EFFECTS OF MODALITY ON INTERRUPTED FLIGHT DECK PERFORMANCE: IMPLICATIONS FOR DATA LINK

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ABSTRACT

Externally-imposed tasks frequently interrupt ongoing task performance in the commercial flight deck. While normally managed without consequence, basic research as well as aviation accident and incident investigations show that interruptions can negatively affect performance and safety. This research investigates the influence of interruption and interrupted task modality on pilot performance in a simulated commercial flight deck. Fourteen current commercial airline pilots performed approach scenarios in a fixed-base flight simulator. Air traffic control instructions, conveyed either aurally or visually (*via* a data link system) interrupted a visual task (obtaining information from the Flight Management System) and an auditory task (listening to the automated terminal information service recording). Some results confirm the hypothesized performance advantage of cross-modality conditions, more compelling nature of auditory interruptions, and interruption-resistance of auditory ongoing tasks. However, taken together, results suggest the four interaction conditions had different effects on pilot performance. These results have implications for the design of data link systems, and for facilitating interruption management through interface design, aiding, and training programs.

INTRODUCTION

The role of the pilot as a task manager on the flight deck is increasingly prominent. As automation distances pilots from manually flying the aircraft and as new technologies accumulate to address other mission goals (communication, terrain and traffic avoidance), pilots adopt more supervisory responsibilities and fewer characteristics of continuous controllers. One aspect of task management is "interruption management," that is to attend appropriately to and to accommodate new, interrupting stimuli and tasks. Interruptions naturally and frequently occur in the dynamic and multi-tasking context of the commercial flight deck. While pilots usually manage interruptions without consequence, basic research shows that interruptions tax performance (Detweiler, Hess, and Phelps 1994; Cellier and Eyrolle 1992; Gillie and Broadbent 1989; Kirmeyer 1988; Field 1987; Paquiot, Eyrolle, and Cellier 1986; Kreifeldt and McCarthey 1981) and can contribute to aviation incidents (Madhaven and Funk 1993, Chou and Funk 1993, Turner and Huntley 1991, Monan 1979) and aviation accidents (NTSB 1988, 1973). Therefore, it is important to identify those attributes of interrupting and ongoing tasks that characterize pilots' interruption management performance.

One attribute of interest is modality. This experiment addresses the performance implications of whether the interrupting task is conveyed visually or aurally and whether this interruption intrudes upon a visual or auditory ongoing task. Modality attributes were chosen both for their pragmatic importance, and because basic research has provided a foundation for interpreting results. Applied research is concerned with the human performance implications of replacing traditional voiced communications to the flight deck with newer, visually-presented communications afforded by digital data link technology.

Data link technology allows digital information communication. In aviation, digital data links may provide an opportunity to relieve congestion of overloaded Air Traffic Control (ATC) radio frequencies. With this new approach, new questions arise concerning the interface for Data Link communications. Most aviation data link studies of messaging system address pilots' acceptability of Data Link interfaces and compare radio and data link-mediated communication performance. It is much rarer to find an investigation that addresses how this new technology affects flight deck performance in other ways. This study explicitly addresses the effects of ATC interruptions presented *via* radio and *via* a visual data link interface on flight deck procedure performance.

Hypotheses

Basic research in human information processing suggests three hypothesizes for task interrupt situations.

1) Interruptions presented aurally should be more quickly attended to than interruptions presented visually.
Auditory information is more attention-directing than visual information (Stanton 1992, Posner *et al.* 1976). Based on this, other authors suggest that an auditory task is more likely to preempt an ongoing task than a visual task (Segal and

Wickens 1991). Although the visually-presented interruptions in this experiment begin with a momentary auditory annunciation, to equalize diversion effects, this annunciation does not persist and therefore does not continue to demand attention. Contrary to this implication, applied data link research found that pilots typically responded more rapidly to data link, or visual, messages than to auditory radio calls (Kerns 1990). Data link, or visually-presented, air traffic control (ATC) messages also precipitated longer delays before resuming interrupted tasks (Williams 1995).

2) Auditory ongoing tasks should be more resistant to interruption than visual ongoing tasks.
Interruptions to tasks that externally retain a marker of the interrupted task position cause less performance degradation than tasks that do not (Field 1987, Kreifeldt and McCarthey 1981). For example, if the interrupted task involved writing a list of numbers, the last number written would cue you to your interruption position in the task. In the present experiment, interrupted visual procedural tasks provide an externally available reminder to resume the interrupted task and therefore do not require subjects to retain an internal representation of the interruption position. This reduced memory load and external aid should facilitate subjects' performance compared to that with interrupted auditory procedural tasks.

3) Same-modality conditions should negatively affect performance more than cross-modality conditions.
Differentiated resource models of attention (*e.g.*, Wickens 1984) suggest, and supporting empirical results from time-sharing research (*e.g.*, Rollins and Hendricks 1980, Triesman and Davies 1973) indicate, that tasks are more easily performed simultaneously when they require different processing resources. A visual task should be easier to perform in concert with a secondary task requiring auditory processing than with another simultaneous, integrated visual task.

METHOD

Fourteen current airline pilots performed approach scenarios in a fixed-base simulator similar to a Boeing 737 aircraft. Each scenario began at cruise altitude, extended to 200 feet above field elevation or landing, and elapsed approximately 17 minutes. Prior to leaving cruise altitude, subjects performed a "Top of Descent" (TOD) procedure in a flightpath leg of approximately 3 minutes duration. The TOD procedure required subjects to: 1) reference and tune the company's frequency on a radio, 2) reference and tune the ATIS (Automatic Terminal Information Service) frequency, 3) listen to a 45-second ATIS message (providing information on terminal conditions) and note three items from this message, 4) reference and tune the tower frequency, and 5) note the inoperative items indicated on the "status" page of the Flight Management System (FMS) CDU. During the TOD procedure, subjects received ATC interruptions instructing them to enter an approach into the FMS CDU. These ATC instructions were either conveyed visually *via* a data link system or announced aurally by playing a pre-recorded sound file. Subjects could receive these interruptions at any one of several points during the TOD procedure or could remain uninterrupted. The conditions relevant for this study inserted these interruptions into the "obtain ATIS information" auditory task and into the "obtain status information" visual task. A confederate air traffic controller operated in real-time with the simulation to respond to flight deck calls to ATC approach control, ATC tower, and airline company services in the performance of procedural tasks or in response to interrupting tasks.

Dependent Measures

Dependent measures (Table 1) were derived from a model of interruption management (Latorella 1997). These measures address integration and performance of the interruption, performance of the ongoing procedure, and flightpath management activity during the TOD procedure leg.

Table 1. Dependent Measures

<u>*Interruption Acknowledgment Time:*</u>
Time from the interruption trigger to subjects' acknowledgement to ATC of interrupting message.
<u>*Interruption Initiation Time:*</u>
Time from acknowledging the interrupting message to beginning the activities to accomplish it.
<u>*Interruption Performance Errors:*</u>
Interruption Performance Errors: Number of keystroke-level errors committed in acknowledging and performing interrupting task.
<u>*Procedure Resumption Time:*</u>
Time from completing the interrupting task to resuming a procedural task.
<u>*Resumptive Flightpath Management (FPM) Activity:*</u>
Number of control inputs between completing the interrupting task and resuming a procedural task.
<u>*Procedure Performance Errors:*</u>
Number of keystroke-level, and sequence errors committed in performing the procedural tasks.
<u>*Ensemble Performance Time:*</u>
Time to complete both the procedural and interrupting task set.
<u>*Ensemble Flightpath Management (FPM) Activity:*</u>
Number of control inputs within the time required to complete the procedural and interrupting task set.

Experimental Design

Effects of task and interruption modality on the interruption management dependent measures were considered in mixed-model, partial factorial analyses of variance of the form: 14 (Subjects) X 2 (Task Modality: Auditory, Visual) X 2 (Interruption Modality: Auditory, Visual) X 2 (Replication). Interaction terms were included for: Subjects X Task Modality, Subjects X Interruption Modality, Task Modality X Interruption Modality, and Subjects X Task Modality X Interruption Modality. Task and Interruption Modality factors were fixed, within-subject variables with two data points *per* subject, *per* condition. Scheffé *post hoc* tests (two-tailed) were conducted on significant task and interruption modality main effects, and same *vs.* different modality conditions were assessed by Scheffé *post hoc* contrasts.

SIGNIFICANT RESULTS[1]

Interruption Acknowledgment Time

Interruptions to auditory tasks were acknowledged more slowly than interruptions to visual tasks, $F(1,13) = 4.303$, $p = 0.0585$. Subject interactions with task modality, $F(13,55) = 5.889$, $p = 0.0001$, and interruption modality, $F(13, 55) = 6.455$, $p = 0.0001$, were highly significant. While not significant ($p = 0.3046$), acknowledgement of auditory interrupting tasks was on average approximately 1.5 seconds faster than for visual interrupting tasks.

Table 2. Interruption Acknowledgment Time.

Task Modality	Interrupt Modality	N	Mean	Std.Dev.
Auditory	Auditory	28	11.904	11.682
Auditory	Visual	28	14.686	14.940
Visual	Auditory	28	7.880	2.459
Visual	Visual	28	9.868	7.136

Interruption Initiation Time

The interaction of task and interruption modalities significantly influenced initiation time, $F(1,13) = 6.976$, $p = 0.0204$. Interruption initiation times for cross-modality conditions were significantly slower than for same-modality conditions, $F(1,13) = 7.402$, $p = 0.0175$. Significant main effects of interruption modality indicated that subjects began performing visually-presented tasks more slowly when they were presented visually, $F(1,13) = 3.159$, $p = 0.0989$, and when the interruption occurred to an auditory task, $F(1,13) = 10.298$, $p = 0.0068$. However, inspection of the interaction and *post hoc* tests on interaction means indicated that interruption modality only differentially affected interruption initiation time for interrupted auditory tasks. In particular, subjects delayed performing visual interruptions to auditory tasks almost twice as long, on average, than any other interaction conditions.

Table 3. Interruption Initiation Time.

Task Modality	Interrupt Modality	N	Mean	Std.Dev.
Auditory	Auditory	28	12.009	10.725
Auditory	Visual	26	23.668	20.322
Visual	Auditory	27	10.197	9.113
Visual	Visual	28	10.951	9.707

Interruption Performance Errors

The interaction between task modality and interruption modality also affected tendency to err in performing the interrupting task, $F(1,13) = 5.2$, $p = 0.0401$. This interaction was explained by a contrast of cross-modality conditions to same-modality conditions. Subjects made more interruption performance errors in cross-modality conditions than in same-modality conditions. Inspection of interaction means indicated that while the interaction effect is obvious, interruption errors were substantially higher when visual tasks were interrupted aurally than for any other conditions.

Table 4. Interruption Performance Errors.

Task Modality	Interrupt Modality	N	Mean	Std.Dev.
Auditory	Auditory	28	0.143	0.448
Auditory	Visual	28	0.250	0.799
Visual	Auditory	28	0.429	0.742
Visual	Visual	28	0.107	0.315

Procedure Performance Errors

The interaction of task and interruption modalities significantly affected procedural errors, $F(1,13) = 9.1$, $p = 0.0099$. A contrast of same-modality and cross-modality conditions indicated that same-modality conditions induced significantly more procedure performance errors, $F(1,13) = 9.1$, $p = 0.0099$. *Post hoc* tests indicated that only the auditory task/auditory interruption condition significantly differed from the other three conditions. The extreme affect of this experimental condition on procedure performance error production created main effects of task modality, $F(1,13) = 16.278$, $p = 0.0014$, and interruption modality, $F(1,13) = 4.5$, $p = 0.0537$.

Table 5. Procedure Performance Errors.

Task Modality	Interrupt Modality	N	Mean	Std.Dev.
Auditory	Auditory	28	0.964	0.637
Auditory	Visual	28	0.286	0.460
Visual	Auditory	28	0.393	0.567
Visual	Visual	28	0.214	0.418

Ensemble Performance Time

Auditory interruptions extended ensemble performance time more than visual interruptions, $F(1,13) = 10.674$, $p = 0.0061$.

Table 6. Ensemble Performance Time.

Task Modality	Interrupt Modality	N	Mean	Std.Dev.
Auditory	Auditory	25	91.043	15.476
Auditory	Visual	24	81.908	9.158
Visual	Auditory	24	87.945	9.081
Visual	Visual	28	82.439	11.768

Individual Differences

Subjects provided a significant source of variation in interruption acknowledgment time, $F(13, 55) = 21.682$, $p = 0.0001$, interruption initiation time measures, $F(13, 52)=5.099$, $p = 0.0001$, ensemble performance time, $F(13,45) = 2.374$, $p = 0.016$, and ensemble FPM activity, $F(13,45) = 3.087$, $p = 0.0025$. What is perhaps more informative is the relative lack of individual differences noted where significant task factor effects were found. Neither subjects nor task

[1] Significance was established at $\alpha = 0.10$.

factors succeeded in reaching significance (all $p > 0.10$) for measures of procedure resumption time and resumptive flightpath management activity.

Table 7. Robust Task Factor Effects.

Modality Effect	Measure	Effect p-value	Subject p-value
Task X Interrupt	interruption errors	0.0401	0.8614
Task Modality	procedural errors	0.0537	0.1133
Interruption	procedural errors	0.0014	0.1133
Task X Interrupt	procedural errors	0.0099	0.1133

DISCUSSION

Agreement with Hypotheses

Aurally-presented interruptions were, on average, acknowledged more quickly than visually-presented interruptions, however this difference did not reach significance. However, as hypothesized, auditory ongoing tasks were more resistant to interruption than visual tasks as evidenced by much longer acknowledgement times and, when interrupted by a visually conveyed task, much longer interruption initiation times. Results indicated some evidence of the hypothesized advantage of cross modality conditions; specifically, subjects committed more than three times as many errors in procedure downstream from the interruption in the auditory/auditory case than any other case. The hypothesized advantage of the cross-modality condition was not exhibited in other measures of interrupted task performance. To the contrary, subjects committed more errors in performing the interrupting task itself in cross-modality conditions. Only two significant main effects appear to be robust in light of interaction effects: 1) Auditory interruptions extend ensemble performance time more than visual interruptions, perhaps because visual interruptions persist and therefore may be integrated more efficiently; 2) Interruptions to auditory tasks were not acknowledged as quickly as interruptions to visual tasks.

Rather than supporting theoretically-derived hypotheses completely, results indicated that interruptions significantly degraded performance on the four experimental conditions in different ways. Performance of visually-presented interrupting tasks in auditory ongoing tasks will not be started for, on average, twice as long as for any other condition. Auditory interruptions to visual tasks produce three times as many procedure performance errors than any other condition. Auditory interruptions to visual tasks appear to produce more interruption performance errors. The visual interruption/visual ongoing task condition was most resistant to performance degradations induced by interruption management. Interestingly, subjects exhibited individual differences in the speed with which they acknowledged interruptions for both the task modality and interruption modality manipulations.

Implications for Data Link

Mean acknowledgment times for the data link conditions in this experiment are slightly longer than the average 10 seconds found in previous investigations (Kerns 1990). The trend observed in this experiment is counter to previous results that suggest pilots interpret and acknowledge data link messages faster than voiced messages (Kerns 1990). There was no significant difference in either procedure resumption time or standardized resumptive FPM activity for data link (visual) and radio (auditory) interruptions in this study. This differs from results that indicated that pilots take longer to resume after a data link interruption than after a radio interruption (Williams 1995). This conflicting evidence of interruption recovery times with previous research suggests differences between dedicated (this study; Knox and Scanlon 1993) and task-shared (Williams 1995) implementations that require further investigation. Taken together, results from this study suggest that a dedicated data link system may afford the pilots more flexible task management and thereby increase efficiency of performance, but may also negatively affect the immediacy of enacting an acknowledged ATC transmission. In addition, results indicate that modality of interruption *vis à vis* modality of the interrupted task induced subjects to commit errors, both procedural and in the interrupting task, without significant variation among subjects. This result highlights the significance of addressing the implications of communications technologies for interrupting situations. This research extends the investigation of modality effects associated with data link implementations beyond traditional measures (*cf.* Kerns 1990) to include effects on performing the interrupting task and disruptive effects on post-interruption performance.

Implications for Facilitating Interruption Management

Based on previous literature and the results of this research, one can postulate several interface features to reduce the deleterious effects of interruptions. The advantages of referenceable interrupting task information were evident in the modality results. Presenting ATC calls *via* data link provides one solution to this problem, however it creates other concerns. Flight deck performance may improve by providing a referenceable version of aurally-presented interrupting tasks, *e.g.*, a playback feature allowing pilots to confirm their interpretation of interrupting annunciations. If a data link system is aboard, radio communications might, through speech recognition technology, be referenceable as a visual playback feature. Several studies demonstrate the potential benefits of providing an externalized marker or reference indicator to the interrupted task (Field 1987; Kreifeldt and McCarthey 1981). Theoretically, interruptions to inflexible task sets should be more destructive than interruptions to procedural task sets (Adams, Tenney and Pew 1995). In this situation, interfaces could provide historical information about tasks performed to improve interruption resiliency.

In addition to these interface features, interruptions may be more gracefully integrated into the ongoing flight deck task set through the development of task management aids that are sensitive to the nature of interrupting and interrupted tasks and by developing interruption management strategies for inclusion in training programs.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of Mr. Paul Schutte and Drs. Colin Drury, Valerie Shalin, and Joseph Sharit in the performance of this work, and the constructive comments of the anonymous reviewers. This work was sponsored by a NASA Langley Graduate Student Researcher Fellowship, #NGT-50992.

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