Assessing the Impact of Communication Delay on Behavioral Health and Performance: An Examination of Autonomous Operations Utilizing the International Space Station

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EXECUTIVE SUMMARY

Operational conjectures about space exploration missions of the future indicate space crews will need to be more autonomous from mission control and act and operate independently, in part, due to the expectation that communication quality between the ground and exploration crews will be more limited by communication delays and other factors than on any mission to date. Given this context of operations, researchers, engineers, and operational training experts have suggested communication delays and the impact these delays have on the quality of communications to the crew will create performance decrements if crews are not given adequate training and tools to support more autonomous operations. The Behavioral Health and Performance Element (BHP) of the NASA Human Research Program (HRP) conducted a research study to examine the impact of implementing experimental communication delays to-and-from the International Space Station (ISS) on individual and team factors and outcomes, including performance, well-being and related perceptions of autonomy and communication quality. To date, very few studies have observed teams in remote environments that perform without communication with management teams (e.g., mission control), and no such studies have been conducted during long-duration expeditions or missions. This study addressed the operationally-constrained criterion of a HRP Directed Research Project (DRP) and was a time-constrained requirement as we: 1) utilized an available ISS Increment to implement this study, 2) incorporated the results of this study to identify future near-term research tasks that relate to autonomy and what countermeasures will be needed to adequately prepare for autonomous long duration missions, and 3) guided future NASA Research Announcement (NRA) calls based on the conclusions that are drawn from this study that will address and close research gaps (including Team Gaps 1, 6, and 7 as well as inform BMed Gaps 1 and 2).

This study examined how interdependent teams (such as those with members in the field and at home base) interact and perform tasks with and without delays in communications between the team elements. It had three specific aims: 1) determine the feasibility and acceptability of conducting a study of communication delays on the ISS; 2) determine if there is an association between delays in communication, individual and team performance and well-being; and 3) determine whether these associations are influenced by task complexity (i.e., criticality and novelty), task-related communication demands, communication quality, and task autonomy.

The study participants included three astronauts on the ISS (two American crewmembers and one European crewmember) and 18 participating mission support personnel who were asked to perform 10 tasks (6 without a delay in communication and 4 with a 50-second one-way delay) over a three-month increment. The tasks performed by the teams varied along two dimensions: 1) those that are either critical or not critical (“criticality”) and 2) those that are either novel or familiar (“novelty”). Tasks included variations in both dimensions as it was assumed that highly novel and highly critical tasks are similar to those that a team may encounter during a long duration mission in which they have no prior training but must address. After each task, participating ISS crewmembers and mission support personnel were asked to complete post-task questionnaires that included questions about individual and team behavior, performance and mood. This study provided a preliminary understanding of the impact of communication delays on individual and team performance and well-being, as well as insight into how teams perform and interact under autonomous conditions in the analog environment most comparable to deep space.
Post-task assessments were completed by participating astronauts 100% (22/22) of the time, and by participating mission control personnel 83.3% of the time (15/18). Qualitative analysis of post-mission 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.

Crew well-being and communication quality were significantly reduced in communication delay tasks compared to control. Communication delays were also significantly associated with increased stress/frustration. Qualitative data suggest communication delays impacted operational outcomes (i.e. task efficiency), teamwork processes (i.e. team/task coordination) and mood (i.e. stress/frustration), particularly when tasks involved high task-related communication demands, either because of poor communication strategies or low crew autonomy. Training, teamwork, and technology-focused countermeasures were identified to mitigate or prevent adverse impacts.

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.
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1.0 INTRODUCTION

Over the last 40 years, NASA has worked to improve communication quality between ground and space crews by reducing and eliminating disruptions in the frequency, duration, and content of communications experienced during spaceflight. Such disruptions in communication quality are believed to adversely affect the performance and well-being of crews that traditionally work closely with ground support. NASA has historically sought out ways to increase the signal strength and availability, as well as modes of communication (for example: certifying internet protocol [IP] phones for flight on the ISS) as a means of preserving communication quality and promoting operational performance. However, the push to send manned missions into deep space environs will likely require NASA to use non-technology based countermeasures to handle threats to communication quality at some point. At this time, NASA does not possess much evidence to help determine the extent of individual and team behavior and performance are negatively affected by a reduction in communications quality. Such information is essential to determine the need for and nature of countermeasures to prevent decrements in behavior, performance and well-being, from occurring. This is especially true in conditions where communication is more disrupted and limited between the crew and ground control than NASA has experienced in missions to date.

Future exploration missions will require a change in the current model of interaction, procedural functioning, and communication between crewmembers and ground control. Due to the nature of future missions (i.e., missions to near Earth asteroids and to Mars), there are expected to be communication delays and associated technical difficulties that are currently not experienced (See Figure 1). These communication delays may impact the quality of communications and team coordination in such a way as to require the crew to work semi-autonomously in order to maximize health and performance during deep space exploration missions.

Within an organizational context, autonomy is defined as the level of discretion and freedom an individual or team is given to perform tasks, including decision making and problem solving, as well as other general duties (Leach, Wall, Rogelberg, & Jackson, 2005). It encompasses much more than the freedom to create one’s schedule and outcomes of an autonomous environment are highly inter-dependent among team members. In the context of spaceflight, autonomy refers to the extent to which the crew will act independently from mission control to complete objectives and/or respond to complications/emergency situations when needed due to environmental conditions (i.e., distance), as well as the extent to which the crew will prioritize mission objectives and schedule activities (Reagan & Todd, 2009). Bounded autonomy is the “involvement of the conditions, constraints, and limits that influence the degree of discretion by the individual and [crew/team] over their choices, actions, and support in accordance with standard operating procedures” (Rubino & Keeton, 2010). Based on the novel demands experienced on long-duration missions (e.g., psychosocial adaptation, chronic stress, strain, communication delays, social tension), studying the concept of bounded autonomy is a necessary step in understanding what challenges astronauts may face in these autonomous environments.
Numerous studies conducted on the ground have found that autonomy influences many individual and team level outcomes. Within organizational research, for example, autonomy has been found to positively influence employee ownership of problems, role breadth and performance (Morgeson, Delaney-Klinger, & Hemingway, 2005) and to be negatively related to personal strain (Bakker, Demerouti, & Euwema, 2005). At the team level, despite the possible negative outcomes that could result from team autonomy (e.g., inadequate skills, lack of cooperation), studies have shown that team autonomy has a positive effect on many valued outcomes, including team cohesion, performance, and well-being (Leach & Wall, 2005; Rasmussen & Jeppesen, 2006). Increased team autonomy has also been found to lead to increased active learning and decreased emotional exhaustion (van Mierlo, Rutte, Vermunt, Kompier, & Doorewaard, 2007). In other words, an autonomous team facilitates team member growth (e.g., learning new skills), which in turn, positively affects team performance and well-being. In fact, a long history of ground research indicates that many things about communication (quality of information, quality of signal, duration, frequency, mode, style, etc.) impact work teams’ levels of frustration with tasks and acceptance of roles, which, in turn, determine team members willingness to cooperate, ability to coordinate, and perceptions of stress and support (Brannick, Salas, & Prince, 1997; Cannon-Bowers & Salas, 1998; Eccles & Tenenbaum, 2004; Guastello, Bock, Caldwell, & Bond Jr, 2005; Harville, Elliott, & Barnes, 2007; Jude-York, 1998; Paris, Salas, & Cannon-Bowers, 2000; Salas, Bowers, & Cannon-Bowers, 1995; Wang, Kleinman, & Luh, 2001).

However, communication delays and the resulting compensatory levels of autonomy effects on performance and health may be different in spaceflight where teams work and live together. The aforementioned studies were all conducted in organizations that provide an environment very different from that of a long-duration mission. With few exceptions (e.g., Kanas et al., 2010), past research has not been based on the same types or degrees of threats to communication quality, specifically such long expected communication delays, or on the same level of autonomy as that expected to be experienced by astronauts on long duration missions. Indeed, rather than examining how teams perform in autonomous environments, past research focused on role- and task- related autonomy-and only in the presence of temporary, discrete and
predictable communication disruptions. Thus, although communication delays and autonomy likely affect performance, crew health, and interactions between crew and ground on long-duration missions, the relationships between these variables may differ from those observed in terrestrial populations. Furthermore, the relationship between communication delays and autonomy and health and performance will undoubtedly have different operational implications than those observed in terrestrial work settings.

For example, time delays experienced in long-duration missions could prohibit mission control from providing critical information to the crew. Therefore, the crew must perform independently to achieve certain mission objectives and address possible issues, including accomplishing some tasks in which the crew has received no prior training. Additionally, as the delays in communication lengthen, decision making and problem solving will have to become increasingly like playing chess, in that the parties (crew or ground) will have to think of all possible scenarios two or three cycles out in order to effectively coordinate. Under these conditions, the ground cannot simply respond to a crew’s query without considering whether the crew had to act in the meantime and if they did act, then what actions might have been taken. The ground response then would have to include all possible responses to all possible actions the crew might have taken while they waited for the ground to respond to their original communication. This may require new training for both ground and crews about how to manage and coordinate communication, decision-making and problem solving in such a scenario. Communication delays may also change the very definition of teamwork for long duration space exploration activities. With no delay in communications, the mission team might be more accurately defined as crew and ground together, but as communication delays increase, the mission team might need to be defined in two ways—as the crew alone (when objectives and tasks are time critical and delays are long) and as crew-ground (when objectives or tasks are not time critical and/or there are no significant threats to the quality of communication between crew and ground).

When considering future exploration mission scenarios, it is acknowledged that the current mission control-crew dynamic will be significantly different from what it is today; most notably, the logistical consequences associated with missions to the Moon or a Near Earth Object (NEO) and missions to Mars will include delayed communications between ground control and the crew. These communication delays may vary from no delay to 20 minutes (which means the time for each complete communication loop could take up to 40 minutes); thus mission control will not be able to oversee all aspects of the mission and it is likely that the crew will have to make some decisions independently. It is therefore essential to consider the constraints of a Mars-like condition (e.g., time delays) and conduct research that will investigate the effect of autonomy on team outcomes in isolated, constrained, and extreme environments.

Past operational experience suggest that communication difficulties (e.g. loss of signal, delays due to malfunctioning satellites or coverage gaps, loss of bandwidth and data) that challenge team coordination have been present beginning with the Mercury Program. Indeed, estimates of communication delays or a lack of communication between the crew and mission control have been observed during Skylab and were estimated to be experienced from 78-82% of the time during flight based on personal communications with key personnel at NASA. As interviews and surveys conducted with flight controllers revealed that mission teams are commonly concerned with team member coordination and communications, and that interpersonal conflicts and tensions exist (Caldwell, 2005; Parke, Orasanu, & Hanley, 2005),
efforts have been made to improve communication length and quality to reduce these possible negative effects. Thus, throughout the operational history of the ISS, multiple efforts have been made to increase the speed, quantity, and content of social communications and streaming media to crewmembers in an effort to offer better psychological support and coordination between the ground and crew (see Table 1).

**TABLE 1. HISTORY OF ISS COMMUNICATION: KU VIDEO CONFERENCING AND IP PHONE MILESTONES**

<table>
<thead>
<tr>
<th>Date</th>
<th>Expedition</th>
<th>Crew-Earth Communication Capability</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 2000 - Jan 2001</td>
<td>1</td>
<td>Videoconferencing with ground required crew to manually flip a switch to enable high data transfer rate and resulted in ISS losing telemetry. Videoconferencing could only occur in Mission Control.</td>
<td>128 kbps</td>
</tr>
<tr>
<td>Feb 2001</td>
<td>1</td>
<td>KU band came online with a data rate at about 50 mega-bits per second.</td>
<td>50 mbps</td>
</tr>
<tr>
<td>2001</td>
<td>4</td>
<td>One IP Phone was activated. Calls averaged about 15-20 hours per crewmember, per month.</td>
<td>50 mbps</td>
</tr>
<tr>
<td>Nov 2002</td>
<td>5</td>
<td>Two-way remote video conferencing from the crewmember’s family home was possible via Polycom videoconferencing systems.</td>
<td>50 mbps</td>
</tr>
<tr>
<td>Feb 2003</td>
<td>6</td>
<td>After the Columbia/STS-107 accident, a second IP phone line was activated when the ISS crew was reduced to a 2-person crew.</td>
<td>50 mbps</td>
</tr>
<tr>
<td>July 2006</td>
<td>13</td>
<td>Total number of IP phone lines was increased to four.</td>
<td>50 mbps</td>
</tr>
<tr>
<td>Oct 23, 2007</td>
<td>16</td>
<td>Moving the P6 solar array from the Z1 truss greatly increased the Acquisition of Signal (AOS) to about 25-30 minutes per pass.</td>
<td>50 mbps</td>
</tr>
<tr>
<td>2007</td>
<td>~16/17</td>
<td>The ISS Downlink data feed increased to 150 Mbps tripling the bandwidth so that video could be routed without interrupting bandwidth necessary for payloads and science.</td>
<td>150 mbps</td>
</tr>
<tr>
<td>2007</td>
<td>17</td>
<td>Total number of IP phone lines was increased to eight.</td>
<td>150 mbps</td>
</tr>
<tr>
<td>2011</td>
<td>27/28</td>
<td>Laptops will be issued to ISS crew families so that they can conduct video Private Family Conferences from locations other than home.</td>
<td>150 mbps</td>
</tr>
<tr>
<td>2012</td>
<td>~30</td>
<td>Potentially, KU updates will increase the downlink rate to 300Mbps.</td>
<td>300 mbps</td>
</tr>
</tbody>
</table>

**Notes:**
- **Ku band** is a portion of the electromagnetic spectrum primarily used for satellite communications.
- **IP** is the principal communications protocol responsible for routing packets across network boundaries.

Crewmembers place a high value on these communication “luxuries” and developments that allow them to maintain better contact with friends, family, and co-workers on the ground throughout the extended duration of a six-month rotation on the ISS. Crewmembers have praised the convenience and stated the necessity of these links in helping them maintain their morale, sense of well-being, happiness, and performance on the job (Kanas & Manzey, 2008). Despite this anecdotal evidence, there is still a lack of systematic examination of how these effects happen in spaceflight. We do not really know the nature of the relationship between communication delays and performance, nor what are the mediating and moderating psychosocial factors that might help support team performance when technical means cannot support more or better quality communications. NASA needs to immediately begin systematically collecting information within our unique operational context if we are to identify and develop countermeasures that can be used to prevent decrements and support optimal team performance in time to fulfill our long-duration/deep space exploration objectives.
The current study expands on these findings by examining the impacts of communication delays in the analog environment most comparable to deep space: the ISS. The ISS offers the best existing high-fidelity environment in which to formally examine the relationships between delays in communication and individual and team outcomes (Keeton et al., 2011). However, conducting a research study in such a setting is likely to involve tradeoffs between operational requirements to insure optimal performance and safety and research requirements for addressing potential threats to performance and safety (Institute of Medicine, 2001; Institute of Medicine and National Research Council, 2006; National Research Council, 1998; Palinkas, Allred, & Landsverk, 2005). As communication delays could potentially jeopardize the successful execution of highly critical tasks in space (Institute of Medicine, 2001), it is essential that the feasibility and acceptability of conducting research on the operational and emotional impacts of such delays in an active operational environment be determined beforehand.

This study examined how interdependent teams (crewmembers on the ISS and mission control personnel on Earth) interact and perform tasks with and without delays in communications between the team elements. The tasks performed by the teams varied across two dimensions of task complexity: 1) those that were either critical or not critical (“criticality”), and 2) those that were either novel or familiar (“novelty”). Tasks included variations in both dimensions as it is assumed that highly novel and highly critical tasks are similar to those that a team may encounter during a long duration mission. This report describes the feasibility and acceptability of conducting such a study on the ISS and recommendations for future studies and presents preliminary results on the impacts of communications delay on individual and team behavior and performance.

Spaceflight behavioral scientists and operational experts have continually suggested that communication quality issues, particularly communication delays inherent in deep space exploration missions will cause frustration, health issues, and performance decrements due to impaired team and task coordination between the ground and crew unless crews are provided with the tools and training to act more autonomously (Institute of Medicine, 2001; Kanas & Manzey, 2008). Concerns about the performance effects of an environmentally imposed delay between a communicated direction to act and the start of an action are not new and are not unique to spaceflight operations (Caldwell, 2000; Hunter, Wojcik, & Cooke, 1992; Jude-York, 1998; Kraut, Fussel, Brennan, & Siegel, 2002; Olson & Olson, 2000). Most of these concerns revolve around the notion that the time between the command issuance and the action taken will significantly change the operational context and render the command obsolete (at best) or dangerously inappropriate. In response, many studies (Olesen & Myers, 1999; Olson, Teasley, Covi, & Olson, 2002) of command delay focused on electronic or computing systems and their more quantifiable reactions rather than the less quantifiable human responses to delayed commands or communications.

However, human systems, such as a team, have both a potential advantage and a potential liability over electronic systems in handling command and information delays. Humans can sense and infer contextual changes directly and take actions without complete or expected informational inputs as necessary, whereas electronic systems cannot (Mackintosh, Berridge, & Freeth, 2009; Olesen & Myers, 1999; Olson et al., 2002). In other words, human systems have much more autonomy, and this autonomy can have both negative and positive influence over the outcomes in situations where communication is delayed. In instances where the context can change more rapidly than information could possibly be relayed, processed, and acted upon, the
autonomy afforded by human systems within the delay period is a critically important asset (Miller, Scheinkestel, & Joseph, 2009; Montoya-Weiss, Massey, & Song, 2001; Olesen & Myers, 1999; Smolensky & Stein, 1998). Specifically, the autonomy to communicate within the human systems allows for the opportunity to mitigate potentially dangerous situations. Indeed, communication is critical to effective performance, especially in times of crisis (Caldwell & Everhart, 1998). Individuals must work as a unit to make decisions and resolve potentially dangerous events. Dunn, Lewandowsky, and Kirsner (2002), for example, conducted a study wherein an emergency management team was faced with controlling a simulated hazardous chemical spill. They found both task-specific and situation-specific factors (i.e., factors relating to the general task at hand and factors relating to the specific situation being encountered, respectively) were important in predicting the pattern of communication among the management team. Furthermore, results showed that verbal exchanges following the 30-minute cycle were important in effectively navigating the situation.

Interrupted communication between team members may also lead to perceptions of an uncertain work environment. These perceptions, in turn, can yield negative individual and organizational outcomes, such as increased stress and decreased job involvement (Ganster & Schaubroeck, 1991). Indeed, a large literature has been amassed showing that negative perceptions of the work environment act as stressors (e.g., crowded space, multiple deadlines) and, in turn, can lead to many of the significant strain outcomes that are common to chronic exposure to stressors among individuals (e.g., burnout, turnover) (Albertsen, Rugulies, Garde, & Burr, 2010; G. Olson & Olson, 2003). Furthermore, communication has been shown to be a significant factor in the development of coordination and cohesion among team members (Kozlowski & Ilgen, 2006). Therefore, delayed communication can be seen as a critical factor in teamwork processes (i.e., coordination and cohesion), individual well-being (perceptions of stress and psycho-physiological indicators of strain), and organizational outcomes (team performance) (Cramton, 2001; Krauss & Bricker, 1967; J. S. Olson & Olson, 2006). However, research has yet to identify what exactly is a critically long communication delay for human systems in any given context, what contextual factors contribute to or buffer critical communication delays, and what informational aids and countermeasures can be provided to best support autonomous decision making and actions during communication delays (Malhotra & Majchrzak, 2004; McComb, Kennedy, Perryman, Warner, &Letsky, 2010; O’Connor, O’Dea, Flin, & Belton, 2008).

As social networking and mobile computing technologies expand globally, more work will be coordinated internationally, and more varieties of communication quality disparities and delays will result in many industries. Additionally, as technologies continue to develop that allow more people to access more information more quickly than ever before, the general population increasingly notices even minute delays in sending or receiving information, and these perceptions impact individual behavior, decisions, and performance (Dennis & Taylor, 2004). Many industries are and will be challenged to discover how and when communication delays impact team coordination and performance—and what factors limit or mitigate disparaging impacts—in order to competitively deliver quality products and services in an expanded global marketplace (Eccles & Tenenbaum, 2004; Edmondson & Roloff, 2009; Malhotra & Majchrzak, 2004). NASA has a unique opportunity with the ISS to be one of the first organizations in the world to test, identify, and catalogue what kind and how communication delays impact remote coordination among a large operational team. The information gathered from studying this issue in low Earth orbit is generalizable not only to future NASA endeavors (e.g., human missions to
deep space), but of use to all terrestrially-based businesses who operate concurrently across multiple time zones and/or in extreme environments or conditions (e.g. International Emergency Management Services, Remote Tele-Medicine, Polar and Undersea Expeditions, Military Special Operation Forces, Telecommunication Companies, News Agencies).

As an organization well known for creating cutting edge technology and ideas that enable quality work to occur even under the most demanding circumstance, like exploring space, NASA has a chance to live up to and further this reputation by being the first to specifically study and document the relationship between communication delays, types of tasks, team coordination, and team performance and health in an extreme operational environment. During long-duration spaceflight such as a mission to an asteroid or even to Mars, communication between ground control on Earth and the team in space will be delayed due to the distance between Earth and the spacecraft. Furthermore, it is important to remember that performance decrements in the isolated and extreme environment of space can have fatal consequences (Institute of Medicine, 2001; National Research Council, 1998). As variable communication delays will be a constraint present in the environment during a long duration mission that forces the autonomy of the crew to increase, it is necessary to understand what effects this delay might have on performance (and the magnitude of this decrement). If the detrimental effect poses a high risk to the success of a long duration mission, it will then be necessary to develop countermeasures (through future research efforts) that can reduce the associated behavior and performance risk to an acceptable level.

This study utilized a model derived from theories of communication (Clark, 1996), stress and coping (Lazarus & Folkman, 1984) and empirical studies of asynchronous communication (Kraut et al., 2002; Olson & Olson, 2000) that addresses how communication delay (as representative of the concept of communication quality, a factor that will likely be affected during autonomous long duration missions) will impact performance and other important team outcomes as demonstrated in ground analogs (Kanas et al., 2010; Love & Reagan, 2013). These evidence-based results were utilized in conjunction with novelty and criticality criteria for tasks that were selected to design a controlled and systematic study of proposed model in a high fidelity environment similar to what is expected for the transit portions of long duration interplanetary mission.

Thus, the goal of this study was to implement an experimental communication delay to examine effects on individual and team performance and well-being aboard the ISS, utilizing methodology and measures that will enable us to systematically document how communication delays impact the coordination and performance of NASA mission teams in this specific operational context. What was learned can and will benefit: 1) the characterization of the risk of communication delay on performance and well-being; 2) the selection, composition of future spaceflight teams; 3) the development of countermeasures to support autonomous operations; and 4) the future of team communication and coordination around the world.
2.0 OBJECTIVES, HYPOTHESES AND CONCEPTUAL FRAMEWORK

2.1 Overall Aim of the Study

The overall aim of the study was to determine whether simulated communications delays to-and-from the ISS result in clinically or operationally significant decrements in individual and team performance and well-being. Specifically, we aimed to:

**Aim 1:** Determine the feasibility and acceptability of utilizing the ISS as a research platform to assess the impacts of communication delays on individual and team performance and well-being.

**Aim 2:** Determine if there is an association between communication delays and individual and team performance and well-being.

**Main Effect Hypotheses:**

1. There is an inverse association between communication delays and individual and team performance.
2. There is an inverse association between communication delays and individual and team well-being.

**Aim 3:** Determine whether these associations are influenced by task complexity (i.e., criticality and novelty), task-related communication demands, communication quality, and task autonomy.

**Moderating Hypotheses:**

3. **Task novelty** and **task criticality** will **moderate** the associations between **communication delays** and individual and team **performance** and **well-being**, such that:
   a) The inverse association between communication delays and performance is significantly greater in high novelty and criticality tasks compared to low novelty and criticality tasks, respectively.
   b) The inverse association between communication delay and well-being is significantly greater in high novelty and criticality tasks compared to low novelty and criticality tasks, respectively.

4. **Task-related communication demands** will **moderate** the associations between **communication delays** and individual and team **performance** and **well-being**, such that:
   a) The inverse association between communication delays and performance is significantly greater when team members perceive high compared to low communication demands when accomplishing a task.
   b) The inverse association between communication delays and well-being is significantly greater when team members perceive high compared to low communication demands when accomplishing a task.

**Mediation Hypotheses:**

5. **Perceived quality of communication** mediates the associations between **communication delays** and **individual and team performance** and well-being such that:
   a) A communication delay is first associated with a decrease in perceived communication quality, which in turn, is associated with a decrease in performance.
   b) A communication delay is first associated with a decrease in perceived communication quality, which in turn, is associated with a decrease in well-being.
6. The level of **task autonomy** mediates the associations between **communication delays** and **individual and team performance** and well-being, such that:
   a) A communication delay is first associated with an increase in task autonomy, which in turn, is associated with an increase in performance.
   b) A communication delay is first associated with an increase in task autonomy, which in turn, is associated with an increase in well-being.

The moderator and mediator hypotheses relate to the overall conceptual model presented below (see Figure 2). Due to the small sample size for the proposed study, the interaction and mediation hypotheses were conducted as post-hoc analyses. However, they were included as part of this study because it will be possible to continue to increase sample opportunities over time. The conceptual model was based on evidence in the literature that demonstrates support for these specific relationships. As previous research concerning the relationships between communication delays and performance and well-being have already been discussed, the following is a summary of relevant research for the other constructs that are proposed in this model.

**Figure 2. Conceptual Model of the Effects of Communications Delays on Individual and Team Performance and Well-Being**
2.2 Moderating Variables

2.2.1 Task Novelty and Criticality

Studies of performance under conditions of asynchronous communication have consistently observed a greater impact of delayed communication on performance of complex tasks than on performance of simple or routine tasks (Krauss & Bricker, 1967; Kraut et al., 2002). For instance, communication among team members during the performance of tightly coupled tasks is more likely to be disrupted by delays than communication during the performance of simple procedural tasks (Bayerl & Lauche, 2010; Cramton, 2001). Tightly coupled tasks are those that are often ill-defined and require closer collaboration between team members for the purpose of making and executing decisions. Similarly, the extent to which performance of a task is judged to be critical (e.g., to address a life-threatening situation or emergency), may be adversely affected by the asynchronous nature of communication among team members (Cramton, 2001; G. Olson & Olson, 2003). Decrements or errors in the performance of critical tasks have been observed in mission control-space crew interactions (Bearman, Paletz, Orasanu, & Thomas, 2010).

2.2.2 Task-related Communication Demands

The moderating effect of task-related communication demands was evaluated since qualitative data from the post-mission interviews indicated high communication demands during completion of study tasks contributed to performance and mood-related issues associated with communication delays. High communication demands also reflected the extent to which those engaged in the communications required and received support from one another. From extensive ground-based evidence, social support is known to improve adaptation to, resilience to, and recovery from various stressors in traditional and military work environments; and the more social support provided before, during, and after work from more sources (e.g., family, friends, supervisors) the better individuals cope in general (Riggio et al., 1993; Seers, McGee, Serey, & Graen, 1983). Social support is any assistance individuals receive from others through interpersonal interactions, including information, emotional care, or instrumental resources (Riggio et al., 1993).

Individuals who receive less social support are more likely to experience decrements in well-being and health outcomes than individuals who have more social support available to them (House et al., 2003; Israel et al., 1989; LaRocco, House, & French, 1980; Nowack, 1991). Additionally, ground-based research indicates that social support plays a positive role in team functioning, team performance, individual achievement, and employee safety (Bhanthumnavin, 2003; Heaney, House, Israel, & Mero, 1995; Hearns & Deeny, 2007; Nowack, 1991; Schaubroeck & Fink, 1998; Seers et al., 1983).

In the context of this study, we hypothesized that social support required and received during completion of a task would serve to counter the negative effects of communication delay (experienced as an increase in perceived stress), on performance and well-being. Indeed, individuals who perceive a strong social support system (e.g., family, organization) will be more likely to be resilient to the negative effects of a communication delay from a personal (i.e., stress) and task (i.e., task autonomy) perspective.
2.3 Mediating Variables

2.3.1 Task Autonomy

This association is based on theories of occupational stress (Karasek Jr, 1979) and studies of team autonomy (Kanas et al., 2010). Workers who experience little autonomy in occupations characterized by high demands and little control experience greater stress than workers in occupations with high autonomy (Karasek Jr, 1979). High autonomy in three analog environments (NEEMO, Haughton-Mars, and Mars 500) was found to be associated with increased creativity and mood (Kanas et al., 2010). Autonomy has been found to be positively related to worker productivity, quality and satisfaction (Bakker et al., 2005), and mediates the negative impacts of workplace demands on strain outcomes (Hall et al., 2006; Tai & Liu, 2007).

2.3.2 Communication Quality

Effective and efficient team communication requires the coordination of communication processes and content among team members to ensure shared information is heard, mutually understood, and relevant to shared goals (Clark, 1996; Clark & Brennan, 1991; Fischer, Mosier, & Orasanu, 2013). Communication quality reflects the completeness, accuracy, timeliness, and usefulness of exchanged information (Gudykunst & Gudykunst, 1996). In addition, communication quality is influenced by the situational context and medium in which communication occurs (i.e. face-to-face versus remote; synchronous versus delayed) (Brennan & Lockridge, 2006; Kraut et al., 2002; Olson & Olson, 2003). For example, when team members are co-located, communication tends to be more frequent and rapid, which allows confusion to be resolved quickly, and task and team awareness to be obtained with minimal effort. Co-present team members can take advantage of a shared visual field, as well as facial expressions and body language to obtain or direct attention, provide feedback on their understanding, and gauge the social climate of the team. These resources help team members ensure mutual understanding is achieved, which in turn facilitates task performance and team cohesion (Cannon-Bowers & Salas, 1998; Fischer, McDonnell, & Orasanu, 2007; Keyton & Beck, 2009).

Effective communication across distributed teams, however, requires more effort since fewer resources are available, especially when such collaborations involve delayed or asynchronous communication (Brennan & Lockridge, 2006; Kraut et al., 2002; Olson & Olson, 2003). Research suggests communication delays complicate communication processes and compromise the ability of teams to develop a shared situational model (Fischer et al., 2013; Love & Reagan, 2013). For example, it is difficult to coordinate the timing and sequence of communications under situations communication delays, such that communications more frequently overlap (i.e. one member initiates an outgoing call at the same time an incoming message is received, which may block the incoming call, or make it more difficult to hear the message), and/or are more frequently out of sequence (which may make it difficult to follow the thread of a conversation) (Fischer et al., 2013; Kraut et al., 2002; Love & Reagan, 2013). These timing and sequence issues often require additional communications to establish common ground, which, given the delayed conditions, may reduce task efficiency since team members need to wait for critical information and increase workload since team members need to keep track of concurrent tasks and conversations (Frank et al., 2013).

In addition, communication delays may exacerbate communication quality issues associated with minimal or ambiguous responses (i.e. use of terms whose meaning was underspecified; failure to identify who was talking or who communication was directed at etc.).
and with the failure to confirm understanding (i.e. repeat important aspects of a message; acknowledge information was received etc.) (Fischer & Mosier, 2014; Fischer et al., 2013; Frank et al., 2013). Ambiguity and uncertainty to whether communications were heard as intended or directed may compromise the ability of team members to communicate effectively, which in turn may impact task efficiency and workload. Delayed or missing responses have also been shown to weaken the rapport between distributed team members (Love & Reagan, 2013).

Given these findings, we predicted communication delays would be inversely associated with communication quality. Furthermore, since team communication has been shown to play an important role in both task performance and team cohesion, we predicted communication quality would mediate the relationships between communication delays and individual and team performance and well-being (Fischer et al., 2007; Fischer & Mosier, 2014, 2015; Frank et al., 2013; Keyton & Beck, 2009; Krauss & Bricker, 1967; Love & Reagan, 2013).

3.0 NASA RISK REDUCTION GAPS

This study aligned with three of the Team risk reduction research gaps of the NASA BHP Element within HRP:

- Team Gap 1: Given the context of long duration missions, what are the most likely and serious threats to task performance, teamwork, and psycho-social performance?
- Team Gap 6: Given the context of long duration missions, what are the optimal ways to support and enable multiple distributed autonomous teams to support task performance, teamwork, and psycho-social performance?
- Team Gap 7: Given the context of long duration missions how does constrained communication impact task performance, teamwork, and psycho-social performance?

The study was also designed to inform assessment and characterization of the Bmed risk for autonomous exploration missions (Risk of Adverse Behavioral Conditions) by better understanding the impact of communication delays to individual well-being.

4.0 RESEARCH DESIGN AND METHODS

4.1 Participants

The study included three astronauts on the ISS (two United States On-orbit Segment [USOS] crewmembers and one European crewmember) who were part of a 6-person crew on an increment aboard the ISS (the other 3 crewmembers were Russians who did not participate in the study). Participants also included 18 Mission Control Center (MCC) support personnel such as the Capsule Communicator (CAPCOM) (the individual who communicates with the crew from the MCC) and Mission Director. All participants were fluent English speakers. 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.
4.2 Procedure

The ISS was utilized to characterize the risk of communication delay on performance and well-being in a spaceflight environment. The original proposal called for an evaluation of 16 tasks in a crossover design. Eight of those tasks were to be completed under the designated one-way communication delay length (50 seconds). To contrast the communication delay intervals, measures were also to be collected under conditions of no delay. The communication delay-tasks and no communication delay-tasks (control) were to be paired together across the timeline to allow for controlled and effective comparisons that will help determine the magnitude of impact that delay has on task performance and well-being.

During the planning and proposal stage, the research team worked with the Flight Operations Directorate (FOD) (at the time of the study, FOD was called the Mission Operations Directorate (MOD)) to identify 10 suitable tasks, negotiated with operations to implement the communication delay, and worked with schedulers to maintain the requirements that were needed in order to ensure the methodological design of this study. The tasks are listed in Table 2 by experimental condition and complexity level. Task requirements included: 1) task duration was at least 60 minutes (to ensure sufficient time to capture behavioral assessments and complete ratings); 2) tasks involved communication between crew and ground (>4 transmitted messages); 3) at least 2 crew members were involved in the task (team-level task); and 4) delays in communication involved all communication mediums (i.e. voice/text) but did not include telemetry or other hardware and/or system communications. A different task was completed each day over a 4-day period early in the mission and late in the mission, and two additional tasks were completed at the mid-point of the mission (to control for team effects over time).

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Experimental Condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew performed weekly cleaning activities</td>
<td>Control</td>
<td>Low</td>
</tr>
<tr>
<td>Crew conducted scientific experiment</td>
<td>Control</td>
<td>Low</td>
</tr>
<tr>
<td>Crew transferred cargo from the automated transfer vehicle to ISS</td>
<td>Control</td>
<td>High</td>
</tr>
<tr>
<td>Crew conducted scientific experiment</td>
<td>Control</td>
<td>High</td>
</tr>
<tr>
<td>Crew conducted scientific experiment</td>
<td>Control</td>
<td>High</td>
</tr>
<tr>
<td>Crew replaced broken equipment used to support ISS habitability</td>
<td>Control</td>
<td>High</td>
</tr>
<tr>
<td>Crew performed weekly cleaning activities</td>
<td>Delay</td>
<td>Low</td>
</tr>
<tr>
<td>Crew replaced broken equipment used in human physiology research</td>
<td>Delay</td>
<td>Low</td>
</tr>
<tr>
<td>Crew began loading disposal items into the Cygnus spacecraft</td>
<td>Delay</td>
<td>High</td>
</tr>
<tr>
<td>Crew performed extravehicular mobility unit maintenance</td>
<td>Delay</td>
<td>High</td>
</tr>
</tbody>
</table>
Data Collection

4.3.1 Pre-Mission Assessments

Individual semi-structured interviews (Appendix A) were conducted with each of the astronaut participants approximately four months prior to mission launch. Participants were asked open-ended questions as to prior experience in working on a team like this, working under conditions of prolonged isolation and confinement in an extreme environment, and experience of communicating with others who are physically separated. Demographic data was also collected from the astronaut participants. However, demographic characteristics were withheld to preserve subject confidentiality and anonymity. The principal investigator (LP) and two behavioral research scientist co-investigators (WV, LL) conducted the interview. Pre-mission interviews lasted approximately 30 minutes.

4.3.2 Post-Task Assessments

After each task, participating ISS crewmembers and mission support personnel were asked to complete post-task questionnaires that included questions about individual and team behavior, performance and mood (Appendix B). The post-task questionnaire took approximately 10 minutes to complete and included the following items:

Individual, crew and team performance. All subjects (ISS crewmembers and MCC personnel) 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 (morale). ISS crewmembers were asked to complete a short instrument containing 7 items from the Group Environment Scale (Moos, 2002): 1) “Participating crewmembers had no difficulty communicating with one another while completing the task”; 2) “Each of the participating crewmembers was given the freedom to cope with the demands of completing the task in his or her own way”; 3) “The crew had no difficulty getting along with one another while completing the task”; 4) “Participating crewmembers were able to focus on getting the job done without distractions”; 5) Participating crewmembers were able to pull together to complete the task”; 6) “Participating crewmembers showed respect to one another while completing the task”; and 7) “Overall, the morale of the participating crewmembers during completion of the study task was quite high”. Each item was rated on a 5-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). However, item one was eliminated because it was too similar in content to the communication quality measures (see below) and items 5-7 were eliminated because of high levels of missing data. Crew morale represents the sum of the remaining three items. The inter-item 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)”. Responses were scored on a scale from 0 (not stressed/frustrated) to 1 (stressed/frustrated). Examples of responses scored as 0 include: “Neither frustrated nor stressed afterwards,” and “Normal.” Examples of
responses scored as 1 include: “A bit more frustrated because several areas were more
difficult to understand than expected,” and “More stressful and frustrated than normal.”

**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 inter-item 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 *Work Redesign* (Hackman & Oldham, 1980): 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.

**Perceived support (task-related communication demands).** Perceived support was
assessed with one open-ended question completed by all participants. 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). The measure ‘Task-related
communication demands’ represents the open-ended responses that discussed the level
of support provided (task-related communications involved), and was scored on a
range of 0 (low level of task-related communication) to 1 (high level of task-related
communication). Examples of responses scored as 0 (low) include: “Not a high level
of back and forth required,” and “I think the crew received the typical amount of
remote guidance.” Examples of responses scored as 1 (high) include: “More
support/comm. was needed than I expected,” and “Quite a lot of support. We had to
use video/photo’s several times to clarify the issues we were having.” When possible,
audiovisual records of the tasks were used in conjunction with the open-ended
responses. Five tasks were identified as having low task-related communication levels
(3 control and 2 delay), and five tasks were identified as high task-related
communication levels (3 control and 2 delay).

In addition, a number of standardized survey instruments included in the original study
protocol were not administered, such as the Perceived Stress Scale (PSS) (Cohen, Kamarck, &
Mermanelstein, 1983), the Brief Scale for Social Support (Bernal, Maldonado-Molina, & Scharron
del Rio, 2003), Big Five Personality (NEO-FFI: Costa & McCrae, 1991) and the Positive and
Negative Affect Scale (PANAS) (Watson, Clark, & Tellegen, 1988) due to concerns expressed
by the Astronaut Office (AO) about the willingness of astronauts to answer certain types of
information in standardized formats.
4.3.3 Post Mission Assessments

Individual semi-structured interviews (Appendix X) were conducted with each of the astronaut participants less than 21 days post-mission to obtain their opinions about the following: 1) feasibility and acceptability of data collection schedules; 2) validity, reliability, and acceptability of specific scales; 3) perception of importance of delays in communicating with one another; 4) factors that might have influenced well-being and performance independent of communication delays; and 5) recommendations for changes in protocol or data collection instruments (Appendix C). The principal investigator (LP) and two behavioral research scientist co-investigators (WV, LL) conducted the interview. Post-mission interviews lasted approximately 45 minutes.

4.3.4 Task Criticality and Novelty

The ten tasks selected across the Increment were representative of the different levels of criticality and novelty (hi novelty, hi criticality; hi novelty, low criticality; low novelty, hi criticality; low novelty, low criticality). For the first segment, (early) 4 tasks were selected based on the criticality/novelty matrix presented in Table 2 (1 with the 50 second delay and 3 without the delay [i.e. control condition]). The second segment (mid) involved 2 tasks with the communication delay only. The third segment (late) involved 4 tasks (1 delay and 3 without the delay). To ensure the correct criticality and novelty ratings of these tasks, subject matter experts (SMEs) rated designed tasks on both dimensions (criticality and novelty) utilizing our collaboration partners within FOD (MOD at the time of the study).

4.3.5 Time Delay Interval

For this particular study, we used a 50 second one way interval in the delay in communications between sender and receiver.

4.4 Data Analyses

4.4.1 Qualitative Analysis

Qualitative feedback from post-mission interviews was analyzed using an inductive coding approach based on “Consensus, Co-Occurrence, and Comparison” (Willms et al., 1990). 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 post-mission interviews were transcribed by a member of the research team (NK), and then reviewed by the principal investigator (LP). 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 a member of the research team (NK) and then reviewed by the principal investigator (LP). 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 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 (Glaser & Strauss, 1967). 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, categories and subcategories. The frequency of each theme was calculated by summing the number of times the coded theme appeared in the transcripts.

4.4.2 Quantitative Analysis

Upon completion of the study, 37 post-task assessments were collected from the astronaut participants (22 assessments) and mission support personnel (15 assessments). Primary outcomes included individual, crew and team performance, crew well-being and individual well-being (stress/frustration). Secondary outcomes included communication quality and task autonomy. We hypothesized communication delays would be inversely associated with performance, crew morale, and communication quality, and positively associated with task autonomy and stress/frustration. For continuous outcomes (performance, crew morale, communication quality, and task autonomy), responses from participating astronauts and mission support personnel were averaged for each task, and compared across control (N=6) and delay (N=4) tasks using an independent samples t-test. Normality of the task-averaged data for communication quality, performance, crew morale and task autonomy was assessed through visual inspection of Normal Q-Q plots, and the Shapiro-Wilk Test (p>0.05). For individual well-being, a Fisher’s exact test was conducted to compare reports of ‘stress/frustration’ verses ‘no stress/frustration’ (coded 1 or 0 respectively) across control and communication delay conditions (N=23, 14 of the 37 observations were omitted due to missing data). The main effect analyses were performed with SPSS for Windows (SPSS, Chicago, IL, USA) and setting 1-tailed alpha to reject the null hypothesis at 0.05.

Two-way analyses of variance (ANOVAs) were used to investigate the influence of communication delays and task complexity on individual, crew and team performance, crew well-being (morale), communication quality, and task autonomy. Task complexity included two dimensions, criticality (low or high) and novelty (low or high), which were analyzed as two independent factors due to the small sample size and the limited number of tasks. We hypothesized task criticality and task novelty would moderate the relationships between communication delays and the dependent variables, such that the predicted inverse relationships between communication delays and performance, crew morale and communication quality, and the predicted positive relationship between communication delays and task autonomy would be stronger in high critical and high novel tasks compared to low critical and low novel tasks respectively.

Furthermore, since previous research on social support in occupational contexts and qualitative data from the post-mission interviews indicated task-related communication demands contributed to performance and mood-related issues associated with communication delays, two-way ANOVAs were also used to investigate the influence of communication delays and task-related communication demands (high or low) on individual, crew and team performance, crew morale, communication quality, and task autonomy. We hypothesized task-related communication demands would moderate the relationships between communication delays and the dependent variables, such that the predicted inverse relationships between communication delays and performance, crew morale and communication quality, and the predicted positive
relationship between communication delays and task autonomy would be stronger in tasks that involved high compared to low task-related communication demands.

All two-way ANOVAs were analyzed using individual response scores, rather than task weighted averages due to the limited number of study tasks. Missing item scores were imputed with the mean task score of the missing item when possible (Communication quality N=2; Crew performance, N=1). Due to the small sample size and limited number of study tasks, we expected the evidence in support of all interaction hypotheses would likely not reach traditional levels of statistical significance (threshold for significance was defined at \( p_{\text{2-tailed}} < 0.050 \)). Accordingly, we also focus on notable trends (threshold for ‘trend’ was defined at \( p_{\text{2-tailed}} < 0.200 \)). Independent pairwise comparisons were conducted to assess the simple main effect of communication delays at each level of task criticality (low/high), task novelty (low/high), and task-related communication demands (low/high) for all significant interactions (or trends). These analyses were performed with SPSS for Windows (SPSS, Chicago, IL, USA).

5.0 RESULTS

5.1 Study Feasibility and Acceptability

Qualitative analysis of the post-mission interviews identified 19 themes from 79 comments, which were grouped into two categories and seven subcategories. Frequencies and percentages of total comments for the 19 themes are presented in Table 3.

| TABLE 3. 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 communication delay filter | 5 (6.3%) |
| | 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 communication tasks | 8 (10.1%) |
| | | ii. Complex tasks | 5 (6.3%) |
| | | iii. Time-critical tasks | 4 (5.1%) |
| | B. Study Location | i. Simulations | 8 (10.1%) |
| | | ii. ISS | 3 (3.8%) |
| | C. Additional questions | i. Performance | 3 (3.8%) |
| | | ii. Mood | 2 (2.5%) |
| | | iii. Communication quality | 1(1.3%) |
| | D. Additional scenarios | i. Personal communications | 2 (2.5%) |
| | | ii. Video communications | 2 (2.5%) |
| | | iii. All day communications delay | 1 (1.3%) |

The first category, ‘Experience with current study’ included 40 comments (50.6% of all 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 ‘general experience’ subcategory included two themes. 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, ‘study tasks’, 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, ‘survey instruments’, 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 the astronauts concerns with the survey instruments. 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 all comments). These comments were grouped into eleven themes, which were further grouped into four 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, ‘additional communication delay tasks’, 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 crewmembers on the ISS and mission support personnel on earth). 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, ‘study location’, 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 long duration 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, ‘additional questions’, 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 communication 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, ‘additional communication delay scenarios’, included three themes relating to additional communication delay scenarios future studies should include. 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 FOD (MOD at the time of the study) and the AO. In addition, the astronauts recommended incorporating communication delays in ‘video communications’, and/or including an ‘all-day communication delay’ (i.e. communication delay filters are included in all communications over the course of a 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.”

5.2 Effects of Communication Delay on Performance and Well-Being

5.2.1 Quantitative Analyses

The primary objective was to determine whether delays in communication were significantly associated with crew well-being (morale), individual, crew and team performance, and reports of stress/frustration. As predicted, crew morale was significantly lower in communication delay (M=12.46, SD=0.71, N=4) compared to
control (M=13.87 SD=0.79, N=5) tasks \[t(7)=2.762, p=0.014, \text{Figure 3a}\]. Communication delays were also significantly associated with individual well-being (Fisher’s exact test one-sided \(=0.030\)), where stress/frustration was more frequently reported in communication delay compared to control conditions: 9 of 12 responses (75.0%) versus 3 of 11 responses (27.3%), respectively (Table 4). On the other hand, there was no statistical difference between control (N=6) and communication delay (N=4) tasks for individual \[t(8)=0.011, p=0.496\], crew \[t(8)=0.592, p=0.285\], or team \[t(8)=0.887, p=0.200\] performance. Sample means for individual (control M=6.93, SD=0.98; Delay M=6.94, SD=0.90), crew (control M=7.79, SD=0.68, delay M=7.46, SD=1.11) and team (control M=7.71, SD=0.41; delay M=7.21, SD=1.31) performance are showed in Figure 3b, 3c, and 3d respectively.

The study also examined whether communication delays were associated with secondary outcomes including communication quality and task autonomy. As predicted, communication quality was significantly lower under communication delay (M=7.88, SD=0.98, N=4) compared to control (M=9.13, SD=0.46, N=6) tasks \[t(8)=2.740, p=0.0127, \text{Figure 4a}\]. However, task autonomy was not statistically different across communication delay (M=17.71, SD=3.27, N=4) and control (M= M=17.44, SD=4.7, N=6) tasks \[t(8)=-0.097, p=0.463, \text{Figure 4b}\].

Legend: Assessment of a) crew well-being, b) individual performance, c) crew performance and d) team performance across control (N=6) and communication delay (N=4) tasks. Independent samples t-test statistics (*)p<0.050. Data are Mean ± SEM (¶ = task averages calculated from ISS crewmembers only, 1 of the 6 observations for control tasks was omitted due to missing data).

**Figure 3. Effect of Communication Delays on Performance and Crew Well-Being**
TABLE 4. ASSOCIATION BETWEEN COMMUNICATION DELAYS AND INDIVIDUAL WELL-BEING

<table>
<thead>
<tr>
<th></th>
<th>No Stress/frustration</th>
<th>Stress/frustration</th>
<th>Total</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>8 (72.7%)</td>
<td>3 (27.3%)</td>
<td>11 (100.0%)</td>
<td>0.030*</td>
</tr>
<tr>
<td>Delay</td>
<td>3 (25.0%)</td>
<td>9 (75.0%)</td>
<td>12 (100.0%)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11 (47.8%)</td>
<td>12 (52.2%)</td>
<td>23 (100.0%)</td>
<td></td>
</tr>
</tbody>
</table>

*Fisher’s exact test (1-sided). *14 of the 37 observations were omitted due to missing data.

Legend: Assessment of a) communication quality and b) task autonomy across control (N=6) and communication delay (N=4) tasks. Independent samples t-test statistics (*p<0.050). Data are Mean ± SEM (¶ = task averages calculated from ISS crewmembers only).

Figure 4. Effect of Communications Delay on Communications Quality and Task Autonomy

5.2.2 Qualitative Analysis

Qualitative analysis of the post-mission interviews identified 25 themes from 189 comments, which were grouped into ten subcategories and ultimately three categories: 1) ‘impacts’ of communication delays, 2) ‘factors’ that may contribute to adverse impacts, and 3) ‘countermeasures’ to mitigate or prevent adverse impacts. Frequencies and percentages of total comments for the 25 themes are presented in Table 5.

5.2.3 Impacts

There were 48 comments related to the ‘impacts’ of communication delays (25.4% of all comments). These comments were grouped into seven themes, which were further grouped into three subcategories: 1) performance’ (14.8% of comments), 2) ‘mood’ (7.9% of comments), and 3) ‘positive outcomes’ (2.6% of comments).
The ‘performance’ subcategory included three themes related to the impact of communication delays on operational outcomes and teamwork processes. Within this subcategory, the astronauts most frequently reported ‘more time wasted’ (*waiting for communications*) under situations of communication delays. For example, one astronaut stated, “Things you could do independently were fine, things where you relied on the ground resulted in lots of time lost and frustration, which is just not going to work.” Similarly, the astronauts reported ‘tasks took longer to complete’ under situations of communication delays. For example, the astronauts suggested, “You can say there was performance degradation because it took longer. But really then it depends on how you define performance. The ‘task’ was not done worse or better by that (*the delay).*” Furthermore, ‘reduced situational awareness’ between the ISS crewmembers and the ground support team was reported as a performance-related challenge. The ‘mood’ subcategory included two themes related to the impacts of communication delays on morale and well-being. Within this subcategory, ‘stress and frustration’ was most frequently reported. For example, the astronauts indicated, “Stress levels did increase with comm. Delay, particularly the cargo ops [operations] ones, because you could not get info in a timely fashion” and, “The only frustrating thing was dealing with conversations where you needed a back and forth with multiple questions and answers.” In addition, ‘disappointment’ was reported as a mood-related challenge.

### Abbreviations

*Comm.(s) = Communication(s); †AMO = Autonomous Mission Operations

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategory</th>
<th>Theme</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Impacts</td>
<td>A. Performance</td>
<td>i. More time waited</td>
<td>13 (6.9%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Tasks took longer to complete</td>
<td>9 (4.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. Reduced situational awareness</td>
<td>6 (3.2%)</td>
</tr>
<tr>
<td></td>
<td>B. Mood</td>
<td>i. Stress/frustration</td>
<td>12 (6.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Disappointment</td>
<td>3 (1.6%)</td>
</tr>
<tr>
<td></td>
<td>C. Positive Outcomes</td>
<td>i. Increased crew-crew comms.</td>
<td>4 (2.1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Crew felt liberated</td>
<td>1 (0.5%)</td>
</tr>
<tr>
<td>II. Factors</td>
<td>A. Task-specific</td>
<td>i. High comm. Tasks</td>
<td>13 (6.9%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Complex tasks</td>
<td>8 (4.2%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. Time-critical tasks</td>
<td>5 (2.6%)</td>
</tr>
<tr>
<td></td>
<td>B. Communication</td>
<td>i. Confusing comms.</td>
<td>9 (4.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Missed calls</td>
<td>9 (4.8%)</td>
</tr>
<tr>
<td></td>
<td>C. Other</td>
<td>i. No prior comm. Delay experience</td>
<td>5 (2.6%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Space-related cognitive disturbances</td>
<td>3 (1.6%)</td>
</tr>
<tr>
<td></td>
<td>D. Non-contributing factors</td>
<td>i. Quality of support</td>
<td>4 (2.1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Personnel issues</td>
<td>4 (2.1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. Crew-size</td>
<td>2 (1.1%)</td>
</tr>
<tr>
<td>III. Countermeasures</td>
<td>A. Training</td>
<td>i. Comm. Skills</td>
<td>14 (7.4%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Task-specific</td>
<td>11 (5.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. Comm. Delay specific</td>
<td>10 (5.3%)</td>
</tr>
<tr>
<td></td>
<td>B. Teamwork</td>
<td>i. Increase crew autonomy</td>
<td>15 (7.9%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Reduce back-and-forth comms.</td>
<td>15 (7.9%)</td>
</tr>
<tr>
<td></td>
<td>C. Technology</td>
<td>i. Recording tool</td>
<td>6 (3.2%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Text/video based comms.</td>
<td>5 (2.6%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. AMO† software</td>
<td>3 (1.6%)</td>
</tr>
</tbody>
</table>
The third subcategory included two themes related to positive impacts of communication delays. Within this subcategory, ‘increased crew-crew communications’ was most frequently reported. For example, one astronaut mentioned, “You have crew discussions popping up instead of just calling down to grounds and waiting for the answer to come back.” In addition, one crewmember suggested he felt liberated under situations of communication delays.

5.2.4 Contributing factors

There were 62 comments related to ‘factors’ that may contribute to adverse impacts (32.8% of all comments). These comments were grouped into ten themes, which were further grouped into four subcategories: 1) ‘task-specific factors’ (13.8% of comments), 2) ‘communication factors’ (9.5% of comments), 3) ‘other factors’ (4.2% of comments), and 4) ‘non-contributing factors’ (5.3% of comments).

The ‘task-specific factors’ subcategory included three themes related to how certain types of tasks contributed to the challenges associated with communication delays. The astronauts most frequently suggested ‘high communication tasks’ contributed to adverse impacts. For example, one astronaut stated, “If we have to wait every time for ground to give us a go or no go, it becomes almost impossible to do certain tasks.” In addition, they suggested ‘complex tasks’ and ‘time-critical tasks’ contributed to performance and mood-related challenges.

The ‘communication factors’ subcategory included two themes related to how poor communication strategies contributed to communication delay challenges. The astronauts indicated ‘confusing communications’, and ‘missed calls’ contributed to the adverse impacts. For example, one crewmember said, “Ground came back and they kind of answered in a little bit of an ambiguous way, which forced me to call again and clarify. And of course that is something that you want to avoid in a comm. Delay situation.”

The third subcategory, ‘other factors’, included two themes describing individual and environmental processes that contributed to communication delay challenges. The astronauts indicated individuals with ‘no prior communication delay experience’ contributed to performance and mood-related challenges because they had not yet learned to adapt the way they communicated to the delayed conditions. For example, one astronaut stated the following:

“There was definitely one weekend when (an individual with no comm. Delay experience) was on as flight director. And a lot of his calls were very brief, very typical calls you would make to a crew. But we were missing all of them. I think we missed 3-4 of them and we were left scratching our heads...but it seems like overall the learning curve was good. The ground started to understand what we would need. Because I think they were experiencing the exact same frustration on the ground that we were experiencing up there.”

In addition, they suggested ‘space-related cognitive disturbances’ that impacted some crewmembers on the ISS (i.e. working memory and cognitive processing difficulties) exacerbated adverse impacts associated with communication delays.

The forth subcategory included three themes describing factors that did not contribute to performance and mood-related issues associated with communication delays. The crewmembers indicated the ‘quality of support’ (from the ground support team) was good regardless of experimental condition. In addition the crewmembers mentioned ‘personal issues’ external to the study and the number of crewmembers working on the task, ‘crew-size’ did not impact performance or mood during the study tasks.
5.2.5 Countermeasures

There were 79 comments related to ‘countermeasures’ to mitigate or prevent adverse impacts (41.8% of all comments). These comments were grouped into eight themes, which were further grouped into three subcategories: 1) ‘training-focused’ (18.5% of comments), 2) teamwork-focused’ (15.9% of comments), and 3) ‘technology-focused’ (7.4% of comments).

The first subcategory included three themes related to training-based mitigation and prevention strategies for long duration missions. Within this subcategory, the astronauts most frequently reported that training focused on improving ‘communication skills’ might prevent or mitigate adverse impacts. For example, they said things like, “You want to be very concise and precise, and give options for answers and make sure there is still useful understanding” and, “Announce your call being made or you make your call twice if it’s important, so you’re not forcing the crew member, if they didn’t hear it to call back to say ‘Hey can you say that again’ and that takes another round trip.” In addition, the astronauts suggested increasing ‘task-specific training’ for both crewmembers and the ground support team, and including ‘communication delay-specific training’ in analog training environments on Earth.

The ‘teamwork-focused’ subcategory included two inter-related themes related to team and task coordination. The astronauts suggested efforts should be made to ‘increase crew autonomy’ and ‘reduce back-and-forth communications’ between crewmembers and the ground support team during long duration missions. For example, one astronaut stated, “I think if we fly to Mars we are going to have a spaceship that is more autonomous than the ISS. So you don’t have as much low-level comm. With the ground on each of the steps of the procedures.”

The third subcategory included comments describing tools to prevent or mitigate adverse impacts. Within this subcategory, the astronauts recommended developing a ‘recording tool’ for voice communications, and they suggested implementing ‘text or video-based communications’ for long duration missions. The astronauts reported these strategies provide crewmembers with a physical record of what was said, which may reduce working memory demands (i.e. reduce the need to remember detailed information over long delay periods), and ultimately may reduce back-and-forth communications (i.e. the need to request repeated and/or clarifying communications). In addition, the astronauts indicated the ‘AMO software’ (Frank et al., 2013) helped increase crew autonomy under situations of communication delays.

6.0 INFLUENCE OF MEDIATORS AND MODERATORS OF ASSOCIATION BETWEEN COMMUNICATION DELAY AND PERFORMANCE AND WELL-BEING

6.1 Mediators and Moderators

6.1.1 Task Criticality and Communication Delay

The two-way ANOVA results are summarized in Table 6. Sample means of dependent variables for high and low critical tasks are displayed in Figure 5 below. There was no significant interaction between communication delays and task criticality on individual [F(1,33)=0.090, p=0.766], crew [F(1,33)=0.312, p=0.580], or team (F(1,33)=0.727, p=0.400) performance. Furthermore, there was no significant main effect of task criticality on individual [F(1,33)=1.604, p=0.214], crew [F(1,33)=0.015, p=0.902] and
team \( F(1,33)=0.370, \ p=0.547 \) performance. The sample means are displayed in Figure 5, which demonstrates there was no difference in performance scores between communication delay and control conditions for high or low critical tasks.

TABLE 6. INFLUENCE OF COMMUNICATION DELAYS AND TASK CRITICALITY ON PERFORMANCE, CREW MORALE, COMMUNICATION QUALITY AND TASK AUTONOMY

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Task Criticality</th>
<th>Control</th>
<th>Delay</th>
<th>Two-way ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean ± SD (N)</td>
<td>Mean ± SD (N)</td>
<td>Source</td>
</tr>
<tr>
<td>Individual Performance</td>
<td>Low</td>
<td>7.3 ± 0.8 (6)</td>
<td>7.3 ± 1.3 (11)</td>
<td>A x B</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>6.9 ± 1.6 (14)</td>
<td>6.5 ± 1.5 (6)</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Crew Performance</td>
<td>Low</td>
<td>7.7 ± 1.0 (6)</td>
<td>7.5 ± 1.1 (11)</td>
<td>A x B</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>8.0 ± 1.6 (14)</td>
<td>7.3 ± 1.6 (6)</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Team Performance</td>
<td>Low</td>
<td>7.7 ± 1.0 (6)</td>
<td>7.6 ± 1.2 (11)</td>
<td>A x B</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>7.8 ± 1.3 (14)</td>
<td>6.8 ± 2.0 (6)</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Crew Morale</td>
<td>Low</td>
<td>14.0 ± 1.4 (5)</td>
<td>13.0 ± 1.9 (5)</td>
<td>A x B</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>13.8 ± 1.8 (6)</td>
<td>12.0 ± 3.1 (5)</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B+</td>
</tr>
<tr>
<td>Communication Quality</td>
<td>Low</td>
<td>9.3 ± 1.0 (6)</td>
<td>8.1 ± 0.7 (11)</td>
<td>A x B</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>9.2 ± 1.0 (14)</td>
<td>7.6 ± 1.4 (6)</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B**</td>
</tr>
<tr>
<td>Task Autonomy</td>
<td>Low</td>
<td>20.0 ± 5.5 (5)</td>
<td>20.2 ± 2.6 (5)</td>
<td>A x B</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>17.1 ± 5.7 (7)</td>
<td>15.2 ± 2.9 (5)</td>
<td>A*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
</tr>
</tbody>
</table>

Legend: Two way ANOVA statistics: A = effect of task criticality (low/high); B = effect of experimental condition (control/communication delay); A x B = interactive effect of experimental condition and task criticality (**p<0.050, *p<0.100, +p<0.200).

For crew morale, the interaction between communication delays and task criticality was not significant \( F(1,17)=0.200, \ p=0.660 \), and the main effect of task criticality was not significant \( F(1,17)=0.393, \ p=0.539 \). However, crew morale was lower in communication delay compared to control conditions for both low and high critical tasks (Figure 5).
Figure 5. Associations Between Communication Delays and Task Criticality.

Assessment of a) individual, b) crew and c) team performance, d) crew morale, e) communication quality, and f) task autonomy by ISS crewmembers and ground-based mission support personnel after they performed tasks with or without communication delays that were either critical or not critical. Two-way ANOVA statistics (** p<0.050; * p<0.100, + p<0.200): A, effect of task criticality (low/high); B effect of experimental condition (no communication delay/communication delay). Data are Mean ± SEM (¶ = ISS crewmembers only).

For communication quality, there was no significant interaction between communication delays and task criticality [F(1,33)=0.274, p=0.604], and no significant main effect of task criticality [F(1,33)=0.869, p=0.358]. However, communication quality scores were lower in communication delay compared to control conditions for both low and high critical tasks (Figure 5).

For task autonomy, no significant interaction between communication delays and task criticality was observed [F(1,18)=0.294, p=0.594]. There was however, a trend towards a significant main effect of task criticality [F(1,18)=3.953, p=0.062], where task autonomy scores were lower in high compared to low critical tasks for both control and communication delay conditions (Figure 5).
6.1.2 Task Novelty x Communication Delay

The two-way ANOVA results are summarized in Table 7. Sample means of dependent variables for high and low novel tasks are displayed in Figure 6 below.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Task Novelty</th>
<th>Control Mean ± SD (N)</th>
<th>Delay Mean ± SD (N)</th>
<th>Two-way ANOVA Source</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual</td>
<td>Low</td>
<td>7.3 ± 1.3 (15)</td>
<td>6.9 ± 1.7 (7)</td>
<td>A x B+</td>
<td>2.634</td>
<td>0.114</td>
</tr>
<tr>
<td>Performance</td>
<td>High</td>
<td>6.0 ± 1.0 (5)</td>
<td>7.1 ± 1.3 (10)</td>
<td>A</td>
<td>1.261</td>
<td>0.270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.413</td>
<td>0.525</td>
</tr>
<tr>
<td>Crew Performance</td>
<td>Low^</td>
<td>8.1 ± 1.3 (15)</td>
<td>7.0 ± 1.5 (7)</td>
<td>A x B+</td>
<td>2.332</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>7.4 ± 1.7 (5)</td>
<td>7.8 ± 1.0 (10)</td>
<td>A</td>
<td>0.019</td>
<td>0.890</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.482</td>
<td>0.492</td>
</tr>
<tr>
<td>Team Performance</td>
<td>Low</td>
<td>7.8 ± 1.1 (15)</td>
<td>6.7 ± 1.9 (7)</td>
<td>A x B</td>
<td>1.490</td>
<td>0.231</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>7.6 ± 1.7 (5)</td>
<td>7.7 ± 1.2 (10)</td>
<td>A</td>
<td>0.654</td>
<td>0.424</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>1.029</td>
<td>0.318</td>
</tr>
<tr>
<td>Crew Morale</td>
<td>Low</td>
<td>14.1 ± 1.6 (7)</td>
<td>12.7 ± 2.0 (6)</td>
<td>A x B</td>
<td>0.014</td>
<td>0.908</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>13.5 ± 1.7 (4)</td>
<td>12.3 ± 3.4 (4)</td>
<td>A</td>
<td>0.302</td>
<td>0.589</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B^</td>
<td>2.002</td>
<td>0.175</td>
</tr>
<tr>
<td>Communication</td>
<td>Low #</td>
<td>9.4 ± 0.9 (15)</td>
<td>7.6 ± 1.3 (7)</td>
<td>A x B+</td>
<td>3.666</td>
<td>0.064</td>
</tr>
<tr>
<td>Quality</td>
<td>High</td>
<td>8.6 ± 0.9 (5)</td>
<td>8.1 ± 0.7 (10)</td>
<td>A</td>
<td>0.325</td>
<td>0.573</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B**</td>
<td>11.461</td>
<td>0.002</td>
</tr>
<tr>
<td>Task Autonomy</td>
<td>Low</td>
<td>18.1 ± 5.9 (8)</td>
<td>17.7 ± 4.7 (6)</td>
<td>A x B</td>
<td>0.014</td>
<td>0.906</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>18.8 ± 5.7 (4)</td>
<td>17.8 ± 2.2 (4)</td>
<td>A</td>
<td>0.025</td>
<td>0.877</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.104</td>
<td>0.750</td>
</tr>
</tbody>
</table>

Legend: Two way ANOVA statistics: A = effect of task novelty (low/high); B = effect of experimental condition (control/communication delay); A x B = interactive effect of experimental condition and task novelty (*p<0.050, **p<0.100, ***p<0.200). Independent pairwise comparisons of communication delay versus control at each level of task novelty were conducted to assess the simple main effect of communication delays for any statistical interaction (or trend; #p <0.050; ^p<0.100).
There was a trend towards an interaction between communication delays and task novelty on individual performance \([F(1,33)=2.634, p=0.114]\). Contrary to expectations, individual performance decreased in communication delay compared to control conditions for low novel tasks, but improved in communication delay compared to control conditions for high novel tasks (Figure 6).

![Figure 6. Associations Between Communication Delays and Task Novelty.](image)

Assessment of a) individual, b) crew and c) team performance, d) crew morale, e) communication quality, and f) task autonomy by ISS crewmembers and ground-based mission support personnel after they performed tasks with or without communication delays that were either novel or not novel. Two-way ANOVA statistics \((^*p<0.100, ^+p<0.200)\): A, effect of task novelty (low/high); B, effect of experimental condition (control/communication delay); A x B, interactive effect of task novelty and experimental condition. Independent pairwise comparisons of communication delay versus control at each level of task novelty were conducted to assess the simple main effect of communication delays for any statistical interaction (or trend; \(^#p <0.050; ^\Delta p<0.100\)). Data are Mean ± SEM (= ISS crewmembers only).

There was also a trend towards a significant interaction between communication delays and task novelty on crew performance \([F(1,33)=2.332, p=0.136]\). Follow-up analysis revealed the interaction was primarily due to decreased crew performance in communication delay compared to control conditions in low \((p=0.093)\), but not high \((p=0.591)\) novel tasks (Figure 6). For team performance, there was no significant interaction between communication delays and task novelty \([F(1,33)=1.490, p=0.231]\), and no significant main effect of task novelty \([F(1,33)=0.654, p=0.424]\). However, visual inspection of the data suggests team performance, like crew performance, decreased in communication delay compared to control conditions for low, but not high novel tasks.
For crew morale, the interaction between communication delays and task novelty was not significant \[F(1,17)=0.014, \, p=0.908\], and main effect of task novelty was not significant\[F(1,17)=0.302, \, p=0.589\]. However, morale was lower in communication delay compared to control conditions for both low and high novel tasks (Figure 6).

For communication quality, there was a trend towards a significant interaction between communication delays and task novelty \[F(1,33)=3.666, \, p=0.064\]. Follow-up analysis revealed the interaction was primarily due to decreased communication quality in low \(p<0.001\), but not high \(p=0.345\) novel tasks (Figure 6).

For task autonomy, a two-way ANOVA revealed no significant interactive effect of communication delays and task novelty \[F(1,18)=0.014, \, p=0.906\], and no significant main effect of task novelty \[F(1,18)=0.025, \, p=0.877\].

### 6.1.3 Task-Related Communication Demands

The ANOVA results are summarized in Table 8. Sample means of dependent variables for high and low critical tasks are displayed in Figure 7 below. The interaction between communication delays and task-related communication demands on individual performance was not significant \[F(1,33)=0.141, \, p=0.710\]. There was however, a trend towards a significant main effect of task related communication demands on individual performance \[F(1,33)=2.995, \, p=0.093\]. The sample means are displayed in Figure 7, which demonstrates individual performance scores decreased in tasks that required high compared to low task-related communication demands, regardless of experimental condition (communication delay or control). Furthermore, there was a trend towards an interaction between communication delays and task-related communication demands on both crew \[F(1,33)=3.253, \, p=0.080\] and team \[F(1,33)=2.453, \, p=0.127\] performance. Follow-up analyses revealed these interactions were primarily due to decreased performance scores in communication delay compared to control conditions when tasks required high (crew performance \(p=0.064\); team performance \(p=0.081\), but not low (crew \(p=0.454\), team \(p =0.592\) task-related communication demands (Figure 7).
TABLE 8. INFLUENCE OF COMMUNICATION DELAYS AND TASK-RELATED COMMUNICATION DEMANDS ON PERFORMANCE, CREW MORALE, COMMUNICATION QUALITY AND TASK AUTONOMY

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Task Criticality</th>
<th>Control Mean ± SD (N)</th>
<th>Delay Mean ± SD (N)</th>
<th>Two-way ANOVA</th>
<th>Source</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A x B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Individual Performance</td>
<td>Low</td>
<td>7.4 ± 1.1 (8)</td>
<td>7.6 ± 1.4 (7)</td>
<td>A x B</td>
<td>0.141</td>
<td>0.710</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>6.8 ± 1.5 (12)</td>
<td>6.6 ± 1.4 (10)</td>
<td>A</td>
<td>2.995</td>
<td>0.093</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.003</td>
<td>0.960</td>
</tr>
<tr>
<td>Crew Performance</td>
<td>Low</td>
<td>7.6 ± 1.2 (8)</td>
<td>8.1 ± 1.2 (7)</td>
<td>A x B</td>
<td>3.253</td>
<td>0.080</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>8.1 ± 1.6 (12)</td>
<td>7.0 ± 1.2 (10)</td>
<td>A</td>
<td>0.594</td>
<td>0.446</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.406</td>
<td>0.529</td>
</tr>
<tr>
<td>Team Performance</td>
<td>Low</td>
<td>7.6 ± 1.2 (8)</td>
<td>8.0 ± 1.3 (7)</td>
<td>A x B</td>
<td>2.453</td>
<td>0.127</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>7.8 ± 1.3 (12)</td>
<td>6.8 ± 1.5 (10)</td>
<td>A</td>
<td>1.216</td>
<td>0.278</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.536</td>
<td>0.469</td>
</tr>
<tr>
<td>Crew Morale</td>
<td>Low</td>
<td>13.7 ± 1.7 (7)</td>
<td>12.4 ± 2.9 (5)</td>
<td>A x B</td>
<td>0.031</td>
<td>0.863</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>14.3 ± 1.5 (4)</td>
<td>12.6 ± 2.3 (5)</td>
<td>A</td>
<td>0.148</td>
<td>0.706</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>2.398</td>
<td>0.140</td>
</tr>
<tr>
<td>Communication Quality</td>
<td>Low</td>
<td>9.3 ± 1.0 (8)</td>
<td>8.6 ± 1.0 (7)</td>
<td>A x B</td>
<td>3.093</td>
<td>0.088</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>9.2 ± 0.9 (12)</td>
<td>7.5 ± 0.8 (10)</td>
<td>A</td>
<td>3.412</td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B**</td>
<td>15.530</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Task Autonomy</td>
<td>Low</td>
<td>17.9 ±5.8 (7)</td>
<td>20.0 ± 3.2 (5)</td>
<td>A x B</td>
<td>1.958</td>
<td>0.179</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>19.0 ± 5.8 (5)</td>
<td>15.4 ± 2.7 (5)</td>
<td>A</td>
<td>0.710</td>
<td>0.411</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.126</td>
<td>0.727</td>
</tr>
</tbody>
</table>

Legend: Two-way ANOVA statistics: A = effect of task-related communication demands (low/high); B = effect of experimental condition (control/communication delay); A x B = interactive effect of experimental condition and task-related communication demands ("p<0.050, "p<0.100, *p<0.200). Independent pairwise comparisons of communication delay versus control at each level of task-related communication demands were conducted to assess the simple main effect of communication delays for any statistical interaction (or trend; "p <0.050; "p<0.100).

For crew morale, there was no significant interaction between communication delays and task-related communication demands [F(1,17)=0.031, p=0.863], and no significant main effect of task-related communication demands [F(1,17)=0.148, p=0.706]. However, crew morale scores were lower in communication delay compared to control conditions regardless of task-related communication demands (Figure 7).
Figure 7. Associations Between Communication Delays and Task-Related Communication Demands.

Assessment of a) individual, b) crew and c) team performance, d) crew morale, e) communication quality, and f) task autonomy by ISS crewmembers and ground-based mission support personnel after they performed tasks with or without communication delays that required either a high or low level of task-related communications. Two-way ANOVA statistics (*p<0.100, †p<0.200): A, effect of task-related communication demands (low/high); B, effect of experimental condition (control/communication delay); A x B, interactive effect of task-related communication demands and experimental condition. Independent pairwise comparisons of communication delay versus control at each level of task-related communication demands were conducted to assess the simple main effect of communication delays for any statistical interaction (or trend; #p <0.050; ∆p<0.100). Data are Mean ± SEM (¶ = ISS crewmembers only).

For communication quality, there was a trend towards a significant interaction between communication delays and task-related communication demands [F(1,33)=3.093, p=0.088]. Follow-up analysis revealed the interaction was primarily due to decreased communication quality scores in communication delay compared to control conditions when tasks required high (p<0.001), but not low (p=0.166) task-related communication demands (Figure 7).

There was also a trend towards an interaction between communication delays and task-related communication demands on task autonomy [F(1,18)=1.958, p=0.179]. Task autonomy decreased in communication delay compared to control conditions when tasks required high task-related communication demands, but increased in communication delay compared to control conditions when tasks required low task-related communication demands (Figure 7).
6.2 Communication Quality as a Mediator of the Association between Communication Delay and Performance and Well-Being Outcomes

As noted above, delays in communication were significantly associated with the two well-being measures of crew morale and individual stress. These delays were also associated with communication quality but not with task autonomy. Communication quality, in turn, was significantly associated with both individual stress and crew morale (Table 9).

<table>
<thead>
<tr>
<th>Correlation Analysis</th>
<th>Comm Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Understood others</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
</tr>
<tr>
<td>Self (N=34)</td>
<td>0.23*</td>
</tr>
<tr>
<td>Crew (N=34)</td>
<td>0.41***</td>
</tr>
<tr>
<td>Team (N=34)</td>
<td>0.34**</td>
</tr>
<tr>
<td>Total (N=34)</td>
<td>0.35**</td>
</tr>
<tr>
<td>Well-being¶</td>
<td></td>
</tr>
<tr>
<td>Self: Stress/frustration (N=23)</td>
<td>-0.56***</td>
</tr>
<tr>
<td>Crew: Crew morale (N=19)</td>
<td>0.32*</td>
</tr>
</tbody>
</table>

As each of the graphs in Figure 8 indicates, while communication delays are significantly associated with communication quality, and communication quality is significantly associated with the three performance outcomes and the two well-being outcomes, there is no independent association between communications delay and any of the aforementioned outcomes. However, there are significant associations between communication delays and communication quality and between communication quality and each of the five outcome variables. Consequently, communication quality may mediate the association between communications delay and performance and well-being.
Figure 8. Associations Between Communication Delay, Communication Quality, and Performance and Well-Being

7.0 DISCUSSION

7.1 Study Feasibility and Acceptability

Research on behavioral and performance issues such the impacts on delays in communication to and from earth that likely to occur during long-duration missions has relied extensively on earth-based analog environments (Institute of Medicine, 2001; National Research Council, 1998; Palinkas, Gunderson, Johnson, & Holland, 2000). Although the ISS has long been viewed as a high fidelity analog to such missions in comparison, the feasibility of conducting such research on the ISS 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 (Institute of Medicine, 2001; Institute of Medicine and National Research Council, 2006; National Research Council, 1998). The results of this study suggest that such research is both feasible and acceptable to potential study subjects.
Assessing the impacts of communication delays aboard the ISS on distributed space teams 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 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 (Palinkas et al., 2005). 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 post-task information on mood and performance from study participants. Study participants were in agreement as to importance of study, and there was little difficulty with recruitment. However, prior to conducting the study there were a number of concerns expressed by FOD (MOD at time of the study) and the AO that resulted in significant challenges to utilizing the ISS as a research platform. To start, 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 may 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 met study criteria and were acceptable to MOD, 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 well-being of the study participants. 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, as noted earlier, 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. Consequently, data on certain moderating influences of communications delay on behavior and performance, such as personality, stress and social support, was limited. The astronauts corroborated the AO’s concerns about standardized formats during the post-mission 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, post-task assessments were completed and returned by the participants 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 (Stuster, 2010).

7.2 Impacts of Communications Delays on Performance and Well-Being

Although the impacts of delayed and asynchronous communication likely to occur during long-duration missions in space have been documented in earth-bound analog environments, this is the first study of such impacts using the ISS. The quantitative results suggest crew morale and the quality of communications were significantly reduced in communication delay tasks compared to control tasks. In addition, both quantitative and qualitative data suggest communication delays increased stress and frustration. However, no significant differences in individual, crew or team performance or autonomy were observed across control and delay tasks. The qualitative data expanded on these findings. The astronauts reported the quality of support from the ground support team was good regardless of whether or not there were communication delays. Furthermore, the performance-related challenges that were reported under situations of communication delays were not explicitly linked to individual or team failures, but rather involved operational outcomes and teamwork processes, such as reduced task efficiency and decreased situational awareness. Given these findings, future studies should consider including post-task questions that assess efficiency and team/task coordination issues.

Apart from the small sample size, the lack of a statistically significant association between communications delay and performance aboard the ISS may be attributed to a number of factors. For instance, the 50-second duration of the delay in communications may have been insufficient to detect meaningful and statistically significant differences in performance. Other studies of the impact of communication delays that have documented such differences have ranged from 5 to 20 minutes (Vessey, Palinkas, & Leveton, 2013). Reliance on single items to assess performance and concerns about the implications of assessment of one’s own performance and the performance of other team members is another potential explanation for the lack of significant differences between the two experimental conditions (National Research Council, 1998). The limited number of study tasks and inability to implement a cross-over design as originally proposed may have also limited the power to detect significant associations.

Qualitative data from post-mission interviews also identified factors that contributed to performance and mood-related challenges of communication delays, including task-specific factors such as high task-related communication demands (either due to low crew autonomy or poor communication strategies), complex tasks, and time-critical tasks. The astronauts reported communication delays interfered with the crewmembers ability to receive the support they needed in a timely fashion, which in turn made it difficult to move forward with the task procedures, and importantly these challenges were amplified in tasks that involved high levels of back-and-forth communications. Given these findings, and the limited availability of crewmember time on the ISS, future studies should prioritize research time on the ISS to include tasks that are most likely to negatively impact individual and team outcomes.

Interestingly, a few positive outcomes of communication delays were reported during the post-mission interviews, including increased ISS teamwork and communication. It is important to note astronauts were not specifically asked about positive outcomes, so this does not reflect an
extensive list. Nevertheless, these findings suggest crewmembers adapted to the constraints of their environment in an effort to mitigate or prevent adverse impacts associated with communication delays. Future studies should further explore these positive outcomes.

Furthermore, three types of countermeasures were identified to mitigate or prevent adverse impacts. The astronauts suggested training-focused countermeasures designed to increase task knowledge and facilitate team communication may improve team and task coordination under situations of communication delays, which, in turn, may improve the quality of communications, task efficiency and situational awareness, and decrease stress and frustration. In addition, although task autonomy was not associated with communications delay in the quantitative analyses, the astronauts suggested crewmembers will need to be more autonomous from the ground support team during deep space missions, and efforts should be made to reduce back-and-forth communications. Specifically, they suggested revising task procedures so crewmembers are not required to check in with the ground support team after each step of a procedure. Lastly, a number of tools designed to reduce task-related communication demands and facilitate crew autonomy were identified.

7.3 Influence of Mediators and Moderators of Association Between Communication Delay and Performance and Well-Being

Results from this study suggest task novelty may moderate the relationships between communication delays and individual and crew performance, and communication quality. However, contrary to our expectations, the inverse relationships between communication delays and crew performance and communication quality were stronger in low compared to high novel tasks. Furthermore, there was a trend for individual performance to improve in communication delay compared to control conditions in high novel tasks. In low novel tasks, participants may have assumed a shared situational model was established, and thus, in the absence of any formal communication delay training, may have inappropriately used minimal or ambiguous responses while performing the task. For example, one crewmember described his experience performing a standard weekly cleaning activity (low novel) with a communication delay, “So you call down and you ask them (mission support team) to disable smoke detection, and then you kind of forget that you even called…And then a minute later a call comes up and just says, OK, smoke detection has been disabled. And the crew is like, well I don’t know, is it Node 1, is it Node 3, what did we even call for?” On the other hand, team members may have been more engaged in and complete with their communications while performing highly novel tasks, and this proactive approach may have mitigated potential adverse impacts. Furthermore, qualitative feedback from the ISS crewmembers indicated detailed task procedures were provided for some of the high novel tasks. For example, one crewmember stated, “For each complicated step, we had short videos imbedded in the procedures to help us. I think those were critical to our overall execution of the task.” Accordingly, detailed task procedures may mitigate or prevent adverse impacts of communication delays on individual and team outcomes during deep space explorations.

In contrast, task criticality did not moderate the relationship between communication delays and performance, crew morale, communication quality or task autonomy in the current study. There was however, a trend towards a main effect of task criticality on task autonomy, suggesting ISS crewmembers felt they had more autonomy when they performed low compared to high critical tasks. Apart from the small sample size, the lack of a statistically significant
interaction between communication delays and task criticality may be attributed to a number of factors, including the short communication delay interval, the type and number of tasks studied, and/or the format and number of survey items administered.

Since qualitative data suggested high task-related communication demands contributed to adverse impacts of communication delays, exploratory analyses were conducted to explore whether these relationships were also observed in the quantitative data. Results from this study suggest task-related communication demands may moderate the relationships between communication delays and individual and team outcomes. Specifically, the inverse association between communication delays and crew and team performance, and communication quality was stronger when tasks required high compared to low task-related communication demands. Furthermore, task autonomy decreased in communication delay compared to control conditions when tasks involved a high, but not low level of task-related communication demands. Collectively, the qualitative and quantitative data suggest communication delays were more likely to negatively impact individual and team outcomes when tasks involve high levels of task-related communication, accordingly countermeasures that reduce back-and-forth communications, either by increasing crew autonomy or improving communication strategies, may mitigate or prevent adverse impacts.

7.4 Study Limitations

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 participants 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, semi-structured interviews were not conducted with mission support team members, thereby limiting the qualitative analysis to the comments from the crewmembers on the ISS. 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, semi-structured interviews were not conducted with FOD (MOD at time of the study) or AO 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 increments 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 (Institute of Medicine and National Research Council, 2006).

With respect to the assessment of the impact on communication delays on performance and well-being, the current study was limited in terms of the number and type of tasks included. It was a challenge to identify a sufficient number of tasks that were both acceptable and met the study criteria, thereby making it difficult to generalize the study findings to a wide range of tasks. Second, the small sample of participants limits the ability to generalize to other astronauts, other ISS increments, and other mission support personnel that are engaged in performance of other tasks. Given the small sample size, the quantitative analysis was intended to provide preliminary insight into the impacts of communication delays across the entire distributed team.
A larger sample may provide the opportunity to examine individual and/or group differences in the outcome measures across the different task conditions. Third, there were a high number of missing responses for the open-ended individual well-being item included in the post-task questionnaire, particularly for ISS crewmembers, thereby limiting the generalizability of the results, and making it difficult to include this outcome in post-hoc interaction analyses. Future studies will need to emphasize the importance of completing all open-ended items. Fourth, similar semi-structured post-mission interviews with astronaut participants were not conducted with the mission support team, thereby limiting the qualitative analysis to the comments from the crewmembers on the ISS. The quantification of qualitative data was intended merely for description of frequency of occurrence of certain topics and not for quantitative hypothesis. Again, 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 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.

8.0 CONCLUSIONS

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.

Findings from this study also provide important insights into the impacts of delayed communication on the ISS. Importantly, these findings are consistent with previously published research. For example, previous work also demonstrates communication delays adversely impact task efficiency, communication quality, and situational awareness in simulated space tasks and in analog space environments on Earth (Fischer & Mosier, 2014; Love & Reagan, 2013). With regards to countermeasures, previous research also suggests crewmembers will need to be more autonomous from mission control during long duration space missions (Frank et al., 2013; Kanas et al., 2010). In addition, recently published work supports the use of training measures focused on improving communication skills and adapting communications strategies to mitigate adverse impacts (Fischer et al., 2013). Furthermore, text-based communications and autonomous mission operation tools have also been shown to improve outcomes under situations of communication delays (Frank et al., 2013).

Overall, these data suggest communication delays impacted operational outcomes (i.e. task efficiency), teamwork processes (i.e. team coordination/cohesion), and individual well-being (i.e. stress/frustration), especially when tasks involved a high level of back-and-forth communications. Training, teamwork and technology-focused countermeasures that increase crew autonomy and decrease task-related communication demand may help prevent or mitigate adverse impacts. Future studies should build upon this work by examining more subjects, including more communication delay tasks and scenarios, and conducting post-mission interviews with ground support personnel. 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.

9.0 ACKNOWLEDGMENTS

This protocol for using the ISS to assess communication delay was adapted and informed by an earlier protocol developed largely by Dr. Kathryn E. Keeton who was the originator of the study and served as the Principal Investigator through November 2011. In addition, we would like to acknowledge and thank Erik Hougland and Daniel Garcia for coordinating the ISS science integration and for their assistance with subject recruitment, and Stephen Gibson and David Korth for their assistance coordinating with Flight Operations to implement the study.
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<tr>
<th>ACRONYMS</th>
<th>Description</th>
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<tbody>
<tr>
<td>AMO</td>
<td>Autonomous Mission Operations</td>
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<tr>
<td>ANOVA</td>
<td>Analyses of Variance</td>
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<td>AO</td>
<td>Astronaut Office</td>
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<td>AOS</td>
<td>Acquisition of Signal</td>
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<td>BHP</td>
<td>Behavioral Health and Performance Element</td>
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<tr>
<td>CAPCOM</td>
<td>Capsule Communicator</td>
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<tr>
<td>DRP</td>
<td>Directed Research Project</td>
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<tr>
<td>FOD</td>
<td>Flight Operations Directorate</td>
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<tr>
<td>HRP</td>
<td>Human Research Program</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<td>ISS</td>
<td>International Space Station</td>
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<td>Mission Control Center</td>
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<td>NEO</td>
<td>Near Earth Object</td>
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<td>NASA Research Announcement</td>
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<td>Positive and Negative Affect Scale</td>
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<td>Perceived Stress Scale</td>
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<td>Subject Matter Experts</td>
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<td>USOS</td>
<td>United States On-orbit Segment</td>
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Assessing the Impact of Communication Delay on Behavioral Health and Performance: An Examination of Autonomous Operations Utilizing the International Space Station

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ABSTRACT (Maximum 200 words)
The Behavioral Health and Performance Element (BHP) of the NASA Human Research Program (HRP) conducted a research study to examine the impact of implementing experimental communication delays to-and-from the International Space Station (ISS) on individual and team factors and outcomes, including performance, well-being and related perceptions of autonomy and communication quality. To date, very few studies have observed teams in remote environments that perform without communication with management teams (e.g., mission control), and no such studies have been conducted during long-duration expeditions or missions. This study addressed the operationally-constrained criterion of a HRP Directed Research Project (DRP) and was a time-constrained requirement as we: 1) utilized an available ISS Increment to implement this study, 2) incorporated the results of this study to identify future near-term research tasks that relate to autonomy and what countermeasures will be needed to adequately prepare for autonomous long duration missions, and 3) guided future NASA Research Announcement (NRA) calls based on the conclusions that are drawn from this study that will address and close research gaps (including Team Gaps 1, 6, and 7 as well as inform BMed Gaps 1 and 2).

SUBJECT TERMS
long duration spaceflight; behavioral health; performance; communication delay