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Assessment of the State of Communication Delay Research in Preparation for Missions Beyond Low Earth Orbit

Lauren B. Landon
KBR

John A. Karasinski
NASA Ames Research Center

Linda G. Morissette
KBR

Kaitlin R. McTigue
NASA Ames Research Center

Megan E. Parisi
NASA Ames Research Center

Shu-Chieh Wu
San Jose State University

Tina L. Panontin
San Jose State University

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Tina L. Panontin
San Jose State University

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California

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NASA Langley Research Center
Hampton, VA 23681-2199

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Acronyms and Definitions

AI	artificial intelligence
BASALT	Biologic Analog Science Associated with Lava Terrains
BLEO	beyond low-Earth orbit
BMed	Behavioral Medicine
CAPCOM	capsule communication
CHAPEA	Crew Health and Performance Exploration Analog
CHP	crew health and performance
CHPO	Crew Health and Performance Officer
D-RATS	Desert Research and Technology Studies
DAG	Directed Acyclic Graph
DSH	Deep Space Habitat
DSN	Deep Space Network
EIHSO	Earth Independent Human-Systems Operation
EVA	extravehicular activity
FCT	Flight Control Team
FOD	Flight Operations Directorate
HERA	Human Exploration Research Analog
HLS	Human Landing System
HSIA	Human-Systems Integration Architecture
HSRB	Human System Risk Board
ICE	isolated, confined, and extreme
IRB	Institutional Review Board
ISS	International Space Station
IVA	intravehicular activity
LEO	low-Earth orbit
MATB	Multi-Attribute Task Battery
MCC	Mission Control Center
MCC-H	Mission Control Center Houston
MSC	Mission Support Center
MTS	multiteam systems
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
NEK	Nezemnyy Eksperimental'nyy Kompleks
NEO	near-Earth object
OPE-L	Onboard Proficiency Enhancer-Light
PFC	Private Family Conference
PPC	Private Psychological Conference
RG	remote guidance
s	second
SIRIUS	Scientific International Research in Unique Terrestrial Station
SME	subject matter expert

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Executive Summary

On missions beyond low-Earth orbit (LEO), communication delays will challenge the traditional mission operations paradigm, reducing ground support and increasing the need for crew autonomy. Communication delays have been known to negatively impact crew behavioral health and performance and to affect the coordination and cohesion of the space-to-ground team. However, research remains to be done to comprehensively assess the issues associated with communication delays and what is needed to overcome them. Our literature review surveyed evidence generated through 20 years of communication delay research to build a picture of what has been studied and how, and to identify gaps in the evidence base that threaten upcoming mission priorities. The gap in studies of short communication delays (i.e., 3 to 14 seconds one-way) possible on lunar missions is of particular interest. We also interviewed subject matter experts, including Flight Operations Personnel, former analog (e.g., Human Exploration Research Analog [HERA]; Crew Health and Performance Exploration Analog [CHAPEA]) crewmembers, and researchers who study communication delay to identify knowledge gaps and research priorities for upcoming analog missions. Our analysis reveals a general lack of fidelity in studies of mission-critical tasks, including problem solving, emergency response, maintenance, and complex procedure execution—likely due to the prioritization of safety and mission objectives in analog missions. There remains a pressing need to study the impact of different delays in combination with specific tasks, contexts, and environments to adequately characterize the risk of reduced ground support for missions to the Moon and Mars. Countermeasures, including training specific to communication delay and tools to facilitate asynchronous collaboration, that may mitigate the impact of communication delay need to be designed and evaluated for specific contexts (i.e., chatting with family vs. getting a briefing from the ground on a maintenance procedure).

[1] KBR.
[2] NASA Ames Research Center; Moffett Field, California.
[3] San Jose State University; San Jose, California.

1. Introduction

National Aeronautics and Space Administration's (NASA) mission-operations paradigm, established during Project Mercury and minimally evolving through the Apollo Program, Space Shuttle Program, and International Space Station (ISS) missions, has largely depended on real-time support from a team of experts on the ground. This ground team has served as the safety net for crewed spaceflight missions over the past 60 years, managing the combined state of the mission, vehicle, and crew. However, this operational paradigm, which has seen little change in its Human-Systems Integration Architecture (HSIA), will face challenges during long-duration exploration missions beyond low Earth orbit. In deep-space crewed missions, the crew will be confronted with infrequent resupply opportunities, no viable options for evacuation or rescue, and high-latency communications prohibiting real-time operational and medical support. Due to the great distances from Earth and the communication architectures involved, lunar missions may experience one-way communication latencies ranging from 3 to 14 seconds, while Mars missions will encounter up to 22-minute one-way (44-minute round-trip) delay at maximum distance from Earth.

NASA's Human Systems Risk Board has identified and assessed the risk associated with reduced ground support and the necessary shift towards more Earth-independent operations. Retrospective analyses of spaceflight anomalies reveal a persistent and significant rate of unanticipated anomaly occurrence (e.g., 1.7/year for ISS). Qualitative causal modeling using a Directed Acyclic Graph (DAG) was employed to assess the consequences of this risk and shows that catastrophic outcomes, such as Loss of Crew, are possible when onboard support is insufficient to mitigate the risk resulting from having reduced ground support as the distance from Earth increases. Given the high likelihood of the Earth Independent Human-Systems Operation (EIHSO) risk (formerly known as the HSIA risk) and its severe consequences, it is assessed as "red" for extended missions on the lunar surface and Mars.

Table 1 shows the estimated latencies for Artemis II-IV, the path of which begins in Orion and ends with flight controllers in Mission Control Center Houston (MCC-H) (or vice versa), as transmitted via the Deep Space Network (DSN), as well as latencies during Apollo missions. Major uncertainties that may increase this latency for future crewed operations include additional optical communications, encryption/decryption durations, and additional paths due to Human Landing System (HLS) and other surface vehicles. Additionally, this delay will not be constant (as seen in Table 1) and will instead vary based on the type of data being transmitted, relative position of the spacecraft and MCC, and which ground station is being used. As of 2024, expected Artemis latencies are twice as long as Apollo, with worst case values up to five times as long as those experienced during Apollo (Flight Operations Directorate Systems Engineer, personal communication, 2024; Keeports, 2006).

<table>
<tr><th colspan="4">Table 1. One-Way Lunar Latency Estimates</th></tr>
<tr><th rowspan="2"></th><th colspan="3">One-way Latency (seconds)</th></tr>
<tr><th>Apollo</th><th>Nominal Orion</th><th>Worst Case Orion</th></tr>
<tr><td>Command</td><td rowspan="3">1.3</td><td>2.7</td><td>3.9</td></tr>
<tr><td>Telemetry</td><td>5.9</td><td>8.6</td></tr>
<tr><td>Voice and Video</td><td>5.6</td><td>6.5</td></tr>
</table>

Understanding the impact of communication delays on executing complex operations and problem solving is key to characterizing and mitigating the risk introduced by reduced ground support. Real-time communication allows the crew to rely on a large, extensively resourced ground team to oversee and direct operations and diagnose and resolve issues. However, as communication delays increase, these responsibilities must increasingly shift to the onboard team, as illustrated notionally in Figure 1. Incremental increases in communication delay will require the onboard crew to gradually assume roles historically filled by the ground team.

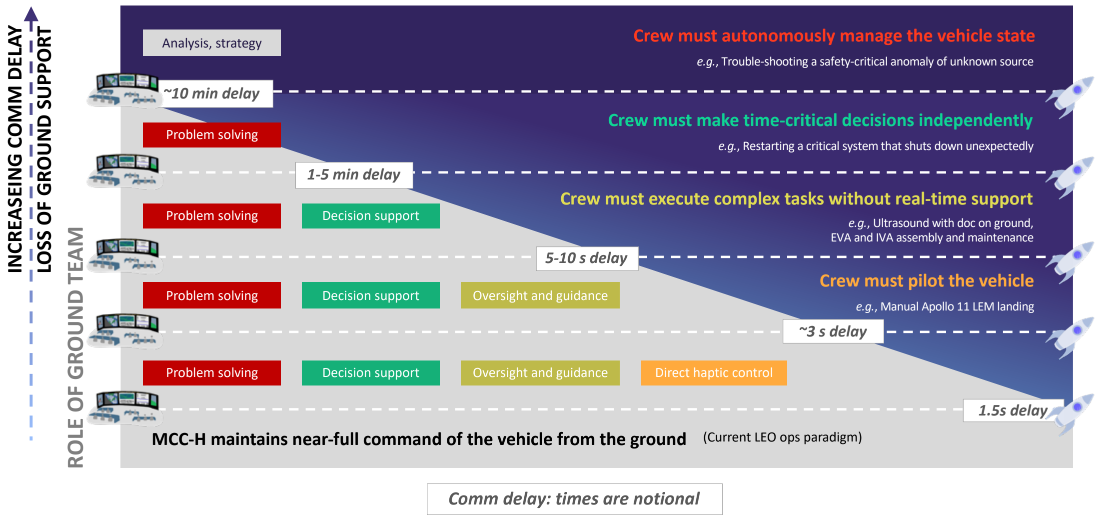


Figure 1. Ground-to-onboard shift of responsibility for critical operations with increasing distance from Earth. Note that non-time-critical and/or longer-term strategic problems that can be worked at a pace that allows interaction with the ground will likely remain ground-led.

In addition to their effects on complex operations, communication delays also negatively impact the behavioral health and performance of individuals and crews operating across the multi-team space-to-ground system. Previous research indicates that increased isolation and the challenges posed by delayed communication led to heightened stress, frustration, adverse behavioral symptoms, and reduced individual performance (Landon et al., 2015). Additionally, family connectedness and satisfaction with interpersonal relationships decline in such environments. At the team and multi-team levels, communication delays undermine shared understanding, team coordination, performance, and cohesion between space and ground teams. The crew experiences greater isolation, compounded by an increased workload and interpersonal friction within the high-tempo environment.

The purpose of this work was to examine the evidence from 20 years of research on communication delays to comprehensively assess the issues associated with communication latencies, integrating findings across Behavioral Medicine (BMed), Team, and EIHSO Risks. Reviewing the published literature contributed to a coherent understanding of what has been studied, how it has been approached, and the outcomes measured. Additional perspectives were gained from interviews with the research participants and researchers themselves. The study also sought programmatic perspectives (e.g., Orion) on communication latencies and ongoing efforts to mitigate these challenges.

2. Approach

2.1. Literature Search

The process through which we gathered communication delay research for review is detailed in Figure A1 in the Appendix. First, we formed a search term seed set drawing from languages used in two papers representative of the previous state of knowledge (Love & Reagan, 2013; Rader & Reagan, 2013) and supplemented it with additional search terms to cover other topics of interest and variations in language usage. We then conducted literature searches using those search terms in Google Scholar, PubMed, and Web of Science. Because search returns from the initial broad sweep revealed that much of the research on communication delays was done in analog settings, we then conducted additional targeted searches for research output from analog missions, drawing candidate analogs and habitats from a comprehensive review by Heinicke et al. (2021). We also searched NASA project archives for output from NASA-sponsored research. This search process yielded close to 150 papers. From this set, we retained research papers from journals and conference proceedings with clear descriptions of the method and results and applied the exclusion criteria listed in Figure A1 in the Appendix. The resulting set included 48 research papers, see Figure 2 below.

These papers were coded using the taxonomy described in the next section. As some papers included the results of multiple studies (i.e., research experiments), the 48 papers yielded 52 studies. After this coding was complete, multiple research team members cross-checked each study's coding to ensure alignment. Finally, we removed studies that did not (1) manipulate communication delay as an independent variable and (2) report or discuss the effects of the delay; this culling resulted in a final set of 15 studies. (For example, many studies we coded took place in analogs and involved participants subjected to communication delay with others outside the habitat. However, most of these studies focused on the effects of isolation and confinement, and their results were based on the number of days their participants were isolated, not the impact of the communication delay itself.) In the results section below, we refer to the set of 52 studies as “all coded” studies and the subset of 15 studies as “communication delay focused” studies.

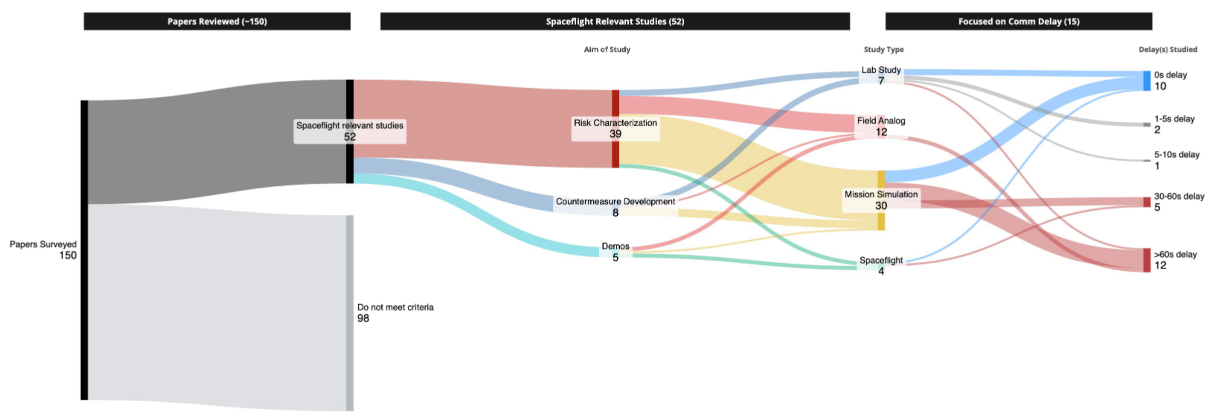


Figure 2. Literature review process. The search process yielded close to 150 papers, which we narrowed down to 48 research papers including 52 spaceflight-relevant studies for coding. Our coding process resulted in a final set of “communication delay focused” 15 studies.

2.2. Literature Coding Taxonomy

We developed a taxonomy tailored to the key constructs of interest for the EIHSO, Team, and BMed to analyze the relevant literature gathered. Topics for coding were iteratively determined and defined using subject matter expertise. Instructions for coding each topic were included in the taxonomy. Throughout the development process, we selected papers for "preliminary coding," during which we tested the effectiveness of the taxonomy instructions, making edits for clarity as needed. These papers were then coded again once the taxonomy was finalized.

This process resulted in 140 topic items grouped into seven high-level categories of interest, including setting/analog meta-data, work/task activities, recreation activities, individual outcomes and predictors, team outcomes and predictors, multi-level support team outcomes and predictors, and measures.

After taxonomy development, one reviewer read and coded identified papers (though the same reviewer did not code each paper). After this initial set of reviews, data were analyzed to assess what topics yielded results. A single reviewer then read the results for these topics and standardized responses. This process led to the dataset being analyzed in the Results section. Because many of the papers reviewed were outputs of mission campaigns, we additionally surveyed analog mission conditions. We linked these conditions with papers from the same analog and mission/campaign. This process allowed us to include data not specified in the paper (e.g., crew member nationalities) in the analysis. These analog mission parameters themselves are also potential data for further analysis.

3. Results

3.1. Literature Review Coding Results

We coded the 52 spaceflight-relevant studies on a variety of aspects. Here, we first consider an overview of the coded literature to provide a landscape of the review, then focus on the subset of studies that evaluated the effects of communication delay on an outcome measure. We provide qualitative and descriptive analysis for the communication delay focused studies, as there is an insufficient agreement in study designs (i.e., communication latency, task types) or outcome measures to allow for a quantitative meta-analysis of the literature. Among those selected for analysis, we focus on the Communication Latency, Study Aim, Study Type, Task Type, and the prevalence of Outcome Measures.

Table 2 and Figure 3 describe the communication delays in the studies. Table 2 also shows the breakdown of communication delays in all coded studies and those identified as being focused on communication delays. Figure 3 visualizes the communication delays present in each study. The one-way study latencies were primarily appropriate for Near-Earth Objects (>10s, n=17) or Mars (>60s, n=38), with only 6–7 papers including lunar appropriate delays (>0, <10s), only 3 of which focused on communication latency.

Table 2. Distribution of the Communication Delays Present in the Coded Studies						
One-Way Latency (s)	*0*	*1–5*	*5–10*	*10–30*	*30–60*	*>60*
All Coded (n=52)	13	4	2	1	17	38
Comm. Focus (n=15)	10	2	1	0	5	12

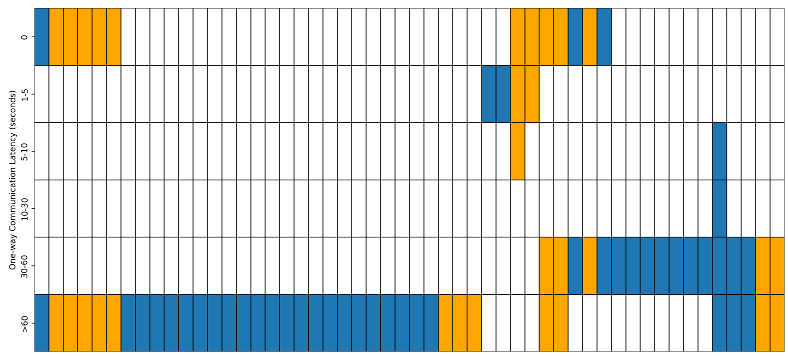
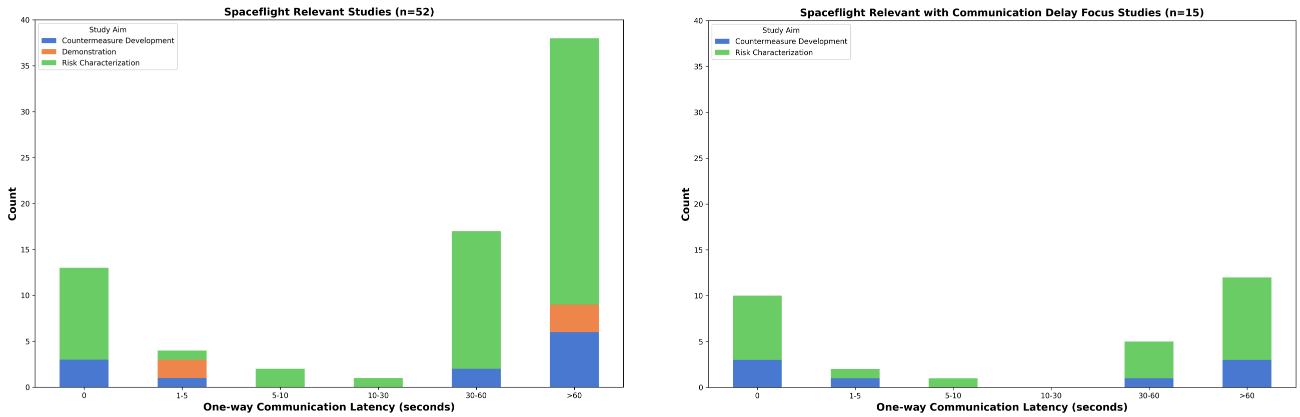


Figure 3. Each column represents a study, with those focused on communication delays highlighted in orange. The y-axis illustrates the one-way communication latency(ies) present in the study. Note that some studies evaluated multiple communication delays >60s.

We coded each study by one of three study aims:

- Risk Characterization: Studies testing the impact of hazards on crew health and performance (CHP) with no mitigations (i.e., there is no experimental comparison with a control condition).
- Countermeasure Development: Studies testing one or more countermeasure(s) to mitigate the impact of hazards on CHP.
- Demonstrations: Studies without a formal experiment that evaluated feasibility.

Figure 4 shows how the study aims were distributed among the communication latencies evaluated. Overall, studies have primarily focused on risk characterization rather than countermeasure development. Thirty-nine studies were identified as risk characterization, eight as countermeasure development, and five as demonstration. There is no significant difference between the overall literature and those only focused on communication delay (though there are no demonstrations in the communication delay focused group due to the definition of that classification).



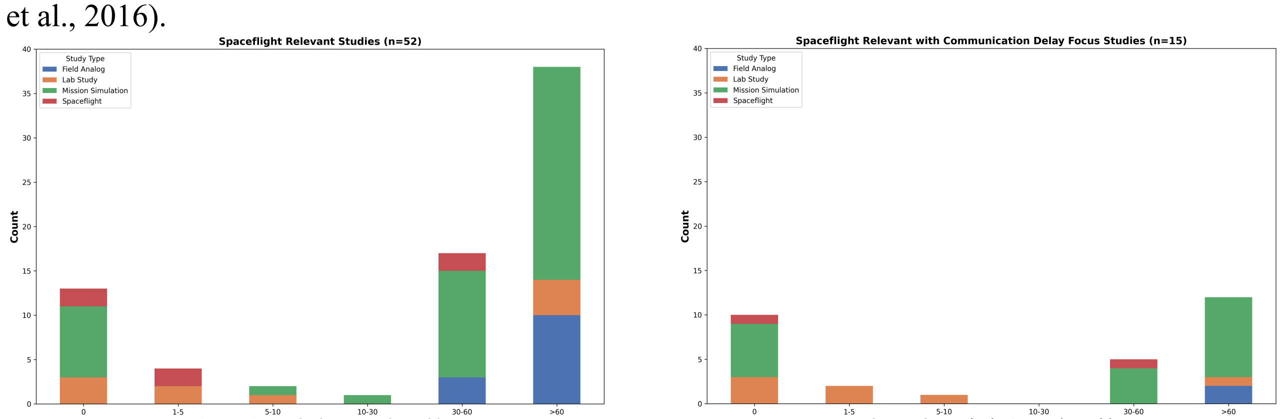
a) b)

Figure 4. Counts of study aim by one-way communication latency: a) Spaceflight relevant studies; b) Spaceflight Relevant with communication delay focus. Note that studies may be represented multiple times, depending on the specific study design.

We coded each study by one of four study types based on the environment it was conducted within:

- Spaceflight: Occurred in space.
- Mission Simulation: Earth-based analogs that simulated a spaceflight mission, including isolated, confined, and extreme (ICE) environments (e.g., HERA, SIRIUS, NEEMO).
- Field Analogs: Analogs which included only a small aspect of a spaceflight mission, usually Extravehicular Activities (e.g., D-RATS, BASALT, Antarctica).
- Lab Study: Occurred in a laboratory outside the other categories (e.g., university laboratory).

Figure 5 illustrates the distribution of different study types across their associated communication latencies. There were 30 categorized as Mission Simulation studies, 12 Field Analog, 6 Lab Study, and 4 Spaceflight. The figure shows that lab studies (though small in number) are more prevalent at lower communication latencies, while mission simulations and field analogs are more common at higher latencies. The single spaceflight study focused on the effects of communication delay was designed to assess the behavioral impacts of a 50-s communication delay to and from the ISS (Kintz et al., 2016).



a) b)

Figure 5. Counts of study type by one-way communication latency: a) Spaceflight relevant studies; b) Spaceflight relevant with communication delay focus.

We also mapped each task into one of seven categories, reflecting tasks that are prevalent in human spaceflight missions, see Table 3 and Figure 6a. The largest category of tasks reflected in our review was extravehicular activity (EVA) (n=19/52), though a relatively small number of these studies focused on communication delay (n=3/15). Contingency/Troubleshooting, Maintenance, and Normal Ops (i.e., Conference Calls, Onboard Science Activities, Piloting a Vehicle, Planning and Scheduling) evenly comprised the remainder of the studies, with Emergency and Medical tasks making up only a small percentage of the studies. Note that we excluded telemedicine from this review, which impacted the number of studies in the Medical category and likely caused us to underrepresent this category of literature. (This is partially because Telemedicine tasks, in particular, tended to focus on technology demonstrations rather than containing a full research study.) We also included an Other category for studies with tasks that could not be easily mapped into the other categories. Most studies in the Other category were associated with Mission Simulation studies that only required participants to fill out surveys (i.e., the studies studied exposure to ICE analogs).

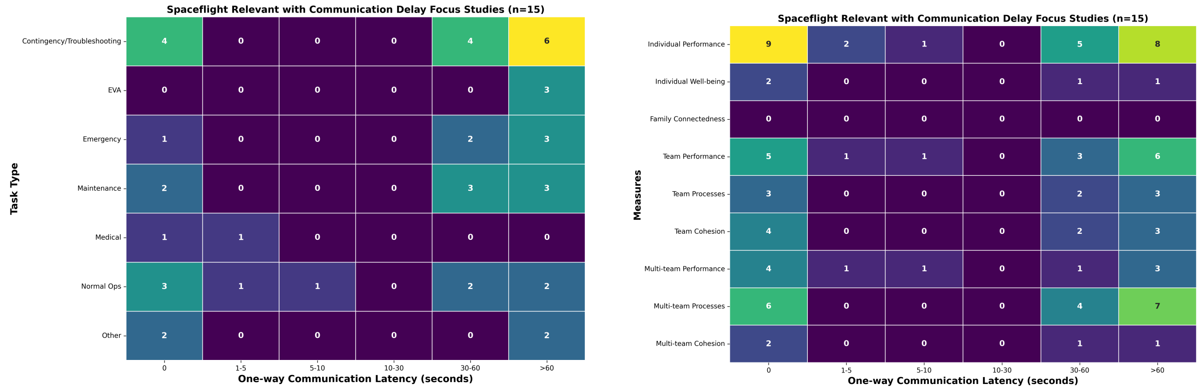
Table 3. Breakdown of the Different Task Type Categories (Note that studies may be represented multiple times, depending on the specific study design.)

Category	*Coded (n=52)*	*Comm. Focus (n=15)*
Contingency/Troubleshooting	11	6
EVA	19	3
Emergency	5	3
Maintenance	10	4
Medical	3	1
Normal Ops	13	4
Other	11	2

We coded the types of individual, team, and multi-team measures within each of the following categories:

- Completion Rate: The percentage of tasks or task objectives successfully completed within a given time frame.
- Error (or Error Rate): Any deviation from the correct or expected performance outcome.
- Accuracy: The degree to which a task is performed correctly.
- Time (or Task Completion Time): The total time taken to complete a specific task from start to finish.
- Task Specific: Any other task specific measure.

As there was insufficient data for any meaningful analysis at this level, the inclusion of any of these categories was rolled up into individual, team, or multi-team performance. We also coded studies for individual well-being, family connectedness, and team and multi-team processes and cohesion, see Figure 6b. Individual Performance, Team Performance, and Multi-team Processes are among the most prevalent measures, while Family Connectedness did not appear at all in this set of literature.



a) b)

Figure 6. Counts of: a) Task Type; and b) Performance Measure by One-way Communication Latency. Note that studies may be represented multiple times, depending on the specific study design.

3.2. Communication Delay Focused Studies

The primary outcomes of the fifteen studies focused on communication delay are available in Appendix A (see Table A2). While there is not enough research to allow for a quantitative meta-analysis (i.e., we cannot claim that a category of tasks takes some percentage of time longer to complete with a 5s delay, compared to no delay), there is sufficient evidence to draw preliminary qualitative findings. Communication delays disrupt communication structure, making it difficult for teams to establish shared understanding. This negatively impacts team performance, particularly for tasks requiring a high level of coordination. This may necessitate a shift towards greater crew autonomy and require adapting work processes to minimize team coordination demands. Communication protocols, training, and technology can mitigate the adverse effects of communication delays.

The first three studies from the literature were laboratory studies:

- Armstead & Henning (2007) investigated the effects of long audio communication delays on team performance using the modified NASA Multi-Attribute Task Battery (MATB). Sixty-seven two-person teams completed tasks with closed-loop audio communication delays ranging from 0 to 16 seconds. They found that performance on the joint fuel management task degraded significantly as communication delay increased, demonstrating a cubic relationship—i.e., degradation occurred non-linearly, with the sharpest decline between 4 and 8 seconds of delay. Delays did not affect individual tasks (tracking or monitoring) that did not require communication between team members. Their results suggest that tasks requiring team coordination are highly sensitive to communication latency. The authors recommend redesigning tasks that require prolonged communication to minimize dependency on direct coordination, thereby improving system resilience when significant communication delays are unavoidable.
- Fischer & Mosier (2014) investigated the impact of communication delays and medium types (text vs. voice) on team performance and communication efficiency in distributed teams tasked with space-related activities. The study simulated spacecraft system failures where teams had to collaborate across a communication delay of up to 5 minutes. Teams experienced significant delays in repairing system failures under

time-delayed conditions compared to synchronous communication. This effect was more pronounced when participants used voice communication, indicating that asynchronous voice interactions were less effective than synchronous ones. When communication was synchronous, teams using voice communication outperformed those using text. However, text and voice mediums led to similar performance outcomes under time-delayed conditions, suggesting that the advantage of voice communication diminishes with delay. Successful teams adapted their communication styles to mitigate the effects of latency. For example, high-performing voice teams used strategies like longer, more informative turns, structuring information clearly, and repeating critical details to facilitate understanding. In contrast, high-performing text teams leveraged the persistent nature of text to manage the increased cognitive load imposed by communication delays, maintaining higher communication density to keep interactions coherent.

- Hurst et al. (2015) investigated remote guidance (RG) ultrasound imaging in space exploration scenarios, focusing on the effects of 5-second communication delays relevant to Lunar missions. The study examines three groups: RG-only, autonomous operation using the Onboard Proficiency Enhancer-Light (OPE-L), and a combination of both RG and OPE-L. Increased communication delays (e.g., beyond 5 seconds) made real-time remote guidance less effective, necessitating more autonomous operation. This shows the limitations of RG in exploration-class missions where real-time support is unavailable. Participants using OPE-L autonomously produced diagnostic-quality images comparable to those obtained with remote guidance. This suggests that well-designed computer-based learning tools can effectively replace real-time RG for some medical tasks. The group using both RG and OPE-L had longer task completion times due to the need to integrate guidance from both sources. However, the overall image quality remained high, supporting the utility of combining instructional tools with RG for these complex scenarios. The study concludes that autonomous operation using adaptive multimedia tools like OPE-L is feasible and effective for diagnostic ultrasound imaging in space missions, especially when communication delays prevent real-time support.

We identified two papers from the Biologic Analog Science Associated with Lava Terrains (BASALT) project that included relevant results. For a comprehensive overview of the BASALT program, we recommend reading Astrobiology Volume 19, Issue 3 / March 2019. The two papers which were included in this literature review were:

- Beaton et al. (2017) explored the impact of communication latency and bandwidth constraints on EVA operations under Mars-like conditions, specifically within the BASALT project. Four different communication conditions—varying latency (5 and 15 minutes one-way) and bandwidth (low and high)—were tested during simulated Mars EVAs at the Craters of the Moon National Monument. They found that increased communication latency negatively affected the efficiency and safety of operations. Under higher latency, the EVA crew experienced challenges coordinating actions with Earth-based support, leading to increased risks in decision-making. The quality of scientific exploration was moderately impacted. The ability to identify and collect samples was hampered by delayed feedback from Earth, requiring changes in strategy to minimize idle crew time and increase task independence. Teams adjusted EVA timelines to incorporate dependent tasks and limit idle time while awaiting feedback, allowing for better task synchronization despite latency and minimizing the impact on mission timelines. The study underscores the need for EVA strategies that reduce dependency on real-time coordination for future Mars missions, given the substantial latency expected.

- Stevens et al. (2019) discussed tactical scientific decision-making during simulated Mars missions as part of the BASALT research program. The research focused on how communication latency (between 5 and 15 minutes) and bandwidth limitations impact EVAs, particularly the coordination between the surface crew on Mars and the Mission Support Center (MSC) on Earth. They suggest that crews must be better trained in relevant scientific disciplines, such as geology, to make critical decisions in the field without immediate feedback. The MSC provided value even under delayed conditions, using tools like a dynamic leaderboard to prioritize sampling locations based on real-time data from the crew. However, effective use of this tool required proper timing and structured procedures to accommodate communication delays. To mitigate the effects of latency, the EVA activities were carefully pre-planned, and sampling decisions were made using standardized protocols to avoid waiting for Earth-based support feedback. This enabled continuous progress without unnecessary delays.

Five of the papers focused on studies completed within NASA mission simulation analogs, NASA Extreme Environment Mission Operations (NEEMO) and Human Exploration Research Analog (HERA):

- Chappell et al. (2016) presented findings from the NEEMO 18–20 missions, underwater analog simulations designed to investigate the effects of communication latency on EVA operations. Conducted from 2014–2015 at the Aquarius Reef Base, these missions simulated Mars-like conditions with 5 to 10-minute one-way communication delays between EVA crews and the Mission Control Center (MCC). Communication latency significantly influenced the ability to coordinate exploration activities, and longer delays necessitated more autonomous EVA timelines to avoid inefficiencies and minimize crew idle time. Introducing latency required the development of hybrid operations concepts that integrated presampling surveys to ensure efficient execution of tasks, minimizing dependence on real-time feedback from MCC. It was found that text and data transfer capabilities were generally preferred over voice communication for interactions between MCC and intravehicular activity (IVA) during latency conditions. This method provided more effective ways to communicate instructions without interruption. The study emphasizes the importance of balancing crew autonomy with ground control input, especially in contexts with long communication delays.
- Tanaka et al. (2020) explored the effects of communication latency on information sharing in space multiteam systems in NASA's HERA, focusing on how communication delays affect the efficiency of message routing within teams. The concept of network acuity—the ability of individuals to leverage their understanding of the network for effective information routing—was introduced to assess these dynamics. The study found that communication delays significantly decreased message completion rates. For example, in a 180-second delay condition, only one out of five messages successfully reached its intended recipient, compared to four out of five messages in the no-delay condition. Teams with higher network acuity—where members better understood optimal pathways for message routing—experienced improved outcomes despite communication delays. Space crews demonstrated higher network acuity than mission support members, indicating that position and role within the network influence information-sharing effectiveness under delayed communication conditions. The study suggests that enhancing network acuity is a key strategy for

improving information flow and mitigating the impact of communication delays in future long-distance space missions.

- Fischer & Mosier (2015) investigated the impact of communication delays on team collaboration during space missions, focusing on using structured communication protocols to support effective collaboration between crewmembers and Mission Control under asynchronous communication conditions. The study was conducted through space-analog simulations using the NEEMO and HERA programs, where astronauts and astronaut-like volunteers were trained in specific communication protocols. Communication delays (ranging from 50 seconds to 5 minutes) led to significant challenges in managing message threads. Participants often misapplied the conventions of synchronous communication to asynchronous contexts, resulting in unnecessary messages, misunderstandings, and cognitive overload when interpreting delayed responses. The use of anaphoric expressions (e.g., pronouns like "that" or "it") became problematic under delay conditions. As related communications were not consecutive, determining the correct referent often became difficult, increasing the cognitive burden on team members. The structured communication protocols were rated as effective in mitigating the negative impacts of delayed communication. These protocols included elements like providing clear topics, using call signs, and maintaining conversational logs to help keep track of message sequences and establish common ground. Crewmembers who received protocol training reported higher effectiveness and were better at maintaining coordination than untrained teams. The study concludes that well-designed communication protocols can alleviate some of the disruptions caused by asynchronous communication.
- Lungeanu et al. (2023) examined the effects of communication delays on multiteam systems (MTS) during a simulated Mars mission, focusing on how task, social, and situational factors shape work patterns and performance. The study involved participants from four disciplinary teams (Geology, Robotics, Engineering, and Human Factors) who were tasked with collaboratively designing a well on Mars under no delay, 60-second delay, and 180-second delay. Communication delays led to longer time spent on tasks by team members, especially when operating under high situational stress or low shared mental models. The delays encouraged extended work on tasks, contributing to higher time-on-task metrics than real-time conditions. Delays promoted stronger information networks among the teams, as the extra time allowed for deeper processing of shared information. This effect was beneficial for building denser information networks, which improved MTS performance when communication occurred with a delay but not in real-time scenarios. Teams with less similar mental models or those prioritizing their own team goals over system-wide (MTS) goals faced greater challenges under delayed conditions. These situational and social factors influenced how effectively teams managed tasks and contributed to collective goals.
- Mosier & Fischer (2023) focused on the challenges of communication delays during space missions and evaluated structured communication protocols designed to mitigate these challenges. The study involved 24 teams using voice- or text-based protocols to simulate responses to spacecraft life-support failures under asynchronous (time-delayed) conditions. Protocol training was provided to some groups to evaluate the impact of structured communication. Communication delays posed significant threats to maintaining common ground between space crews and mission control. Teams experienced issues such as miscommunication, proximity bias (confusion over which messages were responses to prior ones), and difficulties synchronizing conversational

threads. Using structured communication protocols helped reduce issues related to asynchronous communication. Specifically, they improved message clarity and reduced occurrences of information splitting, where related pieces of information were scattered across several messages. However, these protocols did not eliminate all instances of miscommunication, and those related to timing mismatches remained. The protocols were implemented in NASA analog environments, including NEEMO and HERA, which showed high compliance rates. Participants rated them as effective in mitigating the challenges of delayed communication; however, protocol adherence varied, and some teams reverted to synchronous habits, highlighting the ingrained nature of instant communication expectations.

There were four additional studies that took place in other analogs environments:

- Kanas et al. (2011) explored the impact of high vs. low crewmember autonomy on crew performance, mood, and mission control during a 105-day Mars simulation at the Institute for Biomedical Problems in Moscow. The study involved six male crew members and 18 mission control staff. Crew autonomy conditions shifted from low to high, with a 40-minute Mars-like communication delay during the final five weeks. During the high autonomy phase, the crew reported improved mood and greater self-direction, suggesting they preferred having more control over their work schedules. Increased autonomy positively influenced crew emotional well-being and work satisfaction, though mission control personnel experienced increased anxiety and role confusion during the high autonomy period. This was likely due to the reduction in direct oversight, which complicated understanding of their roles in supporting autonomous crew operations. The Russian and European crew members responded differently to the high autonomy. The Russian crew showed a modest improvement in work planning freedom, efficiency, and accuracy, whereas the European crew experienced increased negative emotions and reduced work efficiency and accuracy. These cultural differences may be linked to the operational environment, with Russian crew members being more comfortable with less structured oversight. Overall, the study supports the feasibility of high autonomy for crews during deep space missions but underscores the need to understand and mitigate its effects on mission control dynamics and potential cultural influences on team performance.
- Fischer & Mosier (2020) investigated the effects of crew autonomy and communication delays on the teamwork between space crewmembers and mission control within a MTS. The study was conducted over a 4-month space mission simulation at the Nezemnyy Eksperimental'nyy Komleks (NEK) facility, focusing on team cohesion, role perception, and task performance during increased crew autonomy and 5-minute one-way communication delays. Communication delays and high crew autonomy weakened social and task cohesion between crewmembers and mission control. Mission controllers reported higher cohesion and confidence in the MTS than crewmembers, indicating a discrepancy in perceived effectiveness and unity. Both crewmembers and mission controllers predominantly identified themselves as part of their own component team (crew or mission control) rather than the overarching MTS. This trend persisted despite communication delays, suggesting that delays exacerbated a sense of division rather than promoting integrated teamwork. Crewmembers felt less confident in the overall ability of the space/ground system to communicate and collaborate effectively under delayed conditions. This reduced shared understanding and "siloed" thinking poses a significant risk to successful mission outcomes. The study suggests that

communication delays and increased crew autonomy undermine the cohesion necessary for effective collaboration between space crews and mission control.

- Fischer et al. (2013) explored the impact of transmission delays on mission control-space crew communication, focusing on challenges related to maintaining effective coordination and mutual understanding. The study involved simulated space missions with 50-second and 300-second delays, examining how these time delays affected routine and critical (off-nominal) tasks. They found that transmission delays caused significant disruptions in turn-taking: overlapping contributions (step-ons) and out-of-sequence responses often led to confusion, increasing the cognitive workload as team members had to repeat or adjust their messages to maintain clarity. These disruptions were more frequent in the 300-second delay scenario, making it harder for teams to maintain coherent conversations. The delays required that team members put extra effort into keeping track of open communication threads, which increased cognitive demand and often led to missing or ambiguous feedback. Mutual understanding was more challenging to achieve because the ability to provide immediate feedback was not possible. The study found that some teams adapted by using specific strategies, such as explicitly announcing when they finished their turn ("over") or setting specific times for responses—this improved coordination despite the delayed nature of communications. The study concludes that communication latency significantly challenges mutual understanding and efficient team coordination in space missions and suggests the need for refined communication protocols and strategies to mitigate the effects of asynchronous communication.
- Frank et al. (2013) investigated the impact of communication delays on autonomous mission operations using NASA's Deep Space Habitat (DSH) analog. They simulated scenarios with delays representative of Lunar (1.2–5 seconds), near-Earth object (NEO, 50 seconds), and Mars (300 seconds) missions. Scenarios included nominal activities, spacecraft system failures, and crew medical emergencies. Both crew and Flight Control Team (FCT) members experienced increased workload as time delays grew, especially between 50 and 300 seconds. Delays exacerbated the difficulty of coordinating activities, as crews had to wait for instructions or make autonomous decisions. When mitigation tools—such as advanced procedure execution viewers, caution and warning systems, and text messaging tools—were available, the negative impact of latency on coordination and workload was reduced. These tools improved crew autonomy and enabled more effective decision-making without immediate ground support. Interestingly, task completion rates did not significantly change between different delay conditions, suggesting that while workload increased, mitigation tools allowed for sufficient adaptation to maintain task timelines.

We also identified one spaceflight study that occurred on the ISS:

- Kintz et al. (2016) explored the impact of communication delays on individual and team behavior, performance, and well-being in a study conducted aboard the ISS. The study involved three astronauts and 18 mission support personnel, who performed tasks under control (no delay) and 50-second one-way delay conditions over a 166-day mission. Data were gathered through self-reported questionnaires and post-mission interviews for a mixed-methods evaluation. Astronauts reported significantly higher levels of stress and frustration during tasks involving communication delays. Qualitative feedback indicated that tasks with frequent back-and-forth communications were particularly challenging due to the delays. Communication quality and team mood were significantly lower during tasks with delays. Reduced situational awareness and misunderstandings were also common, negatively impacting the coordination between the ISS crew and mission control. While task efficiency suffered under delay conditions and resulted in longer task completion times, the overall performance quality was not significantly different between the control and delay conditions. Some positive adaptations were noted, including increased crew-crew communication. Astronauts adapted to delays by engaging more directly with each other rather than relying on delayed inputs from mission control, indicating an evolving reliance on crew autonomy. The crew emphasized the need for training that improves communication skills, particularly in delayed scenarios, and suggested training in analog environments to prepare for communication delays. Text/video communication or a recording tool for voice communications was recommended to enhance clarity and reduce cognitive demands during delayed exchanges. Astronauts noted that greater autonomy from mission control would help mitigate the adverse effects of delays. They recommended reducing the need for mission control approval at each step of routine tasks, which could streamline operations under delayed conditions.

3.3. Results and Recommendations

This collection of 15 research studies investigated the effects of communication latency in space mission operations, focusing on the challenges it poses to team coordination, crew autonomy, mission control interaction, and overall mission performance. The literature consistently demonstrates that communication delays significantly impair team cohesion and coordination between space crews and mission control, often leading to miscommunication and challenges in maintaining a shared situational understanding. Papers by Stevens et al. (2019), Kanas et al. (2011), and Mosier & Fischer (2023) show that teams needed help maintaining coherence in their communication sequences; the absence of said help led to misunderstandings and fragmented task progress. Fischer & Mosier (2015) emphasize the issues that arise with message coherence under delayed communication, where participants frequently struggled with conversational aspects, such as the correct use of anaphoric expressions (e.g., “that” or “it”), which made maintaining coherence across long communication gaps especially challenging.

One of the consistent recommendations across these studies has been to increase crew autonomy as a strategy to address the challenges posed by communication latency. The need for enhanced autonomy is prominent in papers such as Kanas et al. (2011), Fischer & Mosier (2020), and Stevens et al. (2019), where mission success depended on reducing reliance on immediate support from mission control. This was particularly evident in studies where mission control's delayed responses required crews to make more independent decisions, especially during EVA sampling activities. The findings from Lungeanu et al. (2023) suggest that information network density improves under delayed conditions, indicating that increased collaboration between different crew disciplines—driven by the necessity to rely less on ground support—could mitigate some of the downsides of communication delays. However, this was accompanied by higher demands on team adaptability and required additional role clarity. Increasing autonomy required developing and deploying effective decision-making tools to help crews operate independently. Hurst et al. (2015) and Mosier & Fischer (2023) explored the effectiveness of training tools like adaptive multimedia resources and structured communication aids that provided real-time guidance even when mission control was out of reach. The tools helped crews perform diagnostic tasks such as ultrasound imaging and complex EVA operations autonomously, maintaining mission quality even under delayed conditions.

Several studies examined the psychological effects of communication delays, finding both positive and negative outcomes. Papers such as Kanas et al. (2011) and Kintz et al. (2016) noted that crews experienced increased stress and frustration during delayed communications, impacting their mood and interaction with mission control. However, greater autonomy was also associated with improved mood and satisfaction among crews, indicating they appreciated controlling their operational timelines. Chappell et al. (2016) found that psychological stress under delay conditions was exacerbated by increased workload and uncertainty about tasks, particularly when teams had to make decisions without immediate input from mission control. This emphasizes the need for careful crew selection and psychological support in missions with significant communication latency.

A strategy used by many studies for mitigating latency effects is using structured communication protocols. Papers such as Mosier & Fischer (2023), Stevens et al. (2019), and Fischer & Mosier (2015) documented the use of protocols designed to maintain coherence during communication, especially under asynchronous conditions. These protocols typically involved setting clear expectations for message timing, ensuring that information was delivered in structured formats, and employing persistent communication tools like text logs. Fischer & Mosier (2015) provides evidence of how structured protocols, such as identifying the addressee multiple times, timestamping messages, and using structured templates for communication, significantly improved the clarity and effectiveness of interactions under delayed conditions. Crewmembers who used these structured approaches were better able to track message threads and maintain situational awareness despite long delays.

The effect of communication latency on task efficiency was a key focus across the studies. Frank et al. (2013) showed that while delays negatively impacted task completion time, the quality of task outcomes remained relatively stable, indicating that crews adapted to delay. Similarly, Beaton et al. (2017) describes that delays often required crews to be more deliberate in planning and decision-making, especially during EVAs, to maintain performance. The findings in Armstead & Henning (2007) and Chappell et al. (2016) showed that while task performance suffered due to latency, structured mitigation tools such as procedure viewers helped offset the decline in efficiency, ensuring that mission objectives were still met.

This literature emphasizes the challenges of maintaining effective communication, crew coordination, and task performance under delayed conditions. The following overarching conclusions can be drawn:

- Many studies, including Kanas et al. (2011), Fischer & Mosier (2020), and Stevens et al. (2019), stress that future long-duration missions must provide crews with greater autonomy, supported by the necessary tools and training. Autonomy allows crews to manage tasks independently when delayed communication limits the ability to receive immediate support.
- Effective decision-making tools were crucial for managing operations without real-time mission control support. Hurst et al. (2015) demonstrated that adaptive training tools could allow crews to perform medical tasks autonomously, while Stevens et al. (2019) and Frank et al. (2013) discussed the broader utility of such tools during complex mission operations.
- Studies such as Kintz et al. (2016) and Chappell et al. (2016) highlighted the importance of preparing crews for the psychological stresses of delayed communication. Training that improves resilience, situational awareness, and independence could help to maintain team cohesion and operational efficiency.
- Communication protocols, such as those tested by Fischer & Mosier (2015), Mosier & Fischer (2023), and Stevens et al. (2019), were found to be effective in mitigating the impact of communication delays. These protocols help maintain conversational

coherence, reduce the risk of misunderstandings, and ensure that communication remains efficient despite delays.

4. Interview Methods

4.1. Subject Matter Expert Interviews and Information Gathering

Concurrent with focusing on the literature review, semi-structured interviews were held with thirteen subject matter experts (SMEs) (see distribution in Table 4). Some interviewees spanned multiple categories and had related experiences to which they could contribute (e.g., military experience). These interviews captured different perspectives on the effects of living and working under communication delays and what is being worked on to mitigate issues associated with communication delay. Participants were contacted via email with information about the study goals, and informed participation in the interviews was voluntary and confidential. All interview notes, transcripts, and voice recordings were stored on an encrypted drive to which only Institutional Review Board (IRB)-approved team members had access. This study was deemed Not Human Subjects Research under NASA IRB STUDY00000723.

Table 4. Interviewees by Experience

Experience	*Interviewees*
HERA/CHAPEA Analog Crew	5
Analog Facility Oversight Scientists	2
Analog Support Psychologist	1
Communication Delay Researchers	5

Questions presented were from the same general topic areas and were tailored to elicit personal perspectives, experiences, and areas of expertise. Interviews were conducted via Microsoft Teams and recorded and transcribed for thematic analysis. One team member conducted the interviews with at least one notetaker and an open platform for the team to ask follow-up questions. The interview was approximately 60 minutes, and 15 topic areas were covered. These question topics included:

- Background of the interviewee.
- Training and preparation for living and working under communication delays.
- Training and preparation for family and family connectedness.
- Roles and responsibilities of crew, MCC, and other support personnel.
- Performance impacts from communication delay.
- Quality and quantity of communication.
- Different impacts of communication delay for lunar vs. Mars.
- Team and multiteam cohesion.
- Team and multiteam processes and performance.
- Stress, frustration, and behavioral health outcomes.
- Existing and needed communication tools and strategies.
- Key research findings (according to the experiences and opinions of participants).
- Key research needs (according to the experiences and opinions of participants).

In addition to the formal interviews conducted for the project, we also reviewed notes from recent discussions regarding lunar communication delays with NASA Flight Operations Directorate (FOD) SMEs for the 2024 Team Risk risk update. Co-investigator L. Landon—in her role as the Team Risk Risk Custodian for research and at the direction of the Human Systems Risk Board—gathered information from NASA program officers, chief training officers, flight controllers, and other FOD personnel developing operations products and conducting simulations in the context of lunar communication delays. Thirteen SMEs contributed to the discussions, and a summary was presented to the Human System Risk Board (HSRB) during the Team Risk closure presentation in June 2024. These notes and follow-up emailed comments were coded with the new interview data collected specifically for this project to provide a more comprehensive perspective of the current thinking and preparations in work for future communication-delayed beyond low-Earth orbit (BLEO) missions.

4.2. Interviews and FOD Discussion Coding

Two research team members coded the interviews and discussion notes using the thematic coding method outlined by Braun and Clarke (Braun & Clarke, 2006, 2012). Thematic analysis is a system for "identifying, organizing, and ordering insight into patterns of meaning (themes) across a dataset." Responses were divided for coding such that each block of text represented a point an interviewee made about their experience. Sometimes interviewees made several points in response to one question, so each point on a topic was separated into a unique response and coded separately (e.g., a question about training may lead to three points about training and one about their motivation for the mission, so that the coders would code four unique points for that one larger response). Coders used a small subset of data to pilot their identification of topics, held a consensus session to develop a shared mental model, and then coded the rest of the response topics independently. Next, coders read the information within each topic code multiple times to familiarize themselves with the content and identify themes across all responses for a given topic. This iterative process allowed theme specifics to be refined and the key responses and illustrative quotes to be organized under the most relevant theme. The process facilitated identifying the most important themes without losing nuances in the data.

5. Expert Interviews/Discussions: Thematic Analysis Summary

Below are high-level summary points for each theme identified in the interview and discussion notes. Analog mission participants reflected on their personal experiences directly, while researchers and mission support personnel spoke of their own experience on the support side of comm delay, as well as their observations of impacts to crew health and performance. Summary points represent the general consensus of the experiences and opinions of interviewees as they reported them to our research team.

5.1. Analog Crew Experiences

5.1.1. Individual Well-Being

Discussion of how communication delay impacted crewmembers' emotional wellbeing during the mission, including stress, fatigue, and feelings of autonomy. Participants were asked to describe how these effects changed over time, and any strategies they used to cope with the psychological stress or challenges related to comm delay.

Summary:

- Communication delay has positive and negative effects on individual well-being. It increases loneliness and isolation but increases autonomy. Communication delay reduced the amount of checking up on or pinging from MCC, which the crew appreciated. However, some stated they missed hearing from humans (see also Family Connectedness).
- Communicating through a communication delay can be frustrating and stress-inducing. These feelings can stem from miscommunications, the lack of easy back-and-forth conversations and synchronous engagement in an activity, and the loss of countermeasures meant to combat stress (e.g., private psychological and family conferences, Private Psychological Conferences [PPCs], and Private Family Conferences [PFCs]).
- Many interviewees stated that this frustration is manageable and/or mild. However, troubleshooting and addressing off-nominal situations that were not time-pressured or deemed an acute concern to crew safety (e.g., equipment breaking, software glitches) was still identified as "very frustrating" to resolve under communication delay from MCC.
- It was also suggested that even if communication delay has a small effect, it is another stressor with a dosage effect over time that can become concerning in long-duration missions. Even for lunar missions with short latencies, seemingly minor frustrations could increase exponentially over time, likely impacting morale and communication quality. In a couple of communication delay studies with short/lunar-like latencies about ultrasounds, participants were more stressed, communication was "garbled," and the quantity decreased, and likely the quality of the communications decreased as well.

5.1.2. Team and Multiteam Cohesion

Discussion of how comm delay impacted the relationships between crewmembers, and the relationships between crew and ground, and how they felt this impacted their efficiency and effectiveness as a team. Participants were asked to reflect on how comm delay impacted team dynamics, crew autonomy, feelings of connectedness, etc.

Summary:

- Communication delays reduce space-to-ground cohesion and rapport due to reduced communication quantity, misunderstandings, and reduced ability for back-and-forth communications (noted as important to have difficult conversations to reduce friction). Reduced cohesion, in turn, reduced performance.
- Many interviewees stated that they would give the crew more autonomy—even during real-time support—using new technology or new training (e.g., self-scheduling with a system alerting crew to constraints). Part of the motivation for increased autonomy is task efficiency, but it also stems from increasing well-being and multiteam trust.
- The crew's "intense mom and dad oversight" at the beginning of the mission was challenging, but the space-to-ground relationship dynamics improved later. When real-time communications returned, the HERA crew felt that the rapport with MCC was better because MCC saw that the crew could work effectively autonomously.
- Crew and ground support are motivated to maintain cohesion, and interviewees reported that they took personal initiative or observed others doing so. Some crew and

ground support desired scaffolding to help them do this (e.g., check-ins address cohesion, not just work; psychologist offers guidance).
- Communication delay can affect crew cohesion—generally positively—as they turn to each other first more readily. Almost all interviewees stated that establishing cohesion before ingress is important.

5.1.3. Family Connectedness

Discussion of how comm delay impacted the relationships between crewmembers and their family and friends. Participants were asked to reflect on how families prepared for the mission, how comm delay impacted their ability to maintain closeness, and any steps or actions they took to help alleviate these challenges.

Summary:

- Family connectedness is seen as very important for maintaining well-being over time, and communication delays are seen as significantly interfering with this connectedness. The HERA crew noted that communication delays with family became increasingly frustrating over time.
- Families and friends of analog crews did not receive communication delay communication training and were frustrated and felt that they wasted "precious" time during PFCs.
- The HERA crew stated that communicating via video only with family, friends, psychologists, and flight surgeons (i.e., people you really need to trust and need help from in a more personal way) was somewhat frustrating but manageable during the 45-day mission with lunar-length communication latencies. They felt it would likely be more significant during a longer mission.
- FOD stated that the likely biggest impact of a communication delay would be on how they conduct PMCs, PPCs, PFCs, and pre-EVAs conferences.

5.2. Performance

5.2.1. Task Performance

Discussion of how comm delay impacted individual and team performance of tasks and responsibilities during the mission. Participants were asked to reflect on how they felt comm delay impacted their own performance and their team's performance, and to describe tasks that were impacted.

Summary:

- FOD, HERA crew, and research interviewees stated that tasks that were time-pressured or off-nominal showed the biggest impact from communication delays. Shorter delays are easier to manage in these circumstances. Critical tasks in the context of communication delays are described as complex activities that need real-time back-and-forth discourse.
- Interviewees recommend that tasks be designed to account for the anticipated communication delay, possibly building in some "extra buffer time" to accommodate troubleshooting when undesired outcomes arise.
- High-performing crews are less likely to be adversely affected by a communication delay if they are prepared and have successfully worked as a team before the delay starts.

5.2.2. Team and Multiteam Processes

Discussion of how communication delay impacted communication and coordination between crewmembers, and between crew and ground, and how they adapted their processes as comm delay increased.

Summary:

- Researchers have found that communication delays exacerbate coordination issues and that subjects overestimate their ability to handle the effects of delays successfully. Timing, threads, and transmission efficiency are the three basic elements of communication that are impacted by delays.
- Shorter delays encourage people to act quickly before receiving all information because they make people feel overconfident and impatient. At Lunar communication latencies, rapid exchanges caused confusion and missed space-to-ground calls, and at Mars delays, too much communication from the MCC was found to be distracting.

5.2.3. Crew Autonomy

Discussion of how communication delay influenced the way crewmembers perceived and exercise autonomy from ground support, including positive and negative effects observed.

Summary:

- Almost all interviewees say the crew acts more autonomously under communication delays. Analog crew often felt that it was easier and faster to resolve issues on their own, especially under communication delays. However, if they had to address an issue independently and did not readily know what to do, they found that they wasted more time trying to act without MCC's guidance.
- Autonomy is preferred in a catastrophic event when everything happens fast, even under lunar communication delay conditions. The crew needs to be able to act or respond accordingly, with full autonomy and decision-making authority.
- Opinions in FOD seem to be mixed as to whether the lunar crew will be highly autonomous or only slightly more autonomous than the ISS. However, all FOD interviewees generally accept that Mars crews will need to be highly Earth-independent.
- According to operations, research, and analog interviewees, the crew's responsibilities will likely be a function of the communication delay; that is, more responsibilities fall to the crew to execute under longer delays.

5.3. Countermeasures

5.3.1. Communication Protocols/Strategies

Discussion of the protocols, tools, and strategies used by crew and ground to communicate, and how they changed under comm delay. Participants were asked to describe lessons learned for communicating under delay conditions, and any strategies they developed that may be useful for future crews.

Summary:

- Interviewees suggested that operations with delayed communications need more and/or different structures than current ISS protocols to prevent confusion and frustration. This may include specific protocol elements such as time, thread, keywords, flow, priority labels, and contingency comm. Communications should be acknowledged when received so everyone knows whether communications systems are working.

- According to our research interviewees, longer-duration analogs (Crew Health and Performance Exploration Analog [CHAPEA]; SIRIUS) have fewer space-to-ground communications over time (number of messages) than shorter-duration analogs. All types of interviewees suggested that there should be some consistent communication events, such as the daily summary message from MCC to the HERA crew and from crew to MCC.
- Researcher interviewees stated that depending on the task and the relationship between the communicators, it may be desirable to "mask" the communication delay-induced disconnect (e.g., the Fischer and Mosier Braiding tool), but at other times, it may be preferred to explicitly acknowledge and manage the delay (e.g., structured communication protocols to enable task coordination).
- Interviewees reported that longer delays made it harder to maintain the context of the communication; they felt more context must be added to the communications.
- Analog crews utilized pre-planned communication "packets" to improve the efficiency of space-to-ground communications. These also supported within-crew shared mental models and cohesion. However, if the amount of communication in packets from MCC became too large, they were found to be disruptive to the crew and unusable.
- Communication modalities (voice vs. text vs. video) can be used strategically to fit the task best, type of communication (work vs. personal), and length of communication delay. Interviewees reported that the preferred back-and-forth communication modality shifts from voice to text as communication delay increases (from real-time/lunar to Mars). Text leaves a record to refer to later, which almost all interviewees agreed was helpful, especially during emergencies. Videos were helpful for just-in-time training. Videos and recorded audio are also notable for supporting personal connection and well-being.

5.3.2. Training

Discussion of the training participants received before and during the mission, particularly in regard to communications protocols and preparation for comm delay. Participants were asked to reflect on how their pre-mission training prepared them for the comm delay, and what types of training they think should be provided for future crews to help mitigate the impacts of comm delay.

Summary:

- According to almost all interviewees, expectation setting (usually via training and practice under communication delay) is critical for task performance and behavioral health. Interviewees emphasized that it is important to set expectations for crew and all ground support (e.g., MCC, psychological and medical support, families). Expectations should include length of delay, bandwidth, communication windows, task cadence, frustration reactions, and what type of communication and communication modality might work best for a given task.
- According to researchers, protocols and skills for communicating with delays should be extensively trained and deeply ingrained before the mission to prevent reverting back to habitual behaviors during times of high stress and/or emergencies.
- Training for communication basics, communication delay strategy and protocol specifics, team coordination processes, Earth independent operations, and support systems and tools combine to mitigate the risk of communication delays. Integrating

all aspects during training is necessary (as FOD says, “train as you fly”). Interviewees also suggested that different groups need different training tailored to them (e.g., work vs personal). Researchers and FOD interviewees stated that training often uncovers other potential space-to-ground communication or coordination issues that had not been considered before practicing the task.

- HERA crew had mixed opinions on their training and preparation—some felt well-prepared for tasks. In contrast, others felt they needed more training and practice on tasks and communication delays (sidenote: this seemed to fall along military or non-military experience). They stated that they felt that they improved their performance as they got more experience in the mission and were under communication delays.
- Researchers mentioned that crew and ground need joint training for space-to-ground to build skills, shared mental models, rapport, and trust. Aviation has joint training events with pilots and air traffic controllers that effectively develop shared understanding.
- Lunar length latencies are not a major focus of FOD training to prepare for near-term Artemis missions as it is not very concerned about their impacts. Further, FOD worries that addressing communication delays will likely induce additional time and costs through extra training and just-in-time training products.
- FOD tests and training incorporating communication delays test only those due to light time delays and not system-driven latencies. Practice operations under communication delay in high-fidelity environments (e.g., Neutral Buoyancy Lab), simulations, tests, and training runs are desired.

5.3.3. System Design/Tools

Discussion of what countermeasures the participants believe should be explored to mitigate the impacts of comm delay based on their personal experiences.

Summary:

- Researcher and operations interviewees recommend that systems and tools be designed to enable greater Earth independence by the crew under communication delay conditions, including that they provide some of the oversight currently performed by MCC. Data systems that integrate and organize documentation and past communication are needed. Suggestions also included providing additional automation and augmentation systems that may utilize artificial intelligence (AI). AI or rules-based logic could help review decisions instead of MCC.
- It was also recommended that designers create built-in oversight and guidance features to support crew in complex task execution and to help them detect errors before they impact mission operations. Procedures must be written for more autonomous operations, recognizing that MCC is not easily accessible for clarification or help.
- Researchers and FOD highlighted the need for new hardware and software tools and protocols to manage asynchronous collaboration between crew and ground and foster shared situational awareness. Different types of tasks or collaboration (e.g., close back-and-forth vs. more passive monitoring and support) require different systems, tools, and functionality.

6. Identified Concerns and Research Needs

As described above, there are not enough studies reported in the literature to allow for a quantitative meta-analysis (i.e., we cannot know that a category of tasks takes a certain percentage longer to complete with a 5-second delay compared to no delay). Nor do these studies provide comprehensive coverage of the conditions, tasks, etc., that are of concern for Lunar and Mars missions.

Only two studies have been performed on the anticipated lunar communication latencies of up to 10 seconds one way. Both were conducted in laboratory environments, addressed normal operations or medical procedures (i.e., ultrasound), and focused on individual, team, and multi-team performance. This paucity of research leaves much of the risk landscape uncharacterized. HRP has recently funded several new studies to focus on the delays that Artemis crews will experience; however, it is unlikely that the results of these studies will provide timely insights or requirements for the next few missions.

While these limited research studies indicate potential performance decrements due to lunar length delays, FOD and Crew Health and Performance Officers (CHPOs) have not formally identified communication latency as a high priority risk to their programs; at most, it is noted as a watch item and has few resources allocated to it. They are conducting tests and simulations focused on lunar missions, but many of these do not take communication delays into account; instead, they concentrate primarily on commanding and telemetry. The effects of communication delays during these tests have not been well quantified or documented. FOD believes there is an increased probability of impacts on mission success but currently assesses the consequences as small because they feel that the crew and MCC adapt quickly to lunar-length communication delays. Others, including those working with ISS operations, believe that lunar communication delays would challenge NASA operations, especially if they tried to stay with the current model for real-time communication. If changes need to be made to Artemis ConOps to account for communication delay, these need to begin as soon as possible; FOD may be proceeding at risk by not including realistic latency in their training simulations and Ops development. A detailed analysis of the impacts of procedures and latencies is needed to understand the risks; this is more likely to be addressed in operations planning than in research studies.

More research has been conducted on longer communication latencies; for instance, those associated with near-Earth object (NEO) missions (30–60 sec) or Mars missions (> 60 sec). For those focused on the spaceflight domain, most studies on longer delays were mission simulations within Earth-based analogs, and most examined contingency and troubleshooting tasks, identifying the effects of communication delay on individual and team performance as well as multi-team processes. However, the variation of tasks has been limited. Evident in mission simulations of this type is that current analogs lack sufficient fidelity compared to actual operational environments. Systems simulating spacecraft hardware and software have limited complexity and few operational consequences if they become nonoperational; troubleshooting, maintenance, and other tasks are often simple, lacking urgency or consequences. Because current analog missions cannot 'fail,' these simulations cannot study what happens if there are actual consequences to tasks that take a long time or are not completed in time. NASA should consider upgrading its simulation environments to include more realistic systems, scenarios, and outcomes, and to test a more varied set of operational tasks.

Currently, analogs will break from communication delays if there is an actual safety event to minimize harm and meet ethical and IRB guidelines. This practice should not be changed, but populations must be studied in field settings or other analogous environments with actual danger to the participants. NASA analog missions should consider how to have real (but not dangerous) consequences for analog crews when they perform poorly.

Current communications delay training for NASA analogs is inadequate and can affect assessments of the impacts on team and individual well-being and performance associated with communication latencies. NASA must enhance the fidelity of communication training for everyone involved in analog missions, including families and support personnel (i.e., psychologists and flight surgeons), the MCC, and crew members. Building cohesion between the crew and support personnel (including psychologists, flight surgeons, capsule communication [CAPCOM)] and key MCC staff) is essential before ingress to create a more mission-like environment. Further research is needed to identify the appropriate content for training different groups, ensuring that everyone has the necessary skills before ingress.

What is seen generally in the communication delay research reviewed herein is that many studies did not compare a no-delay condition to a delay condition, hindering risk characterization and countermeasure validation. Control conditions in general—no-delay vs. delay, no-countermeasure vs. countermeasure, etc.—should be required for future communication delay research. In addition, analog mission communication delays should be gradually increased during simulations to mimic those experienced during an actual mission rather than being introduced in a sizeable stepwise fashion, as has been a typical research approach. While CHAPEA has embraced this approach, HERA still uses stepwise jumps (e.g., from tens of seconds to hundreds of seconds). Most studies involved only one team or a multi-team system and did not evaluate different team structures; this should also be remedied. Another area requiring attention is how to definitively separate the effects of experimental covariates, such as task complexity, task-specific communication demands, crew autonomy, and exposure to isolation and confinement, from those of communication delay.

Beyond analogs, additional research in diverse settings across various communication latencies is needed, including in isolated habitats, extreme environments, and analogous aviation or other time- and safety-critical domains. Lab studies and spaceflight research are also important, and the ISS should be used to support this research in an operational environment while considering the risk/reward benefit of conducting such research in spaceflight. Additional risk characterizations are required, for example, to assess different team structures, the cumulative effects of communication delays over time, connectedness with family and friends, and nominal versus off-nominal operations. Countermeasure development and validation should also continue to be pursued to address tools and processes that support crew autonomy and protocols tailored to specific communication situations, including wait periods and high coordination tasks. Even with 20+ years of research, there is still much to learn.

7. Conclusions

This work reviewed, characterized, and synthesized the past 20+ years of research concerning the effects and mitigation of communication latencies during spaceflight missions. Fifty-two spaceflight-relevant, published studies on a variety of aspects were examined first; the review was then focused to a subset of studies (15) that evaluated the effects of communication delay on an outcome measure. Reviewing the published literature contributed to a coherent understanding of what has been studied, how it has been approached, and the outcomes measured. Additional perspectives were gained from interviews with the researchers, research participants, and operations experts. Analyses were integrated across BMed, Team, and EIHSO Risks.

Findings from this review highlight the lack of research for lunar length latencies—only two lab studies have been performed and documented for one-way delays < 10 sec, revealing that risks associated lunar missions remain largely uncharacterized. More research (17 studies) has been conducted on longer communication latencies (30 to >60 sec). The majority of these were conducted in Earth-based analogs, simulations that can be hindered by overly simplified tasks, unrealistic habitat system mock-ups, and mild operational consequences.

Overall, the studies reviewed indicate the following effects of communication delays:

- Even short communication delays can disrupt interactions between MCC and the crew.
- As transmission delays increase, space-ground communications degrade significantly.
- Degraded communications adversely affect team performance.
- Individuals experience increased stress and reduced effectiveness of countermeasures, including PPCs and PFCs.
- Over time, space-to-ground cohesion diminishes, including reduced connectedness with family and friends.
- Countermeasures for asynchronous communication require more study.

A number of limitations were noted from these studies, including the:

- Lack of experimental controls for variables
- Limited range of team structures tested
- Inability to separate effects of experimental covariates
- Lack of simulation fidelity (e.g., physical fidelity including implementation of communication delays, task and functional fidelity)
- Lack of situational or task complexity
- Insufficient measures of outcomes
- Insufficient sample sizes, repeatability

This work found that additional research is needed to characterize risks and mitigate the effects of communication latencies. In addition to analogs, research should be pursued in diverse simulation settings, such as isolated habitats, extreme environments, and analogous aviation or other time- and safety-critical domains as well as in lab studies and aboard the ISS. Crew autonomy, in particular, requires much more study across a range of conditions, tasks, and countermeasures. Training and preparation for managing communication delays is also an understudied area.

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Appendix A

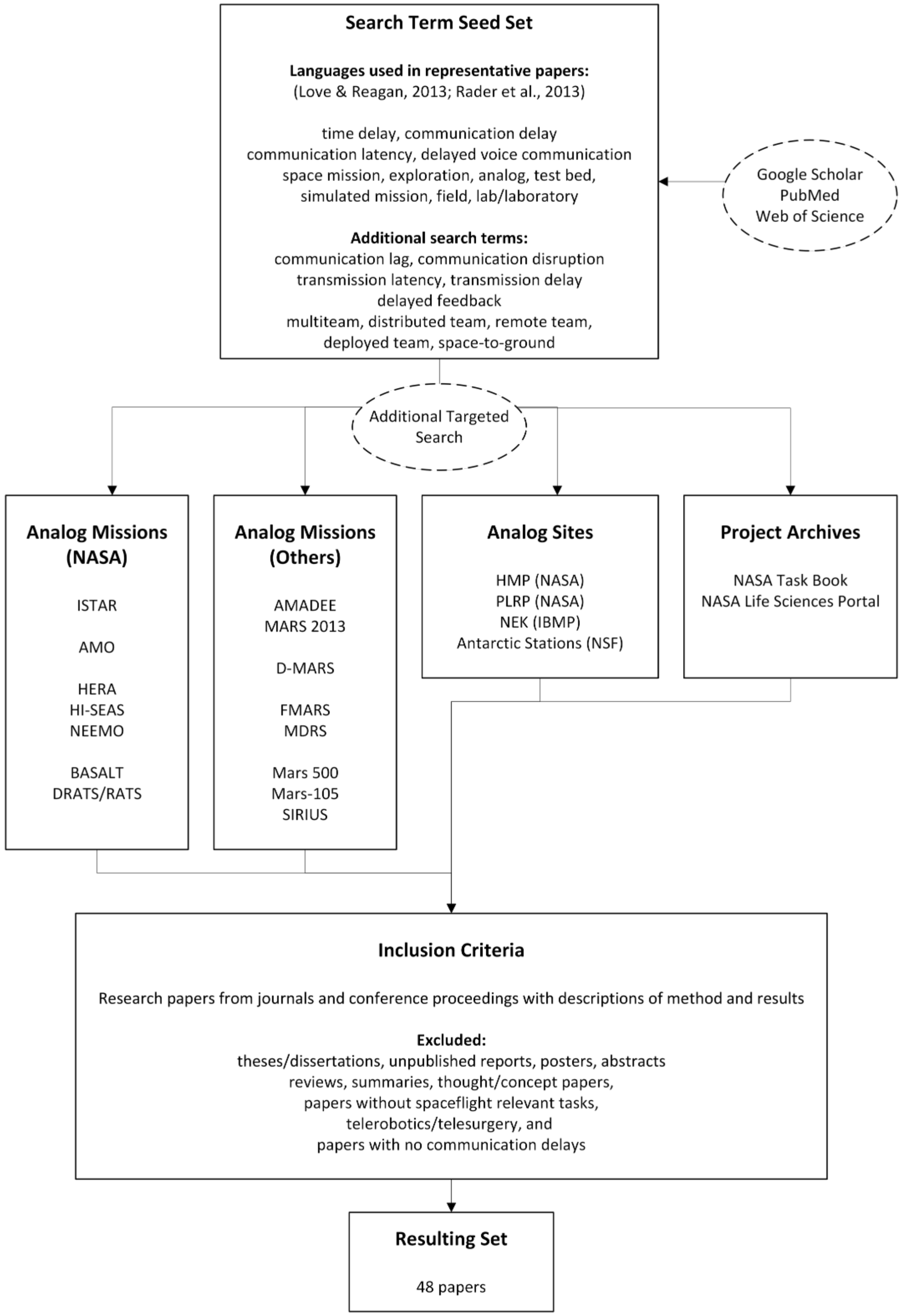

Figure A1. Communication delay literature search flow.

Notes: ISTAR (ISS Testbed for Analog Research); AMO (Autonomous Mission Operations); HERA (Human Exploration Research Analog); HI-SEAS (Hawai'i Space Exploration Analog and

Simulation); NEEMO (NASA Extreme Environment Mission Operations); BASALT (Biologic Analog Science Associated with Lava Terrains); DRATS/RATS (Desert Research and Technology Studies); D-MARS (Desert Mars Analog Ramon Station); FMARS (Flashline Mars Arctic Research Station); MDRS (Moon Desert Research Station); SIRIUS (Scientific International Research in Unique Terrestrial Station); HMP (Haughton-Mars Project); PLRP (Pavilion Lake Research Project); NEK (Nezemnyy Eksperimental'nyy Kompleks).

Table A1. High-Level Descriptions of the Identified Communication Delay Focused Studies

Title	Study Aim	Study Type	Outcomes
Armstead & Henning (2007)	Risk Characterization	Lab Study	Longer communication delays were predictive of progressively poorer performance on the resource management task.
Fischer & Mosier (2014)	Risk Characterization	Lab Study	Teams took significantly longer to repair system failures under time delay than when they had no time delay. The difference was concentrated in the voice medium. The data suggest that the no time delay condition may have been more conducive to incorrect repairs than the time delay condition.
Hurst et al. (2015)	Countermeasure Development	Lab Study	The study demonstrates that a one-way communication delay of 2.5s did not affect an expert' s ability to guide non-US experts to collect diagnostic-quality US images. However, further increases in communication delay could impair the effectiveness of RG, especially in complex procedures requiring more than mere identification of standard and easy-to-recognize target images.
Beaton et al. (2017)	Risk Characterization	Field Analog (BASALT)	There were little to no reported differences between the 5-minute one-way latency and 10-minute one-way latency.
Stevens et al. (2019)	Risk Characterization	Field Analog (BASALT)	There was an interesting juxtaposition of the perception of how much the MSC could influence the EVA activities and the time pressures introduced by the communication latency. In the 5 min OWLT low latency case the decisions in MSC were generally more "frantic" and pressured in an attempt to influence the EVA more directly. This is counterintuitive but seemed related to the fact that the MSC felt better connected to the EV crew under low latency, whereas under high latency there was less opportunity to directly influence the EV crew. In the high latency case there seemed to be a more "measured" approach as the MSC knew that it was more limited in how much it could influence the EVA.

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Kanas et al. (2011)	Risk Characterization	Mission Simulation (Mars 500)	The results suggest that high crew autonomy is well received by crewmembers working in isolated space analog settings, and crewmember mood, self-direction, and freedom to plan work were rated as being higher. However, the effects of high autonomy were confounded with the communication time delay, and it is difficult to partial out the relative influence of these two factors.
Fischer & Mosier (2020)	Risk Characterization	Mission Simulation (NEK)	Crewmembers' perception of MTS social and task cohesion was not highly impacted by communication delay; but instead may have declined as the mission progressed, especially after the midpoint of the mission.
Fischer et al. (2013)	Risk Characterization	Mission Simulation (AMO/DSH)	Transmission delays disrupted the timing and structure of turns as communications by different speakers cooccurred or were out of sequence.
Frank et al. (2013)	Countermeasure Development	Mission Simulation (AMO/DSH)	Workload ratings and coordination difficulty between the flight control team and the crew increased with time delay. Workload and coordination difficulty decreased as a result of the mitigation configuration. Flight controller workload ratings responded differently to configuration and time delay than the crew workload; specifically, crew workload was reduced by time delay in the Mitigation configuration, while flight controller workload increased with time delay regardless of configuration.
Chappell et al. (2016)	Risk Characterization	Mission Simulation (NEEMO)	The science team reported that better tools are necessary to provide input within a 5 minute window compared to a 10 minute window.
Fischer & Mosier (2015)	Countermeasure Development	Mission Simulation (NEEMO & HERA)	The present research suggests that asynchronous communication may be facilitated by protocols that aid conversational partners in keeping track of conversational threads and the temporal sequence of messages.
Mosier & Fischer (2023)	Countermeasure Development	Mission Simulation (NEEMO & HERA)	Trained crewmembers rated the effectiveness of their interactions with MC during time delay on a par with those on non-delay days, suggesting that the protocols did facilitate crewmembers' communications with mission control on days with communication delay. In contrast, untrained crewmembers gave considerably lower effectiveness ratings on time-delayed days compared to days with synchronous communication. MC noted they performed tasks improperly with poor compliance with procedure and required time-consuming additional assistance from ground. Control over task performance was another issue apparent in MC comments; for instance, MC stated that communication delay impacted their ability to assert themselves on the crew.

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Tanaka et al. (2020)	Risk Characterization	Mission Simulation (HERA)	At the team level, communication delays negatively impact the message routing completion rate. In the 180-second communication delay condition, only one out of five reached the destination, compared to four out of five in the no communication delay condition.
Lungeanu et al. (2023)	Risk Characterization	Mission Simulation (HERA)	Our findings suggest aspects of social isolation and communication delay affect task duration, information network development, and MTS performance.
Kintz et al. (2016)	Risk Characterization	Spaceflight (ISS)	The quantitative results suggest self-reports of crew well-being and the quality of communications were significantly reduced in communication delay tasks compared to control. In addition, both quantitative and qualitative data suggest communication delays were associated with stress and frustration.

Table A2. Communication Delay Focused References and Associated Study Information*

Reference	Study Aim		Study Type				One-way Latency (seconds)					
	RC	CD	LS	FA	MS	S	0	1-5	5-10	10-30	30-60	>60
Armstead & Henning (2007)	✓		✓				✓	✓	✓			
Beaton et al. (2017)	✓			✓								✓
Chappell et al. (2016)	✓				✓							✓
Fischer & Mosier (2014)	✓		✓				✓					✓
Fischer & Mosier (2015)		✓			✓		✓					✓
Fischer & Mosier (2020)	✓				✓		✓					✓
Fischer et al. (2013)	✓				✓						✓	✓
Frank et al. (2013)		✓			✓						✓	✓
Hurst et al. (2015)		✓	✓				✓	✓				
Kanas et al. (2011)	✓				✓		✓					✓
Kintz et al. (2016)	✓					✓	✓				✓	
Lungeanu et al. (2023)	✓				✓		✓				✓	✓
Mosier & Fischer (2023)		✓			✓		✓					✓
Stevens et al. (2019)	✓			✓								✓
Tanaka et al. (2020)	✓				✓		✓				✓	✓
Totals	11	4	3	2	9	1	10	2	1	0	5	12

* For Study Aim, RC = Risk Characterization, CD = Countermeasure Development. For Study Type, LS = Lab Study, FA = Field Analog, MS = Mission Simulation, and S = Spaceflight.

A1. Research on Communication Delays in Other Domains and Topic Areas

Delays occur in any communication involving multiple parties. As such, research on communication delays exists in other domains and topic areas, many outside of space operations. In the following, we provide a brief overview of some of them.

A1.1. Air Traffic Management

Air Traffic Management (ATM) is the dynamic, integrated management of air traffic and airspace achieved partly through seamless services performed in collaboration with all parties supported by real-time communication (Joint Planning and Development Office, 2010). Three types of time delays are present in air-ground communication between human pilots and air traffic controllers: audio delay, pilot delay, and controller delay (Rantanen et al., 2004). Audio delay is the product of the technology used in voice communication. Pilot delay refers to the delay introduced by the pilot in executing controller-issued maneuvers or responding to the controller. Controller delay likewise refers to the delay introduced by the controller in responding to the pilot's request. Operation of Unmanned Aerial System (UAS) aircraft incurs additional delays due to the pilot not being co-located with their remotely operated aircraft. Therefore, the FAA's plan to integrate UAS aircraft into the National Airspace System (NAS) requires research to specify acceptable remote pilot response delays so that those UAS aircraft can meet the same operational and certification standards as crewed aircraft (Vu et al., 2013).

In the management of crewed aircraft, Rantanen, McCarley, and Xu (2004) found that while short communication delays (from 150 to 1000 msec) did not substantially degrade controller performance, audio and pilot delays significantly reduced separation between aircraft. In the management of UAS aircraft, Vu et al. (2013) found that controllers rated UAS pilot verbal communication and execution delays as acceptable 92% of the time when they were short (1.5 sec); their level of acceptability decreased to 64% when the delays were long (5 sec).

A1.2. Conversation

Conversations that take place over any type of communication technology network (e.g., telephone, internet, satellite, cable) experience circuit transmission delays. Transmission delays arise from the substantial amount of time required for signals to traverse long paths (Krauss & Bricker, 1967). Voice communication also suffers from the interference of echoes. Newer technology such as Voice over Internet Protocol (VoIP) introduces new components into transmission delays: speech encoding, packet transmission, and packet queued in a jitter-buffer waiting to be unpacked, decoded, and played out (Schoenenberg, Raake, Egger, et al., 2014). Their disruptive effects on communication have become a staple of the daily working life of people using videoconferencing applications such as Teams and Zoom (Boland et al., 2022). Riesz and Klemmer (1963) found that roundtrip delays of 0.6 and 1.2 sec went unnoticed in telephone conversations when echoes were not present or suppressed. Krauss and Bricker (1967) found that a roundtrip delay of 1.8 sec deleteriously affected communication efficiency. Transmission delays also alter communication surface structure, which in turn impacts conversational quality (Schoenenberg, Raake, & Koeppe, 2014).

A1.3. Computer-Supported Remote Collaboration

Collaborative virtual environments, or Groupware, support real-time collaboration among distributed team members through the use of computer and communication technology (Ellis et al., 1991; Kraemer & King, 1988; Stefik et al., 1987). Like in conversations, network delays pose a challenge. There are two types of delay: latency and jitter (Gutwin, 2001). Latency refers to the lag between sending a message and receiving that message at the other end. Jitter refers to the variance in transmission time, manifesting as halting speeches or jerky movements. Latency combined with jitter can cause packets of messages to be delivered out of sequence, impacting processes that require strict sequencing like commanding. The magnitude of latency and jitter experienced in the actual use of groupware also depends on the power of the client machines, the bandwidth of network segments, the distance that message must travel, the number of routes the message goes through, and the current traffic level (Gutwin, 2001). Delays can impact the timeliness of feedback and coordination (turn-taking). They can also impact understanding of the shared situation: people may experience different orderings of events and arrive at different causal inferences (Gutwin et al., 2004).

Gutwin (2001) found that players of a real-time groupware game could deal with the latency and jitter (both in the range between 0 and 1000 msec) pretty well; game performance did not suffer and players did not report major difficulties. Park and Kenyon (1999) found that the effects of network latency and jitter on performance depend on the difficulty of a task that involves motor control; jitter had the greatest impact when the latency was high (200 msec) and the task was difficult.

A1.4. System Response Time

System response time measures in human-computer interaction the delay between a user's input command and the consequential output by the computer. The literature on system response time informs how long the delays can be before they begin to impede the user's subjective experience of interacting with an external partner (a computer or electronic device in this case). It bears implications on the impact of communication delays in communications with other parties from a subjective experiential aspect.

The idea behind the system response time literature is that systems should respond fast enough to not induce psychological blocks user's part that would prevent their full involvement in an interaction. The most typical psychological blocks are boredom, panic, frustration, confusion, and discomfort (Foley & Wallace, 1974). Because humans spontaneously organize activities into clumps terminated by the completion of a subjective purpose or subpurpose, the desired level of system response time corresponds to a user's subjective sense of completion or closure (Miller, 1968). According to Foley and Wallace (1974), human action occurs at three distinct levels of closure: lexical, syntactic, and semantic. The lexical level is characterized by reflex, either natural or trained. Such actions take about 50 msec to perform, approximately the period between key depressions for a very fast typist. Therefore, system response to lexical actions must be within the same time interval to support a smooth interaction. The syntactic level is characterized by actions that require constructing a complete thought or sentence. Such actions take about 1 sec; as a result, 2–4 sec delays may be tolerated. The semantic level is characterized by the generation of thoughtful answers. Such actions can take humans tens of seconds or more, therefore tolerable response time can be highly variable, from 2 sec to respond to a simple hello to 10+ sec to generate an answer to a complex question without causing the user to lose their train of thought.

A1.5. Space Teleoperation

Like crew-ground communication, space teleoperation is subject to the same light time signal transmission delay and delays incurred from computer processing at sending and receiving stations and at satellite relay stations. Teleoperation allows the manipulation of remote objects by providing the operator with a manipulator or joystick called the master. The operator issues a motion command by imposing a force on the master manipulator. That force is translated to a displacement, which is then transmitted to the remote slave to be realized in actual movement (Hokayem & Spong, 2006). Remote manipulation differs from continuous control situations in that the operator's job is to modify certain initial positions of objects in the remote environment to achieve given final positions rather than forcing the dynamic response of the object's movement continuously to match a specified time function. As a result, the trajectories and timing of the intervening positions are arbitrary within broad tolerance (Sheridan & Ferrell, 1963). Sheridan and Ferrell (1963) observed that when time delays were introduced, an experienced human operator used a move-and-wait strategy to operate a remote hand: making an open-loop movement first, waiting until the remote hand had responded, and repeating this process until the necessary accuracy had been achieved. With this strategy, task completion time increases linearly with time delay. To break away from the dependence on feedback in remote manipulation, Ferrell and Sheridan (1967) proposed a supervisory control approach that would additionally give the remote device the capability to interpret high-level symbolic (linguistic) commands issued by the operator, translate them into movements, and execute them autonomously (Hokayem & Spong, 2006).

According to Sheridan (1993), roundtrip delays in low-Earth orbit (LEO) are minimally 0.4 sec. The roundtrip delays increase to 3 sec for vehicles on or near the Moon and 6 sec for Earth-orbiting space shuttles due to multiple up-down links and buffering delays. Teleoperation means operating at a distance. Timman et al. (2023) found that a long-time delay condition (3 sec) increased the time and perceived workload to complete a lunar teleoperation sampling task and decreased heart rate variability compared to other shorter delay conditions (0.5 sec and 0 sec). Yang and Dorneich (2017) found that variability in time delays that resulted in intermittent and variable feedback lags (randomly set at 2 or 3 sec, averaging 12 delays per minute) in remote controlling a robotic vehicle through mazes led to increased operator frustration, anger, and workload and decreased usability and task performance.

A2. Playbook Mission Log

NASA Playbook's Mission Log (Marquez et al., 2019) was identified as a prominent tool which was used to collect data across 5/15 of the identified communication delay-focused studies (Beaton et al., 2017; Chappell et al., 2016, p. 18; Fischer & Mosier, 2015; Mosier & Fischer, 2023; Stevens et al., 2019). Playbook is the integrated timeline and operations software tool for nearly all NASA analogs, including HERA, NEEMO, AMO/DSH, RESOLVE, MVP, BASALT, DRATS, CHAPEA, HI-SEAS, and NextSTEP Hab. The primary function of Playbook is to visualize the shared mission Timeline view, which the analog team can modify, and concurrently support texts and file exchange between mission control and analog astronauts with a view called the Mission Log. As many of these studies and analog missions simulate varied amounts of space-to-ground communication latencies, Playbook dynamically adjusts to the required simulated latencies. Thus, Playbook changes (e.g., timeline modifications or messages) done by analog astronauts are only seen by mission control once the required time delay expires, and vice versa.

The Mission Log has an interface very similar to most modern text and multimedia-based chatting software (Marquez et al., 2019). Figure A2 shows a screenshot; the upper part of the user interface is dedicated to composing and sending messages, while the lower part is dedicated to viewing a running log of all messages going between MCC and crew. The user must select their role and then compose their message in the text box. The Mission Log supports multiple languages, GIF animations, and emojis. Currently, Playbook allows all crewmembers and MCC to view all messages at all times, increasing situation awareness across the team. Additionally, the user can attach a file, including photos and videos, which appear inline. Most recently, Mission Log's augmentations allow selecting receiver, attaching voice notes, and initiating message threads.

Unlike other communication platforms, the Mission Log provides multiple cues and indicators that provide insight into the effect of communication transmission latency. Users are given the following information:

- Timestamp for when a message was sent.
- Dynamic countdown timer for when the message will be received (i.e., after transmission delay).
- A timestamp for the earliest expected response time.

The countdown timer provides a clock timer in each sent message to indicate how much time remains before it arrives at the receiver's site. This capability is helpful and heavily used as users requested more precise timing information. It was previously observed that users need an easy way of tracking the effects of communication latency. Users often wondered why the other person had not replied to their message, not realizing that the delay between the crew and MCC had yet to transpire. The earliest expected response time provides that information, calculating the round trip of the one-way latency time.

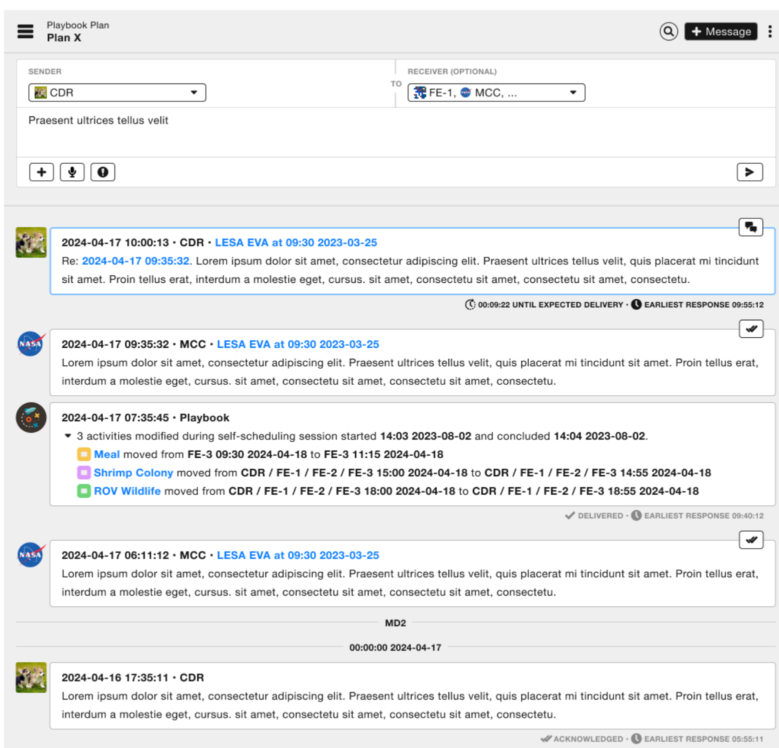

Figure A2. Playbook Mission Log, showing several example messages between Mission Control and crew.