

## AUDITORY VS. VISUAL DATA LINK: RELATIVE EFFECTIVENESS

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Pilots flew a GA simulator based on ATC-instructed maneuvers, while scanning outside for traffic. Various length ATC instructions were delivered through a textual, voice, or redundant data link format. Pilots read back the instructions, then complied with the maneuver. Visual scanning was measured. Results indicated the visual display provided greatest accuracy of communications read back and least disruption of traffic monitoring and flight-path tracking. The voice-only condition was most disruptive, partially because the pilot's eyes were drawn into the cockpit longer while note taking, compared to the two visual text displays. The redundant display never supported better performance than the visual display. This cost resulted, partially because arrival of the discrete auditory communications disrupted flight-path performance. Pilots allocated ~60% of visual attention to the instrument panel, and communications accuracy was degraded by longer ATC instructions. Results are interpreted referencing mechanisms of attention, working memory, and the pilot's task priority hierarchy.

### INTRODUCTION

Breakdowns in **cockpit task management** have been cited as causes of both incidents (Dismukes, 1998) and accidents (Chou, Madhavan, & Funk, 1996) in the airspace. Such breakdowns involve a number of different failures; including the delays in undertaking important tasks (Raby & Wickens, 1994), the interruptions of certain tasks by others (Damos & Lyall, 1986; Dismukes, 1998; Latorella, 1998), or the total failure to perform some tasks at all, involving a breakdown in prospective memory. A key to analyzing many of these types of errors is to determine what the optimal order of performing tasks **should** be, if they cannot be performed concurrently. That is, it may indeed be considered appropriate behavior for a higher priority task to interrupt one of lower priority, or for the latter to be delayed until completion of the former.

In aviation, the priority hierarchy of "aviate-navigate-communicate-systems management" is a general task management strategy that is both traditional and highly appropriate (Schutte & Trujillo, 1996). That is, for example, the pilot should generally assure that the aircraft is flying (not stalling) prior to assessing where he or she is. That is, *aviate* before *navigate*. Correspondingly, understanding one's location, with respect to earth coordinates and air hazards, should take priority over communicating. In this regard, a prevailing finding has been that communicating tends to interrupt or be disruptive of the higher priority tasks of *aviating* and particularly *navigating* (Dismukes, 1998; Latorella, 1998). Here it is not always easy to establish if the communications interruptions are a result of the communications task per se, or the fact that this information is traditionally delivered through a voice

channel, in which the auditory modality is inherently more "preemptive" than the visual (Wickens & Liu, 1988). One focus of the current study will be to compare the preemptive properties of two modalities for the delivery of communications information.

Task prioritization has often been measured in terms of a pilot's actual visible "actions" (i.e., initiation of a voice articulation, movement of a control, pressing of a button, etc.). However, for many tasks that lack discrete "action elements" – for example the tasks of monitoring or problem solving – investigator assessments of task prioritization (or neglect) can be carried out through the analysis of eye movements (Wickens, Xu, Helleberg, & Marsh, 2001). As an example, a pilot who never fixates upon an altimeter in IMC can be assumed to be "neglecting" the task of altitude control, even if his or her aircraft does not exceed tolerable altitude limits. In the current experiment we will use eye scanning to infer the allocation of attention, and hence the degree of compliance with appropriate task management strategies.

In the present experiment, we examine the relative prioritization of the three tasks: *aviating* (flying the aircraft), *navigating* (maintaining awareness of traffic hazards), and *communicating* (comprehending ATC instructions), as these are revealed by visual scanning measures. Our particular interest is in comparing a digital **data link** visual display of communications information (Navarro & Sikorski, 1999; Kerns, 1999), with an auditory delivery of the same information, (which could either represent the standard "baseline" format of current radio-telephone communications, or a possible implementation of data link in which up-linked instructions from ATC are voice synthesized within the cockpit). We also assess a third data link configuration, involving the redundant

presentation of both information sources simultaneously. In all conditions message length is varied, in order to change the demands of this lower priority communications task, and visual scanning to the three sources of information relative to the three tasks is measured.

We hypothesize that scanning measures should reflect the general order of prioritization, and that the higher priority tasks of "aviate" and "navigate" should be protected from the increasing demands of communicating (as imposed by longer ATC messages). Further interest is in the difference in interference and scanning between the auditory and visual communications displays. According to a multiple resources hypothesis (Groce & Boucek, 1987), a visual display of data link information should disrupt the higher priority tasks (or be disrupted by them) more than the auditory display. However, according to a preemption/interruption hypothesis (Latorella, 1998; Wickens & Liu, 1988), the auditory delivery of communications should disrupt the higher priority tasks more than the visual delivery.

Operationally we have defined visual attention to the "aviate" task as fixations upon the instrument panel. This is because it is on this panel where the primary sources of information are found to prevent stall (airspeed and attitude). We have defined visual attention to the "navigate" task as fixations upon the outside world in our visual simulation. This is because our far domain was populated with "traffic aircraft" which could only be sighted visually. While none of these explicitly represented conflicts that required avoidance, our pilots were instructed (as in normal flight) to keep a vigilant lookout for such aircraft and to call out "traffic in sight" whenever they were spotted. We have defined visual attention to the "communicate" task in two different ways. During the visual data link trials, this was naturally defined as fixations upon the data link display, to the left of the instrument panel. During the auditory trials, it was defined as fixations upon the clipboard, which pilots, following their standard practice, used to jot down the ATC instructions as they heard them.

## METHODS

Fifteen certified flight instructors from the University of Illinois flew seven 10-leg flight scenarios in the simulator configuration shown in figure 1. Each 25-minute scenario contained ATC instructions 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 simultaneously. The ATC information presented at the beginning of each leg varied in its length by the number of key elements that needed to be accurately perceived (i.e., heading, altitude, airspeed, a transponder squawk code, barometric altimeter and a communications 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. As soon as they had read back the clearance, they were instructed to begin the maneuver (if any) to the new trajectory.

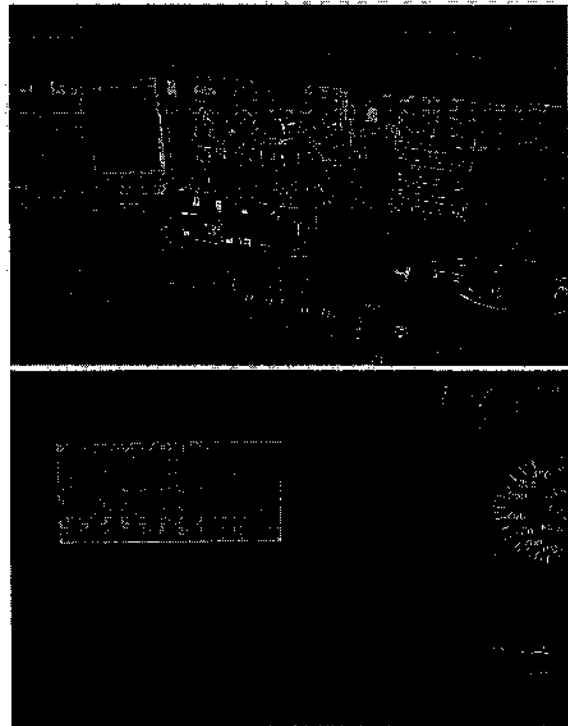


Figure 1. Simulator setup with instrument panel layout and data link display close-up

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 7<sup>th</sup> 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.

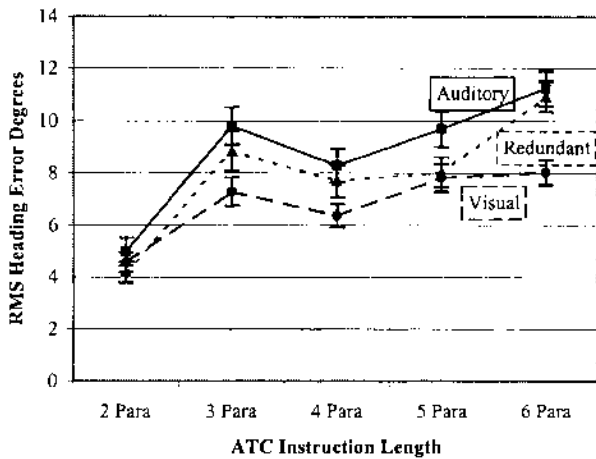


Figure 2. Heading error of different display modalities across ATC instruction length

Figure 2 presents the tracking RMS error on the heading axis, as a function of the message length and the data link display. Most notably there is a main effect of display, indicating the superiority of performance with the visual over the auditory display, ( $F=15.9, p<.01$ ) and intermediate performance with the redundant display. There was also a main effect of message length, indicating that dealing with longer messages resulted in progressively more disruption of the aviate task, across all three display conditions ( $F=156.4, p<.01$ ). These two variables did not interact. Similar effects were observed for vertical (altitude) control ( $F=9.5, p<.01$ ;  $F=190.8, p<.01$ ) and longitudinal (airspeed) control ( $F=6.3, p<.01$ ;  $F=99.4, p<.01$ ) respectively.

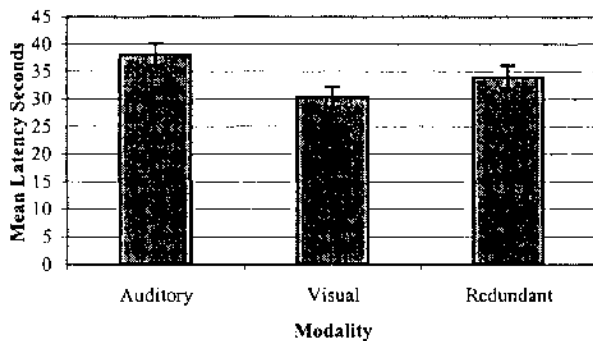


Figure 3. Traffic detection latency across display modalities

Figure 3 presents the performance measure of our "navigation" subtask, the time required for the pilot to call out "traffic in sight." As with flight control, performance in the traffic detection task 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.

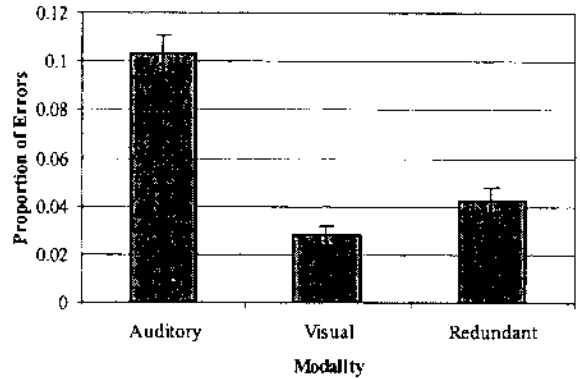


Figure 4. Proportion of read back errors across display modality

Figure 4 presents the performance data for the communication subtask (i.e. the number of errors in the read back). These data again mimic the trends found in both the "aviate" and "navigate" tasks (display effect:  $F=17.52, p<.01$ ). The greatest accuracy was observed with the visual format (97%), intermediate accuracy with the redundant format (96%) and lowest accuracy with the auditory-only format (90%). The analysis also revealed a clear, and generally monotonic trend for more errors to occur with longer messages, observable across all three display formats ( $F=2.22, p=.08$ ). The two independent variables did not interact.

### Visual Attention Allocation

The major focus of our interest is in how the pilot's allocation of visual attention, as assessed by scanning to the three major areas of interest, reflected both the inherent prioritization of the three subtasks, and the experimental manipulations of communications load and display modality. Figure 5 presents the percentage of time (y-axis) that pilots spent fixating upon the areas of interest for each of the three tasks, as these are modulated by both communications modality (separate lines) and by message length (the x-axis).

The most evident characteristic of the figure is that the percentage of dwell time closely matches the task priority hierarchy, such that across all three display formats, the dwell time was dominated by the instrument panel (~59%), followed by the outside world (19-22%) followed by the communications information source (10-14%). Second, we note that increases in message length, appropriately require the allocation of more visual attention to the communications AOI, and that such allocation is "borrowed" from the mid priority "navigate"

task, rather than from the high priority "aviate" task, a moderate form of optimal behavior. Finally, we note that considerably more visual attention is required to monitor the clipboard, for both writing and reading back, than to monitor the data link display, and that this visual attention, like that for longer messages, is borrowed from navigating, not aviating. Pilots thus appear to do a good job of "protecting" the primary "aviate" task.

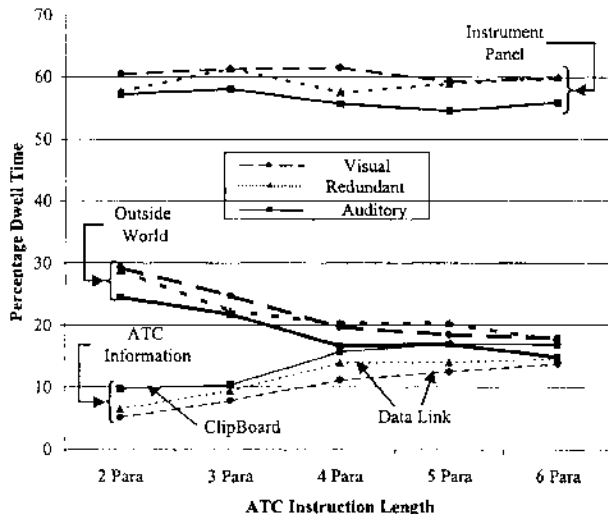


Figure 5. Visual attention allocation to 3 AOIs for each display modality across ATC instruction length

To this point, the data are quite consistent with a multiple resources hypothesis. The clipboard (note taking and read back) demands more visual processing, which is borrowed from the outside world, thus sacrificing traffic detection. What is the role of preemption? The influence of this second mechanism is found when we examine performance on the flight path maintenance task and visual scanning allocation within the redundant condition, for which no clipboard is available nor needed. Were visual resource competition the only mechanism operating, we should find that this condition is *less* disruptive than the visual only display, since the pilots would have more opportunity to use the auditory channel to process communications information in parallel with the visual processing of the data link. However, the redundant display is no better than, and often worse than the visual-only display in terms of its disruption of the higher priority aviate and navigate tasks. This disruption occurs despite the essential equivalence of visual attention allocated to the instrument panel and outside world across the two visual conditions. We attribute this pattern of effects to an **auditory preemption** or interruption effect, by which discrete auditory tasks have a tendency to interrupt ongoing continuous visual ones. This effect has been

described in basic dual task paradigms by Wickens and Liu (1988), and observed directly in a laboratory based data link simulation by Latorella (1998).

## DISCUSSION & CONCLUSION

The pilots appear to be using a reasonable strategy for dividing their visual resources between the 3 different sources of information, which matches their general task priority hierarchy of "aviate-navigate-communicate-systems management" (Schutte and Trujillo, 1996). The results also indicate that the visual display format supported the best performance, the auditory display format yielded relatively poor performance, and the redundant display format facilitated intermediate performance.

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 two visual conditions. This added cost reduced the pilot's available visual resources for both outside world and instrument panel scanning resulting in hampered traffic detection and flight path maintenance.

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 so 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 two and six parameters, but resulted in note-taking on every single leg regardless of the instruction's length. Furthermore, the demands associated with the manual task of note-taking were also unique to the auditory-only display and may have contributed to the disruption of the ongoing flight path maintenance task.

We expected pilots to have similar read back performance in the auditory condition when utilizing the clipboard for a memory aid. However, despite this note-taking support, pilots still made substantially more read back errors than when the visual display was present. It is likely that pilots could have performed the communication

task with similar accuracy across the display conditions, but due to their task priority hierarchy, they may have been somewhat 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 and therefore allowed performance on this lowest priority task to suffer.

We were somewhat surprised that the redundant format did not yield better performance (and more visual resources outside) than the visual 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.

The results from this study suggest 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, a conclusion supported by the scanning data. The data also point to the "preemption" effects of auditory communications within the redundant display.

The current study did not specifically examine the base rate of visual resource competition associated with a visual-only display of data link information. Future research which models the pilot's visual scan needs to be conducted in order to determine the relative costs associated with visual resource competition, auditory preemption, and working memory limitations associated with presenting data link information within a general aviation cockpit.

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