing certain study tasks on ISS operations. For example, there were concerns that communication delay tasks might compromise the crewmembers' ability to complete all scheduled activities. In addition, there were concerns about allowing the astronauts to perform certain types of tasks that may be dangerous or life threatening, especially if they did not have sufficient training and would not have access to timely support or guidance. Accordingly, it was a challenge to identify a sufficient number of tasks that were sufficient and acceptable, thereby making it difficult to determine the impacts of communication delays across the different dimensions of task complexity. Building on this, the astronauts indicated their participation in the study was limited both in terms of the number and the types of tasks included. Despite these limitations, all study tasks were completed, and no significant adverse impacts were reported, both with regards to ISS operations, as well as the health and safety of the study subjects. It is important to note that even though no significant adverse events occurred, communication delays were associated with a number of performance and mood-related challenges (as mentioned above, these results will be published in a separate paper). Since safety and operations on the ISS were maintained in the current study, future studies may have stronger leverage to study additional types of tasks under situations of communication delays. Importantly, future studies should try to prioritize the research time on the ISS to include tasks that are most likely to negatively impact individual and team outcomes, including high communication level tasks, complex tasks, and time-critical tasks.

In addition, the AO expressed concerns about the willingness of the astronauts to answer certain types of information in standardized formats. In light of these concerns, a number of standardized survey instruments included in the original study protocol were not administered, including the Perceived Stress Scale (PSS),[3] the Brief Scale for Social Support,[1] Big Five Personality,[4] and the Positive and Negative Affect Scale (PANAS).[24] Consequently, data on certain moderating influences of communications delay on behavior and performance, such as personality, stress and social support, were limited. The astronauts corroborated the AO's concerns about standardized formats during the postmission interviews. They indicated they preferred open-ended items to scale-based questions, and thought certain scaled items did not capture all relevant information. Despite these limitations, posttask assessments were completed and returned by the subjects the majority of the time, and the research team was able to collect meaningful information on a number of measures including individual, crew and team performance, individual and crew well-being, communication quality and task autonomy. Moving forward, future studies should consider including more open-ended questions, or even interview-based assessments upon completion of each study task. The open-ended approach to collecting data on psychosocial issues and performance has been used on previous studies conducted aboard the ISS, including an analysis of astronaut diaries.[23] Furthermore, future studies should consider working with SME's to develop task-specific questions to ensure all relevant information is captured.

In drawing conclusions from this particular study with respect to feasibility and acceptance of studies that might adversely impact operations aboard the ISS, certain limitations should be kept in mind. First, the small sample of subjects limits the ability to generalize to other astronauts and other ISS increments that are engaged in performance of other tasks. Accordingly, future studies will need to include additional increments to achieve an adequate sample size. Second, semistructured interviews were not conducted with mission support team members, thereby limiting the qualitative analysis to the comments from the ISS crewmembers. Future studies should include interviews with both team components since communication delays are two-sided in nature, and comments from the mission support team may offer an important and potentially unique perspective. On a similar note, semistructured interviews were not conducted with MOD or AO personnel. Rather, an understanding of the rationale for the recommendations provided with respect to available tasks and procedures for data collection and the establishment of a 50-s time delay were based on emails and notes of conversations with these personnel. Lastly, the quantification of qualitative data was intended merely for description of frequency of occurrence of certain topics and not for quantitative hypothesis testing. Given the small sample size, the frequencies were intended to illustrate the opinions of a single crew rather than examine the range of opinions expressed by three separate individuals. A larger sample collected across several ISS might provide an opportunity to examine such variation; more crews might provide an opportunity to examine occurrence of themes across crews as well as between individual crewmembers.[11]

Despite these limitations, the study subjects were in agreement as to the importance of the study. They indicated the study reflected important challenges space crews will likely face during long duration missions, and encouraged future studies to delve deeper and include more communication delay tasks and scenarios. Understanding the impacts of communication delays on the ISS may benefit the characterization of risk of communication delay on performance and well-being, the selection and composition of future spaceflight teams, the development of countermeasures to support autonomous operations, and the future of team communication and coordination around the world.

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