The Impact of Transmission Delays on Mission Control-Space Crew Communication

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During long duration missions space-ground communications will involve delays up to 20 minutes one way, a reality that poses a formidable challenge to team communication and task performance. In the present research we examined how transmission delays impacted the interactions between mission controllers and space crews during routine and off-nominal tasks. **Method**: Four teams of NASA flight controllers and astronauts participated in a space simulation study involving two 2-hour scenarios with transmission delays of 50 sec and 300 sec. Audio-recordings of space - ground communications were transcribed and their structure (turn taking and sequence) and content examined; specifically, whether speakers identified addressees or themselves, and whether listeners confirmed their understanding. **Results and Discussion:** Transmission delays disrupted the structure of space-ground communications as contributions by flight controllers and astronauts overlapped or were out of sequence. Space crewmembers and flight controllers did not consistently mark the end of their turn; however, our findings suggest that they were more likely to do so under the longer transmission delay. Omissions of identifiers and inadequate listener feedback were observed under both delay conditions. Strategies supportive of grounding processes were also identified.

Effective and efficient communication between Mission Control and space crews is essential for successful task performance and mission safety. The importance of team communication is heightened when unforeseen problems arise, such as system failures that are time-critical and require extensive coordination and collaboration between space and ground crews. However, fractious interactions between space crews and mission control personnel have been observed during past missions and space simulation studies and posed a risk to mission success (Kanas & Manzey, 2008). These problems are likely to be exacerbated as missions travel further from the Earth. During long duration missions and missions beyond Low Earth Orbit, space-ground communications will involve delays up to 20 minutes one way, a reality that poses a formidable challenge to team communication and task performance.

Team communication involves the collaboration between speakers and addressees. 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). During face-to-face interactions conversational partners are co-located and thus may presume as mutually known information that is in their shared visual field. 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 that 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. Temporally co-present partners are also able to indicate understanding and agreement as messages are produced. In contrast, remote collaborations that involve time delays in team members' communications come with a considerable "cognitive overhead" (Olson, G. & Olson, J., 2003). The timing of turns is challenging, and individual contributions may be out of sequence, making it difficult for team members to follow the thread of a conversation and thus to develop shared situation models (Kraut, Fussell, Brennan & Siegel, 2002; Olson, G., & Olson, J., 2000). Mutual understanding is more effortful and misunderstandings more likely in asynchronous communication due to a lack of immediate feedback.

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). However, given the current limitations of earth-space transmission technology, it is essential to explore solutions that focus on communication processes per se, rather than on transmission speed.

Our project involves several studies with the overall goal to develop and validate protocols supporting mission control–space crew communication and collaboration under time-delayed conditions. In the present paper we report initial findings from a space mission simulation study. Analyses examined how transmission delays impacted the interactions between mission controllers and space crews and their joint performance during routine and off-nominal tasks. Specifically, analyses focused on communication problems as well as identified communication strategies that may have helped the mission controllers and space crews establish and maintain common ground (i.e., mutual task and situation awareness).

METHOD

In the present study we analyzed communications between mission controllers and space crews that were collected as part of the Autonomous Mission Operation (AMO) study

 DOI 10.1177/1541931213571303

conducted by Frank et al. (under review). The AMO project addressed the allocation of responsibility among flight crew, ground crew and automation given time delay between the space vehicle and earth. These issues were examined during simulated space missions involving routine (procedural) tasks, and unanticipated (ill-defined) events.

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. Simulations took place in NASA's Deep Space Habitat. Each day consisted of one training session and two experimental sessions. The first day of the experiment, the Baseline condition, involved present day equipment and space crew and mission control (MC) communicated via voice-loop. The second day, the Mitigation condition, introduced new automation and communication equipment (texting) to support space crew – mission control collaboration. Both experimental days included one mission in which space-ground communications were delayed by 300 seconds (representing missions to Mars) 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. The present analysis considers only the team communications that occurred during the two missions on day 1 (i.e., when team members communicated by voice loop).

Communication Coding

Communications between flight controllers and space crews were transcribed and subsequently coded. Our analysis of team members' communications addressed both structural and content variables. Coding categories were adopted from past research on team communication, in particular from studies of distributed but co-present teams, such as air traffic controllers and pilots (Fischer, McDonnell, & Orasanu, 2007; Morrow & Fischer, 2013).

The analysis of structural aspects concerned the timing and sequence of 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 in which flight controllers and space crewmembers talked over each other (i.e., step-ons). We also noted the presence of strategies that may facilitate turn taking, such as the use of specific phrases (i.e., *over*) to mark the end of one's turn.

The analysis of communication content focused on the following issues: whether space crew members identified themselves when they talked to CAPCOM in the mission control center; whether CAPCOM identified the crewmember to whom his/her communication was directed; and whether CAPCOM and space crewmembers confirmed their understanding of a communication directed at them. Communications from mission control 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 ; and FE-3). Likewise, the astronauts had to identify themselves in their communications to mission control to ensure that CAPCOM responded to the correct partner. Content coding also examined how addressees confirmed their understanding: 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.

Structural Aspects

Inefficiencies in turn taking. Disruptions in the turn sequence were observed under both time delay conditions (see Table 1), and involved contributions that were out of sequence or instances in which a team member—for instance a space crewmember—was speaking as a communication from CAPCOM came in that had been transmitted 50 or 300 seconds before. 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, 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).

Table 1. Number and Type of Disruptions in Turn Sequence (by team and transmission delay)

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

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 1 space crewmembers and flight controllers 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. This finding suggests that team members were sensitive to the increased uncertainty associated with the longer delay between their communications. 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.

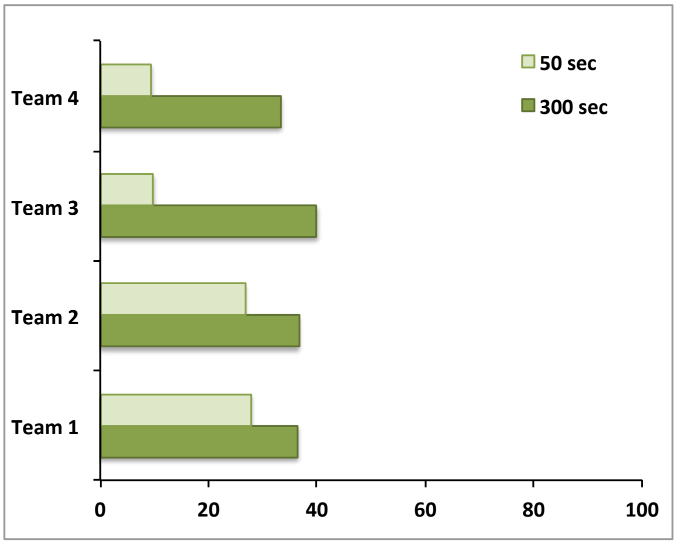

Figure 1. Percentage of turns by CAPCOM and space crews with turn ending explicitly marked

Contributions that were out of sequence could undermine mutual understanding in at least two important respects. When related contributions by CAPCOM and a space crewmember did not immediately follow each other but were disrupted by contributions by other team members, 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 4 and 5 below. Contributions that were out of sequence could also come too late; that it, a communication was overtaken by events and thus reached the addressee after the fact. This situation is depicted in Figure 2 that summarizes an exchange between CAPCOM (MC) and a flight engineer (FE-2) during a 50 sec delay. In the example FE-2 requested input from MC concerning step 4 in a procedure. As he did not hear back from MC in time, he proceeded with the procedure just to encounter a new ambiguity in the subsequent step, and thus again turned to MC 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 request, which ultimately got addressed 4 minutes after it was first posed.

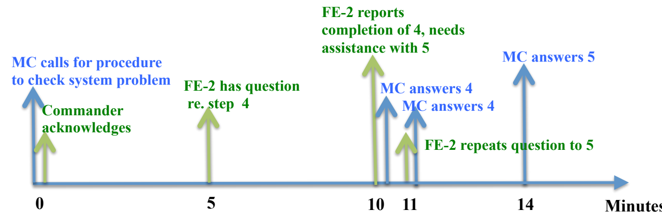

Figure 2. Depiction of a conversation in which turns are out of sequence

Supporting turn taking. In three of the teams (see Table 2 below) CAPCOM and space crewmembers 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 team interactions (such as ATC-pilots), presumably because co-present 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 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.

Communication Content

Inefficient collaborations on content. Space crewmembers sometimes did not identify themselves when they called MC. Likewise, CAPCOM failed to specify the space crewmember to whom his or her contribution was directed.

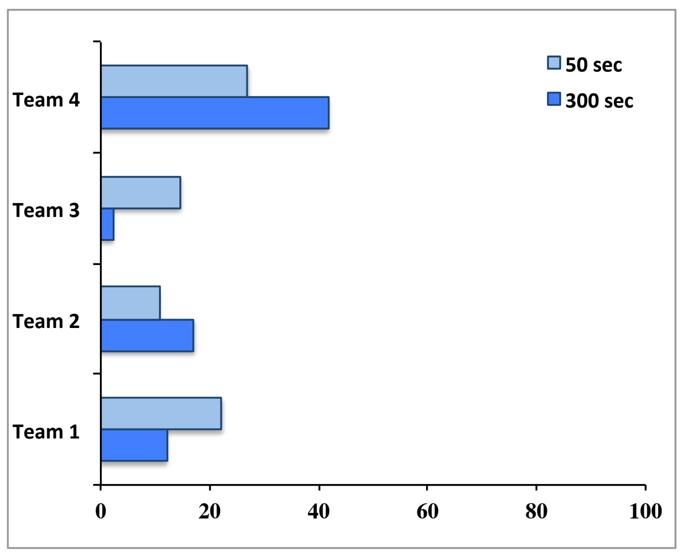

Figure 3. Percentage of turns by CAPCOM and space crew with dropped identifiers

These omissions, shown in Figure 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 the correct inferences and thus may mistake the identity of the speaker or recipient of a communication and ultimately may misunderstand its intended meaning.

Figures 4 and 5 show that listener feedback was frequently not optimal as space crews and CAPCOM provided minimal or ambiguous evidence of their understanding, or failed to respond altogether to a partner's communication.

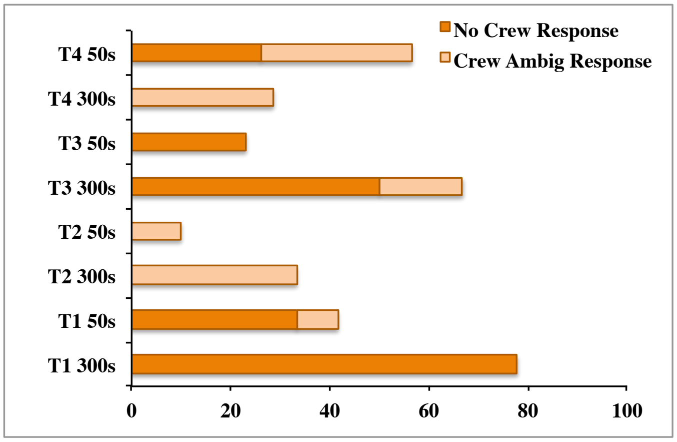

Figure 4. Percentage of turns by CAPCOM that received no or an ambiguous crew response

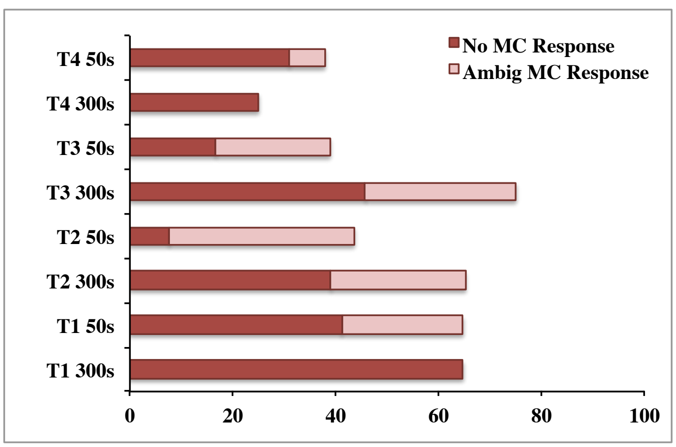

Figure 5. Percentage of turns by space crew that received no or an ambiguous response by CAPCOM

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 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*.

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.

Table 2. Strategies Employed by Space – Ground Teams to Support Turn Taking and Mutual Understanding

	Team 1		Team 3		Team 2		Team 4	
	300s	*50s*	*300s*	*50s*	*300s*	*50s*	*300s*	*50s*
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

Mutual understanding was likely aided by team members presenting 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 if speakers announced specific times at which their addressees could expect a transmission and if 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.

On the other hand, the present study is limited by its small sample and the fact that there was no synchronous condition included in the experimental design. To determine the impact of time delay on team communication we are currently conducting a lab experiment that involves a large sample and examines team communication under synchronous and asynchronous conditions.

Acknowledgments

Funding for this research was provided by Cooperative Agreement NNX12AR19G between NASA Johnson Space Center, Georgia Institute of Technology and San Francisco State University. We are grateful to Jeremy Frank and Robert McCann for sharing with us the communication data from the Autonomous Mission Operations study.

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