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Hazard Alerting and Situational Awareness in Advanced Air Transport Cockpits

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Abstract

Advances in avionics and display technology have significantly changed the cockpit environment in current "glass cockpit" aircraft. Recent developments in display technology, on-board processing, data storage, and datalinked communications are likely to further alter the environment in second and third generation "glass cockpit" aircraft. The interaction of advanced cockpit technology with human cognitive performance has been a major area of activity within the MIT Aeronautical Systems Laboratory. This paper presents an overview of the MIT Advanced Cockpit Simulation Facility. Several recent research projects are briefly reviewed and the most important results are summarized.

1. Introduction

The implementation of advanced technology has significantly changed the cockpit environment in current "glass cockpit" aircraft. Recent developments in display technology, on-board processing, data storage, and datalinked communications are likely to further alter the environment in second and third generation "glass cockpit" aircraft. It is, however, important that these technologies be implemented in a manner which will enhance both the human and systems performances, in terms of both safety and efficiency. Because many of the changes in cockpit technology center around information management, proper design of advanced cockpit systems requires careful consideration of the human performance issues, particularly in the cognitive domain.

The interaction of advanced cockpit technology with human cognitive performance has been a major area of activity within the MIT Aeronautical Systems Laboratory. This paper presents an overview of the MIT Advanced Cockpit Simulation Facility. In addition, several recent research projects are briefly reviewed and the most important results are summarized. It should be noted that the experimental programs are summarized and that the authors or references should be consulted for complete details on the experimental methods and results.

2. The MIT Advanced Cockpit Simulator[1]

The principal experimental facility used by he MIT ASL for studies of advanced information management issues is the MIT ASL Advanced Cockpit part-task simulator shown in Figure 1. The facility is a part task simulator which replicates the automatic flight components of a modern "glass cockpit" transport category aircraft. The simulator is implemented on a series of graphical workstations. This allows rapid prototyping of advanced displays, digital communications systems, and information management systems.

The MIT ASL Advanced Cockpit Simulator is a part-task facility based on Boeing 757/767 and 747-400 flight displays. The facility utilizes two computers and several control panels to emulate aircraft autoflight systems. In addition, a third computer is linked to the cockpit simulation which can be used either as an ATC station or for experiment control.

A Silicon Graphics 4D-25G graphics workstation is used to simulate the aircraft dynamics and present the primary flight displays. Airspeed, altitude, and vertical speed are indicated using tape displays similar to those found on the 747-400. An Electronic Attitude Director Indicator (EADI) is provided, and is used to display the artificial horizon, ground speed, radio altitude, and Instrument Landing System (ILS) localizer and glideslope deviations.

The flexibility of the graphical workstation allows rapid prototyping of new display concepts. Prototype displays can be implemented in a matter of days and the primary flight displays can be configured to accommodate new displays for experimental evaluation.

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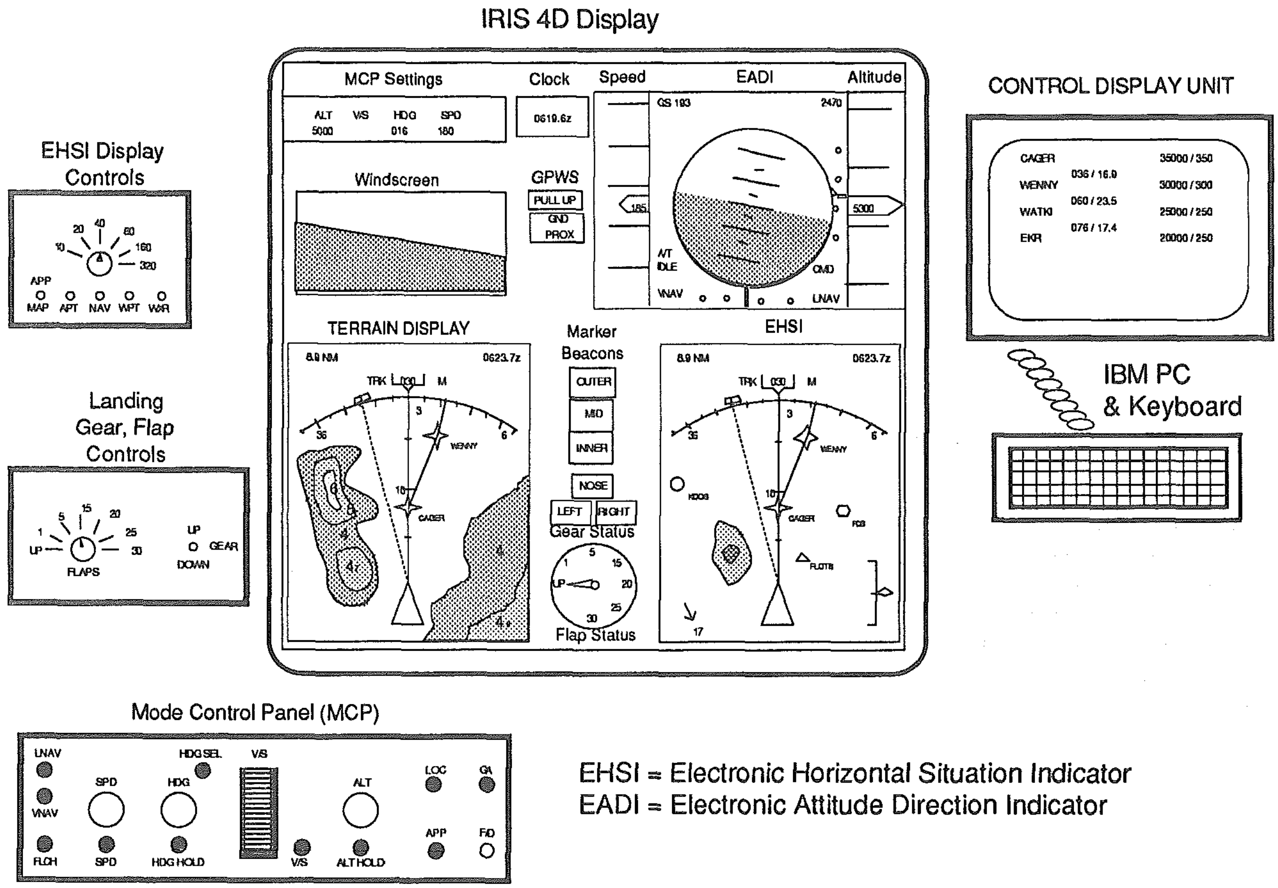

Figure 1. MIT Advanced Cockpit Simulator.

In the nominal display configuration, the Electronic Horizontal Situation Indicator (EHSI) is located below the EADI, as in the 757 or 767. The EHSI displays the 757/767 map mode, including aircraft heading, ground track, and programmed route.

A control panel is provided to allow the pilot to configure the EHSI in a manner similar to the actual aircraft. The pilot can select and de-select airports, navaids, intersections, and weather information, as well as scale the map display from 10 to 360 nautical mile range.

Flap, gear, and marker beacon light displays are provided to the left of the EHSI. Controls are provided to allow the pilot to set the flaps and lower or raise the landing gear during the approach. Additional controls such as a manual pressurization valve can be added to the simulation if a side task is necessary to increase the ambient crew workload.

A simple perspective out-the-window view is provided as a means by which to cue the pilot that the aircraft has descended below the cloud deck. While in instrument conditions, the display appears gray. When descending out of the cloud deck a single runway appears, representing the airport.

The Control Display Unit (CDU) for data entry into the FMC is simulated with an IBM/XT computer. It provides the necessary subset of the FMC functions required for the simulation, including basic route programming and destination selection.

Non-FMC control of the aircraft is performed through an autopilot Mode Control Panel (MCP), similar to the one used on the Boeing 757/767. A standard set of autothrottle and autoflight modes are available, including LNAV/VNAV flight (i.e. following FMC-programmed lateral and vertical flight paths) and the various capture ("select") and hold modes for airspeed, heading, vertical speed, and altitude.

In a typical experimental set up, an experimenter acting as air traffic controller is stationed at the ATC/Experimental Control Station and is in contact with the pilot through a simulated VHF link. The controller monitors the progress of the flight and

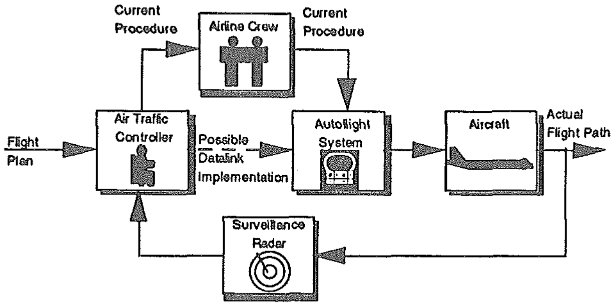

Figure 2. The ATC-to-Aircraft Communications Loop.

issues vectors and approach clearance amendments according to a script for each scenario.

A second experimenter, acting as the Pilot Not Flying (PNF), is seated next to the subject pilot. In most experiments, the PNF experimenter handles ATC communications and is available to answer any questions about the simulator that occur during the experiment.

The cockpit is videotaped during the experiment to record ATC and intra-cockpit communications and actions. In addition, the simulator records all flight data and control input parameters for the entire experimental run.

In order to maximize the validity of the results and minimize simulator training requirements, the subject pool is normally limited to professional air carrier pilots currently qualified on autoflight aircraft.

3. Datalink Delivery of ATC Clearance Amendments[2,3]

Motivation

The Federal Aviation Administration (FAA) has mandated the use of digital ground-to-air datalink for Air Traffic Control (ATC) services in the mid-1990's time frame. The delivery of ATC clearance amendments in-flight holds the potential to reduce voice congestion and information transfer errors associated with VHF radio communications.[4,5] However, there is some concern that datalink, especially when combined with automation, may actually decrease the crew's level of situational awareness.[6]

The FAA and the National Aeronautics and Space Administration (NASA) are studying systems which would automatically gate clearance amendment information into the onboard Flight Management System (FMS). While all proposed datalink systems would require pilot authorization before the aircraft would execute a new clearance automatically, there is some concern that pilots will become less involved in the clearance amendment processing loop and therefore may not be fully aware of the consequences of new amendments. Figure 2 shows the ATC-to-aircraft communications loop, which currently requires all clearance information to be processed by the crew. However, automation of datalink may inadvertently exclude the crew from the loop because they would assume a supervisory rather than participatory role in clearance communication.

Prior studies on automatic gating of clearance information using the MIT ASL Advanced Cockpit Simulator had shown that pilots preferred this option over voice or textual datalink delivery because of the advantages of the graphical presentation of the clearance information.[7,8] In these experiments, situational awareness was tested by issuing erroneous clearances and measuring the ability of the crews to detect these errors. This preliminary study was inclusive, however, there were indications that incorrect implementation of automatic clearance delivery could decrease situational awareness.

Approach

A simulation study was conducted to study the effect of automated clearance delivery on situational awareness as measured by pilots ability to detect errors in clearance amendments. The testing protocol was that the subject pilot was occasionally presented with nominally unacceptable ATC clearance amendments during terminal area operations. The ability of the pilot to recognize the errors was recorded as the dependent variable. Additionally, subjective ratings and comments by the subjects were collected.

The independent variables in the experiment were; automated verses manual programming of the datalinked clearance amendments into the FMS, procedural readback of the clearance amendment, and the mode of display of the information (verbal, textual, or graphical).

The experiment was a "within subject" design. Each subject flew the 10 scenarios required to fill the entire test matrix to control for differences between subjects. To ensure uniformity in notification, each amendment was enunciated using aural and visual alerts regardless of delivery mode or procedure. Each experimental run began during descent, approximately 120 nautical miles from the destination airport (thus requiring approximately twenty minutes to complete). After each scenario, subjects were asked for comments on the preceding scenario.

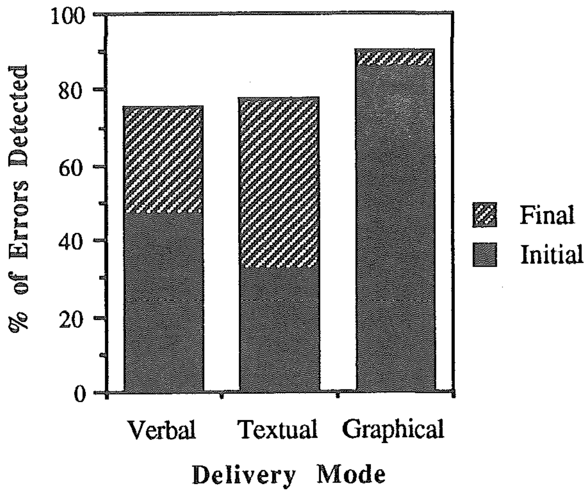

Figure 3. **Detection of All Events by Delivery Mode.**

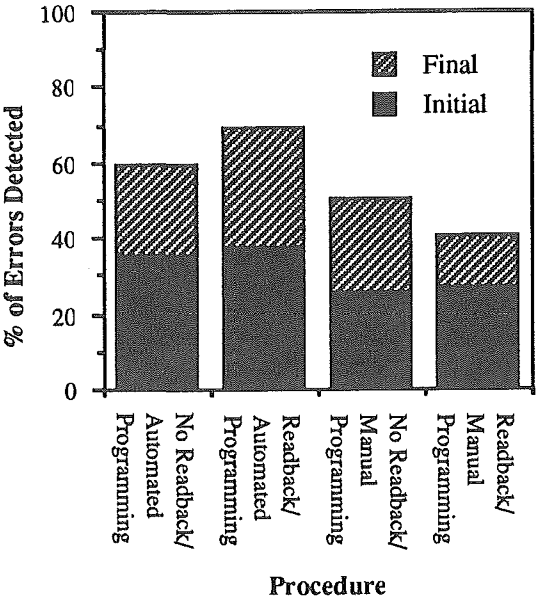

Figure 4. **Detection of Routing Events by Procedure.**

The scenarios were designed to represent the Northeast Corridor of the United States (i.e. the airspace between Washington DC, New York City, and Boston), with heavy traffic and weather in the entire region. Each scenario included a total of five clearance amendments, of which two were nominally unacceptable (i.e. an "error"). One error in each experimental run involved a clearance into weather, while the other was related to routing. During unacceptable routing clearances, pilots were given one of the following types of errors: 1) clearance to an incorrect initial fix to an approach for landing, 2) clearance to an incorrect destination, or 3) an illogical routing which headed the aircraft in a direction opposite to the intended flight path.

Results

Nine male B-757/767 qualified air transport pilots participated in the study. It should be noted that the subjects were volunteers. Because of this and the small sample size, the sample population may be biased towards favoring new technology when compared with the mean pilot population.

As shown in Figure 3, the graphical delivery mode yielded the best performance in detecting unacceptable clearances. In addition to the best apparent situational awareness, it also had the advantage that the vast majority of events were detected rapidly upon initial review of the clearance. In addition, graphical was outstanding in the detection of clearances into weather, with 100% of weather events detected immediately upon receipt of the clearance. This may illustrate the possible benefit of having a display which is simultaneously displays both the clearance routing and the location of potential hazards.

As shown in Figure 4, automated FMC programming appeared to aid in the ability to detect unacceptable routing amendments. This was supported by subjective opinions as the majority of subject pilots preferred automated programming with datalink. It was also clear from subjective comments that manual programming does not appear to aid in situational awareness even though each component of the clearance was entered into the FMS. In contrast, automated programming appears to allow the pilot to concentrate on evaluating the clearance on the strategic level.

Based on this study, automated FMS programming does not appear to adversely affect situational awareness and should be considered for the datalinked delivery of ATC clearances.

In contrast, no clear effect of readback performance was measured. Clearance readback showed a small improvement in error detection with automated programming. However, this effect was not statistically significant. Additionally, pilots rated the procedures with readback and automated FMS programming higher, on average, than any other procedure in terms of subjective situational awareness. Taken together, there is an indication that readback may have a benefit when used with automated FMS programming. While it is recommend that readback be retained on this basis, further study on the effectiveness of readback is warranted.

The primary advantage of the graphical delivery mode was in the rapid evaluation of clearances. However, details of the clearance can sometimes be difficult to interpret in most likely graphical implementations such as the one tested. Textual delivery has the advantage of having all the information in one place in a concise format. Nevertheless, textual delivery seems to have few decision-aiding advantages over the current verbal delivery. It seems likely that a simultaneous presentation in both text and graphics will combine the advantages of the individual modes, and eight of nine subject pilots desired this. This is also consistent with the current dual representation of information in existing FMS/EFIS Systems. Further investigation into this possible "mixed" delivery mode is warranted.

4. "Party Line" Information Studies[9,10]

Motivation

Air/ground digital datalink communications are an integral component of the FAA's Air Traffic Control (ATC) modernization strategy.[11] With the introduction of datalink into the ATC system, there is concern over the potential loss of situational awareness by flight crews due to the reduction in the "party line" information available to the pilot.[4,5,12] "Party Line" Information (PLI) is gleaned by flight crews overhearing communications between ATC and other aircraft. In the datalink environment, party line information may not be available due to the use of discrete addressing.

Approach

Information concerning the importance, availability, and accuracy of party line elements was explored through an opinion survey of 187 active air carrier flight crews. Specific party line information elements were ranked for importance, availability, and accuracy for various phases of flight. The survey identified numerous important party line elements. These elements were scripted into a full-mission flight simulation using the "Advanced Cab" in the NASA-Ames Man-Vehicle System Research Facility.

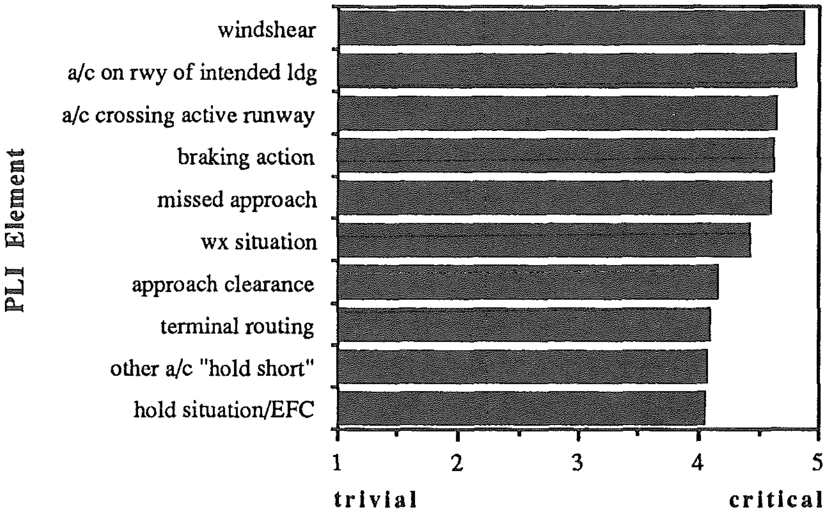

Figure 5. Importance of Specific PLI Elements.

The flight simulation experiment examined the utilization of party line information by studying subject responses to the specific information elements. The pilot responses to the PLI stimuli were rated according to level of awareness and action taken.

Results

The mean values of importance, availability and accuracy of the surveyed party line information elements were high. An example is shown in Figure 5 where information elements perceived as most important are shown. It is interesting to note that the most important elements occur during operations on or near the airport. This indicates that consideration of party line information should be given if datalink is to be implemented in near airport control sectors.

The results from flight simulation study of the important information elements are presented in Table 1. The scripted Party Line Events are presented in rank order by action taken and level of crew awareness of the Party Line Event. Some party line elements perceived as important, such as windshear or holding EFC validity, were effectively utilized by flight crews in the simulated operational environment. However, other party line elements stimulated little or no increase in situational awareness. The ability to assimilate and use party line information appeared to be dependent on workload, time availability and the tactical/strategic nature of the situations. For example, the aircraft crossing the active runway event occurred during takeoff roll where the crew was fully occupied with other critical tasks.

In addition, the results of both the survey and the simulation indicated that the importance of party line information appeared to be greatest for operations near or on the airport. This indicates that caution must be exercised when implementing datalink communications in these high workload, tactical sectors.

Table 1. Ranked PLI Event Results

PLI EVENT #	NOT AWARE	AWARE	ACTION TAKEN
Windshear	0	0	6
Holding EFC	0	1	6
Turbulence and weather	1	1	5
Aircraft hold short at taxiway	1	4	2
Aircraft on runway	0	7	0
Traffic watch/climb	1	6	0
Aircraft Sequencing	1	5	0
Traffic watch/holding	5	2	0
Aircraft crossing active runway	6	0	0

5. Hazardous Wind Shear Alerts[8,13,14]

Motivation

In the past few years, systems for the detection of low altitude wind shear hazards, particularly microbursts, have been under steady development. These include ground-based systems such as Terminal Doppler Weather Radar (TDWR) and an enhanced version of the anemometer-based Low Level Windshear Alert System (LLWAS), as well as airborne forward-looking systems such as infrared radiometers, doppler radar, and doppler lidar. In order to incorporate these new sensors into an effective alert system, the problem of dissemination to flight crews must also be addressed. The variety of systems under development for both wind shear detection and ground-to-air datalink, combined with the advent of electronic cockpit instrumentation, allow many options for alert generation and dissemination. A critical part of the dissemination task is presentation of alerts to the flight crew in an easily understood and timely manner.

Approach

Two piloted flight simulator experiments have been conducted at MIT to study this issue. The first experiment focused on comparing verbal, alphanumeric, and graphical modes of presentation in the context of both ATC amendments and microburst alerts.[8,13] Eight active 757/767 pilots volunteered for the experiment.

In this experiment, pilots were asked to fly nine descent and approach scenarios under weather conditions conducive to wind shear. During the descent, ATC clearance amendments were given in the various modes; this portion of the experiment is discussed in detail in Reference 8. When the aircraft was vectored onto the final approach course, microburst alerts were issued in one of the presentation modes. Microbursts were positioned either as a threat on the approach path or as a non-threat on the approach or departure end of another runway. In addition, microbursts were sometimes positioned on the missed approach path.

Microburst alerts always contained warnings for all possible approach runways, not only the one being used by the simulated aircraft. This was to ensure that all modes had the same information content, and to allow measurement of the pilot's facility to discriminate between threatening and non-threatening situations.

Verbal microburst alerts were given as radio messages by the controller. Text microburst alerts appeared in an alphanumeric window just below the EHSI display. A typical verbal or text alert: "IRIS 354, Microburst Alert. Expect four-zero knot loss, 2 mile final approach runway one-seven-left." Graphical microburst alerts appeared in the appropriate location on the EHSI as flashing white circles with the intensity (headwind-to-tailwind change, in knots) drawn in red inside them.

Verbal cues were given (i.e. "IRIS 354, Microburst alert.") in all modes, so that the time of notification was kept constant. This would not be true of an actual cockpit, where an automated audible alert would most likely be used. Over the subjects tested, all scenario blocks were tested in all the modes, and the order in which the subjects encountered the modes was rotated. This process was used to attenuate learning and scenario-dependent effects.

Results

The results demonstrated that graphical alerts have significant benefits. The measure of pilot performance for the microburst alerts was the percentage of "correct decisions" made in each presentation mode. An incorrect decision was scored for either: (1) avoidance action taken when none was necessary, (2) no avoidance action was taken in a clearly hazardous situation. The data in Figure 6 show that the highest percentage of correct decisions

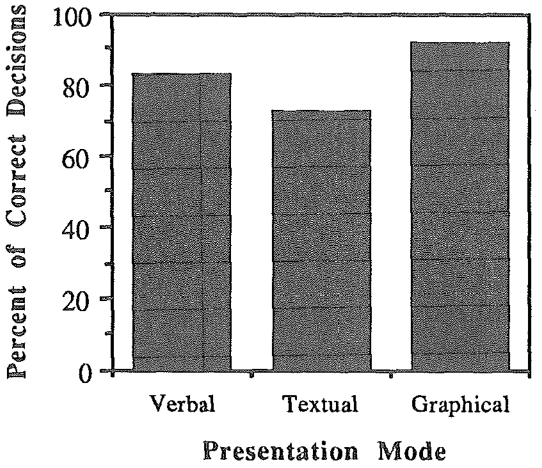

Figure 6. Decision-making performance for microburst alerts by mode of alert presentation.

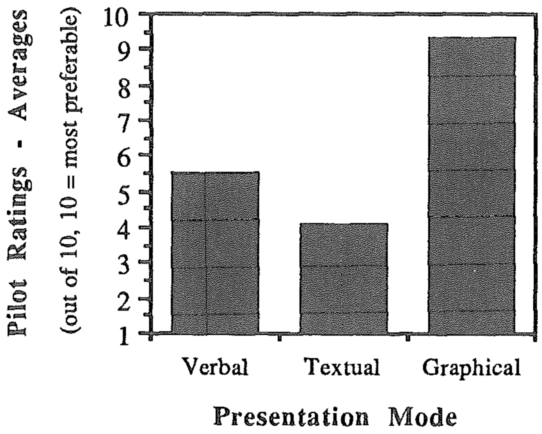

Figure 7. Pilot preference ratings for modes of microburst alert presentation.

were made with graphical microburst alerts, and the largest number of errors were made with textual alerts. When asked to rate the desirability of the three modes, pilots overwhelmingly preferred the graphical mode of communication (Figure 7). In addition, the text mode was consistently rated less desirable than the verbal mode. Pilots disliked in particular the additional head-down time required to read textual information.

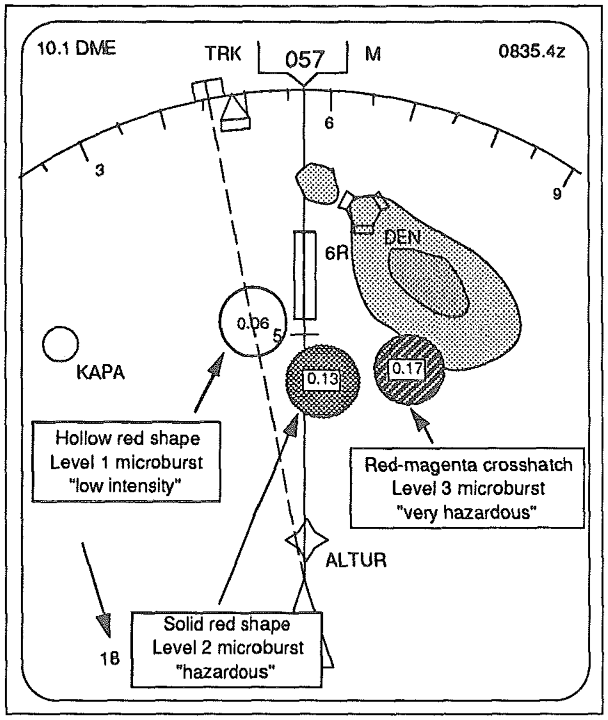

Figure 8. Example multi-level microburst alert display on the EHSI.

Based on these demonstrated advantages of graphical alerts, a second piloted simulator experiment was designed to evaluate specific format and implementation issues associated with graphical microburst alert displays.[14] Issues addressed included display clarity, usefulness of multi-level microburst intensity information, and whether information from multiple sensors should be presented separately or "fused" into combined alerts. Three different candidate graphical alert formats were tested. Nine active airline pilots of EFIS-equipped aircraft participated in the study.

Pilots found that graphical presentation of microburst alerts on a moving map display (the EHSI) was visually clear and useful and did not induce unacceptable display clutter. Also, multi-level intensity information coded by colors or patterns was found to be important for decision-making purposes, and was strongly preferred to displaying only "hazardous" microbursts in a single intensity level format. The intensity levels were defined using the "F-factor" hazard criterion,[*] which was found to be acceptable by the pilots.

A sample multi-level display format (including F-factor values) is illustrated in Figure 8. Also, the positional information included in the graphical alert presentation was found useful by the pilots for planning lateral missed approach maneuvers, but may result in deviations which could interfere with normal

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[*] F-factor is a hazard criterion, including both headwind loss and downdraft components, which indicates the instantaneous loss of aircraft available climb rate due to the immediate windfield. It is described in detail in Reference 15.

airport operations. This experiment is described in detail in Reference 14.

6. Electronic Instrument Approach Plates[16]

Motivation

This study investigated the systems and human engineering design issues of electronic approach chart systems. Currently, IAP information is presented in paper format only. Information for all user groups and situations is normally contained on a single chart for each approach because it is too expensive to produce separate charts for different user groups. The small size of the charts (8.5 x 5 in.) forces the symbology and text to be quite small in order to accommodate all the information; consequently, current IAPs tend to be information dense.

Electronically based Instrument Approach Plates (EIAPs) offer a more flexible medium to present approach information to the pilot, as well as an opportunity to re-evaluate and modify conventional IAP design parameters. However, electronic display limitations require increases in minimum display element size to avoid aliasing problems. Methods are required to avoid display clutter problems which occur as a result.

Approach

An experimental study using the MIT ASL Advanced Cockpit Simulator was conducted in order to evaluate several Electronic Instrument Approach Plate (EIAP) formats. Two groups of three IAP formats were used in the experimental study. Paper, Monochrome, and Color formats comprised the first group of three. They were constructed in order to investigate the transition from paper to electronic IAP formats. Since the complete information set was always present on these charts, they were referred to as "non-selectable".

North-Up (Static), Track-Up (Moving Map), and EFIS Integrated formats comprised the second group of three. They were all color, and were constructed in order to evaluate potential EIAP design features and investigate decluttering issues. Since these three charts provided pilots with a prototypical decluttering capability, they were referred to as "selectable". These IAP formats were constructed in increasing technical levels toward more advanced electronically based IAPs. Each EIAP was based on the current paper IAP format and current EHSI, and was designed to utilize the format flexibility provided by electronic systems.

During the approach scenarios, each pilot responded to a total of 45 performance questions that were scripted into each approach in order to explicitly measure the efficacy of each format. Response time and error rate were used as an indicator of the ease and accuracy with which information could be extracted from the chart. Display order was counterbalanced across subjects in order to minimize learning effects.

Four of the twelve approaches that were flow by each subject entailed a scripted ATC clearance into terrain in order to implicitly measure the efficacy of terrain information depiction by spot elevations. In each case, the erroneous vector required no course deviation and entailed a premature descent clearance. Prior to commencing the approach , the pilot had ample time to orient himself to the heading assigned by ATC and to study the situation. If the pilot accepted the erroneous descent clearance without noting the hazardous terrain, a "terrain fly-through" event was recorded. If the pilot correctly identified the hazardous terrain, ATC immediately complied with his request for a climb to a safe altitude or a vector clear of terrain.

Twelve pilots who averaged 10,300 total flight hours, including 1,850 hours in autoflight equipped aircraft participated in this experimental study.

Results

Pilots ranked all six chart formats that were used in the experiment from the most desirable (1) to the least desirable (6). Results from this procedure are depicted in Figure 9. The general preference for the "selectable" formats indicates the desirability of color, information selectability and the depiction of real-time aircraft position information.

The subjects consistently indicated that the pilot selectable IAP decluttering capability helped to reduce clutter problems. Those who used the prototypical decluttering technique in the experiment unanimously agreed that it was desirable. Pilots unanimously agreed that the decluttering capability was desirable, and helped to reduce clutter problems.

Information retrieval response times and error rates indicate that there appears to be no loss in performance, and possibly a limited gain in information retrieval performance when IAP information was presented in electronic format. Response times to the performance question concerning the location of the highest obstacle on the chart were considerably faster when this information was presented in Color format.

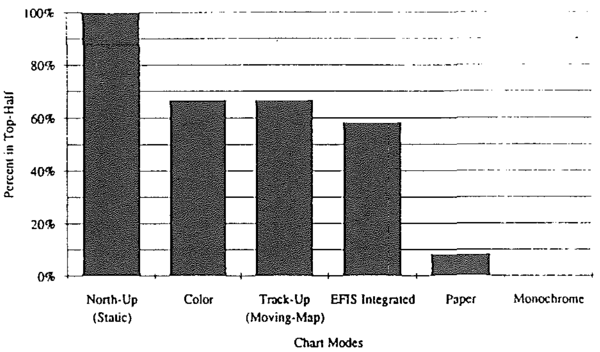


Figure 9. Preference Ranking For All Formats.

The ability of the flight crews to identify the hazard associated with terrain was found to be low. When using the "non-selectable" charts, pilots accepted the erroneous ATC clearances and penetrated hazardous terrain without question 38 times out of 39 opportunities, generating a hazard recognition rate of only 3%. When using the "selectable" charts, pilots accepted an erroneous ATC clearance and penetrated hazardous terrain 11 times out of 13 opportunities, generating a terrain penetration rate of 15%.

The extremely high number of recorded terrain "fly-through" events indicates that the current methods of terrain depiction were not being used to their full potential. While adequate terrain information was available on the IAP or EIAP format, pilots did not appear to have been aware that a hazard existed. The fact that pilots often accepted ATC clearances without checking the IAP to confirm adequate terrain separation indicates a general tendency to rely on ATC for terrain clearance.

7. Advanced Terrain Depiction[17]

Motivation

Controlled flight into terrain is the leading cause of Air Carrier fatal accidents world wide resulting in 47% of the fatal accidents from 1979 to 1989 [18]. This, along with the low hazard recognition rates found in the EIAP experiment discussed in Section 6, motivated a study to investigate the effectiveness of two methods of terrain depiction. Two primary methods of terrain presentation are currently used on paper Instrument Approach Charts. The first method depicts hazardous obstacles using spot elevation symbols on the chart. These symbols provide detailed terrain or obstruction altitude information at the specific locations of high points on the chart. However, the pilot must interpolate the terrain altitude in areas between the spot elevation symbols.

The second method of terrain depiction is smoothed contour depiction. Contours offer an advantage over spot elevation symbols in that terrain information is depicted throughout the chart, providing a continuous representation of the terrain near the airport.

Approach

An experimental study was conducted using the MIT ASL Advanced Cockpit Simulator to investigate the relative effectiveness of the two current terrain presentation methods. Each subject flew 12 approaches on the simulator while viewing a prototypical electronic terrain display. A Spot Elevation Display was used in six of the approaches, and a Smoothed Contour Display was used in the remaining six approaches. Display order was counterbalanced across subjects to minimize learning effects to the extent possible. Nine subjects participated in this study, with an average of 6400 hours of civil flight experience, of which 1275 hours were in autoflight aircraft.

Four of the twelve approaches flown by each subject included a scripted ATC clearance into terrain. In each case, the clearance was issued near the start of the scenario, at a point when the pilot had ample time to evaluate the situation. The erroneous clearance involved vectoring the aircraft close enough to terrain (i.e., within 1000') such that the simulator's Ground Proximity Warning System would activate. If the pilot did not recognize the terrain threat, the simulator's GPWS system would alert the pilot, and a terrain proximity event was recorded.

If the pilot recognized the terrain hazard and requested a new clearance to avoid the terrain, an appropriate clearance was immediately issued by ATC.

Results

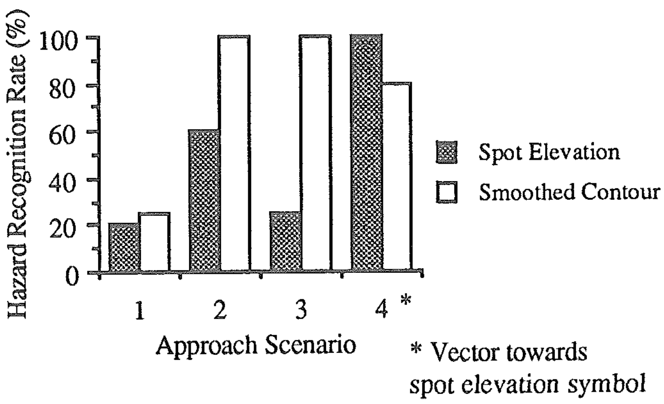
The results are given in terms of the *hazard recognition rate*, which is defined as the ratio of incidents in which pilots determined that a hazard existed, to the total number of erroneous clearances given with a display format.

Figure 10 shows the hazard recognition rates for both terrain display types broken down into each terrain proximity scenario. In the first terrain proximity scenario, when the pilots may have assumed ATC was providing terrain clearance, pilots had a low hazard recognition rate (20-25%). In addition, there was little difference between the Spot Elevation and the Smoothed Contour display formats. Once the subjects became aware that erroneous vectors were possible, they appeared to assume more responsibility for terrain clearance and there was an acute improvement in display effectiveness and a difference in performance between the two formats. When averaged over both display formats, hazard recognition rates increased from 22% for the first scenario to 78% for the subsequent scenarios (when the pilots were aware that erroneous vectors might be issued). This increase in hazard recognition is statistically significant ($p < 0.01$).

Hazard recognition rates improved from 20% to 62% (averaged over the last three scenarios) when using the Spot Elevation Display once the pilots apparently assumed more responsibility for terrain separation. A greater improvement was observed with the Contour Display: recognition rates increased from 25% to an average of 93%. However, the difference in performance between the two display formats when pilots appeared to assume terrain separation responsibility (62% vs. 93%) is not statistically significant ($p > 0.05$).

The high rate of terrain proximity incidents by qualified active air crews in this experiment indicates that current methods of terrain depiction were not being used to their full potential. Although the necessary information to depict hazards was available, the fact that a hazard existed was not always readily evident.

The combination of high workload levels, reliance on ATC, and the fact that pilots do not have access to intuitively presented terrain information appear to be primary factors in the low hazard recognition rates observed in this study. The lack of effective terrain information in the cockpit and the excellence of ATC in providing safe terrain clearance appear to have led pilots to implicitly transfer the responsibility for terrain separation to ATC.



* Vector towards spot elevation symbol

Figure 10. Scenario Hazard Recognition Rates.

When pilots appeared to depend on ATC for terrain separation, the type of terrain display did not make a difference in performance. However, in situations where pilots assume more responsibility for terrain clearance, it appears terrain situational awareness is improved when using a Smoothed Contour Display instead of a Spot Elevation Display.

8. Conclusion

The results presented above indicate that part task simulation studies using facilities such as the MIT ASL Advanced Cockpit Simulator can be effective in identifying important issues for cockpit information systems. While detailed results depend in the specific implementation, graphical presentation of alert and flight control information has generally been found to be effective for situational awareness and subjectively preferred by flight crews. Graphical display is most effective when it is consistent with the pilots cognitive map of the situation or process being displayed.

Acknowledgments

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