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Protocols for Asynchronous Communication in Space Operations: Communication Analyses and Experimental Studies

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EXECUTIVE SUMMARY

The safety and success of future space missions will depend on the ability of crewmembers and Mission Control to collaborate effectively, even when communication between them is delayed. As mission travel further from the Earth, space-ground communication will involve significant delays, up to 20 minutes one way for missions to Mars. While the presence of communication delay will require future space crews to operate more autonomously than crews in current operations, the necessity of space-ground collaboration will remain. Solutions to mitigating the impact of communication delay that focus on faster transmission technology may succeed some day in providing seamless communication but current technology is not able to do so. It is therefore essential to explore solutions that focus on the communication process itself rather than transmission speed. The present research represents one such approach.

Currently little is known about how communication delay will impact space-ground collaboration and task performance, and how different communication media may mediate its effect. Nor do we know how best to support space-ground collaboration during periods of communication delay. Several studies involving communication delays of various lengths were conducted to address these gaps. One study consisted of an analysis of the communications between astronauts and Mission Control personnel recorded as part of the Autonomous Mission Operation (AMO) study conducted by Frank, Spirkovska, McCann, et al. (2013). In a second, laboratory, study we examined the impact of communication delay in relation to different communication media. Findings from these studies informed the design of medium-specific communication protocols as they highlighted which aspects of the communication process need support to ensure successful communication between remote partners under asynchronous conditions. The effectiveness and feasibility of communication protocols for space operations was subsequently assessed in two studies, resulting in refinements of the protocols and the design of a communication training module.

Analysis of the AMO data provided first insights into the effects of transmission delays on team communication. Specifically, we observed that transmission delays disrupted the timing and structure of turns (i.e., communications by different team members). Communications by different speakers co-occurred (i.e., step-ons in which team members talked over each other) or were out of sequence (i.e., related turns by partners did not follow each other as one partner inserted a turn before the addressee could respond to the initial contribution). Both types of disruptions likely increased team members' cognitive workload and jeopardized common ground (i.e., mutual task and team awareness). Step-ons compromised mutual understanding insofar as parts of a message were inaudible and required additional turns to repair which, given the transmission delay, were likely associated with considerable costs both in terms of time and workload (as partners had to wait for critical information and keep track of concurrent tasks). Contributions that were out of sequence could undermine mutual understanding in at least two important respects. When related contributions by members of the flight control team and the space crew did not immediately follow each other, partners had to keep track which conversation was still open requiring a response. This increased cognitive demand on team members may account for the finding that they frequently failed to respond to a partner's communication. Contributions that were out of sequence could also come too late; that is, a communication was overtaken by events and thus reached the addressee after the fact.

In a companion laboratory study we explored the impact of transmission delay on team communication and task performance in relation to varying task demands (procedural vs. ill-defined), and different communication media (voice vs. text). Spatially distributed teams of three collaborated in a computer-based task environment and communicated either by voice-over-internet or via a texting tool. The micro-world for the study was AutoCAMS 2.0 (Manzey et al., 2008) which simulates the life support system of a spacecraft and requires team members to monitor and control different subsystems, and to diagnose and repair failures. Each team was required to perform procedural and problem solving tasks during one synchronous and one asynchronous flight segment (5-min one-way delay in communications transmission). Each flight segment lasted for 90 minutes. In order to guarantee the requirement of communication and collaboration on the experimental tasks, task-related expertise concerning diagnostic and repair procedures was differentially distributed among team members. The Flight System Engineer (FSE) received extensive training on AutoCAMS systems, diagnoses, and repairs, and had access to a comprehensive reference manual. The two Pioneer crewmembers were given basic training on AutoCAMS and were instructed to contact the FSE for guidance on diagnosis and repair whenever a failure occurred on their system.

Analyses of team performance revealed that transmission delay impacted time required to initiate a successful repair and more importantly, that its effect varied by communication medium. When communication was delayed, teams used a comparable amount of time to repair system failures, irrespective of the communication medium used. However, when communication was synchronous, voice teams outperformed text groups. Likewise, teams' accuracy in performing system repairs was influenced by communication medium. Overall, teams communicating by text undertook more incorrect repairs than teams communicating by voice.

Analysis of FSE/Pioneer communications revealed that communication delay influenced both the rate of turns by team members and the length of their contributions. Team members made fewer but longer contributions when they communicated under time delay than when no time delay was present. Moreover, these effects were more pronounced for teams communicating by voice than those communicating via text. This finding suggests that team members using text may have been more concise than team members in the voice condition. However, subsequent content analyses of Pioneer Crew/FSE interactions during transmission delay revealed that text communication was also associated with an increased potential for misunderstanding. Text teams were more likely than voice teams to split up related information and present it in separate turns. Related communications (adjacency pairs such as question and answer) by distributed team members were also further apart (i.e., more unrelated messages intervened) in text- than in voice-based communications. Text communication also included more threats to common ground, in particular missing responses and anaphora (i.e., terms whose meaning could not be established within a turn but depended on information provided in preceding turns).

These differences are consistent with medium-specific affordances and constraints. Text provides team members with a written record of their on-going conversation, and thus may enable them to keep track of related contributions and the identity of referents across turns. However, as the presence of communication problems in the text group indicates team members may have overestimated the benefits of text-based communication. Voice communication is cognitively more taxing than text-based communication insofar as participants need to remember their ongoing discourse to interpret new information. Voice teams apparently adapted to this constraint by packing more information into one turn than text teams, behavior that kept related communications more closely aligned and may have aided comprehension.

Both text and voice teams showed instances of miscommunication in which team members misapplied assumptions and conventions of synchronous discourse to asynchronous conditions. Team members displayed proximity bias; that is, they mistook a remote partner's communication that immediately followed their own transmission as a response to it, or they showed insensitivity to the delay by repeating a message before they could have received a response from their partner. These instances required additional communication in which team members clarified their situation understanding, or they spiraled into misunderstanding from which team members never recovered and thus were unable to repair a system failure.

Both the AMO and the lab study also underscored the importance of several strategies that could support team communication under time-delayed conditions. Turn taking seemed to be facilitated when speakers announced specific times at which their addressees could expect a transmission. Mutual understanding may also be enhanced when speakers specify the topic of a message, present complex messages in meaningful chunks and repeat crucial information. Listeners, in turn, need to provide evidence of their understanding so that problems of hearing and comprehension are detected and repaired as quickly as possible.

Medium-specific communication protocols created as part of this project incorporated these strategies, as well as recommendations by Love and Reagan (2013). A protocol's structural characteristics were based on schema-based approaches to instruction design (Morrow & Rogers, 2008; Morrow et al., 1996; 1998; 2005). A communication protocol is a structured communication template consisting of four segments (Call Sign, Topic, Message, Closing) with specifications regarding their content and organization, and several communication conventions that address the major challenges of asynchronous communication—Time, Conversational Thread, and Transmission Efficiency. Media-specific instructions concern aspects of the call sign and conventions that are consistent with the affordances and constraints associated with voice or text communication. Medium-independent instructions concern the topic section of a message, the message body and the final—closing—section as well as several conventions designed to support conversational coherence, message comprehension and shared task understanding, as well as communication efficiency. The feasibility of the communication protocols for space missions was assessed in two analog environments (NASA's Extreme Environment Operations facility, NEEMO, and the Human Exploration Research Analog, HERA). A complimentary laboratory study was conducted to examine further whether the availability of protocols enhanced remote team members' communication and task performance during periods of communication delay.

The same task environment (AutoCAMS) as in the previous laboratory study on medium effects was used to assess whether the availability of protocols enhanced team communication and task performance of remote teams during communication delay. AutoCAMS (Manzey et al., 2008) simulates the life support system of a spacecraft, and in our task design, requires teams of three, spatially-distributed participants to diagnose and repair system failures. Teams were randomly assigned to either the Protocol (i.e., experimental) or No-Protocol (i.e., control) condition. Participants in the experimental group received the communication protocols and 30 minutes of communication instruction as part of their position-specific (Flight systems Engineer, FSE, or Pioneer crewmember) task training. Participants in the control group received only task specific training. After training, participants completed two 90-min sessions, one in which the communication between the Pioneer crew and the FSE was voice-based, and one that provided only text communication. Communication between remote team members in both sessions was delayed by 5 minutes one-way.

Analysis of task performance showed that the availability of communication protocols did not have a significant effect on the Pioneer crews' task performance in terms of time to resolve failures, incorrect repair attempts, or number of correct repairs. However, the availability of protocols was found to mitigate some communication issues associated with transmission delay. Specifically, protocols seemed to have helped team members with the structure and content of their contributions. On the other hand, training on the protocols apparently did not make it easier for team members to keep track of the time lag between their own and their remote partners' contributions; rather, aided team members were just as likely as unaided participants to misalign their partners' contribution or to repeat messages without allowing sufficient time for their partner to respond. These failures suggest that the expectation of immediacy is an ingrained habit of synchronous communication and to overcome it, may require more training than study participants received. We therefore increased the allotted time for the communication training in subsequent analog studies from 30 to 60 minutes to give participants more experience with the challenges of transmission delay as well as practice using the protocols. Another factor that may explain why trained participants persisted in relying on habits of synchronous communication, is the complexity of AutoCAMS, the micro-world used in our study. To cope with the workload associated with the task, some Protocol teams may have fallen back onto well-rehearsed and thus easy communication habits of synchronous discourse which, in turn, resulted in miscommunication and likely increased their workload even more. This explanation is also consistent with the finding that the availability of communication protocols did not lead to improved task performance. A final explanatory comment is that our study participants did not always conform to their assigned condition, and thus blurred the lines between control and experimental groups.

The communication protocols were also included in several space-analog simulations at NASA's Extreme Environment Operations (NEEMO) facility and the Human Exploration Research Analog (HERA). Participants in NEEMO-18 and NEEMO-19 and two HERA crews (Campaign-1 missions 3 and 4) received 30 minutes of communication training prior to their missions. Training for participants in the four missions of HERA Campaign-2 was increased to 60 minutes in response to feedback by crewmembers in the earlier missions and as a consequence of our lab study. Communication training identified the challenges of asynchronous communication and explained the elements of the communication protocols and conventions. Crewmembers of missions 1 and 2 of HERA Campaign 1 served as control and thus did not participate in any communication training.

In all NEEMO and HERA missions, communication delay occurred on consecutive mission days. Communication between crew and Mission Control was delayed by 5 minutes or 10 minutes one-way. In some simulations (NEEMO-18; HERA Campaign-1) communication medium was limited to voice or text on a given day with transmission delay, or the crewmembers could choose their communication medium (NEEMO-19, HERA Campaign-2). Copies of the communication protocols were given to trained participants at the start of a mission to serve as a reference aid on days with a communication delay.

Surveys were administered throughout a mission asking participants to rate the effectiveness of the protocols and their interactions with mission control, and in a final survey to provide feedback on individual elements of the communication protocols. Trained crewmembers generally rated protocol elements and conventions as fairly critical to ensuring effective communication during asynchronous conditions. Very high ratings across crews for several items—providing a topic, using a log to track related messages, and announcing complex or critical messages—reflect the value of protocols for keeping track of message threads. Compliance with the protocols was also high as crewmembers generally followed the protocols in their communications on mission days with a transmission delay.

Concurrent with these research efforts we conducted interviews with domain experts (Flight Surgeons, CapCom and PayCom). The goal of these interviews was to characterize challenges of space-ground communication in current operations, to discuss the impact of communication delay and to learn about communication strategies experts have adopted. Experts mentioned several strategies to ensure effective communication and emphasized the importance of joint training of ground support and crewmembers to establish mutual trust. These strategies are consistent with the communication protocols we developed as well as our training approach that involved a joint session with HERA crewmembers and HabComs.

Overall these research findings suggest that asynchronous communication may be facilitated by protocols that aid conversational partners in keeping track of conversational threads and the temporal sequence of messages. Our findings let to the development of a communication training module that can be used to prepare crewmembers and members of Mission Control for the challenges of communication delay. Moreover, the communication protocols not only target how to speak or write during asynchronous conditions but also point to specific technological solutions. One example is the text tool that was adopted in NEEMO-19 and assisted the crew with the temporal aspects of asynchronous communication. Further improvements might be a less chat- and more email-like text tool that includes a subject header and links between related messages to make it easier for conversational partners to follow a conversational thread. A text tool could also provide a template that gives structure to a message and highlights its components. Likewise, voice communication could be facilitated if recordings of messages were available to both sender and receiver, and if the recording indicated when a message was transmitted. And lastly, it is conceivable that the recording tool would include prompts for specific message components.

I. INTRODUCTION

The safety and success of future space missions will depend on the ability of crewmembers and Mission Control to collaborate effectively, even when communication between them is delayed. As missions travel further from the Earth, space-ground communication will involve significant delays, up to 20 minutes one way for missions to Mars. While the presence of communication delay will require future space crews to operate more autonomously than crews in current operations, the necessity of space-ground collaboration will remain. Unforeseen problems for which crews will need assistance from mission control, such as system failures or medical emergencies, may arise as examples from Apollo missions to the present day illustrate.

Communication delays can have a substantial impact on the efficiency and success of distributed team collaborations (Krauss & Bricker, 1966; Kraut, Fussell, Brennan, & Siegel, 2002), especially those that are complex and time intensive. Investigations of asynchronous communication in domains such as telemedicine have identified communication delays as a primary impediment to effective telesurgery, and have prescribed faster transmission technology (e.g., asynchronous transfer mode) as the solution (e.g., Eadie, Seifalian, & Davidson, 2003). Given the current limitations of earth-space transmission technology, however, it is essential to explore solutions that focus on the communication process itself rather than transmission speed. The present research represents one such approach.

Research Goals

The overall aim of this research project was to develop and validate medium-specific communication protocols that enable flight controllers and space crews to establish and maintain common ground (i.e., mutual task and situation awareness) and coordinate problem solutions in response to different operational tasks during periods of communication delays. To achieve this objective several ground-based studies (space analog and laboratory) were conducted. The first set of studies had the goal to determine how transmission delays of various lengths impact team communication and performance under different media conditions. Findings then informed the design of medium-specific communication protocols. Their feasibility for space missions was assessed in two analog environments (HERA and NEEMO). A complimentary laboratory study was conducted to examine further whether the availability of protocols enhanced remote team members' communication and task performance during periods of communication delay.

These accomplishments directly address the BHP Team Risk (*Risk of performance decrements due to inadequate cooperation, coordination, and communication, and psychosocial adaptation within a team*) as well as BHP team-related gaps:

- *Team Gap 3: We need to identify a set of countermeasures to support team function for all phases of autonomous, long duration and/or distance exploration missions.*
- *Team Gap 5: We need to identify validated ground-based training methods that can be both preparatory and continuing to maintain team function in autonomous, long duration, and/or distance exploration missions.*

Theoretical Framework

Common ground theory of communication (Clark, 1996; Monk, 2009) guided our research as it seemed better suited to capture relevant aspects of team communication in the context of collaborative work than the information processing approach prevalent in cognitive engineering and human factors research. While the latter approach focuses on the encoding and decoding of messages, common ground theory characterizes communication as a collaborative effort by speakers and addressees towards sense-making. Moreover, common ground theory relates communication processes to the opportunities that different communication media provide to conversational partners. Conversational partners need to coordinate the communication process (e.g., when to speak) as well as its content (e.g., speakers present information and addressees have to confirm their understanding or request clarification) to ensure that the information becomes part of their common ground—that is, it is accepted as mutually understood, accurate and relevant to shared goals (Clark, 1996). To do so effectively, partners need to adapt their behavior to the opportunities and constraints associated with different communication situations and media (Brennan & Lockridge, 2006; Clark & Brennan, 1991; Olson, G. & Olson, J., 2007). Table 1 compares different communication situations and media with respect to the resources they provide to conversational partners, contrasting synchronous communication with asynchronous situations space and ground crews may experience during long-duration space missions.

Table 1. Resources Provided by Different Communication Media

	Media				
	Synchronous			Asynchronous	
Affordances of Media	Face-to-face	Audio-only (e.g., VOIP)	Text-based (chat)	Audio-only (e.g., VOIP)	Text-based (chat)
Physical co-presence: Aware of shared physical environment; possible to see what other is doing and looking at	++	--	--	--	--
Visibility: Can see other but not necessarily what they do or look at	++	--	--	--	--
Audibility: Can hear each other	++	++	--	++	--
Co-temporality: Present at same time, messages received without delay	++	++	++	--	--
Simultaneity: Messages can be sent and received at the same time	++	++	++	--	--
Sequentiality: Turn taking proceeds in orderly fashion, relevance of a turn signaled by adjacency	++	++	++	?	?
Reviewability: Messages do not fade over time	--	--	++	--	++
Revisability: Messages can be edited prior to transmission	--	--	++	--	++

During face-to-face interactions conversational partners are co-located and thus may presume that information in their shared visual field is mutually known. Turn-taking between partners is rapid and in sequence, and partners may rely on gestures and facial expressions to direct the other's attention and provide feedback on their understanding. Remote partners who communicate synchronously—e.g., air traffic controllers and pilots—lack a shared visual field and visibility; however, turn-taking can be rapid as messages can be received almost instantaneously, and their order easily determined. Voice communication enables remote team members to indicate their understanding and agreement (via backchannel behavior, such as '*hmm'*) concurrently as messages are produced; in text-based communications (chats) responses will follow the initial message with a slight delay. Written communication enables partners to re-read and thus remember their past contributions, and to review and revise their messages prior to sharing them with others. These resources are not available in spoken discourse where participants have to rely on their memory or may use external aids (e.g., note pad) to keep track of the flow of the conversation and to compose their contributions.

Communication between remote partners involves several challenges. In voice-based communication team members may miscalculate the timing of their contribution and talk over each other; i.e., they start to speak at the same time or before their partner is finished. When remote team members do not have a common visual field, grounding is more effortful and misunderstandings more likely than in face-to-face or video-supported communications. As they cannot monitor others for comprehension, remote partners need to provide more information to ensure mutual understanding, resulting in lengthy contributions that take longer to produce, especially in text-based communications (Kraut, et al., 2002). A pernicious issue in remote collaboration is that team members overestimate the extent to which their task- and team awareness is shared by their partners, and thus fail to communicate relevant information, neglect to highlight the criticality of information, or misunderstand their partners' intended meaning (Cramton, 2001; Mark, 2002; Olson, J. & Olson, G., 2006). This problem may remain undetected for quite some time while team members seem to communicate successfully. Such errors have been noted in mission control–space crew interactions (Bearman, Paletz, Orasanu, & Thomas, 2010) as well as in ATC-pilot communications (Bearman, et al., 2010; Davison, Fischer, & Orasanu, 2003) and have contributed to commercial aviation accidents (e.g., Eastern Air Lines 401 near Miami in 1972; collision of KLM 4805 and PanAm 1736 on Tenerife in 1977; Avianca Air 52 at Cove Neck, NY in 1990; American Airlines 965 near Cali in 1995).

II. THE CHALLENGES OF ASYNCHRONOUS COMMUNICATION

Communication delays can have a substantial impact on the efficiency and success of distributed team collaborations (Krauss & Bricker, 1966; Kraut, Fussell, Brennan, & Siegel, 2002), especially those that are complex and time intensive (Olson, G. & Olson, J., 2000). For instance, Palinkas and colleagues (Palinkas, Kintz, Vessey, Chou & Leveton, 2016) report that even a delay as short as 50 seconds significantly decreased team members' perception of their communication quality. In addition to the obvious threats inherent in having to wait for responses to potentially time-critical communications, problems with message management and comprehension are likely to occur. Specific problems may include simultaneous and repeated communications by remote team members because the coordination and timing of contributions is difficult under time delayed conditions. Likewise, as related communications by team members may not be in sequence they likely will find it more difficult to follow the thread of a conversation and thus to develop shared situation models. As mutual understanding becomes more effortful, misunderstandings are more likely in asynchronous communication, especially because there is no immediate feedback. We explored these issues in two studies involving communication delays of various lengths. One study consisted of an analysis of the communications between astronauts and Mission Control personnel recorded as part of the Autonomous Mission Operation (AMO) study conducted by Frank, Spirkovska, McCann, et al. (2013). In a second study we examined the impact of communication delay in relation to different communication media.

AMO STUDY: CREW – MISSION CONTROL COMMUNICATION UNDER DIFFERENT ASYNCHRONOUS CONDITIONS

The AMO project addressed the allocation of responsibility among flight crew, ground crew and automation given communication delay between the space vehicle and earth. These issues were investigated during two days of simulated space missions in NASA's Deep Space Habitat. Each day consisted of one training session and two experimental sessions presenting crewmembers with routine (procedural) tasks and several unanticipated (ill-defined) events. The first day of the experiment, the Baseline condition, involved present day equipment, and the space crew and flight control team (FCT) communicated via voice-loop under varying levels of time delay. The second day, the Mitigation condition, introduced new communication equipment (a Texting Client to be used by the crew for non time-critical and non-emergency communications) and automation to support the space crew in identifying and recovering from system failures. Our analysis of the AMO communication data considers only the crew-mission control communications that occurred during the two experimental sessions on day 1 (i.e., when team members communicated by voice loop). The purpose of our analysis was to examine how transmission delays of various lengths impacted the interactions between flight controllers and space crews during routine and off-nominal tasks, and to identify communication strategies that may have helped the flight controllers and space crews establish and maintain common ground (i.e., mutual task and situation awareness).

Method

Participants

Four teams of NASA flight controllers and astronauts were recruited for the study. Each team consisted of eight flight controllers and four space crewmembers.

Procedure

The teams participated in six simulated space missions over two days. Both experimental days included one mission in which space-ground communications were delayed by 300 seconds (representing deep space missions) and one in which the delay was 50 seconds (representing missions to Near Earth Objects). Each mission lasted for 2 hours and required teams to complete 12 activities. One of these was either a medical emergency or a system failure (= ill-defined task); the remaining 11 activities were routine maintenance (= procedural) tasks. The sequence of transmission delays was fixed with the first session always involving a 300 sec time lag between space-ground communications; medical and system failures were counterbalanced across mission control - astronaut teams.

Communication Coding

Communications between flight controllers and space crews were transcribed and subsequently coded. Our analysis of team members' communications addressed both communication process and content variables. The analysis of process variables concerned the timing and sequence of team members' contributions (= turns). In particular, we examined whether there were turns that were out of sequence (i.e., related turns by partners did not follow each other as one partner inserted a turn before the addressee could respond to the initial contribution), and we looked for instances of step-ons (i.e., flight controllers and space crewmembers talked over each other). We also noted the presence of strategies that may facilitate turn taking, such as the use of specific phrases (e.g., over) to mark the end of one's turn.

The analysis of communication content examined whether space crewmembers identified themselves when they talked to the flight control team (FCT), and whether flight control identified the crewmember to whom his/her communication was directed. Communications from the FCT to the space crew were conducted by one specific flight control position (= CAPCOM). As there were four space crewmembers, it was important for CAPCOM to specify the addressee of his/her communication: the crew as a group; the commander; or one of three flight engineers (FE-1, FE-2, or FE-3). Likewise, the astronauts had to identify themselves in their communications to mission control to ensure that CAPCOM responded to the correct partner. On the other hand, communications regarding the medical emergency involved only the Flight Surgeon at Mission Control and one space crewmember, the Crew Medical Officer (CMO) and were conducted via a separate (private) communication line. The identity of speaker and addressee was thus not an issue during these conversations; consequently, these communications were not considered in this analysis.

Content coding also focused on how addressees—CAPCOM, Flight Surgeon, and space crew—confirmed their understanding during conversations: whether they repeated information, simply acknowledged receipt with phrases such as *copy all*, or failed to provide any feedback. Communication failures—i.e., when addressees indicated that they did not hear part of a communication or incorrectly repeated information—were noted, as well as strategies supportive of mutual understanding, specifically whether speakers structured complex information into concise units or repeated critical pieces of information.

Results and Discussion

Given the small sample size only descriptive analyses were conducted. Individual examples of communication problems and of strategies that likely facilitated common ground and team coordination are provided as illustrations of our analytic approach.

Process Variables

Inefficiencies in turn taking. Disruptions in the turn sequence were observed under both time delay conditions (see Table 2.1), and involved contributions that were out of sequence or instances in which a team member—for example a space crewmember—was speaking as a communication from CAPCOM that had been transmitted 50 or 300 seconds before came in. These so-called step-ons compromised mutual understanding insofar as parts of a message were inaudible and required additional turns to repair which, given the transmission delay, was likely associated with considerable costs both in terms of time and workload (as partners had to wait for critical information and keep track of concurrent tasks).

TABLE 2.1. Number and Type of Disruptions in Turn Sequence (by team and transmission delay)

	Team 1		Team 2		Team 3		Team 4	
	300 sec	*50 sec*	*300 sec*	*50 sec*	*300 sec*	*50 sec*	*300 sec*	*50 sec*
Step-on	2	0	0	3	2	7	0	1
Out of Sequence	6	5	6	7	9	13	5	4

Note. *The sequence of transmission delays was fixed with the first mission always involving a 300 sec time lag between space-ground communications*

Turn-taking could be facilitated if partners marked the end of their contribution with phrases such as *over*; *that's all*; or *Thank you*. However, as shown in Figure 2.1 space crewmembers and members of the Flight Control Team (CAPCOM and Flight Surgeon) did not consistently adhere to this strategy, especially when the time delay was 50 seconds. In contrast, when communications were delayed by 300 seconds, they were more likely to do so; albeit at most 40% of the time. This finding suggests that team members were sensitive to the increased uncertainty associated with the longer delay between their communications and took steps to reduce it. That is, by explicitly indicating that they had nothing more to say (and thus there was nothing more to wait for), they handed the floor to their partner.

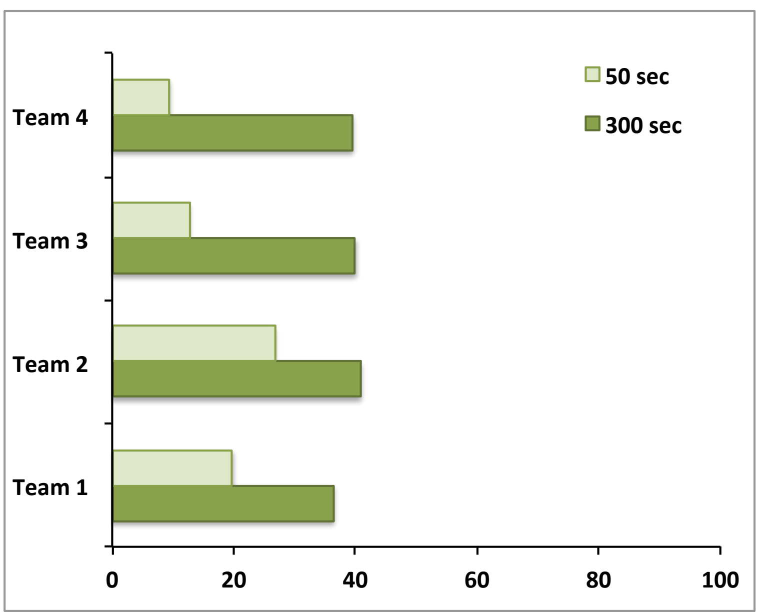

Figure 2.1. Percentage of turns by FCT and space crews with turn ending explicitly marked

Contributions that were out of sequence could undermine mutual understanding in at least two important respects. When related contributions by members of the flight control team and the space crew did not immediately follow each other, partners had to keep track which conversation was still open requiring a response. This increased cognitive demand on team members may account for the finding that they frequently failed to respond to a partner's communication, as shown in Figures 2.4 and 2.5 below. Contributions that were out of sequence could also come too late; that is, a communication was overtaken by events and thus reached the addressee after the fact. This situation is depicted in Figure 2.2, which summarizes an exchange between CAPCOM and a flight engineer (FE-2) during a 50 sec delay.

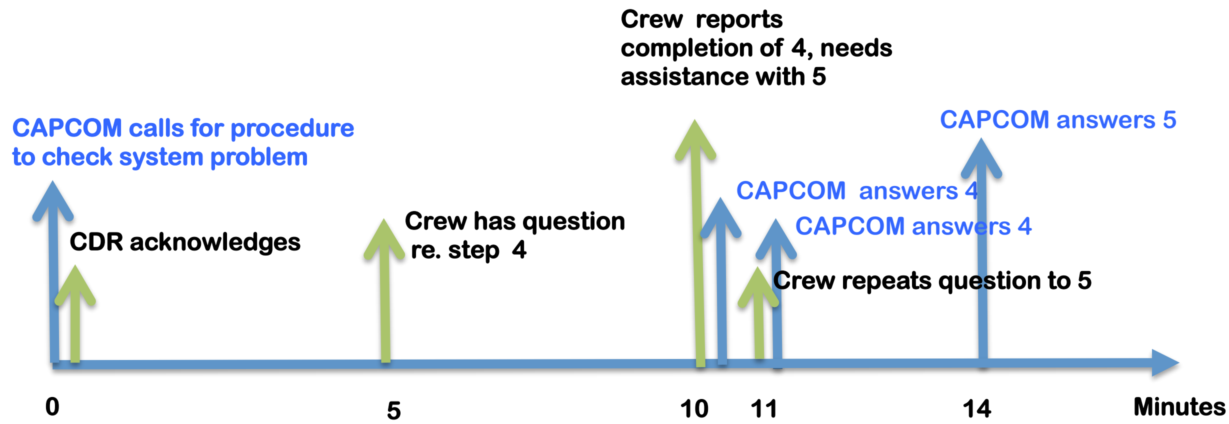

Figure 2.2. Depiction of a conversation in which turns are out of sequence

In the example FE-2 requested input from CAPCOM concerning step 4 in a procedure. As he did not hear back from mission control in time, he proceeded with the step just to encounter a new ambiguity in the subsequent step, and thus again turned to mission control for help. However, CAPCOM answered the initial request before receiving his second one, and, apparently because he did not hear any acknowledgment from FE-2, repeated his by now superfluous answer instead of responding to FE-2's second request. Meanwhile FE-2 repeated his second query, which ultimately got addressed 4 minutes after it was first posed.

Supporting turn taking. In three of the teams (see Table 2.2 below) space and flight control team members announced a specific time (e.g., *we will have step 3 to copy in five seconds*) at which their partner could expect further communication from them. This strategy has not been observed in past research on synchronous distributed team interactions (such as ATC-pilots), presumably because the partners can immediately respond to one another and thus an orderly progression of turns is rather effortless. On the other hand, when team members communicate asynchronously, they do not know when their remote partner will talk to them. Setting a time for one's communication eliminates this uncertainty and may thus mitigate both out of sequence communications and step-ons.

TABLE 2.2. Strategies Employed by Space – Flight Control Teams to Support Turn Taking and Mutual Understanding

	Team 1		**Team 3**		**Team 2**		**Team 4**	
	300 sec	*50 sec*	*300 sec*	*50 sec*	*300 sec*	*50 sec*	*300 sec*	*50 sec*
Timing	4	4	0	0	4	0	0	2
Topic	2	1	0	4	2	6	0	1
Chunking	2	2	1	4	2	3	2	1
Repetition	0	1	0	1	2	2	1	3

Note. *Numbers reflect frequencies of occurrence during sessions*

Communication Content

Inefficient collaborations on content. Space crewmembers sometimes did not identify themselves when they called FCT. Likewise, CAPCOM sometimes failed to specify the space crewmember to whom his or her contribution was directed. These omissions, shown in Figure 2.3, required CAPCOM (or the space crew) to infer the identity of the caller (or the addressee) from the content of the message. While dropped identifiers apparently did not hamper space-ground communications in our sample, this behavior could potentially impair mutual understanding as it creates ambiguity concerning the identity of the speaker (or addressee). In time-critical or high workload situations, partners may fail to make correct inferences and thus may mistake the identity of the speaker or recipient of a communication - and ultimately may misunderstand its intended meaning.

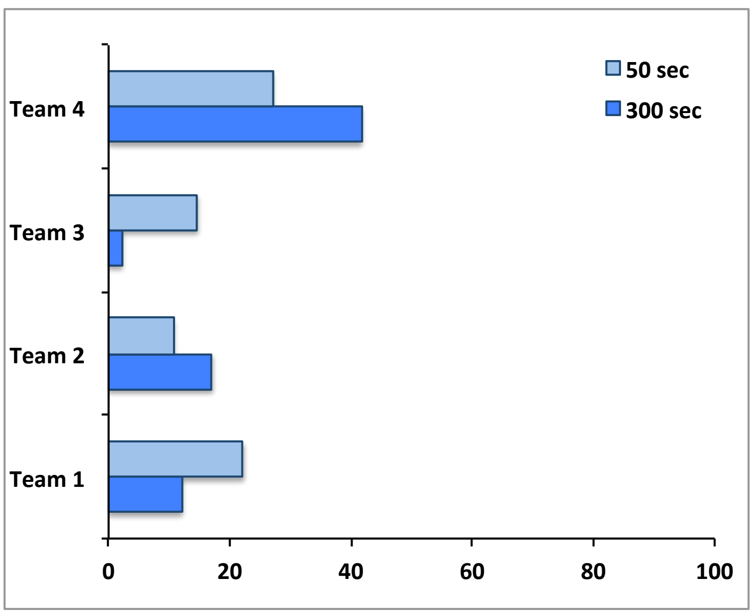

Figure 2.3. Percentage of turns by CAPCOM and space crew with dropped identifiers

Figures 2.4 and 2.5 show that listener feedback was frequently not optimal as space crews and FCT members provided minimal or ambiguous evidence of their understanding, or failed to respond altogether to a partner's communication. Minimal and ambiguous responses, such as *we copy all*, or *we copy your last* (after several transmissions by the same speaker), are short acknowledgments with which addressees indicate receipt of a message and their belief that they correctly understood. However, these responses do not convey *what* addressees understood and thus deprive speakers of the opportunity to verify that their message was understood as intended. Read-backs are standard operational procedure in space operations and are intended to catch misunderstandings before they lead to incorrect actions. Missing responses by addressees also introduce ambiguity as they could indicate that addressees did not hear, are too busy to respond, or disagree. They likely increase speakers' workload and could result in frustration and miscommunication. For example, in one situation the flight surgeon had to instruct a space crewmember (FE-3) on how to conduct an ultra sound for a bladder scan. As FE-3 did not respond to the surgeon's communications, she (the surgeon) apparently got concerned that there was a transmission problem and finally requested: *Make sure that you copy after you received this message, please. I would like to have an understanding that you are hearing me correctly.*

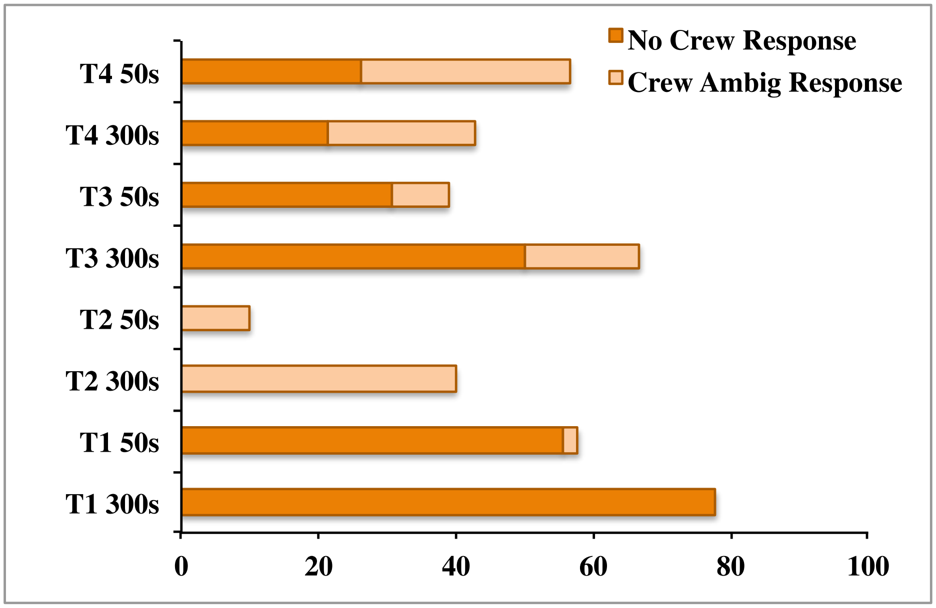

Figure 2.4. Percentage of turns by FCT that received no or an ambiguous crew response

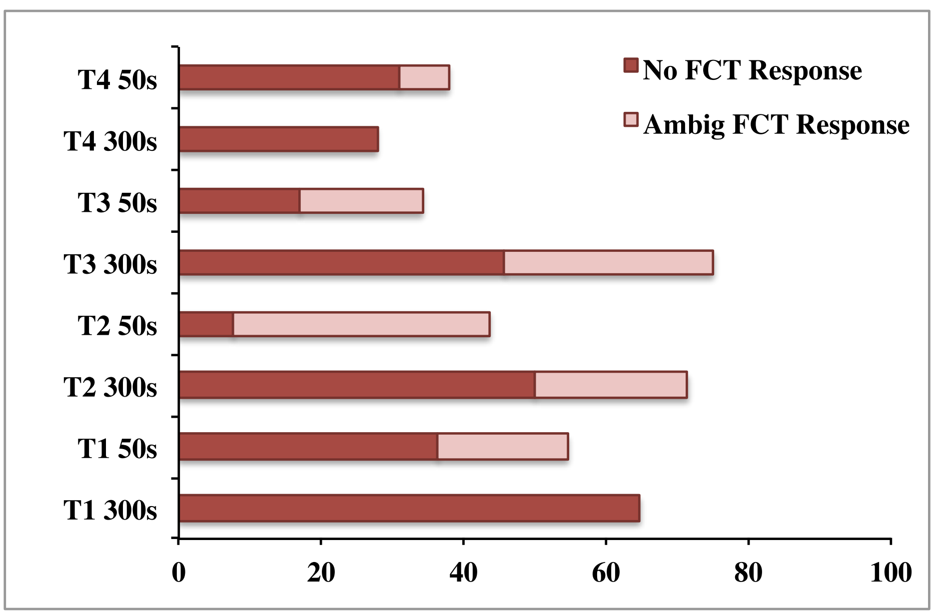

Figure 2.5. Percentage of turns by space crew that received no or an ambiguous response by FCT

Supporting mutual understanding. Addressees can facilitate mutual understanding by repeating what they heard and understood. In so doing, speakers can verify that their message was understood as intended and if necessary, can correct any problems. The value of read-backs was apparent in an instance in which a flight engineer (FE-3) misunderstood one value to be used in configuring a robotic camera. Fortunately, CAPCOM caught the error and corrected it right away - even though there was a transmission delay of 50 sec, the flight controller's correction reached FE-3 just after 2 minutes and thus in time to prevent him from starting the survey with an incorrect configuration.

Mutual understanding was likely aided by team members' presentation of information in a well-structured manner. Flight controllers and space crew members sometimes prefixed complex messages with a topic summary, akin to a subject header in emails, such as *Houston FE-3 with a status on procedure 8 decimal 1*. In so doing, team members grounded their contribution in their ongoing discourse and thus may have facilitated comprehension. This strategy seems particularly helpful when communication is asynchronous and team members need to keep track of individual contributions and their relationship over an extended period of time. Likewise, flight controllers supported grounding by packaging complex instructions into meaningful chunks. A typical example of this behavior is the following communication by CAPCOM: *We have DPC [Daily Planning Conference] comments for you today. First off with respect to the fluid transfer we have a supply tank level of 81%, an atrium rank level of 19 % and a desired tank level of 90%. The comma value that we will use in step 2 is 39 minutes. That takes care of it for the fluid transfer. With respect to the vehicle survey in procedure 8 decimal 1 we like you to give us a heads up after you completed step 1 decimal 4. … And that's all we have from Houston.*

Conclusions

Team communication requires the collaboration of conversational partners to ensure mutual understanding. Our analysis of mission control – space crew interactions identified several problems that distributed teams may encounter when their communications are asynchronous. Specifically, we observed that transmission delays disrupted the timing and structure of turns as communications by different speakers co-occurred or were out of sequence. Both types of disruptions likely increase team members' cognitive workload. The former necessitates that speakers repeat their contributions while the latter requires team members to keep track of multiple open issues.

Our analysis also underscored the importance of several strategies that could support team communication under time-delayed conditions. Turn taking seemed to be facilitated when speakers announced specific times at which their addressees could expect a transmission and when they marked the end of their contributions. When a team involves more than two individuals it may be important that speakers identify themselves and their addressees to ensure that that the intended audience is listening. Listeners, in turn, need to provide evidence of their understanding so that problems of hearing and comprehension are detected and repaired as quickly as possible. Mutual understanding may also be enhanced when speakers specify the topic of a message, present complex messages in meaningful chunks and repeat crucial information.

The analysis of the AMO data provided first insights into the effects of transmission delays on team communication; however, it was limited by its small sample size, the absence of performance data and its focus on voice communication. To address these limitations, a laboratory study was conducted that examined the impact of transmission delay on remote team members' task performance and collaboration in relation to different communication media.

THE IMPACT OF COMMUNICATION DELAY AND MEDIUM ON TEAM INTERACTION AND TASK PERFORMANCE

In this study we examined the effects of transmission delay on team communication and task performance under different media conditions (voice vs. text). The study design was a 2 (communication medium – voice vs. text) x 2 (task type – simple vs. difficult/problem-solving failure) x 2 (time delay – no delay vs.

5-min delay) mixed design. Communication medium was a between-teams variable; task type and time delay were varied within teams.

Communication medium and transmission delay were predicted to significantly impact team communication and task performance. Transmission delay was hypothesized to be associated with decrements in task performance, and to disrupt the structure and coherence of team communication making it difficult for distributed team members to establish common ground. These effects were predicted be most evident when team members relied on voice communication.

Method

Participants

The study included 72 (24 teams of 3) undergraduate and graduate students between the ages of 21-55. All participants were fluent English speakers, had at least two years of college, and had experience with computers.

Experimental Task

The micro-world for the study was AutoCAMS 2.0 (Manzey et al., 2008) which simulates the life support system of a spacecraft and requires team members to monitor and control different subsystems, to diagnose failures and to repair them. This micro-world can mimic critical aspects of Mission Control-flight crew interactions during space operations, has been used in spaceflight research (e.g., Lorenz, DiNocera, Röttger, & Parasuraman, 2002), and has considerable face validity. The operators' task is to observe the systems and to take action whenever any malfunctions or failures are detected. An automated decision aid, AFIRA (Automated Fault Identification and Recovery Agent), can be programmed to support this task by providing a warning light indicating a malfunction and information about the nature of the failure. For this study, AFIRA was programmed to be accurate 75% of the time, so that one out of four indications was incorrect (requiring additional diagnostic steps). Additionally, AutoCAMS included two secondary tasks intended to increase cognitive and attentional load: 1) a "connection check" that confirmed the goodness of the connection between the spacecraft and, in our simulation, the fictional US Space Station; and 2) a "recording task" that required periodic checking the CO_2 level and logging its value in a databank. The interface, shown in Figure 2.6 below, contains: a) history graph; b) flow chart; c) control panel; d) master alarm; e) repair menu; f) AFIRA message display; g) elapsed time display; h) connection check; and i) CO_2 check.

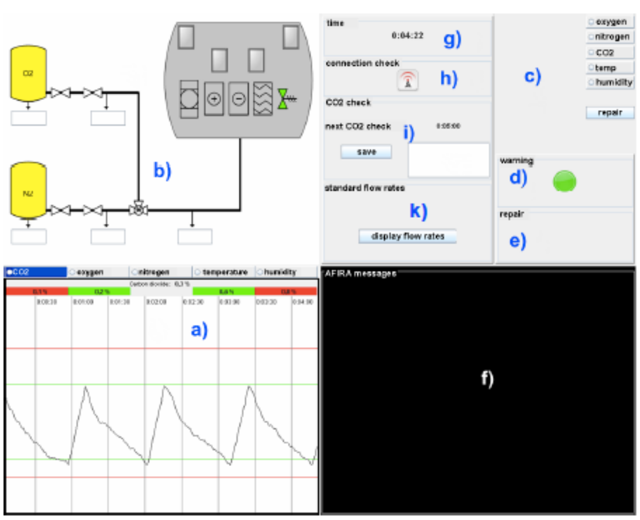

Figure 2.6. AutoCAMS 2.0 interface (From Manzey et al., 2008)

Procedure

Teams of three participants were randomly assigned to one communication mode condition. One participant in each team was assigned to the role of Flight Systems Engineer (FSE) and AutoCAMS expert onboard the fictional US Space Station; the other two participants were told they were *Pioneer* spacecraft crewmembers on an exploratory mission in deep space. In order to guarantee the requirement of communication and collaboration on the experimental tasks, task-related expertise concerning diagnostic and repair procedures was differentially distributed among team members.

Team members were given 2-4 hours training, depending on their roles and until they could demonstrate task proficiency for their respective roles. The FSEs received extensive training on AutoCAMS systems, diagnoses, and repairs, and had access to a comprehensive reference manual. The FSE was responsible for monitoring and maintaining the life support systems of the Space Station and assisting the Pioneer crew with system failures on their vehicle (two failures were programmed to occur during each leg). Pioneer crewmembers were given basic training on AutoCAMS: they were trained on how to access diagrams of its systems, but did not receive any instruction on failure diagnosis and repair. When a failure occurred on their system, the Pioneer crew had to contact the FSE for guidance on the diagnostic process and repair procedures. The collaborative demands of this situation were analogous to events in space operations for which astronauts lack in-depth expertise; for example, the medical emergency situation included a space-analog simulation study conducted by Frank and colleagues (Frank et al. 2013). Each role also required several secondary tasks (CO2 logs each minute; Connection checks; System parameter reports by Pioneer crew to FSE and recording of parameters by FSE; GEO lab rock specimen classification; asteroid emergency landing plan) that tapped prospective memory, reaction time, and attention to detail, and were intended to provide a moderate-to-high level of workload, similar to the workload astronauts might experience. During the experimental session (usually the day following training), FSE-Pioneer teams collaborated in two 90-min flight segments, one with synchronous communication and one with a 5-min transmission delay, with order counterbalanced across teams.

Task type. During each flight segment, the Pioneer spacecraft experienced two AutoCAMS malfunctions for which the crew needed assistance from the Flight Systems Engineer. One failure was simple (the automated alarm specified the failure) and its diagnosis involved only confirmation of diagnostic parameters before repair. The more complex failure presented the crew with ambiguous system indications and required several back-and-forth communications with the FSE to discover the specifics of the malfunction and prescribe the appropriate repair. The order of tasks was counterbalanced across media and communication-delay conditions.

Communication mode. The Pioneer crew communicated with the FSE via either text or voice as assigned. Text-based communications used Pidgin, a multiprotocol instant messaging program. Voice communications between Pioneer crews and the FSE employed a voice over internet protocol (VOIP). Transmission delay of voice and text communications in the asynchronous flight segment was achieved by routing them through a Linux-based emulator developed by NASA engineers at Kennedy Space Center and set up on a San Francisco State University server.

Task Performance Measures

Task performance data (i.e., interactions with AutoCAMS) were collected by the computer-based experimental system. Task performance was measured in terms of time required to initiate a successful repair as well as accuracy of the repair procedure. The duration of a failure was measured from the appearance of a red alarm and corresponding failure message to the initiation of the correct repair (time in red). Performance data on secondary tasks were also collected but will not discussed here.

Communication Measures

Communication analysis focused on the interactions between the FSE and the Pioneer crew during the failure repair tasks. Audio-recordings of the voice communications between the crewmembers and the

FSE were loaded into Audacity, an audio-editing software, and transcribed for subsequent analysis. Logs of team members' text-based communications were directly uploaded for analysis.

The unit of analysis for the communication coding was a turn. In the voice condition, "turn" refers to an uninterrupted speech segment by a speaker usually marked by turn signals (e.g., *Thanks*; or *Ok*?), falling intonation, or pauses. In text-based communications, any text written by a participant before pressing the send button constitutes a turn.

Communication analyses examined quantitative characteristics (i.e., communication rate and length) of Pioneer crew - FSE communications during both synchronous and asynchronous flight segments. Structural aspects and content variables of their communications were analyzed only for the asynchronous flight segment. Structural aspects concerned *information splitting* (related information, such as diagnostic cues, is presented in separate turns) and the *distance between adjacency pairs* (i.e., the number of turns intervening between pairs of related communications by conversational partners, such as question-answer). Content coding focused on communication problems and threats to common ground as well as strategies aimed at managing communication delay. *Communication problems* included instances in which a team member did not provide information requested by his/her partner, or when the team member asked the partner to clarify information or repeated an earlier contribution that had not been acknowledged. A subcategory of communication problems concerned instances in which a team member displayed proximity bias (i.e., misinterpreted a partner's contribution that immediately followed his/her own most recent communication as a response to it). *Threats to common ground* included instances in which team members showed insensitivity to the transmission delay (i.e., they repeated information or requested feedback before they could have received a response), or did not respond to or acknowledge contributions by a partner. Threats to common ground also concerned responses that were out of sequence (i.e., response was received after events had rendered it outdated), as well as the use of terms whose meaning could not be established within a turn but rested on information that had been given earlier in preceding turns. For instance, "We completed the repair" required the addressee to remember elements in previous communications to identify the relevant repair. Likewise, to understand what the phrase "Roger that" acknowledged, depended on immediately preceding context.

Two raters with extensive experience in communication analysis independently coded structural and content characteristics of 1/3 of the Pioneer/FSE communications during each media condition. Interrater agreement was assessed using Cohen's Kappa (Cohen, 1960), a more conservative measurement of interrater reliability than percent agreement since it takes chance agreement into account. Reliability was found to be adequate (Cohen's Kappa = .73) as values of .70 or larger are considered sufficiently high as to rule out that agreement was due to chance (Bakeman & Gottman, 1986). One expert proceeded to code the remaining team communications.

Results and Discussion

Task Performance

Mixed-design Analysis of Variance (ANOVAs) on time in red indicated that as predicted teams took significantly longer to repair system failures under time delay (TD) than when they had no time delay (NTD), $F(1,22)=7.54$, $p=.012$, partial $eta^2=.253$. Surprisingly, this difference was concentrated only in the voice medium, as reflected in a significant time delay x medium interaction, $F(1,22)=7.98$, $p=.01$, partial $eta^2 =.266$. Under time delay, teams using either media performed comparably in terms of time to repair. When communications were synchronous, however, the voice condition provided an advantage and voice teams took significantly less time than text teams on system failure tasks (see Table 2.3). No significant effects of medium, $F(1,20) = .001$, ns., or transmission delay, $F(1,20) = 2.67$, ns., were observed on number of correct repairs. Two crews attempted an unusually high number of repairs without direction from the FSE, and were excluded as outliers from any analyses of the number of correct and failed repairs.

The number of incorrect repairs that crews initiated was also analyzed as a measure of performance. Significantly more incorrect repairs were committed in the text condition than when communicating via voice, $F(1,20)=10.16$, $p=.005$, partial $eta^2=.149$, though this effect seems mainly driven by the NTD condition. The data suggest that the NTD condition may have been more conducive to incorrect repairs than the TD condition, $F(1,20)=3.50$, $p=.076$, partial $eta^2=.337$. Both of the outlier crews excluded from these analyses were text medium crews, and each crew made an excessive number of failed repair attempts during the NTD leg, providing additional support for this interpretation.

TABLE 2.3. Task Performance Measures

	Average Time in Red (in min) (N=24)		Mean Number of Correct Repairs (N = 22)		Mean Number of Incorrect Repairs (N = 22)	
	TD	NTD	TD	NTD	TD	NTD
TEXT	56.21 (24.99)	56.76 (20.54)	1.40 (.8433)	1.70 (.6750)	3.4 (2.76)	5.8 (3.74)
VOICE	61.63 (20.77)	29.84 (25.65)	1.42 (.7930)	1.67 (.7785)	1.58 (2.02)	2.75 (2.80)

Note. TD = Transmission Delay; i.e., FSE/Pioneer communication was delayed by 5 min. NTD = No Transmission Delay; i.e., FSE/Pioneer communication was synchronous. Standard deviation is provided in parentheses.

Team Communication

The presence of transmission delay impacted the structure of team members' communications. Separate Analyses of Variance on communication rate and density revealed that communication delay influenced both the rate of turns by team members ($F(1,20)=87.80$, $p<.0001$, $eta^2=.81$) and the length of their contributions ($F(1,20)=74.36$, $p<.0001$, $eta^2=.79$)[1]. As can be seen in Table 2.4, team members made fewer but longer contributions when they communicated under time delay than when no time delay was present, irrespective of the communication medium they used. Moreover, as shown in Table 2.4, these effects were more pronounced for teams communicating by voice than those communicating via text. The medium by time delay interaction was significant for rate of communication, $F(1,20)=26.39$, $p<.0001$, $eta^2=.57$, as well as for the length of the communication, $F(1,20)=42.63$, $P<.0001$, $eta^2=.68$. In response to the transmission delay, voice teams reduced their communication rate by a factor of 13; text teams' rate decreased by a factor of 3. Interestingly, while voice and text teams communicated in comparable rates under delayed conditions, team members in the voice condition made contributions that were considerably longer (Mean number of words/turn = 61.84) than communications by text teams (M = 13.5). This finding suggests that team members using text may have been more concise than team members in the voice condition. However, subsequent content analyses indicated that text communication was also associated with an increased potential for misunderstanding.

TABLE 2.4. Communication Rate and Density in Text and Voice Teams during TD and NTD Conditions

	TEXT		VOICE	
	NTD	**TD**	**NTD**	**TD**
Communication rate (turns/min)	2.5 (1.26)	.86 (0.53)	6.15 (2.56)	.46 (0.15)
Communication density (words/turn)	6.43 (1.63)	13.5 (6.14)	10.73 (4.08)	61.84 (21.97)

Note. TD = Transmission Delay; i.e., FSE/Pioneer communication was delayed by 5 min. NTD = No Transmission Delay; i.e., FSE/Pioneer communication was synchronous. Standard deviation is provided in parentheses.

[1] Note that for these analyses the Voice Condition included only 10 instead of 12 teams. Due to an equipment failure communications by two vocie teams during the NTD condition were not recorded.

TABLE 2.5. Structure and Content of Communications by Text and Voice Teams during TD

	TEXT	VOICE
Turns intervening between adjacency pairs	10.64 (4.59)	6.57 (2.66)
Information Splitting	7.67 (7.6)	.83 (1.27)
Communication Problems	**4.92** (2.84)	**3.75** (4.45)
- *Request clarification*	*1.67 (0.95)*	*0.17 (0.58)*
- *Repeat*	*1.00 (1.04)*	*1.00 (1.48)*
- *Proximity bias*	*1.00 (1.13)*	*0.75 (1.22)*
- *Requested information not provided*	*1.25 (1.49)*	*1.83 (2.69)*
Threats to Common Ground	**33.83** (18.83)	**17** (10.29)
- *Anaphora*	*19.42 (11.87)*	*8.58 (3.42)*
- *Missing responses*	*5.08 (4.76)*	*2.17 (3.01)*
- *Insensitivity to delay*	*3.75 (3.25)*	*3.17 (2.48)*
- *Contribution out of sequence*	*5.58 (3.70)*	*3.08 (2.99)*

Note. Mean numbers are provided for main categories as well as sub-categories (in italics). Standard deviations are in parentheses.

Content analysis of team communication focused on Pioneer Crew/FSE interactions during transmission delay. Medium-specific differences concerned structural aspects of team communication, $F(2,21)=4.7$, $p=.02$, $eta^2=.31$, as well as content variables, $F(2,21)=3.65$, $p=.04$, $eta^2=2.58$. As can be seen in Table 2.5, text teams were more likely than voice teams to split up related information and present it in separate turns, $F(1,22)=9.45$, $p=.006$, $eta^2=.30$, and to have more turns come between related communications (adjacency pairs such as question and answer) by distributed team members, $F(1,22)=7.03$, $p=.015$, $eta^2=.24$. Text communication also included more threats to common ground, $F(1,22)=7.38$, $p=.013$, $eta^2=.25$, in particular missing responses ($M_{Text} = 5.08$; $M_{Voice}=2.17$) and anaphora (i.e., terms whose meaning depended on information provided in preceding turns; $M_{Text} = 19.42$; $M_{Voice}=8.58$). No significant media effects were observed concerning the occurrence of communication problems, $F(1,22)=.59$, ns.

These differences are consistent with medium-specific affordances and constraints. Text provides team members with a written record of their on-going conversation, and thus may enable them to keep track of related contributions and the identity of referents across turns. However, as the presence of communication problems in the text group indicates team members may have overestimated the benefits of text-based communication. Voice communication is cognitively more taxing than text-based communication insofar as participants need to remember their ongoing discourse to interpret new information. Voice teams apparently adapted to this constraint by packing more information into one turn than text teams, behavior that kept related communications more closely aligned and may have aided comprehension.

However, both text and voice teams showed instances of miscommunication in which team members failed to account for the communication delay. Team members displayed proximity bias; that is, they mistook a remote partner's communication that immediately followed their own transmission as a response to it, or they showed insensitivity to the delay by repeating a message before they could have received a response from their partner. These instances required additional communication in which team members clarified their situation understanding, or they spiraled into misunderstanding from which team members never recovered and thus were unable to repair a system failure. This situation is depicted in Figure 2.7, which summarizes the first 20 minutes of dialogue between a Flight Systems Engineer (FSE) and his Pioneer crew (P) after the occurrence of a system failure. The lower portion of the graph presents the turn sequence from P's perspective; the top portion shows the temporal sequence of the same turns as experienced by the FSE. Colored rectangles represent individual turns by P or FSE; numbers (e.g. P1, P2 …, F1, F2 …) designate the first, second etc. turn by a Pioneer crewmember or the Flight Systems Engineer. As can be seen the temporal sequence of turns differs for P and FSE, and more importantly, contributions that for one partner are related and following each other (as the FSE's response (F2) to P1) are not adjacent for the other partner. If team members misalign contributions, serious misunderstandings can arise. This problem happened to the crew whose discourse is depicted in Figure 2.7. The Pioneer crew erroneously assumed that the repair instruction provided by the FSE in F8 was a response to their failure announcement in P17. However, the FSE's instruction was in response to previous requests by the Pioneer crew (P9 and P10) and was incompatible with their current malfunction. The team never recovered from this misunderstanding and failed to repair their second system failure.

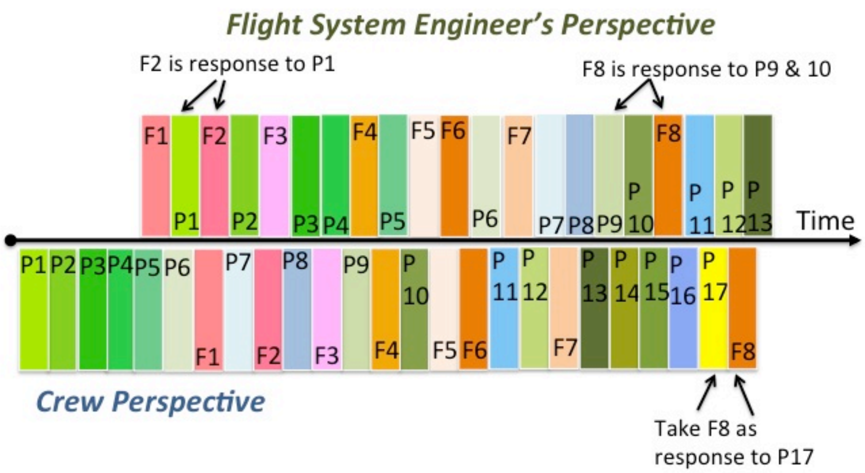

Figure 2.7. Representation of the same conversation under TD as perceived by different team members

TABLE 2.6. Communication Strategies Used by High- and Low-Performing Text and Voice Teams when FSE/Pioneer Communication was Delayed

	TEXT		VOICE	
	High	**Low**	**High**	**Low**
Indicate end of turn	0	0	29.89 (35.25)	24.14 (30.17)
Heads-up	0	0	0	5 (6.08)
Provide topic or reference to previous turn	10.17 (10.43)	1.67 (2.89)	22.71 (12.52)	12.14 (5.92)
Structure/chunk complex information	11.45 (10.57)	5 (8.66)	9.70 (10.01)	6.96 (7.45)
Highlight critical information	0	0	8.02 (9.28)	6.96 (9.40)
Reference time	0	0	12.12 (20.99)	17.71 (17.74)
Push information	5.24 (6.49)	2.57 (2.32)	20.27 (9.09)	8.27 (11.63)

Note. *Numbers indicate mean percentage of turns during TD flight segment that adhere to a given strategy; SD in parenthesis*

Further analyses examined communication strategies three high- and three low-performing teams in each medium condition employed to identify measures supporting team collaboration under time delay. Mean times (in min) to repair system failures for these teams were: $\text{Text}_{\text{High}}$ = 32.2; Text_{Low} = 84.35; $\text{Voice}_{\text{High}}$ = 33.83; $\text{Voice}_{\text{Low}}$ = 83.57). Coding of communication strategies was informed by our previous analyses of the AMO data and distinguished the following strategies: *Indicate end of one's turn* (e.g., by saying "Bye," or "Out"); give partner a *heads-up* (i.e., alert partner to upcoming transmission of critical information); prefix own message with *topic* or *refer to a partner's preceding contribution*; present *complex* *information in* a *structured fashion* (e.g., by numbering steps in repair procedure); *highlight critical information* (e.g., by repeating it within the same turn); and *push information* (i.e., volunteer critical information before partner requests it).

Table 2.6 (above) shows that high-performing teams, in particular high voice team members, relied on several strategies that may have helped them to maintain conversational coherence when communication was delayed. They identified messages by topic, presented information in a well-structured manner and repeated critical information, apparently in an attempt to facilitate comprehension. Members of high-performing voice teams also seemed attuned to the fact that their perspective on evolving events may be different from their remote partners as a result of the time-delay. They tended to push information to remote partners in a timely manner.

Conclusions

Perhaps the most interesting finding of this study was that when communication was delayed by 5 minutes, task performance of distributed teams was comparable irrespective of the communication medium they used for collaboration. That is, neither of the communication media we investigated –voice or text—was better suited for remote collaborations under time-delayed conditions. This finding was not as predicted since we had hypothesized that text communication would provide an advantage over voice communication. On the other hand, consistent with our predictions we observed that transmission delay disrupted the turn sequence of remote partners' contributions and led to misunderstandings. Our research further suggests that successful teams in each media condition were those who adapted to the constraints of their communication medium to establish shared task understanding.

Our research also demonstrates the validity of conducting research involving a student population. Analysis of the communication by student teams revealed communication issues identical to those seen in research involving astronauts. Specifically, in both populations we observed proximity bias and insensitivity to transmission delay. These problems have also been noted by an astronaut who experienced communication delay during a space analog study in NEEMO: "We looked at the voice loops, we looked at the text loops that occurred during these scenarios, and we saw afterwards that it was broken ten ways to Sunday. We were talking past each other; we were taking one response to mean, to be a response to a totally different question, you know, it was incredibly broken, and you could only see it when you took the time to really analyze it afterwards" (quoted in Palinkas, 2013). Likewise, the student participants sought to mitigate the disruptive effects of the communication delay by inventing strategies that were also used by astronauts, such as marking the end of a turn, announcing a time when critical information is to be transmitted, prefixing a message with a topic, presenting complex information in a structured fashion, and repeating important information within a turn.

SECTION SUMMARY

Collaborating with remote partners when team communication is delayed, is challenging because individuals tend to misapply assumptions and conventions of synchronous discourse to asynchronous conditions—behavior that as our research showed results in unnecessary turns, or worse, in misunderstandings. When student and astronaut participants in our studies made an effort to employ communication strategies that were adaptive to the transmission delay, it facilitated their communication and their performance. However, they did not adhere to these strategies consistently; instead, they frequently fell back onto ingrained habits and expectations based on synchronous interactions.

One of the problems concerned team members' use of anaphora; that is, the use of expressions, such as pronouns or definitive articles, whose meaning was underspecified within the context of the team member's turn but instead relied on information that was provided in preceding turns. The use of anaphora rests on the assumption that conversational partners have a shared perspective on their evolving communication, an assumption that may be erroneous when communication is asynchronous. Participants in synchronous communication can and do use anaphora to link their respective contributions, and can trust that the referent of the anaphora is easily identified because related communications are consecutive. However, in asynchronous communication related contributions may be temporally adjacent only for the responding partner while for the other participant unrelated contributions may intervene. Consequently, establishing the correct referent for an anaphoric expression such as "that repair didn't work," or "got it" may be cognitively taxing, if not impossible.

A related issue is team members' tendency to break-up related information and present it in small portions. When communication is synchronous it is an efficient strategy to present information, especially if it is complex, in small units and wait for a partner's feedback. Communication problems can thus be detected early and resolved quickly. In asynchronous communication, in contrast, information splitting may impede comprehension insofar as related content may be separated by several turns requiring partners to keep in mind individual pieces of information for an extended period of time before a coherent representation is achieved.

Another problem is proximity bias; that is, the inclination of team members to interpret a communication by a remote partner that immediately followed their own contribution to be their partner's response to it. While this is a feature of synchronous discourse it may not necessarily be true under asynchronous conditions. A final problem was the result of participants' insensitivity to time constraints insofar as they repeated information or requested feedback before their remote partner could have responded to their original message. These findings informed our design of communication protocols as they highlighted which aspects of the communication process need support to ensure successful communication between remote partners under asynchronous conditions.

III. PROTOCOLS TO SUPPORT ASYNCHRONOUS COMMUNICATION

Communication protocols created for this effort are structured templates designed to facilitate remote collaboration under time-delayed conditions utilizing medium-specific affordances. Specific design goals included: 1) to help remote team members keep track of conversational threads and the temporal sequence of contribution; and 2) to establish common ground in an efficient manner. The content of the protocols addresses the problems associated with asynchronous communication that were identified in the previous two studies and incorporate recommendations by Love and Reagan (2013); their structural characteristics are based on schema-based approaches to instruction design (Morrow & Rogers, 2008; Morrow et al., 1996; 1998; 2005).

As can be seen in Figures 3.1 and 3.2, protocols consist of four segments and several communication conventions that address the major challenges of asynchronous communication—Time, Conversational Thread, and Transmission Efficiency. Media-specific instructions concern aspects of the call sign and conventions that are consistent with the affordances and constraints associated with voice or text communication. Call signs during voice communication for instance need to do more than identify who is talking to whom. They also need to catch the remote partner's attention (thus the addressee's name should be called out twice), and they need to anchor a message in time to highlight the temporal sequence of participants' contributions and thus safeguard against proximity bias. References to time need to be independent of a partner's perspective and should be linked to an objective time, such as standard time. As text messages typically include time stamps and the identity of the sender, call signs need to identify only the addressee. On the other hand, because a texting tool may not have an attention-getting feature such as announcing incoming messages with a chime, protocol conventions direct partners communicating via text to note the time of both their transmission and the expected response and to check for new messages accordingly. Text communication provides a written record of partners' contributions; thus no record keeping is required. In contrast, when distributed team members communicate by voice, protocols require them to maintain a log of their ongoing discourse to keep track of conversational threads.

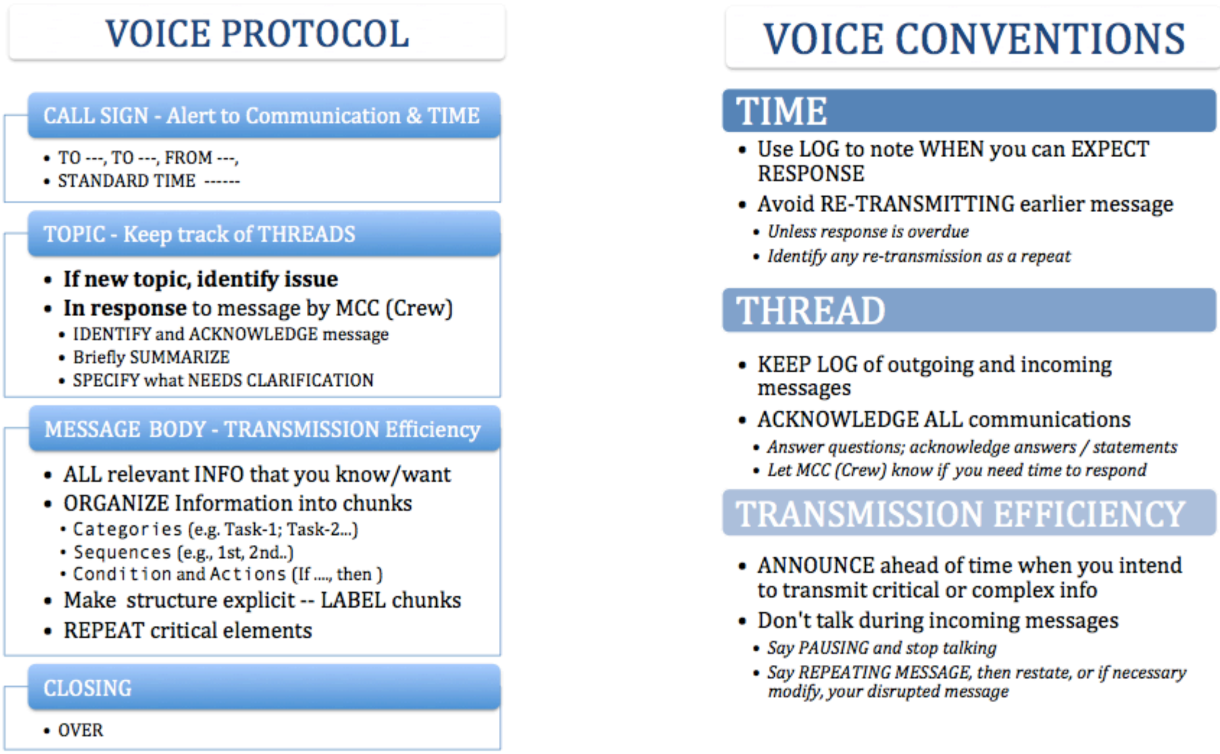

Figure 3.1. Protocol template for voice communication

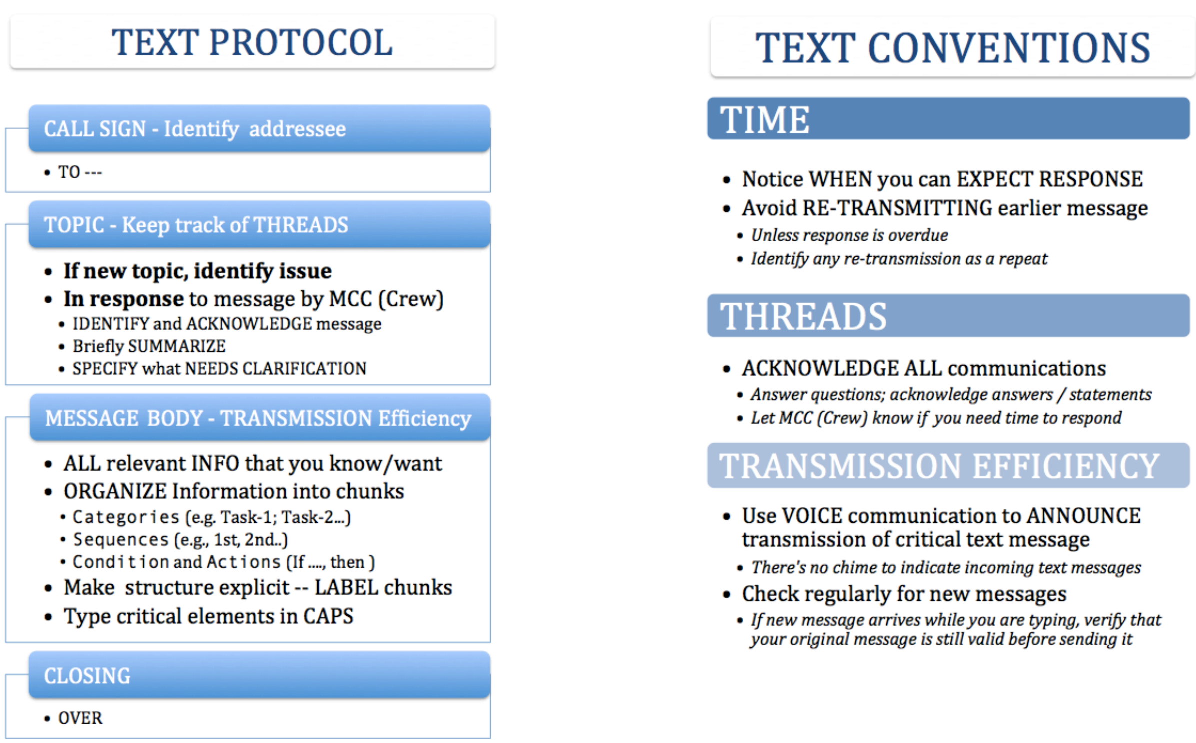

Figure 3.2. Protocol template for text communication

Medium-independent instructions concern the topic section of a message, the message body and the final—closing—section as well as several conventions designed to support conversational coherence, message comprehension and shared task understanding, as well as communication efficiency. Team members are trained to preface their message with a topic, or to make explicit the relationship of their message to a preceding one from their partner. Doing so enables partners to keep track of conversational threads and avoid proximity bias. Team members are also instructed to transmit all relevant information in one turn, to present it in a clearly structured fashion, to repeat critical items and to postpone transmission of non time-critical information while they awaited crucial input from their partner. These elements facilitate comprehension and maintain communication efficiency as related information is kept together. Mutual understanding is further enhanced when team members explicitly acknowledge and paraphrase a partner's messages instead of providing generic feedback, such as "copy all." Moreover, by indicating their understanding of a partner's message, team members can preclude unnecessary communication. If no feedback is given, partners may repeat their message or ask for verification. Likewise, team members are told to note when they should receive a response to discourage unwarranted repetition that could potentially confuse their partner. Lastly, team members are instructed to announce when they plan to transmit important information to give their remote partner time to attend to it, and to mark the end of a transmission to let partners know that their message is complete.

LABORATORY STUDY TO ASSESS THE EFFECTIVENESS OF THE COMMUNICATION PROTOCOLS

The objective of this research was to assess whether the availability of protocols enhanced team communication and task performance of remote teams during communication delay. The study involved a 2 (communication mode) x 2 (availability of communication protocols) x 2 (task type) mixed design. Communication mode and task type were manipulated within teams (all teams performed both types of tasks and alternated communication medium across their two missions). Communication training and availability of communication protocols was a between-group variable. Teams following the protocols were hypothesized to show more efficient and effective communication than teams without the aid of protocols. Specifically, communication in aided teams was expected to be more compact (i.e., fewer information splitting), involve fewer threats to common ground and fewer miscommunications than communication in unaided teams. Aided teams were also expected to show superior task performance. No media-specific effects were hypothesized.

Method

Participants

72 graduate and undergraduate students were recruited for participation and assigned to teams of three (24 teams in total). Volunteers were between the ages of 21-55, had basic computer knowledge and were fluent English speakers.

Experimental Task

The same task environment (AutoCAMS) as in our previous laboratory study was used to assess whether the availability of protocols enhanced team communication and task performance of remote teams during communication delay. AutoCAMS (Manzey et al., 2008) simulates the life support system of a spacecraft, and in our task design required teams of three participants to diagnose and repair system failures. One participant in each team was assigned the role of Flight Systems Engineer (FSE) whom the Pioneer crew, comprised of the other two team members, had to contact for assistance with failures in the life support system onboard their exploration spacecraft. The FSE was located onboard the fictional US Space Station.

Procedure

Teams were randomly assigned to either the Protocol Training (i.e., experimental) or No-Protocol Training (i.e., control) condition.

Task-specific training. As in the previous lab study, team members were given 2-4 hours of AutoCAMS training, depending on their roles, FSE or Pioneer. Each role was trained separately, and was given position-specific practice. The FSE was trained to diagnose and repair failures on all systems, practiced resolving every failure as well as diagnosing ambiguous system indicators, and completed one or more failure scripts of 15-30 minutes until he or she felt comfortable with the system. *Pioneer* crewmembers received training on basic AutoCAMS functions only.

Communication training. Participants in the experimental group received the communication protocols and 30 minutes of communication instruction as part of their position-specific (FSE or Pioneer crewmember) task training. This consisted of an introduction to the pitfalls of time-delayed communication, demonstration of the protocols, and explanation of the rationale for using each protocol element. In addition, teams in the protocol condition were provided with written communication protocols to be used during the experimental tasks as well as log sheets to record incoming and outgoing messages. Participants in the No-Protocol group had only task-specific training.

At the end of training, teams in the experimental condition practiced using the protocols to communicate and collaborate on failures in a 15-minute joint session with a one-minute transmission delay. They received feedback on protocol adherence. Control teams also completed the joint practice scenario at the end of their training; however, without any aid (i.e., protocols) or communication feedback.

FSE-Pioneer teams subsequently completed two 90-min missions, one in which the communication between the Pioneer crew and the FSE was voice-based, and one that provided only text communication. Communication between remote team members in both sessions was delayed by 5 minutes. During each mission, the Pioneer spacecraft experienced two AutoCAMS malfunctions for which the crew needed assistance from the FSE. One failure was simple (the automated alarm specified the failure) and its diagnosis involved only confirmation of diagnostic parameters before repair. The more complex failure presented the crew with ambiguous system indications and required several back-and-forth communications with the FSE to discover the specifics of the malfunction and prescribe the appropriate repair. As in the previous lab study, each team member was also required to complete several secondary tasks to simulate a level of workload astronauts may experience.

The order of failure type (procedural vs. ambiguous) and communication medium (voice vs. text) was counter-balanced order across teams.

Task Performance Measures

Task performance data (i.e., interactions with AutoCAMS) were collected by the computer-based experimental system. Task performance was measured in terms of repair accuracy, time required to initiate a successful repair, incorrect repair attempts, and number of correct repairs. The duration of a failure (time in red) was measured from its appearance (announced by a red alarm) and corresponding failure message to the initiation of the correct repair

Communication Measures

Communication analysis focused on the interactions between the FSE and the Pioneer crew during the failure repair tasks. Audio-recordings of the voice communications between the crewmembers and the FSE were loaded into Audacity, an audio-editing software, and transcribed for subsequent analysis. Logs of team members' text-based communications were directly uploaded for analysis. As in the previous study, the unit of analysis for the communication coding was a turn.

The coding of the FSE-Pioneer communication involved the same categories as in our previous lab study. As before the following categories were distinguished: Information splitting (i.e., related information was presented in separate turns), communication problems (i.e., failure to provide requested information, request for clarification, mistaking partner's incoming message as response to one's most recent communication), and threats to common ground (i.e., repeat information or request feedback without consideration for time lag, failure to respond to or acknowledge partner's communication, anaphora, or communications that were out of sequence). Two student assistants were trained in the coding categories by the expert rater who coded the team communications in the previous study. Students' codes were checked by the expert and disagreement were resolved through discussion.

Results

Task Performance

Mixed-design Analyses of Variance (ANOVAs) showed that procedural failures were resolved more quickly than ambiguous failures, $F(1,22)=83.96$, $p<.001$, and involved fewer incorrect repair attempts, $F(1,22)=42.75$, $p<.001$. No effects for medium were found, $F(1,22) =.334$, ns. Surprisingly, the availability of communication protocols did not have a significant effect on the Pioneer crews' task performance in terms of time to resolve failures, $F(1,22)=.989$, ns, incorrect repair attempts, $F(1,22) = .052$, ns, or number of correct repairs, $F(1,22)=1.00$, ns.

Team Communication

A mixed-design Analysis of Variance was conducted on the number of communication issues in aided and unaided teams. Medium and communication issues were repeated variables. Since no significant effect of communication medium was found, $F(2,42)=1.69$, ns, dependent measures were collapsed across medium to assess the effectiveness of communication protocols on team communication. A mixed-design Analysis of Variance on the number of communication issues revealed that communication protocols facilitated some aspects of team communication, $F(3,19)=3.73$, $p=.02$, $eta^2=.37$[2]. Specifically, the differences between aided and unaided teams concerned the number of threats to common ground, $F(1,21)=6.70$, $p=.02$, $eta^2=.30$, and information splitting, $F(1,21)=11.42$, $p=.003$, $eta^2=.35$, but not instances of communication problems, $F(1,21)=.65$, ns.

TABLE 3.1. Mean Number of Communication Issues Observed for Teams in the Protocol and No-Protocol Condition

	Protocol Condition	*No-Protocol Condition*
Communication Problems	**5.18** (2.93)	**5.91** (2.67)
- *Request clarification*	*0.91 (0.70)*	1.83 (2.08)
- *Repeat*	*0.82 (1.08)*	0.50 (0.67)
- *Proximity bias*	*0.55 (0.82)*	0.67 (0.89)
- *Requested information not provided*	*2.91 (1.86)*	2.92 (2.43)
Threats to Common Ground	**18.91** (7.26)	**27.58** (8.67)
- *Anaphora*	7.82 (4.21)	15.33 (6.20)
- *Missing responses*	2.73 (2.57)	3.17 (0.72)
- *Insensitivity to delay*	3.36 (2.62)	3.25 (2.01)
- *Contribution out of sequence*	5.00 (2.24)	5.83 (2.76)
Information Splitting	**1.82** (1.89)	**10.67** (8.48)

Note. Standard deviations are in parentheses

As can be seen in Table 3.1, team members in the Protocol condition tended to use fewer underspecified terms within a turn and to be more responsive to partners than members of unaided teams. Aided team members were also more likely to present related information, such as diagnostic cues, together in one

[2] One protocol team was not included in this analysis because their text communications were only partially recorded as a result of a technical malfunction.

turn rather than across several turns. As a result, their communication appeared more coherent and compact.

Discussion and Conclusions

The study provided partial support for the effectiveness of communication protocols to facilitate team communication under asynchronous conditions. The availability of protocols was found to mitigate some communication issues associated with transmission delay but failed to do so for all the issues identified in our previous research. Specifically, the protocols seemed to have helped team members with the structure and content of their contributions. Their messages involved fewer anaphoric expressions and tended to be more comprehensive in terms of the information provided. That is, compared to the communications by the Control group, team members' communications in the Protocol condition appeared cognitively less taxing since their meaning could be established within a given turn and was less dependent on information presented in preceding turns. On the other hand, training on the protocols apparently did not make it easier for team members to keep track of the time lag between their own and their remote partners' contributions; rather, aided team members were just as likely as unaided participants to misalign their partners' contribution or to repeat messages without allowing sufficient time for their partner to respond. These failures suggest that the expectation of immediacy is an ingrained habit of synchronous communication which to overcome may require more than the 30 minutes of training study participants received. In subsequent analog studies (to be discussed in the next section) we increased the allotted time for the communication training to 60 minutes to give participants more experience with the challenges of transmission delay as well as practice using the protocols. Another factor that may explain why trained participants persisted in relying on habits of synchronous communication are task characteristics of the AutoCAMS micro world used in our study. AutoCAMS is a fairly complex system and the diagnosis of failures, in particular of ambiguous failures, is cognitively challenging as different system indicators need to be checked and integrated. To cope with the workload associated with the task, some Protocol teams may have fallen back onto well-rehearsed and thus easy communication habits of synchronous discourse; a move that because of the associated communication issues, likely increased their workload even more. This explanation is also consistent with the finding that the availability of communication protocols did not lead to improved task performance.

A final explanatory comment is that our study participants did not always conform to their assigned condition, and thus blurred the lines between control and experimental groups. We noted that those who were trained to use communication protocols did not consistently follow them, or adhered to some, less critical elements (e.g., use of a call sign) instead of elements important to problem solving (e.g., presenting relevant information in a coherent and well-structured manner). Conversely, there were teams who were not given communications training but spontaneously adopted protocol-like conventions. For example, protocols instructed team members to push all relevant data or instructions at once, and to organize the information into lists. One No-Protocol FSE sent the following messages to the *Pioneer* crew:

> *for any errors you receive I need the following information. 1. Does the tank level of the O2 decrease by the same amount as the flow rate. 2. Does the tank level of the NO2 decrease by the same amount of the flow rate. 3. what is the 02 flow rate 4. what is the no2 flow rate. 5. is oxygen in normal range on graph? If not is it high or low. 6. Is pressure in normal range on graph? if not is it high or low*
>
> *….any error you get I need to know the 6 things I sent you earlier. Preferably in a listed order with numbers. Otherwise I could incorrectly diagnose the error and too much time will be wasted between transmissions.*

Other No-Protocol FSEs attempted to push repair steps:

> *Preemptively, in the case of a malfunction, please consider the following:.- If Oxygen values change significantly (i.e. move beyond the red lines), please click on the "Oxygen" button in the upper right, then select "flow on" (if levels are too low) or "flow off" (if levels are too high).- If*

Pressure values change significantly, do the same with the upper right Nitrogen button.- Report behavior of Oxygen and Pressure values to me, as well as action taken, and await further instruction.

ANALOG RESEARCH TO ASSESS THE FEASIBILITY OF COMMUNICATION PROTOCOLS FOR SPACE OPERATIONS

The communication protocols were included in several space-analog simulations to assess their usability for space operations. One set of studies was conducted at the NASA Extreme Environment Operations (NEEMO) facility. The second set of studies took place in NASA's Human Exploration Research Analog (HERA) at Johnson Space Center.

Method

Participants

Crewmembers participating in two NEEMO missions, NEEMO-18 and NEEMO-19, agreed to use the communication protocols during space-ground interactions on days with a communication delay. Each mission involved four crewmembers from the astronaut corps of NASA and its international partners (CSA; ESA; JAXA). A second set of studies involved participants in eight space-mission simulations conducted in HERA. Participants were astronaut-like research volunteers; that is, they were comparable to astronauts in terms of education, personality and age. Each HERA mission included four crewmembers.

Procedure

Crewmembers of HERA Campaign 1 - Missions 1 and 2 served as control and did not participate in any communication training. NEEMO crewmembers and two HERA crews (Campaign 1 - Missions 3 and 4) received 30 minutes of communication training prior to their missions. Training for HERA Campaign 2 was increased to 60 minutes in response to feedback by crewmembers in the earlier missions. Communication training identified the challenges of asynchronous communication and explained the elements of the communication protocols and conventions. NEEMO participants were trained jointly, five weeks prior to NEEMO-18 and 13 weeks prior to NEEMO-19. The NEEMO-19 crew received a refresher training three weeks before their mission started. HERA crewmembers (except for the control teams) and Mission Control personnel (HabComs) received training during the week preceding their mission.

Mission Schedule

NEEMO-18 was a 9-day mission with four days of communication delay. Two days involved a delay of 5 minutes one way, the other days presented a 10-min delay. Communication medium (voice vs. text) was crossed with communication delay. NEEMO-19 lasted for 7 days. On four days communication between the crew and mission control was delayed by 5 minutes one way, and remote partners could choose which medium (voice or text) to use during a given interaction.

HERA missions of Campaign 1 were 7 days long and included two days on which communication was delayed by 10 minutes one way. On the first of these days, communication between the crew and mission control was voice-only; on the second day participants were given a choice of communication medium. HERA missions of Campaign 2 lasted for 14 days and included four days of communication delay, two days with a delay of 5 min one-way and 2 days with a 10-min delay. Remote team members could choose the communication medium (voice or text) on the days with a delay.

In all NEEMO and HERA missions communication delay occurred on consecutive mission days. Copies of the communication protocols were given to trained participants at the start of a mission to serve as a reference aid on days with a transmission delay.

Communication Survey

A daily survey administered to NEEMO-18 crewmembers included one question that asked participants to rate the effectiveness of their communications with mission control on a scale of 1-5. In addition, a separate communication survey was given on the days on which communication with mission control was delayed. In this survey crewmembers were asked to evaluate the extent to which the communication protocol and conventions were effective in supporting communication with mission control during two important events of the day: Extravehicular Activity (EVA), and re-planning and prioritization. In addition, respondents were asked to explain any rating lower than 4 (with 5 as the highest rating). On the mission day immediately following the days with communication delay, crewmembers received a survey in which they were asked to rate how critical each of the elements of the protocol and individual conventions was in facilitating asynchronous communication. NEEMO-19 crewmembers received only the communication-specific and final survey due to mission constraints.

HERA crewmembers in Campaign-1were given daily communication surveys assessing the effectiveness of their interactions with mission control during assigned tasks. HERA crewmembers in Campaign-2 were given communication surveys only on the days with a transmission delay. Respondents were asked to provide an explanation for any rating lower than four. HERA crewmembers who received communication training also completed a final survey at the end of their mission evaluating protocol elements and communication conventions.

Communication surveys were administered electronically, either as a Word document (HERA Campaign 1 - Missions 1-3) or via Qualtrics software (HERA Campaign 1 - Mission 4; HERA Campaign 2; NEEMO-18 and -19), and took 5 to 10 minutes to complete.

Protocol Use

The communications between remote team members on days with a transmission delay were coded for protocol use. Text-based crew-mission control communications were recorded in Playbook and uploaded for analysis. Audio recordings of their voice communications were exported into Audacity, an audio-editing software. Codes were tagged directly onto audio segments using Audacity's track labeling tool. Codes referred to presence/absence of protocol elements: whether there was a call sign (e.g., "MCC, MCC, Aquarius"); whether message was preceded by topic (e.g., "message re. potting" or, for voice communication, time specification ("time is 10:55"); whether a message was clearly acknowledged (i.e., acknowledgment referred to content or time of acknowledged message); if message was complex, whether information was structured in chunks (e.g. spacing or bullets in text message) and whether information was highlighted (i.e., emphasized or repeated); whether team members announced transmission of important message; and whether voice messages had an explicit closing sign (such as "over"). A rating of 2 (= fully compliant) was given if communication in a turn had all required protocol elements; a rating of 1 (partial compliance) indicated that critical elements (such as call sign, explicit acknowledgment; closing sign) were missing; and a rating of 0 meant that communication did not include any protocol elements.

Results and Discussion

Given the small sample size, we report only descriptive statistics. As can be seen in Table 3.2, trained participants considered the protocols to be effective in supporting crew-mission control communication when there was a transmission delay. Astronauts in the NEEMO missions as well as trained volunteers in the HERA simulations gave an effectiveness rating greater than 4 (out of 5). Moreover, participants' ratings suggest that the protocols did facilitate crewmembers' communications with mission control on days with communication delay. As shown in Table 3.2, trained crewmembers thought that the effectiveness of their interactions with mission control did not suffer when communication was delayed. In contrast, untrained HERA crewmembers gave considerably lower effectiveness ratings on time-delayed days compared to days with synchronous communication. Untrained HERA participants also commented that they were less willing to contact mission control for guidance on tasks when their communication was delayed. As a result, as Mission Control noted, they performed the tasks improperly and required time-consuming additional assistance from ground.

TABLE 3.2. Crewmembers' Mean Effectiveness Ratings of Their Communications with Mission Control (MC)

	Effectiveness of Crew-MC Communication	
	No Comm Delay	Comm Delay
NEEMO-18	4.46 (0.69)	4.31 (0.48)
NEEMO-19	N/A	N/A
HERA-C1 M3/M4 (trained crews)	3.93 (0.89)	3.87 (1.14)
HERA-C1 M1/M2 (untrained crews)	4.07 (1.09)	2.95 (1.68)
HERA-C2		4.21 (0.84)

Note. *Numbers reflect mean ratings across days (i.e., days with communication delay vs. no delay); standard deviations are in parentheses. Maximum rating was 5.*

Table 3.3. Crewmembers' Mean Criticality Ratings of Individual Protocol Elements and Conventions

	NEEMO-18	NEEMO-19	HERA-C1	HERA-C2
Overall EFFECTIVESS	4.69 (0.52)	4.14 (0.35)	4.25 (0.46)	4.06 (0.57)
Repeat addressee (voice)	3.75 (1.26)	N/A	2.75 (1.28)	3.75 (1.48)
Include time (voice)	3.50 (1.73)	N/A	4.25 (1.04)	4.38 (0.88)
Provide topic	4.75 (0.50)	4.88 (0.35)	4.63 (0.52)	4.19 (1.22)
Acknowledge communications	4.00 (0.82)	4.25 (0.89)	3.75 (1.04)	3.88 (0.96)
Push information	3.25 (0.50)	3.33 (1.53)	4.63 (0.74)	4.08 (0.90)
Chunk information	3.50 (0.56)	3.33 (0.58)	4.25 (0.71)	3.81 (0.91)
Repeat critical Info (voice)	4.25 (0.50)	N/A	4.50 (0.76)	4.27 (0.88)
Type critical info in caps (text)	2.50 (0.56)	3.50 (1.29)	3.00 (1.07)	2.87 (1.55)
Note earliest time to expect response	3.00 (1.41)	3.75 (1.23)	4.25 (0.71)	3.67 (1.35)
Use log to track related messages	4.75 (0.50)	4.75 (0.50)	4.00 (1.60)	3.53 (1.19)
Announce complex or critical messages	4.50 (1.00)	4.25 (0.96)	4.75 (0.46)	4.27 (0.80)

Note. *Standard deviations are in parentheses. Maximum rating was 5. NEEMO-19 crew used text communication only.*

As shown in Table 3.3, crewmembers generally rated protocol elements and conventions as fairly critical to ensuring effective communication during asynchronous conditions. The majority of the items received a criticality rating of at least 3.5. Very high ratings across crews for several items—providing a topic, using a log to track related messages, and announcing complex or critical messages—reflect the value of protocols for keeping track of message threads. However, ratings by NEEMO crewmembers for some items—most notably, pushing and chunking information and tracking time—were surprisingly low and pointed to specific training needs and technological improvements.

The importance of technological improvements is apparent in NEEMO 19. During this mission the crew opted to use exclusively text as their communication medium on time-delayed days. This finding may reflect the implementation in this mission of a new text tool (VOXER) whose features seem better suited to meet the demands of asynchronous communication than the text tool available in NEEMO-18 and HERA. For instance, the time a message was sent was prominently displayed and messages included a time stamp that indicated the earliest time a response could be received.

Compliance with the protocols was high. As can be seen in Table 3.5, crewmembers generally followed the protocols in their communications on mission days with a transmission delay. This finding together with crewmembers' favorable assessment of the protocols attests to their feasibility as an effective countermeasure to the negative impacts of transmission delay.

Table 3.5. Crewmembers' Compliance with Protocols

Analog	Compliance (Percent of Communications)
NEEMO-18	93.85%
NEEMO-19	90.61%
HERA-C2	
- Mission 1	83.91%
- Mission 2	89.74%
- Mission 3	89.13%
- Mission 4	90.28%

INTERVIEWS WITH DOMAIN EXPERTS ON THE CHALLENGES OF SPACE-GROUND COMMUNICATION

Semi-structured phone interviews were conducted with two Flight Surgeons, one CapCom, and one PayCom to characterize challenges of space-ground communication in current operations, to discuss the impact of communication delay and to learn about communication strategies gleaned from operational experience.

A common sentiment of the practitioners interviewed to date was that space-ground communication is especially critical in situations that are time-limited and dynamically changing, and in which mission control needs to aid crewmembers who have less technical or medical knowledge and expertise. Voice communication was the preferred medium that should be augmented by video and text as required by a task. Experts mentioned several strategies to ensure effective communication: avoid the use of technical jargon and rely on generic terms instead, or establish a shared vocabulary up front; clearly structure your communication and, dependent on the situation, anticipate potential task outcomes and information needs; provide detailed instructions and specify what information the crew needs to report back; mentally tag individual communications to maintain the thread. Experts also emphasized the importance of joint training of ground support and crewmembers to establish mutual trust. These strategies are consistent with the communication protocols we developed as well as our training approach involving a joint session with HERA crews and HabComs.

OVERALL CONCLUSIONS

Overall our research findings suggest that asynchronous communication should be facilitated by protocols that help remote team members keep track of conversational threads and the temporal sequence of messages. Astronauts and astronaut-like professionals showed high acceptance of the communicational protocols and rated them as highly effective in supporting their interactions with ground support. Likewise, highly experienced mission control members identified communication strategies compatible with the protocols developed in this effort.

Our findings let to the development of a communication training module that can be used to prepare crewmembers and members of Mission Control for the challenges of communication delay. Moreover, the communication protocols not only target how to speak or write during asynchronous conditions but also point to technological solutions. In fact, some technological changes have already been implemented in response to our early findings. One example is the text tool that was adopted in NEEMO-19 and assisted the crew with the temporal aspects of communication. Further improvements might be a less chat- and more email-like text tool that includes a subject header and links between related messages to make it easier for conversational partners to follow a conversational thread. A text tool could also provide a template that gives structure to a message and highlights its components. Likewise, voice communication could be facilitated if recordings of messages were available to both sender and receiver, and if the recording indicated when a message was transmitted. And lastly, it is conceivable that the recording tool would include prompts for specific message components. (e.g., This message is in regard to….).

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Palinkas, L. A. (2013, Feb. 11-14). *The impact of communication delay on individual and team performance*. Poster presented at BHP Investigator meeting, Houston, TX.

Palinkas, L. A., Kintz, N., Vessey, W. B., Chou, C.-P. & Leveton, L. B. (2016, Aug. 9). *Impact of communication delays on performance and well-being aboard the international space station.* Paper presented at NASA JSC, Houston, TX.

Other Information and Materials

Listing of Publications

Fischer, U., Miller, C., Morrow, D., Mosier, K., Orasanu, J., & Veinott, B. (2013). Exploring communication in remote teams: Issues and methods. In *Proceedings of the Human Factors and Ergonomics Society 57th Annual Meeting* (pp. 309-313). Santa Monica, CA: HFES.

Fischer, U. & Mosier, K. (2014). The impact of communication delay and medium on team performance and communication in distributed teams. In *Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting* (pp.115-119). Santa Monica, CA: HFES.

Fischer, U. & Mosier, K. (2015). Communication protocols to support collaboration in distributed teams under asynchronous conditions. In *Proceedings of the Human Factors and Ergonomics Society 59th Annual Meeting (pp.1-5).* Santa Monica, CA: HFES.

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Gonzalez, K., Mosier, K. L., Lam, J., & Fischer, U. (2015). Characteristics impacting teamwork and performance for space operations. In *Proceedings of the Human Factors and Ergonomics Society 59th Annual Meeting* (pp. 936-940). Santa Monica, CA: HFES.

List of Presentations

Fischer, U., Mosier, K., & Orasanu, J. (2013). *Issues of Grounding and Team Coordination in Asynchronous Communication.* Poster presentation at the 21st International Conference on Naturalistic Decision Making, Marseille, France.

Fischer, U. & Mosier, K. (2016). *Protocol for asynchronous communication in space operations*. Paper presented at NASA JSC, Houston, TX.

Mosier, K. L. (2014) *Decision Making and Communication across Time and Space: Lessons from NASA.* Paper presented at the Modern Management Methods LKNA14 Conference, San Francisco, CA.

Mosier, K. & Fischer, U. (2015). The challenges of asynchronous communication for distributed teamwork: Task performance and media effects. Paper presented at the 11th International Conference on Naturalistic Decision Making, June 9-12, McLean, VA.

Mosier, K. L., & Fischer, U. (2016). *Supporting Communication and Space-Ground Collaboration during Long Duration Exploration Missions*. Paper presented at SIOP 2016, Anaheim, CA.

Mosier, K., Fischer, U., Munc, A., Reich, K., Fox, D., Swarts, J., et al. (2013). *Asynchronous Communication in Space Operations*. Poster presented at the WASC review of San Francisco State University and at the San Francisco State University Graduate Studies Showcase.

List of Undergraduate and Graduate Research Assistants

The following SFSU and Georgia Tech graduate and undergraduate students were supported during this project via student training stipends:

- Eric Benzel, graduate student (MS awarded May, 2015)
- Laura Carucci, graduate student (MS awarded May, 2014)
- Jessica Dow, undergraduate/graduate student (MA awarded May, 2016)
- Danielle Fox, graduate student (MS awarded August, 2013)
- Kathy Gonzalez, undergraduate student (BS awarded May, 2015)
- Amanpreet Kaur, graduate student, (MS awarded May, 2015)
- Laura King, graduate student, (MS awarded May, 2015)
- Casey LaHonta, graduate student, (MS awarded May, 2015)
- Jessica Lam, undergraduate/ graduate student (MS pending Dec. 2016)
- Daniel Maurath, graduate student (MS awarded May, 2014)
- Alec Munc, graduate student (MS awarded May, 2013)
- Kendra Reich, graduate student (MS awarded May, 2013)
- James Swarts, graduate student (MS awarded May, 2013)
- Savanna Valdes, undergraduate/graduate student, (MA awarded May, 2015)

Students at Georgia Tech:

- Raine Haines, undergraduate student (BS awarded May, 2015)
- Keenan Jones, undergraduate student (BS awarded May, 2015)
- Sandeep Manchem, graduate student (MS awarded May, 2014)