THE IMPACT OF COMMUNICATION DELAY AND MEDIUM ON TEAM PERFORMANCE AND COMMUNICATION IN DISTRIBUTED TEAMS

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Long duration space missions will involve communication delays of up to 20 minutes one way, a reality that will make it challenging for space crews and flight controllers to coordinate and pool their efforts, especially when unforeseen problems occur that may require extensive collaboration. The present study was conducted to examine how communication delay will impact distributed team performance, and whether communication media will moderate or exacerbate its effect. **Method**: Twenty-four teams of three were assigned the roles of space crewmember (2 participants) or flight controller (1 participant) and had to collaborate remotely on computer-based tasks simulating failures in the spacecraft's life support system. Communication medium (text vs. voice) was a between-group variable; presence/absence of communication delay was a within-group variable. Performance variables included time to repair system failures and number of incorrect repairs. Audio-recordings of team members' voice communications were transcribed and logs of their chats uploaded for further analysis. **Results and discussion:** Teams took significantly longer to repair system failures when team communication was asynchronous rather than synchronous. While communication medium had a significant effect when team interactions were synchronous, it had no differential impact under time-delayed conditions. Preliminary communication analyses suggest that under time-delayed conditions, successful teams in each media condition were those who adapted to the constraints of their communication medium to establish shared task understanding.

Effective and efficient communication between Mission Control and space crews is essential for successful task performance and mission safety. Mission Control has significant resources to assist the crew with problem resolution, but such joint efforts will require communication and distributed teamwork. The importance of teamwork and 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. 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 distributed teamwork and 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. Research is needed to identify effective communication strategies to enable Mission Controllers and space crews to establish and maintain common ground (i.e., mutual task and situation awareness) and to facilitate positive interactions despite communication delays. 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 communication processes, per se, rather than transmission speed, and to devise process strategies to mitigate problems associated with asynchronous communication.

Common ground theory of communication (Clark, 1996; Monk, 2009), which emphasizes the interactive and goal-directed nature of communication and relating communication processes to constraints inherent in different communication media, served as the framework in the present research to examine the impact of delayed communication on remote team collaboration. Common ground theory views communication as a 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, is accepted as mutually understood, accurate and relevant

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to shared goals. 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-present; they can presume as mutually known information that is in their shared visual field and may rely on gestures and facial expressions to direct the other's attention and provide feedback on their understanding. Turn-taking between co-present partners can be rapid, with messages received almost instantaneously, and their order easily determined. Co-present partners are also able to convey nuances of meaning and indicate understanding and agreement as messages are produced. To establish common ground in conversations with remote partners is more effortful as fewer resources are available. Remote communication with partners who are temporally co-present (synchronous communication, such as telephone or instant messaging) eliminates visual cues and thus requires more explicit grounding. Voice communication maintains the meaning nuances of face-to-face interactions that is lacking in text-based conversations. On the other hand, writing enables partners to re-read and thus remember past communications, and to review and revise their messages prior to sharing them with others.

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). Establishing mutual understanding is more effortful and misunderstandings more likely in asynchronous communication due to a lack of immediate feedback.

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. This study is part of a research program to address this knowledge gap. Specifically, we examined the effects of transmission delay on team communication, teamwork, and task performance under different media conditions.

METHOD

Participants

The study included 72 (24 teams of 3) adult 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.

Procedure

The micro-world for this study, AutoCAMS 2.0 (Manzey et al., 2008), simulates the life support system of a spacecraft and requires team members to monitor and control different subsystems. This micro-world mimics critical aspects of flight crew activities during space operations and has considerable face validity. The interface contains real time and trend information for 5 subsystems, carbon dioxide, oxygen, pressure, temperature, and humidity and includes an Automatic Fault Identification and Recovery Agent, which can be programmed to give true, false, or ambiguous indications of system failures. 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. The design was a 2 (communication medium – voice vs. text) x 2 (task type – simple vs. difficult/problem-solving AutoCAMS failure) x 2 (time delay – no delay vs. 5-min delay) mixed design. Medium was the 'between' variable; task type and time delay were varied within teams. Teams collaborated in two 90-min flight segments for which time delay and task order were counterbalanced.

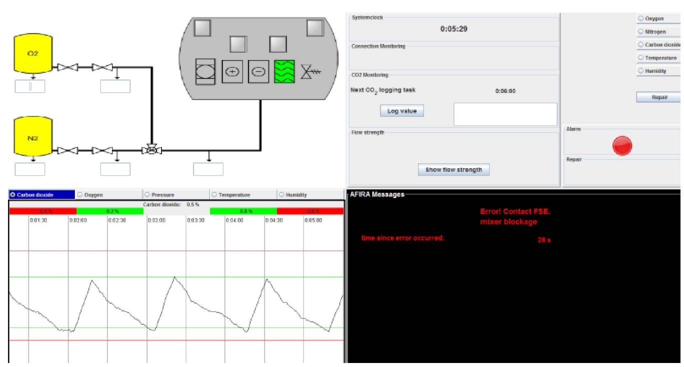

Figure 1. AutoCAMS display.

Team members were given 2-4 hours training, depending on their roles. The FSE was responsible for monitoring AutoCAMS on the US Space station and for taking care of any system failures on the Space station. Additionally, because only the FSE was thoroughly trained on AutoCAMS, any subsystem failures on the *Pioneer* required assistance from the FSE. When a failure occurred, the *Pioneer* crew had to contact the FSE for guidance on the diagnostic process and repair procedures. Each role also required several secondary tasks tapping prospective memory, reaction time, and attention to detail. For this paper, we focus on the two collaborative AutoCAMS failure tasks (one simple, one difficult/problem solving) that occurred during the time delay leg.

Team 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. Performance data on secondary tasks were also collected but will not discussed here.

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 spacecraft crewmembers and flight controller 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*?) or pauses. In text-based communications, any text written by a participant before pressing the send button constitutes a turn.

Communication analysis examined structural aspects as well as content variables. Structural aspects concerned *communication density* (i.e., number of turns per minute) and *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* (i.e., requests for clarification) as well as threats to common ground and strategies aimed at managing communication delay. Threats to common ground included contributions that indicated an *insensitivity to the transmission delay* (e.g., conversational partner repeated message before he/she could have received a response), *missing responses* (i.e., failure of an addressee to respond to or acknowledge contributions by his/her partner) and the *use of terms whose meaning was underspecified* (e.g., "We have a problem") or could not be established within a turn but rested on information in preceding turns (e.g., In order for the addressee to identify which repair the speaker referred to in "We completed the repair," he/she had to remember elements in their previous communications). The coding of communication strategies identified efforts by team members to mitigate the disruption of the turn sequence and the cognitive demands posed by communication delays. Specific strategies will be discussed in the results section below.

RESULTS AND DISCUSSION

Discussion of findings will focus on team communication and performance under time-delayed conditions and in relation to different communication media. Performance data of teams as they communicated synchronously will be provided but not discussed in any detail.

Task Performance

Mixed-design Analyses of Variance (ANOVAs) on time in red indicate that teams took significantly longer to repair system failures under time delay than when they had no time delay, $F(1,22)=7.54$, $p=.012$, partial $eta^2=.253$. The difference was concentrated 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 both media performed comparably. 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 1).

Table 1. Task performance measures.

	Text	Voice
Min in Red Time Delay, TD (N=24)	56.21 (24.99)	61.63 (20.77)
Min in Red No Time Delay, NTD (N=24)	56.76 (20.54)	29.84 (25.65)
Incorrect Repairs TD (N=22)	3.4 (2.76)	1.58 (2.02)
Incorrect Repairs NTD (N=22)	5.8 (3.74)	2.75 (2.80)

The number of incorrect repairs that crews initiated was also analyzed as a measure of performance. Two crews attempted an unusually high number of repairs without direction from the FSE during the NTD leg. Data from these crews were excluded as outliers from any analysis on the repair procedure. Analysis on the remaining 22 teams showed that significantly more incorrect repairs were attempted 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 $eta^2=.337$.

Team Communication

Presently the communications of half of the teams (N = 12) have been analyzed in detail and therefore only descriptive analysis will be provided. High-performing and low-performing teams in each media condition (Average time (min) to repair: $Text_{High}$ = 32.2; $Text_{Low}$ = 76.15; $Voice_{High}$ = 34.77; $Voice_{Low}$ = 79.15) were selected and their communication coded.

Structural aspects of team communication. A higher communication density was observed for the high-performing text teams (about 1 turn every minute) than for the low-performing text team and the voice teams (all about 1 turn every 2 minutes). The distance between adjacency pairs –i.e., the number of turns intervening between an initiating communication and its intended response—was largest in high-performing text teams and lowest in high performing voice teams with intermediate values for low-performing teams (see Table 2). While large distances between adjacency pairs could make it cognitively challenging for addressees to follow the thread of a conversation, the success of high-performing text teams suggests that the written record may have sufficiently supported team members' memory and comprehension. In contrast, high-performing voice teams had a lower communication rate and kept related contributions more closely aligned. This behavior may have helped voice team members to manage the cognitive effort involved in keeping track of spoken discourse.

Table 2. Communication measures observed for high- and low performing text and voice teams during the TD flight segment

	TEXT		VOICE	
	Performance		Performance	
	Low	High-	Low	High
Number of turns	36	41	34.67	16
Communication density (turns/min)	0.48	1.23	0.44	0.49
Turns intervening b/w adjacency pairs	8.53	13.93	8.58	6.18
*Communication problems	4.46	2.5	3.88	0
*Insensitivity to transmission delay	12.37	9.91	6.27	10.88
*Use of ambiguous terms	18.63	22.75	18.15	8.62
*Failure to provide response	12.37	6.84	4.3	0

* Numbers refer to percentage of turns

Content analysis. Likewise, content analysis indicated differences between high-performing text and voice teams that are consistent with medium-specific affordances. High-performing text teams seemingly exploited the fact that team members could rely on a written record to establish common ground. We found that on average 23% of their turns included terms (e.g. "valve leak") whose meaning (oxygen valve leak as opposed to nitrogen valve leak) became clear only on the basis of information presented in preceding or in subsequent turns, and 7% of their turns were left unacknowledged. Voice communication is cognitively more challenging than text-based communication insofar as participants need to remember their ongoing discourse to interpret new information. Ambiguous terms may thus be easily misunderstood as participants fail to retrieve the appropriate clarifying information. High performing voice teams in our study displayed behavior that may indicate sensitivity to the constraints of their communication medium. Ambiguous terms were rare—occurring in 9% of their turns—and participants consistently acknowledged their partner's communications. High performing voice teams also consistently employed several strategies that may have helped team members to maintain conversational coherence under time delay. They used longer turns compared to the no-time delay condition; thus providing more information at once. In so doing, they 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 well 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. No consistent strategy use was observed for high-performing teams in the text condition. Only one of these teams adopted the same strategies as high performing teams in the voice condition.

CONCLUSION

Perhaps the most interesting finding of our research 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. Moreover, our research suggests that successful teams in each media condition were those who adapted to the constraints of their communication medium to establish shared task understanding.

This study also demonstrates the validity of conducting research involving a student population to examine issues relevant to space operations. While communication problems were more pronounced in the student population than in an astronaut sample that participated in a simulation study –for instance with respect to the use of ambiguous terms—the nature of the problems was identical. Likewise, student participants generated the same strategies as astronauts in an analog environment study (Fischer, Mosier & Orasanu, 2013).

Additional analyses are planned to explore further the relationship between communication strategies adopted by teams in the voice and text condition and task-specific performance measures. Findings from this study are being used to develop communication protocols in support of mission control–space crew communication and collaboration under time-delayed conditions.

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