Presented at the 11th International Symposium on Aviation Psychology. Columbus, OH: The Ohio State University. 2001.

EFFECTS OF DATA LINK MODALITY ON PILOT ATTENTION AND COMMUNICATION EFFECTIVENESS

John Helleberg and Christopher D. Wickens
University of Illinois, Aviation Human Factors Division
Savoy, Illinois

ABSTRACT

The effectiveness of three different data link interfaces, involving auditory, visual and redundant presentation of ATC information, was evaluated in a single pilot general aviation simulation. Fifteen pilots flew a Frasca flight simulator with full visual display of the outside world, through a series of ATC-instructed maneuvers, while scanning outside for traffic. ATC instructions, of various lengths, were delivered through a text based data link display, through recorded voice (mimicking the demands of the current system), or through a redundant voice-text format. Pilots read back the instructions and then complied with whatever maneuver was instructed, while monitoring for traffic. Visual scanning was measured. The results revealed that the visual display provided greatest accuracy of communications read back, and was least disruptive of both traffic monitoring and flight path tracking (ATC instruction compliance). The auditory-only condition was most disruptive of these tasks, in part because the pilot's visual attention was drawn into the cockpit for longer periods while note taking, compared to the amount of such attention diversion with the visual text display. The redundant display condition provided many of the same benefits as the visual-only display, but never supported better performance than that display, and was sometimes inferior to it. This cost resulted, in part because the arrival of the discrete auditory communications appeared to disrupt performance of the ongoing visual flight task. Across all conditions, the pilots allocated approximately 60% of their visual attention to monitoring the instrument panel, and their communications accuracy was degraded by the longer ATC instructions. The results are interpreted in terms of mechanisms of attention and working memory in information processing, and in terms of the pilot's task priority hierarchy.

INTRODUCTION

The conventional proposal to provide data link information in the cockpit has been to offer a text-based display in a head down location (Kerns, 1999; Navarro & Sikorski, 1999). Such a display will offer the "permanence" of information, in a way that buffers the vulnerabilities of working memory. At the same time, a change from an auditory to a visual display has several other implications for how pilot information is processed. For example, visual errors (confusing similar symbols like 5 and S), may replace auditory confusion; the visual data link may inhibit the sharing of party line information between aircraft (Midkiff & Hansman, 1992), or between pilots within an aircraft (Mackintosh, McGann, Lozito, and Logsdon, 1999). Of particular interest in our studies are two somewhat competing attentional issues: visual resource competition, and auditory interruption or "preemption."

On the one hand, it is clear that reading a digital data link display **must** bring the pilot head down into the cockpit, in a way that can be avoided if the pilot merely listens to a voice transmission (whether from the air traffic controller over the radio, or from a voice synthesizer of a data link message in the cockpit). This potential cost of head down time is consistent with an overall view of multiple resources (Sarno & Wickens, 1995; Wickens & Hollands, 2000), in which multiple task performance will be improved to the extent that tasks can be distributed between modalities, (auditory data link with visual guidance and traffic monitoring) rather than focused exclusively within a modality (visual data link, with visual guidance and traffic monitoring).

On the other hand, there is another factor related to "auditory preemption" that might mitigate the advantages of distributed resources (Latorella, 1998; Wickens & Liu, 1988). This is the observation that discrete auditory information, when it arrives in the stream of an ongoing visual task (such as traffic monitoring or instrument processing), will be more likely than discrete visual information to preempt one or both of the ongoing visual tasks. Thus, while the discrete information would be better processed if delivered auditorially than visually, the ongoing continuous visual tasks would be more disrupted by the discrete auditory than the discrete visual task. In short, auditory data link could actually harm, rather than help, continuous visual monitoring, at least in the initial period following the arrival of a data link message when this preemption would take place. Two explanations may be offered for this auditory interruption effect. First, the auditory modality is intrinsically more "attention grabbing," hence accounting for its preferred use as an alerting tool

(Stanton, 1994). Second, because the auditory modality **is** transient, pilots may feel a need to deal with it immediately, before it is lost from working memory. The visual message, in contrast, can be dealt with more flexibly (Latorella, 1998; Lozito, McGann, & Corker, 1993), and its processing can be deferred until an ongoing visual task reaches a more "interruptible" period. In this regard, Disumkes, Young, & Sumwalt (1998) have noted that over 50% of task interruption incidents, taken from an ASRS database, were as a result of a communications task interrupting an ongoing task.

We also note a final factor that may in fact, offset any advantage of the auditory over the visual data link, again regarding multiple resources. In a conventional auditory system, good pilots will adopt strategies to attempt to cope with their limited working memory. One such strategy is to write down key aspects of a message, a technique that, like the appearance of the text-based visual display will also bring the pilot's head into the cockpit, cutting into the time available for outside scanning.

It may be the case however that a **redundant** combination of both display modalities can capture the best of both worlds, in the same manner that redundant displays have assisted in other domains (Wickens & Hollands, 2000, chapter 6). With such a combination, pilots could hear the message while looking outward, but also look downward to check a message on the visual display if they believe that their working memory is faulty.

In the present experiment (see Helleberg & Wickens, 2000 for details), pilots flew a series of flight legs, responding to instructions of various lengths, conveyed over either a visual-only, auditory-only, or redundant display. Pilots repeated the instructions, and read back accuracy was employed to assess communications performance. Traffic would periodically be visible in the outside world, forcing pilots to monitor outside (as would be expected in real flight; AIM 4-4-13) in a way that might confer an advantage on the auditory display conditions. In the auditory-only condition, pilots were allowed to use a clipboard to take notes, in a way that is typical of their normal flight.

METHODS

Fifteen pilots, certified flight instructors from the University of Illinois Institute of Aviation, volunteered to participate. Each pilot flew in the simulator configuration shown in Figure 1, and flew a total of seven flight scenarios. Each scenario took approximately 25 minutes. Within each scenario, ATC

Figure 1. Instrument panel layout and data link display location.

instructions prior to each leg were delivered in one of three formats. An auditory format employed recorded voice; a visual format employed a data link display configured to the left of the instrument panel, and a redundant format, presented both modalities. The ATC information presented at the beginning of each leg varied systematically in its length, defined operationally in terms of the number of key elements that needed to be accurately perceived. These elements included heading, altitude, airspeed, a transponder squawk code, a barometric altimeter setting, and a radio frequency setting. Across all legs, the number of elements could vary from 2 to 6. Elements that did not change from a prior leg were not displayed. Pilots were instructed to read back the elements accurately as is their normal custom. In the auditory condition they were encouraged to use a clipboard as necessary. They were informed on-line of any mistakes in their read back, so that they would not implement an incorrect change to the flight path. As soon as they had read back the clearance, they were instructed to begin the maneuver (if any) to the new trajectory.

Traffic was potentially visible out the window at one of three times: immediately after the issuance of the data link information, just after the information was estimated to have been processed (e.g., while pilots were beginning to implement any trajectory changes) and "well after" it was assumed to have been processed (e.g., while pilots were on a steady course). Traffic could appear at random locations on the outside screens, and required a "traffic in sight" callout. However, this traffic was never designed to produce a threat to the pilot's aircraft.

Following introduction and practice flights, the first six scenarios were used for data collection, and the order of formats was counterbalanced across pilots. Of these six, the last three employed eye movement measurements. The 7th flight was presented with the auditory display, in which pilots were requested to rely **only** on their memory for the read back (i.e., note taking on the clipboard was disallowed). This was done to obtain a measure of the vulnerability of working memory. However due to space constraints, this condition will not be discussed here.

RESULTS

Three independent variables were important in interpreting the results of the experiment: the display type, the length of the ATC message, and, for the traffic monitoring task, the **time** at which the traffic aircraft appeared, relative to the ATC message. We describe the results below in order of the importance of the pilots' three subtasks in the order: aviate, navigate and communicate (Schutte and Trujillo, 1996). Then we describe the effects on scanning strategy.

Aviation: Flight Path Control. The results yielded clear evidence of a disruption of flight path control by the ATC messages. Across all three display conditions, longer ATC messages led to significantly greater deviations in altitude, heading, and airspeed. Disruptions on all three axes were however least with the visual display, and larger (and generally equivalent) with the two displays using the auditory modality (auditory-only and redundant). There was however a trend within both the heading and airspeed error for the redundant display to disrupt tracking less than the auditory-only display ($p = .08$, $p = .06$ respectively).

Navigation: Traffic Detection. The detection of traffic was clearly and understandably disrupted by the ATC messages. Those traffic aircraft appearing while a message was being processed were detected more slowly than those which appeared just after (and, generally, while the pilot was initiating the ATC maneuver), and still slower than when the traffic appeared well after the ATC maneuver was complete ($F=58.3$, $p<.01$). Furthermore, traffic detection was significantly affected by display modality ($F=4.16$, $p<.02$). Detection was fastest with the visual display, intermediate with the redundant display and slowest with the auditory only display.

Communications: ATC Read back Errors. The analysis revealed a clear, and generally monotonic trend for more errors to occur with longer messages, observable across all three display formats ($F=2.22$, $p=.08$). There was also a significant effect of format on read back errors ($F=17.52$, $p<.01$), with the greatest accuracy observed with the visual format (97%), intermediate accuracy with the redundant format (96%) and lowest accuracy with the auditory-only format (90%). The two independent variables did not interact.

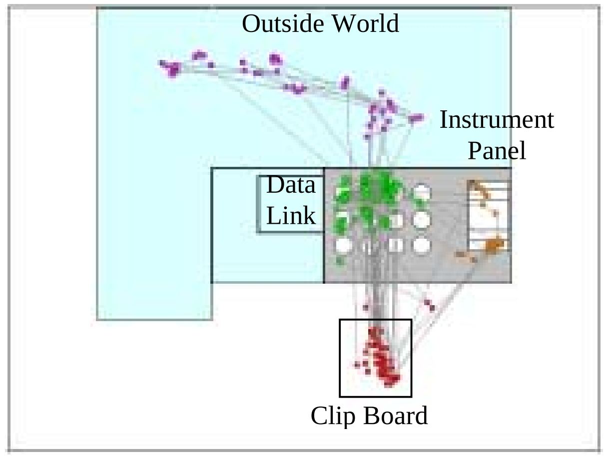

Figure 2. Example of eye scanning data collected in auditory only condition.

Attention Allocation Strategies: Visual Scanning Analysis. Figure 2 provides an example of the type of eye scanning data that was captured on each leg of the experimental flights. Each dot represents a single fixation and the connecting dashed lines indicate where the eyes moved on subsequent fixations. This particular example is from the auditory only condition and therefore had no fixations on the data link display.

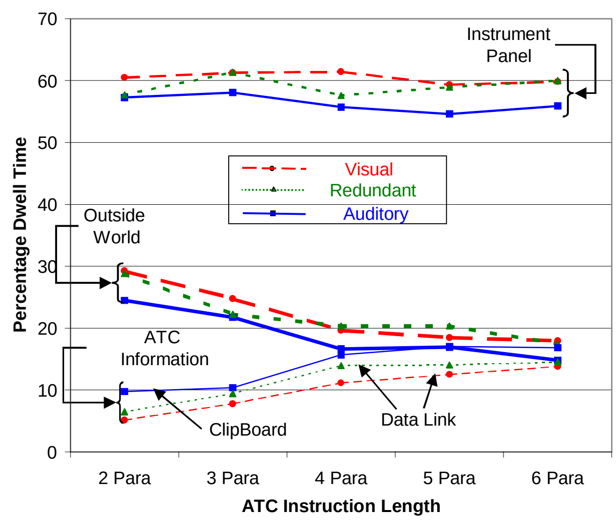

Figure 3. Distribution of visual attention across areas of interest (AOIs).

Figure 3 depicts the relative distribution of visual scanning across the different information sources available to the pilots. Across all three display formats, the percentage dwell time (PDT) was dominated by the Instrument panel (approximately 59%), followed by the outside world (19-22%) followed by the **source of ATC information** (10-14%). We defined this source to be the data link display for the visual and redundant conditions. In the auditory display, this source was defined as the clipboard, since this is where pilots directed their gaze while taking notes (to retain information for the longer messages). These fixation distributions were equivalent between the visual and the redundant conditions. However the auditory condition appeared to pull more attention away from the outside world, and allocate it to the ATC source (clipboard: 14%) than did the two visual conditions, in directing attention allocation to the data link display (11%).

The analysis of mean dwell duration (MDD) on each AOI indicated that the instrument panel yielded longest dwells (approximately 4 seconds), considerably greater than the 1 - 2 second dwells that characterized all of the other AOIs. Dwells on the clipboard ATC source, for the auditory format (2 seconds), were considerably longer than dwells on the data link display (1.3 seconds) as the ATC source for the visual and redundant formats. Finally, there was a very faint shortening of MDD across all three formats as the ATC messages increased in length.

DISCUSSION

An overall comparison of the three key performance variables and the attention allocation visual scanning measure, as a function of the three display formats, is represented in Table 1, in which a "**+**" indicates that the display format supported good performance relative to the others, a "**-**" indicates poor performance relative to the others, and a "**0**" indicates intermediate performance relative to the other display formats. This judgment of relative preference is based jointly on the statistical significance of the differences reported above, and upon their magnitude. Furthermore, within the rows depicting the amount of visual scanning a "+" indicates that relatively more visual scanning occurred and a "-" indicates relatively less visual scanning occurred within that display condition.

In examining the table, three overall features are evident: first, the visual display format fairs best, the auditory format fairs most poorly, and the redundant format is intermediate. Second, for each of the aviation subtasks (aviation, communication, and navigation) the pattern of visual scanning measures is consistent with the ordering of the display formats. That is, a greater allocation of visual resources to the Instrument Panel and Outside World leads to better flight path tracking and traffic detection performance, while allocating fewer visual resources to the ATC information source resulted in fewer communication errors. The overall pattern of effects revealed in the table can be interpreted within the context of three information processing mechanism as described below: preemption or attention switching, multiple resources, and the strategies adopted to deal with working memory constraints. We will use these mechanisms to account for performance on each of the three aviation subtasks.

AVIATION SUBTASK		DISPLAY FORMAT		
		Auditory	Redundant	Visual
Aviate	**Flight Path Control**	**-**	**0**	**+**
	IP Scanning	-	+	+
Navigate	**Target Detection**	**-**	**0**	**+**
	OW Scanning	-	+	+
Communicate	**ATC Instruction Read Back**	**-**	**0**	**+**
	CB and DL Scanning	+	-	-

Table 1. Summary of Results, Depicting the Relative Difference Between Measures.

Aviate. We have operationally defined this highest priority task of **aviating** in terms of the pilots' ability to maintain the prescribed flight path in vertical, lateral, and airspeed components, as achieved by allocating visual attention to the instrument panel. The results suggest that the visual data link format supports the best performance, the auditory format supports relatively poor performance, and the redundant format supports intermediate performance. The poorer performance seen within the auditory display format can be at least partially explained by a decrease in visual attention allocation to the instrument panel (approximately 56%) and a corresponding increase in visual attention allocated to the clipboard (approximately 15%) for note taking. With the auditory only data link display, pilots were not only required to allocate visual attention to the task of reading back the ATC instructions (as was also required in both visual conditions), but in addition to this they were also required to allocate visual attention to note taking while the ATC instruction was being played. This may have resulted in a dual resource competition cost within the auditory condition, which was not present in either of the visual conditions. Furthermore, the manual task of note taking was also unique to the auditory only display and may have contributed to a manual disruption of the ongoing flight path maintenance task.

One feature of the experiment, which may have made the multiple resource theory benefits of auditory information difficult for pilots to realize, was the unpredictable nature of the ATC instruction length. This independent variable was varied randomly (rather than blocked), such that pilots were unaware (at the time of the onset of each ATC instruction) of the number of parameters that the instruction would ultimately contain. The longest parameters were included to encourage note taking, but it was expected that pilots might rely on working memory for the shorter instructions. However, due to the unpredictable nature of instruction length, pilots always assumed the instruction would require note taking. Therefore, pilots adopted a strategy of immediately beginning to take notes at the onset of each instruction. This was likely the optimal strategy, given that each instruction could vary between 2 and 6 parameters, but this resulted in note taking on every single leg regardless of the instruction's length.

While resource competition had an important influence, it was not the only factor affecting the pilot's task of aviating. It is evident that the differences in performance across the two visual display formats (visual only and redundant) are observed **despite** the essential equivalence of visual attention allocated to the instrument panel (approximately 59% for each), as well as the data link display (approximately 11% for each), across the two visual display formats. We attribute this pattern of effects on the aviate subtask to an **auditory preemption** or interruption effect, by which discrete auditory tasks have a tendency to interrupt ongoing continuous visual ones. This effect had been described in basic dual task paradigms by Wickens et al., (1988), and observed directly in a laboratory based data link simulation by Latorella (1998), and described in ASRS reports (Dismukes, et. al, 1998). The fact that this pattern of disruption was **not** echoed by the visual attention allocation measure, suggests that this preemption is a qualitatively different phenomenon from the visual resource competition, which, as we describe below, appears to underlie the disruption of visual target detection. Further evidence for the role of an auditory preemption mechanism that is distinct from visual resource competition, is the fact that the preemption effect appears to be common to both formats with the auditory display. The preemption effect may therefore represent more of a sudden **cognitive** switch, induced by the discrete appearance of the auditory message, (and imposing momentary deviation from the required flight parameters), than a reallocation of **visual** attention away from the instrument panel, the source of information necessary to aviate.

Navigate. We have defined the traffic detection task as a navigation subtask because of the importance of hazard (traffic) awareness in safe navigation. It is apparent that this subtask suffered, as a consequence of the greater head down time and visual resource demand (relative to the data link display) imposed by the clipboard note taking in the auditory-only condition. As noted above, dwells on the clipboard were longer than those on the visual display, and correspondingly, the auditory display availed less scanning out the window (19%) relative to the two visual conditions (22%). The RT cost for the auditory display format was not large, but was nevertheless in a direction that supports the visual display of data link information, **relative to** conditions in which pilots must use note taking to compensate for auditory working memory constraints. We were somewhat surprised that the redundant format did not yield **better** detection performance (and more visual resources outside) than the visual-only format, given that the redundant format should allow pilots to continue their outside scan, and only look down to refresh their memory for the longer messages. It is possible that this failure of redundancy to offer advantages might have resulted from the **interruption** characteristics of the auditory display, described above in the context of the aviate subtask. In addition, pilots using the redundant display may have been reluctant to rely on their working memory for the ATC instruction read back and instead may have chosen to consult the visual display on each leg. This "head down time" coupled with the interrupting nature of the auditory information may have prevented the realization of the "best of both worlds" with the redundant display.

Communicate. The failure of the auditory display to support good performance on the read back task, relative to the two formats using visual displays (redundant and visual), is not surprising, and indeed documents one of the major reasons why the data link system has been advocated in the first place (Kerns, 1999). That is, auditory working memory is vulnerable, and subject to forgetting. Less expected however was the failure of pilots to be able to use the clipboard and note taking facilities to fully compensate for the frailties of their working memory with the auditory display. That is, despite this note taking support, pilots still made more read back errors than when the visual display was present. Furthermore, the use of the clipboard demanded more visual resources both in terms of Mean Dwell Duration (2.1 seconds) and Percentage Dwell Time (14%) than did the readout of the visual data link display (1.3 seconds MDD, 11% PDT), a cost imposed on both outside world and instrument panel scanning which hampered traffic detection and flight path maintenance. It is likely that pilots could have performed the communication task with equal accuracy across display conditions, but due to the ANCS task priority hierarchy (Schutte et. al, 1996), they were hesitant to take visual resources away from the primary tasks of aviating and navigating in order to reallocate those resources to the lowest priority task of communication.

One surprising finding was the failure of the redundant display format to offer the best of both modalities and hence provide superior performance to the visual display format. In fact, the level of accuracy was slightly lower in the redundant, relative to the visual display format, a cost that can possibly be attributed to pilots sometimes trusting their memory of the auditory instructions, without cross checking the visual display for assurance.

CONCLUSION

It appears that the proposed visual data link display is indeed a format that supports best overall performance for general aviation pilots. Despite the requirement that this format imposes for head down activity, the permanence of the visual display allows pilots to allocate that head down time in a manner that is more flexible and less disruptive of ongoing visual tasks, than is the need to process (and take notes on) the auditory transmission of data. The failure of the redundant use of both channels to support "the best of both worlds" is surprising. This failure may result in part from the preemptive aspects of the auditory component of the redundant display. In addition, the unpredictable and rather lengthy nature of the ATC instructions may have made pilots reluctant to utilize the multiple resource benefits that the auditory information offered. It is however possible that a redundant format could provide advantages if training was offered as to the appropriate use of each display modality within the redundant pair, an issue that requires further investigation.

ACKNOWLEDGMENTS

The authors wish to acknowledge the invaluable contributions of graduate student Xidong Xu and undergraduate student Tony Pape to this research. Equally important has been the programming contributions of Roger Marsh, Ron Carbonari, and Jonathan Sivier in developing software and assisting in data analysis. This research was supported by a Grant #DFTA 98-G 022 from the Federal Aviation Administration. Dr. Dennis Beringer was the scientific/technical monitor, and also provided important contributions to the design of this experiment.

REFERENCES

ASA's. (2000). FAR/AIM 2001. Newcastle WA: Aviation Supplies & Academics (pp 4-4-8, 4-4-9).

Dismukes, R.K., Young, G., & Sumwalt, R. L. (1998). Cockpit interruptions and distractions. ASRS Directline, 10, 4-11.

Helleberg, J. & Wickens, C. D. (2000). Data link modality in general aviation (ARL-00-7/FAA-00-4). Savoy, IL: University of Illinois, Aviation Research Lab.

Kerns, K. (1999). Human factors in air traffic control/flight deck integration: Implications of data-link simulation research. In D. J. Garland, J. A. Wise, & V. D. Hopkin (Eds.), Handbook of aviation human factors (pp. 519-546). Mahwah, NJ: Lawrence Erlbaum.

Latorella, K. (1998). Effects of modality on interrupted flight deck performance: Implications for data link. Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society (pp. 87-91). Santa Monica, CA: Human Factors and Ergonomics Society.

Lozito, S., McGann, A., & Corker, K. (1993). Data link air traffic control and flight deck environments: Experiment in flight crew performance. In R. E. Jensen and D. Neumeister (Eds.), Proceeding of the Seventh International Symposium on Aviation Psychology (pp. 1009-1015). Columbus, OH: The Ohio State University.

Mackintosh, M. A., McGann, A., Lozito, S., & Logsdon, E. (1999). Information transfer in data link communication for ATC clearances. Proceedings of the Tenth International Symposium on Aviation Psychology (pp. 136-142). Columbus, OH: The Ohio State University.

Midkiff, A. H., & Hansman, R. J., Jr. (1992). Identification of important "party line" information elements and the implications for situational awareness in the datalink environment. SAE Technical Paper Series 922023. Warrendale, PA: Society of Automotive Engineers, Inc.

Navarro, C., & Sikorski, S. (1999). Datalink communication in flight deck operations: A synthesis of recent studies. International Journal of Aviation Psychology, 9(4), 361-376.

Sarno, K. J., & Wickens, C. D. (1995). The role of multiple resources in predicting time-sharing efficiency: An evaluation of three workload models in a multiple task setting. International Journal of Aviation Psychology, 5(1), 107-130.

Schutte, P. C., & Trujillo, A. C. (1996). Flight crew task management in non-normal situations. Proceedings of the 40th Annual Meeting of the HFES. Santa Monica, CA: HFES.

Stanton, N. (1994). Human factors of alarm design. London: Taylor and Francis.

Wickens, C. D., & Hollands, J. (2000). Engineering psychology and human performance (3rd ed.). New York: Prentice Hall.

Wickens, C. D., & Liu, Y. (1988). Codes and modalities in multiple resources: A success and a qualification. Human Factors, 30, 599-616.