The Impact of Voice, Data Link, and Mixed Air Traffic Control Environments on Flight Deck Procedures

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Abstract

A simulation was conducted at NASA Ames Research Center that compared how crews handled voice and data link air traffic control (ATC) messages in a single medium versus a mixed voice and data link ATC environment. The interval between ATC messages was also varied to examine the influence of time pressure. Results indicated that for messages sent via voice, transaction times were lengthened in the mixed media environment for closely spaced messages. The type of environment did not affect data link times. However, messages times were lengthened in both single and mixed-modality environments under time pressure. Closely spaced messages also increased the number of requests for clarification for voice messages in the mixed environment and review log use for data link messages. Thus, when time pressure is introduced, the mix of voice and data link does not necessarily capitalize on the advantages of both media. These findings emphasize the need to develop procedures for managing communication in mixed voice and data link environments.

Introduction

Controller Pilot Data Link Communication (CPDLC) is a means of communicating between controllers and pilots using electronic messaging. A number of studies examining incident and accident reports have identified problems arising from voice communication, including those associated with frequency congestion and communication errors [1, 2]. Because data link (DL) will be supplemental to voice communication, a mixed environment where pilots and controllers will be required to move from radio to data link media is anticipated [3]. Voice amendments to data link clearances can also be foreseen due to potential difficulties with pilot-controller negotiations via data link communication. Early data link research concentrated on single medium voice or data link environments. Research findings have shown an increase in accuracy and consistency for data link at the cost of speed for the transfer of information (see [4] for a review). In this data link research summary [4], it was reported that a dual-media environment of voice and data link requires fewer total transmissions than an all-voice environment. While research has indicated reluctance by pilots to use data link in the busy terminal area and for non-routine transmissions [4], little research exists that examines how the two media will best coexist.

Relevant research that may illustrate some potential issues around a mixed media environment, found that the time interval between messages impacts both voice and textual data link communication [5]. The study also revealed longer overall acknowledgement times for both voice and data link when there was a short interval between messages.

Additionally, voice and data link communications have different procedural constraints. One such constraint is the ability to respond to the message. Because voice is more temporal and often more salient than the visual modality [6], a voice clearance may draw a more immediate response. In contrast, a suggested benefit of data link is its flexible access where the pilot can manage the communication task around other flight duties [4]. However, the permanent nature of the data link message allows for flexibility when the message is retrieved.

Combining the data link and voice media in a mixed environment may alter their characteristics in a way that does not maintain the advantages of each medium separately. To examine whether there may be an impact in switching between voice and data link communication due to the change in modality and communication procedures, the researchers [7] examined the flight deck perspective of voice and data link communication in both single medium and mixed media environments. The interval between air traffic control messages was also varied to look at the influence of time pressure in voice, data link, and mixed ATC environments. Results from this part-task simulation indicated that voice transaction times were longer in the mixed than in the single medium environment, while data link transaction times were unaffected by the environment. Time pressure resulting from short intervals between messages increased data link transaction times in both the single medium data link and mixed data link-voice environments. However, message interval influenced voice communication only in the mixed environment when a voice clearance closely followed a data link message. Closely spaced messages also increased the number of requests for clarification for voice messages and review log use for data link messages. Pilots appeared to handle all communication sequentially, closing out a data link message prior to attending to the voice message. Because the voice clearance was ephemeral, pilots had trouble remembering the voice message and this resulted in more clarifications.

There were some potential weaknesses to the previous study by McGann et al. [7]. The testing environment used for the experiment was a single pilot part-task simulator. One participant performed all of the flight tasks, including data link operations. Thus, workload was likely different from what would be expected in an actual commercial aircraft with multiple crewmembers.

The present study was designed to follow up on the part-task study described above. Several differences exist between the two experiments. The current study involves a full-mission simulator, with two crewmembers, and a different flight deck implementation of data link. The first study had a dedicated display of data link, whereas the current study had a data link display that was time-shared with the Flight Management System/Control Display Unit (FMS/CDU). There were also other interface differences associated with each of these display differences related to alerting, message access, and responses available.

The goal of this research was to re-examine the issues involved in shifting modalities in a mixed media, domestic, en route environment using a current implementation of data link and recommended procedures in a high fidelity simulation. Specifically, we were interested in comparing voice, data link, and mixed ATC environments under time pressure caused by short intervals between messages. We expected that voice communication would be most impacted by the mixed environment and that closely spaced messages would result in more communication problems and longer transaction times.

Method

Participants

Ten airline pilots (all male) were paid to participate as flight crewmembers. All participants were either currently type-certified on the B747-400 or retired for less than one year. Average total flight time for the participants was 11,100 hr, ranging from 3,500 to 20,000 hr.

Simulation Facilities

Crews flew in the Boeing 747-400 simulator at the Crew-Vehicle Systems Research Facility at NASA Ames Research Center. This NASA simulator was built by CAE Electronics and is certified to the FAA Level D certification requirements (for a more detailed description of the aircraft simulation facility, see [8]).

Data Link Functionality

The simulator was equipped with FANS 1/A data link capability as exists on the 747-400. This is a Flight Management Computer (FMC)-integrated data link utilizing either of the forward CDUs as an interface. An ATC function key on the CDU keyboard allowed both crewmembers access to the ATC data link information on their respective CDUs. Each of the forward CDUs can also be used to interact with the FMC for data input or output (e.g., altitude, route, or speed data).

Upon receipt of a data link message, the visual alert and aural alert would notify the crew of the presence of a message. An ATC function key was used to access a new message or the ATC Index page if no new messages were in the queue. Once a message was accessed, it was displayed on the CDU. The message page consisted of the message content, the text ATC UPLINK at the top, a time stamp representing the time a message was sent, and a page number over the pages available for the message. In addition, the message acknowledgment options were displayed at the bottom of the message, which included “ACCEPT”, “REJECT”, and “STANDBY”.

For a limited number of clearances, there was also a "load" prompt and an "arm" prompt, which would enable the direct entry of the message contents into the FMC. Due to a simulator limitation, crews were instructed to ignore the "load" and "arm" prompts and to enter all information manually. Other capabilities included in the data link system were the ability to review previous messages and the ability for the pilot to construct and transmit messages to the controller.

Instructions and Training

Participants were given an overview of the experiment. They were told that the focus of the study was on air-ground communication in the different experimental conditions. They were not briefed on the differences in message interval until after the experiment.

Although all participants were already FANS 1/A qualified, all crews participated in a short briefing and training on the data link system. Based on the recommendation of the aviation community, crews were asked to follow some general procedural guidelines [3]. Specifically, the pilot-not-flying (PNF) was asked to handle the ATC communication tasks, as is done today, but both pilots were requested to read ATC uplink clearances directly from the display. Crews were also advised as to the relative priority of the different communication media: ATC voice communication was to be handled with the highest priority, followed by ATC data link communication, and finally company communication should be considered the lowest priority. After the briefing, the crews participated in a short 30-minute training scenario, in which the crews flew the simulator and operated data link following the procedures that were given during the training.

Procedure

Participants flew a total of six short flight segments 20–30 min in duration. Each crew flew two legs with voice communication, two legs with data link communication, and two legs with a mix of voice and data link communication. Each leg was scripted with a different set of clearances with the help of current and former controllers. A retired TRACON controller serving as a researcher confederate was available to respond via radio to any pilot communication.

Analyses focused on four pairs of messages (a total of eight target messages) in each scenario. Each of the target messages under investigation contained two commands. Commands for voice and data link included such directives as altitude, speed, and route changes, as well as transfer of communications. The interval between the paired messages was varied: either 5 s or 1 min after the pilot accessed the data link clearance or after the readback of the voice clearance. Because the previous study [7] only found problems in the mixed environment when a voice message closely followed data link, we focused on that sequence only. Thus for the mixed environment, data link was always followed by voice. The order of legs, communication medium, and interval was counterbalanced.

This study was designed to assess the effects of communication medium (voice, data link or mixed), message interval (5 s or 1 min), message order (first or second), message urgency, and data link message page length on pilot communication. The effects of message urgency and page length will not be discussed in the paper, but can be found in Dunbar, McGann, Mackintosh, and Lozito [9]. Also, the total transaction time and the number of communication problems (clarifications and errors) will be discussed, in this paper.

Results

Total Transaction Time

Total data link transaction time included time for the pilot to access the message, read it, and acknowledge it to ATC. Total voice transaction time included time from the controller onset of the message (i.e., the time the experimenter sent the prerecorded message) to the end of the pilot readback including any clarification. These data were collected from the videotapes by two coders. Total transaction times for both data link and voice messages were extended to include any communication by either crewmember with the air traffic controller about the content of the message. These are the operational measures most commonly used for transaction time [10, 4, 7].

Total transaction time was analyzed in a 3 (medium: voice single medium, data link single medium or mixed) x 2 (interval: long or short) x 2 (order: first or second message) repeated measures Analysis of Variance (ANOVA). The analysis for total transaction time revealed a significant three-way medium by interval by order interaction, $F(2, 8) = 4.80$, $p < .05$. See Figure 1 for means and standard errors of total transaction time. Because the highest order interactions were found, lower level interactions and main effects will not be discussed. To interpret these results, we analyzed the data separately for each environment (voice single medium, data link single medium and mixed).

Comparison of Communication Media

Single medium environments

Based on the previous study, it was hypothesized that for the single medium environments, both time pressure and message order would interact in the data link single medium environment causing the second message in the short interval condition to be lengthened. However, time pressure and message order would not significantly impact message timing variables in the voice single medium environment.

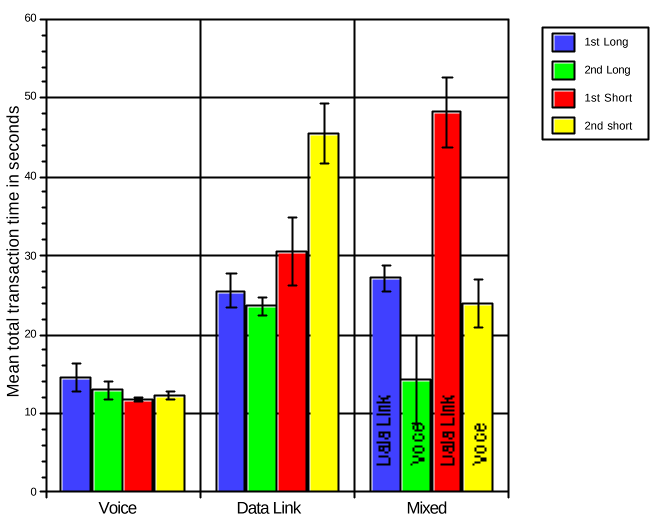

Figure 1. Mean Total Transaction Time for Message Interval and Order

For each of the two single-medium environments (voice single medium and data link single medium), a separate 2 (interval) x 2 (order) repeated measure ANOVA was conducted on total transaction time. For messages in the data link single medium environment, significant main effects for interval, $F(1, 4) = 26.91$, $p < .01$, $\omega^2_A = .139$, and order, $F(1, 4) = 7.86$, $p < .05$, $\omega^2_A = .041$, were identified. Total transaction times for data link messages in the short interval pairing ($M = 38.05$ s, $SD = 19.21$ s) were significantly longer than those with a longer interval between messages ($M = 24.54$ s, $SD = 7.58$ s). Additionally, messages that were second in the pairing had significantly longer acknowledgment times ($M = 34.55$ s, $SD = 16.50$ s) than the first message in the pairing ($M = 28.04$ s, $SD = 15.04$ s). In the voice single medium environment, no significant interaction or main effects were found. It took crews an average of 12.88 s ($SD = 4.95$ s) to acknowledge a voice message in the single medium voice environment.

Mixed media environment

We hypothesized that the total transaction time for voice messages would be lengthened in the mixed environment under conditions of time pressure. For the mixed media environment, we analyzed total transaction time in a 2 (interval) x 2 (order) repeated measures ANOVA. Recall that in the mixed condition, data link was always the first in a pair of messages followed by a voice amendment. This sequence was chosen for the study based on the previous finding that data link followed by voice was the only problematic sequence (i.e., not voice followed by a data link message). Thus, the order of the messages also distinguishes the clearance medium (data link vs. voice). In the analysis for total transaction times, there were main effects for both interval, $F(1, 4) = 45.00$, $p < .01$, $\omega^2_A = .216$, and order, $F(1, 4) = 20.56$, $p < .05$, $\omega^2_A = .109$. The data link clearances (first message in each pair) resulted in longer transaction times ($M = 37.65$ s, $SD = 18.18$ s) compared to the voice clearances (second message in the pair: $M = 19.15$ s, $SD = 11.24$ s). It seems that pilots interrupted the data link clearance to attend to the voice message before closing out the data link message. Interval had a large effect on total transaction times (accounting for 21.6% of the variance, $\omega^2_A = .216$), in that a short interval between messages significantly lengthened total transaction times ($M = 36.04$ s, $SD = 20.71$) compared to long intervals between the two messages ($M = 20.76$ s, $SD = 9.15$ s).

In summary, the modality by which a message was sent from ATC to the flight crew affected the time crews took to acknowledge the message. Total transaction times in the voice single medium environment were unaffected by time pressure and message order. However, in the data link single medium environment, we found that time pressure and message order each independently affected total transaction times, with short intervals between messages and subsequent messages having lengthened times. When the two message modalities were used in the same flight segment (data link followed by voice), it took crews significantly longer to acknowledge a data link message compared to a voice message (order effect). Also, time pressure affected both modalities, with longer total transaction times in the short interval sequence.

Single-Medium vs. Mixed Media Environments

To further analyze the impact of the mixed environment on communication, we conducted separate analyses to directly compare each medium (voice and data link) in the single and mixed environments. Since in the mixed environment the data link message was always first in the pair of messages, only the first in each pair of messages in the single medium data link environment was used in this comparison. We analyzed data link total transaction times in a 2 (environment: single medium DL vs. DL in mixed) x 2 (interval: long v/s short) x 2 (page length: 1 vs. 2-page messages) repeated measures ANOVA. This analysis revealed a significant main effect for interval, $\underline{F}(1, 4) = 14.22$, $\underline{p} < .05$, $\omega^2_A = .076$. As was found in the previous analyses of the data link messages, total transaction times were longer in the short interval pairing ($\underline{M}$ = 39.38 s, $\underline{SD}$ = 21.11 s) compared to long interval messages ($\underline{M}$ = 26.32, $\underline{SD}$ = 8.42 s). No main effect for environment was found.

A similar analysis for transaction times was conducted for the voice messages. In this case, voice was always the second in the pair of messages in the mixed environment. Therefore, only the second in each pair of messages in the single medium voice environment were used for this comparison. We analyzed voice transaction times in a 2 (environment) x 2 (interval) repeated measures ANOVA. The analysis revealed a significant environment x interval interaction, $\underline{F}(1, 4) = 7.60$, $\underline{p} < .05$, $\omega^2_A = .040$. Post-hoc analyses indicated that the voice message following the short interval in the mixed-modality environment had a significantly longer total transaction time than the other three message types.

In summary, we found that the type of environment (single medium versus mixed modality) influenced the length of acknowledgement times for voice messages, but not for data link transactions. For messages sent aurally, total transaction times were significantly longer for messages in the mixed environment when under time pressure (short interval in mixed environment). Type of environment did not affect data link timing variables. However, we did find that data link total transaction times were lengthened under time pressure.

Errors and Clarifications

Communication problems, such as requests for clarification, were also examined. We hypothesized that the mixed communication environment and short inter-message intervals would produce more communication problems. Communication problems were defined as actions performed by the crew to clarify an ATC message. There were two kinds of actions. First, pilots could call ATC to clarify a voice or data link message (e.g., by asking for a repeat or confirmation, such as “Say again the altitude”). This definition was used in earlier studies of air and ground communication problems [11, 7]. Second, for data link single medium, pilots could use the review log to clarify message content. Conceptually, use of the review log is similar to voice clarification because the crew performs an action to check or clarify the message. Operationally, they are different because voice clarification ties up the radio frequency whereas review log usage involves only the crew and not the controller.

For this analysis, we wanted to compare the number of voice clarifications across all conditions. There were no clarifications in the short interval messages in the single medium voice condition. Therefore, the voice single medium environment was dropped from the statistical analysis investigating the impact of interval. Overall, there were 18 voice clarifications and 41 data link “clarifications” (messages reviewed through the review log) in the 240 target messages under investigation (see Table

1). A 2 (environment: data link single medium vs. mixed) x 2 (interval) repeated measures ANOVA was conducted on the total number of clarifications made by each crew (voice clarifications and data link review log usage). As predicted, a significant main effect for interval was found, $\underline{F}(1, 4) = 90.00$, $\underline{p} < .001$, $\omega^2_A = .681$. The short interval significantly increased the number of clarifications.

In order to investigate the impact of medium, the number of clarifications made per crew was summed across the two levels of the interval manipulation. A one-way repeated measure ANOVA was conducted on the number of messages clarified in each of the three mediums (voice single medium, data link single medium, and mixed). No significant effect was found, $\underline{F}(2, 8) = 2.08$, $\underline{p} = .187$. It is interesting to note that only six messages or 10% of all clarifications occurred in the single medium voice medium ($\underline{M}$ = 1.2 clarifications per crew, $\underline{SD}$ = .84). The data link single medium environment accounted for 46% of the clarifications ($\underline{M}$ = 5.2 clarifications, $\underline{SD}$ = 1.48), while 44% occurred in the mixed environment ($\underline{M}$ = 5.4 clarifications, $\underline{SD}$ = 6.07). The large amount of variance in the mixed environment may be masking possible differences between environments.

Table 1. Frequency of message clarification types for each level of medium and interval.

Clarifications		**Voice**	**Data Link**	**Total**
Voice Single Medium	Short	0	**	0
	Long	6	**	6
Data Link Single Medium	Short	0	18	18
	Long	0	9	9
Mixed Medium	Short	7	9	16
	Long	5	5	10

** Review log not available

Additionally, we examined the types of voice communication problems since they may indicate which cognitive processes are impacted by the mixed media environment and time pressure. Voice clarification type included 1) a request to repeat the clearance, 2) a request for confirmation, and 3) incorrect readbacks. Of all radio clearance clarifications, 67% of clarifications occurred in the mixed environment and 33% occurred in the single medium voice environment. (Only once in the mixed condition was a data link clearance clarified via the voice frequency.) There were no pilot readback errors in this study. In the mixed condition, pilots asked the controller for confirmation of a clearance half of the time and the other half of the time requested ATC to repeat the clearance. For the single medium voice condition, requests for confirmation of a clearance occurred most frequently (83%) and there was only one request for a repeat of the clearance (17%). These results suggest that crews experienced more difficulty hearing or remembering voice messages in the mixed ATC environment than in the voice-single medium environment.

We expected that the mixed environment and short inter-message interval would produce more errors. Two types of communication errors were coded from the videotapes. First, in four cases, crews missed responding to an entire voice message. All of these missed clearances occurred in the mixed environment, three with a short inter-message interval and one with a long inter-message interval. Second, in seven cases, crews failed to implement one element of a clearance message. Six of these seven errors of omission occurred in the mixed environment and one in the single medium data link environment.

Taken as a whole, the results of clarifications and errors analyses suggests that voice messages in the mixed environment were most likely to be problematic, especially under time pressure. Voice messages in the mixed environment had a clarification rate four times that of voice messages in single medium voice environment (taking into account that there were half as many messages sent in the mixed environment). In addition, most of the missed clearances and messages with implementation errors occurred for voice messages in the mixed environment. Data link messages in both environments (data link single medium and mixed) had equal rates of clarifications (via the review log), and both suffered when time pressure was present. Crews had by far the fewest problems handling messages in the voice single medium environment.

Messages Acknowledged Out of Order

It is interesting to note that time pressure caused by a short interval between messages sometimes resulted in messages being acknowledged out of order. That is, the second message in a short interval sequence was sometimes acknowledged prior to a response for the first message. Messages were acknowledged out of order in 17 cases (across 240 opportunities). Thirteen of these cases occurred in the mixed environment and four of these cases were from the single medium data link environment.

Subjective Data

After the simulation, participants responded to a questionnaire and all questions were rated on a five-point scale, where a high score corresponds to a favorable rating. When asked about the use of data link crews indicated feeling that data link improves the effectiveness of air-ground communication (M = 4.10, SD = .99) and that they would be satisfied with the data link system as a safety enhancement in the en route phase of flight (M = 4.70, SD = .48). The pilots also felt that the review log was pretty effective for providing a reference to clearances during the single medium data link scenarios (M = 4.50, SD = .53), but only moderately useful during the mixed data link and voice scenarios (M = 3.30, SD = 1.25).

When comparing the single medium environment with the mixed media environment, pilots reported that handling voice messages in the mixed environment was no more difficult than handling voice messages in the single medium voice environment (M = 2.80, SD = 1.14, where 5 is "easy to use" and 1 is "difficult to use"). Crews indicated that data link messages in the mixed environment were only slightly more difficult to handle than in the single medium data link environment (M = 2.10, SD = .88). Finally, pilots were asked about the specific data link procedures used in the study and they reported that they were comfortable with the procedures (M = 4.60, SD = .52).

In summary, flight crews reported positive attitudes about their ability to use this implementation of data link for air-ground communication in the domestic, en route phase of flight. However, pilots did recognize the diminishing value of the data review log in the mixed environment.

Discussion

This study extends a previous study by McGann et al. [7] to better understand how a mixed voice and data link environment affects crew communication. Specifically, the factors of communication modality (voice, data link or mixed), message interval (5 s or 1 min), and message order (first or second) were evaluated. The principal measures collected were total transaction time and number of communication clarifications and errors.

Total Transaction Time

Medium: Data link v/s Voice

The results from this study indicate that the time pressure present in closely spaced messages differentially impacted voice and data link. Direct comparison of the single-medium environments in this study allowed us to determine a baseline of communication performance for both voice and data link. Data link transaction times were significantly longer than voice transaction times. This is partly due to the data link implementation requiring discrete procedural steps to open and acknowledge data link clearances. However, despite the longer transaction times, it appears that crews usually implement the clearance data prior to acknowledging a data link message. Voice and data link transaction times were also differentially impacted by time pressure. A short interval between messages significantly lengthened transaction times for data link messages, but closely spaced messages had no impact on voice transaction times in the single medium environment. Thus, the single medium voice environment was robust enough to handle a short interval between messages with no impact on acknowledgment times.

The finding that voice and data link transactions were differentially affected by time pressure replicates the results from the previous study [7]. Both voice and data link have particular characteristics, when considering acknowledgment time. Voice is the faster and more flexible of the two media while data link has the advantage of message permanence, but is slower and more sequential in nature. It is also interesting to note that data link total transaction time was always impacted by interval, regardless of whether the data link message was in the single medium data link environment or the mixed environment. The sequential nature of the textual data link, which requires a variety of visual and manual tasks, seems to be incompatible with time pressure when responding to a clearance message.

Environment: Single v/s Mixed

Based on the findings of the previous study, we expected that voice transaction times would be lengthened in the mixed environment relative to the single medium voice environment. Moreover, while we expected that data link messages would be affected by a short inter-message interval, we did not expect the mixed environment to impact data link transaction times although we found it did.

Single pilots in the part-task study handled messages sequentially in the mixed environment, completing a data link message before attending to a subsequent voice message, whereas crews in the present study seemed to interrupt the data link message to attend to the subsequent voice message. Despite the different strategies used in the two studies, voice transaction times were lengthened in the mixed environment for both simulations. Procedurally, both crew members were required to read the data link messages from the display, and this could explain why in the present study the PNF did not close out the data link clearance before attending to the voice message in the mixed environment. It also explains why the second message in the single medium data link environment had longer transaction times compared to the first. These data reflect crew comments that it was more difficult to handle voice messages in the mixed environment than in the single medium environment.

Clarifications

With regard to message clarification, there were communication problems in the voice condition. As was found in the previous simulation, data link reduced the need for verbal communication with the controller to resolve problems and misunderstandings, largely because messages were permanently stored and available for pilot review. When review log usage was taken as a measure of message clarification, there were more uses of the review log in data link than there were clarifications in the voice environment. This suggests that the textual messages were not easier to remember, they were simply more available for review. Although frequency congestion was reduced in the data link condition relative to the voice condition (6 out of 40 messages were clarified verbally), pilots clarified via voice more in the mixed environment (11 out of 20 voice messages were clarified verbally). Apparently, the value of a review log is diminished when voice and data link messages are mixed. Pilots cannot rely on their data link review log for confirmation of the most recent clearance when many clearances are transmitted by voice. In fact pilots commented that the review log was only moderately useful in the mixed scenarios. Hence, one of the primary benefits of data link communication, permanent message storage, may be reduced in the mixed environment.

Finally, the mixed environment also resulted in more errors than either the single medium voice or single medium data link environments. Crews were requested to respond to a message in the medium in which it had arrived, so a data link message would necessitate a data link acknowledgment while a voice message would be responded to verbally. However, the controller was always available during each run, so it was possible to respond to a data link message over the voice channel. In four cases, crews missed hearing the entire voice message in the mixed environment. Crews did not miss a voice message in the single medium voice environment, even with the time pressure caused by closely spaced messages. Additionally, in seven cases, crews missed implementing one element of a clearance message. All of these errors of omission occurred in messages separated by a short interval. Six of these errors were in the mixed environment while one was in the data link environment. These errors may have occurred because crews sometimes acknowledged closely spaced message out of order. It appears that in switching back and forth between messages, some elements were overlooked.

Conclusion

Inefficiencies in an overloaded voice radio communication system have galvanized the aviation community to advance the use of data link communication between controllers and pilots to create additional capacity on the voice channel. The implementation of CPDLC throughout the U.S. national airspace will involve a mixed environment, requiring pilots and controllers initially to switch attention between textual data link and voice media. Some research shows that data link can help reduce transfer of information problems including missed or blocked transmissions [4]. Other studies have shown that a dual-media system requires fewer overall transmissions than the single medium voice system [12].

The results of the present study illustrate what may occur when mixing voice and data link environments under conditions of time pressure. The simulation revealed longer transaction times in the mixed environment than in the single medium voice environment. Additionally, flight crews missed entering more clearance data with mixed voice-data link communication than with either of the single medium conditions. Finally, relative to the single medium voice environment, there were more voice clarifications in the mixed environment. When comparing the mixed environment to the single medium data link environment, however, the numbers of clarifications (as measured by review log usage in data link) are the same proportionately given that there are more data link messages in the single medium data link environment. Again, this seems to be an indication of the added difficulties of shifting between the voice and data link media. Clarifying message content over voice with the controller contributes to frequency congestion and adds workload to the controller.

However, the use of the review log may be problematic since it may not reflect voice amendments and could therefore be inaccurate. In the mixed condition, crewmembers are using both methods in an apparent attempt to compensate for some of the possible confusion.

Our research findings substantiate the conclusions from the previous part-task simulation, demonstrating that when time pressure is introduced, the mix of voice and data link does not necessarily capitalize on the efficiency of voice and the precision of data link. To ensure the development and use of an effective system, we need to address the human performance concerns for all users in the complex mixed media environment.

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