An Evaluation of Automation for Flight Path Management in Transport Category Aircraft

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Abstract

A two part user centered study of levels of automation for the clearance amendment process for advanced transport category aircraft was conducted. First, a survey on cockpit automation was distributed to pilots of Boeing 767 and Boeing 737-300 aircraft in order to obtain their evaluation of the current flight path management system, and their suggestions for improvements. A simulation of the Boeing 757/767 Electronic Flight Instrumentation System and Control Display Unit were also developed. This apparatus was used for the second part of the study, an experiment in which six qualified Boeing 757/767 pilots compared three modes of communication for the clearance amendment process: standard voice procedures, a textual delivery method and a graphical delivery method. The textual and graphical methods of delivery will be feasible in the near future with the development of the Mode S transponder. Overall, the graphical mode was found to be superior, both in terms of a quantitative model of the task, and in terms of pilot reviews.

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1 Chapter One: Introduction

The pilot's role has evolved considerably over the years as a result of advances in the technology and design of aircraft. The primary goals of providing stability, control, and guidance remain the same, but today's advanced transport category aircraft allow the pilot to play a less active role in achieving these goals. Instead, it is now commonplace to have a sophisticated autopilot system which measures and controls the fundamental flight parameters for the pilot. The pilot's primary tasks are now to monitor these systems and to ensure that the vehicle is proceeding along the cleared route, initiating control commands only as necessary.

1.1 Flight Deck Automation and Information Management

There is the potential today to automate higher-level pilot tasks. This potential leads to the difficult issue of how much automation is too much? Obviously, some automation is necessary to control such complex aircraft. Too much automation, though, can lead to boredom or complacency, possibly resulting in poor pilot response in the event of an emergency. An important factor in this issue is that although the performance capabilities of aircraft have improved significantly over the years, human information processing capabilities remain limited.

In the past, pilots have been eager to know any and all reliable information about the state of their vehicle. So, more instruments became standard as the technology was developed. The result was a dramatic increase in the number of cockpit flight instruments. Early combat aircraft, for example, had on the order of ten flight instruments. Nowadays, these aircraft commonly require the pilot to assess more than 300 instruments and displays (Huntoon, 1985). Not surprisingly, such a barrage of information can sometimes overwhelm the pilot.

Even with automation systems that pre-process information, the pilot can be overloaded during high workload phases of flight. In fact, it is possible for advanced control and display systems to add to workload rather than to alleviate it under some conditions. An example of such a system is the Flight Management Computer (FMC) which assists the pilot with flight path management. Using a Control Display Unit (CDU) to enter data, the pilot may store the complete planned route in the FMC prior to leaving the gate area. Given the actual flight conditions (acquired by other on-board systems in real-time), the computer calculates and displays appropriate statistics such as fuel consumption and estimated arrival times. This system works well in general, but there is a problem: due to the complexity and variability of the Air Traffic Control system, routings are often amended and re-programming is required in flight. This situation is not a problem en route, when crew workload is low. In approach and departure, however, workload is already high, so re-programming the FMC at these times can be a distraction that could lead to a dangerous situation. One crew member is occupied with the programming task, the other is flying the aircraft, and neither is free to scan the visual field for other aircraft in the vicinity. This high workload situation is a recognized problem; some airlines prohibit reprogramming at low altitudes.

As illustrated by the example above, automation is not necessarily the solution to the pilot's workload problems. Some experts have recognized this and question the current tendency to view automation of all pilot tasks as a desirable goal. Edwards (1977) states that "...little or no systematic attempt has been made to design and implement automatic systems in relation to the needs, capabilities and limitations of human performance." One item on his list of the criteria of whether a system should be automated is: "Engineering Feasibility; there is a tendency to proceed once the relevant technology is available." In the Weiner and Curry (1980) review of automation and its "...promises and problems," Weiner advocates that a system should be automated only after careful consideration of the ramifications. In another (1985) article, he:

> advances the view that the time-honored recommendation that humans should serve as monitors of automatic devices must be reconsidered, and that the human must be brought back into a more active role in the control loop...

It is now generally recognized that humans are not good monitors.

1.2 Recent Advances in Technology

The most automated aircraft in commercial service today were designed in the 1970's and came into service when computers were still relatively esoteric. There have since been major technological advances. With new technology, not only the performance of cockpit computers, but also their human interface could be refined. Two areas of development which are directly applicable to cockpit automation are microprocessor technology and datalink technology.

Significant progress has been made in the field of computer technology, both in terms of hardware and software. The possibility of a "glass" cockpit, consisting entirely of computer generated displays, has become feasible with these tools. Microprocessors, for example, provide more computational power and speed for their size. These hardware improvements allow the design of customized software to produce a myriad of displays, an unheard of degree of flexibility compared with traditional instrumentation.

High speed, aircraft selective, digital datalink capability will soon be realized with the Mode S transponder. This equipment allows direct electronic communication between ground and airborne computers. The Mode C transponder used currently is only capable of broadcasting an electronic aircraft identification tag to ground based computers, whereas Mode S would allow ground computers to send information to aircraft computers as well. At present, nearly all communications between Air Traffic Control (ATC) and the pilot are verbal messages. Unfortunately, miscommunications are not uncommon and have been identified as the cause of numerous altitude deviations as well as of more serious incidents (NASA ASRS, 1980). Electronic communications can be made less error prone than human communications.

The new technology noted above opens up a variety of possibilities for designers of the glass cockpit, but changes have to be evaluated thoroughly before they can be implemented safely. Each display mode must be carefully planned and evaluated, taking many issues into account. It would be wise therefore to take advantage of the large base of knowledge that has accumulated about the human-computer interface in recent years. For example, display design and perception issues must be assessed, since the presentation of information affects the way humans interpret it. Input and output devices should also be easily manipulated for routine tasks such as data entry and route alterations. Before such details, albeit complex ones, are researched, though, it is necessary to evaluate the issues on a more general scale.

1.3 Objectives

In a broad sense, the goal of this research has been to develop a methodology to evaluate levels of cockpit automation. In order to accomplish this, an interdisciplinary approach combining the principals of cognitive science with engineering and design was pursued. The underlying premise is that computer systems that are designed to emulate fundamental human representations of information facilitate human information processing and are therefore easier to learn and more acceptable to users. In human-computer interaction terms this means that it is desirable for the user's mental model of the computer to be simple, containing a few generally applicable rules.

In order to study the issues of information management and levels of automation, it was necessary to first select an appropriate task. This study examines the flight path management task or, more specifically, the process of accomplishing a routing change (or "clearance amendment") when initiated by ground controllers. When the pilot receives such a request, he must decide whether or not to accept the changes. If he accepts them, he is expected to comply with the new routing. This process is currently conducted through a series of verbal communications between the pilot and the controller.

With the Mode S tranponder, it is possible to automate the clearance amendment process; updated clearances would be transmitted directly to the flight management computer on board. It is also possible to choose and automate separate sub-tasks of the procedure. These sub-tasks are shown in Figure 1.1 which is a flow chart of the information transfer involved in the clearance amendment task. Three levels of automation were chosen for testing: (1) current verbal procedures, (2) textual delivery of clearances, and (3) graphical delivery of clearances. Each of these is a different "mode" for communication of the flight path information.

1.4 Thesis Overview

Each chapter in this document examines the clearance amendment process from a different perspective. Chapter 2 begins with a review of past approaches to cockpit design. The clearance amendment process is then evaluated in a theoretical framework. It is concluded that past approaches are unsuitable for this research issue. A user centered design philosophy is adopted instead. The methodology for this research was to first conduct a survey on the use of currently available cockpit automation for flight path management and then to conduct a part-task simulation of the clearance amendment task employing varying levels of automation. Chapter 3 deals with the survey design and results. Chapter 4 concerns the development of the simulation experiment. The results of this experiment are then presented in Chapter 5. A summary of the conclusions of this research and suggestions for future work are presented in Chapter 6.

Figure 1. 1 The Clearance Amendment Task

A generic breakdown of this process is given for the verbal mode, *Figure 1a*, the textual delivery mode in *Figure 1b*, and the graphical delivery mode in *Figure 1c*. These methods are presented in increasing order of automation. Each mode of delivery was tested in the experimental simulation, discussed in Chapters 4 and 5.

Figure 1a. Current Verbal Amendment Delivery

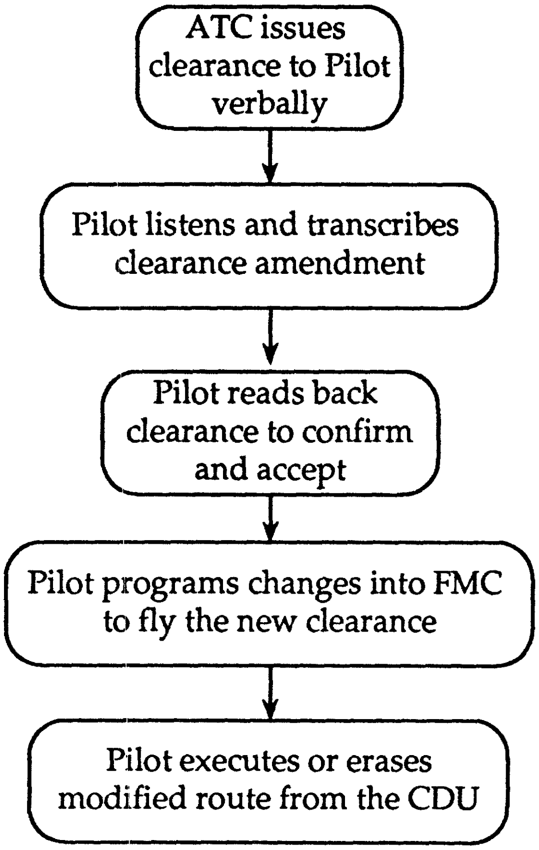


Figure 1b. Proposed Textual Amendment Delivery

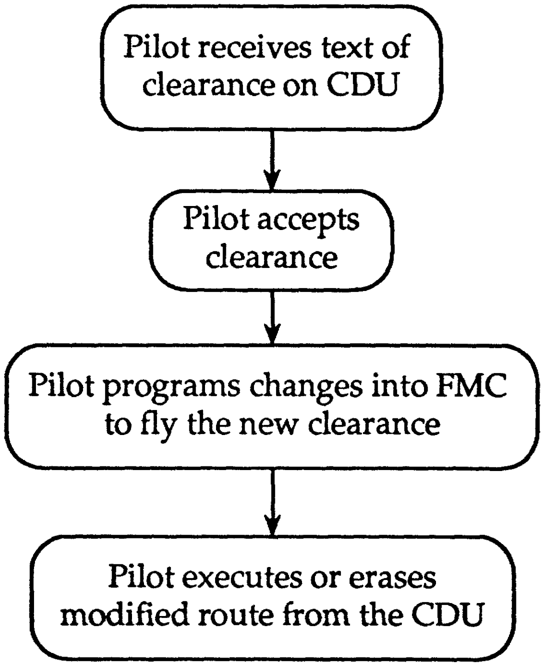
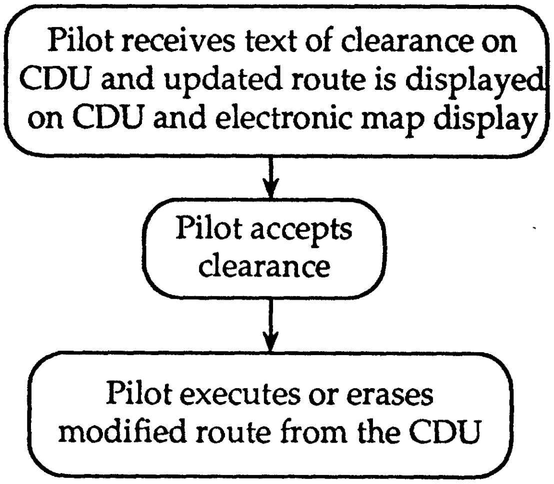


Figure 1c. Proposed Graphical Amendment Delivery



2 Chapter Two: Approaches to Cockpit Design

The purpose of this chapter is to show the reasoning behind the choice of a user centered design methodology for this study of the clearance amendment task. A task analysis which illustrates a cognitive hierarchy of piloting tasks is first presented. Next, a review of past approaches to cockpit design is presented, relating each approach to the task hierarchy. Then the clearance amendment task is analyzed in terms of this task hierarchy, showing that none of the past approaches are suitable for this task. Finally, the user centered methodology is described and proposed. This methodology has not been applied to such a task before, so in a sense, its use is also an experiment.

2.1 A Flight Deck Task Hierarchy

In the terminology of Rasmussen (1982), the behavior of the process operator can be separated into three levels: skill-based, rule-based, and knowledge-based. Tanaka et al. (1983) applied this hierarchy to the mental workload of pilots flying highly automated aircraft. In their analysis, skill-based workload was associated with conventional manual control tasks such as maintaining aircraft flight path. These tasks typically involve little or no cognitive workload for the pilot; they are performed "automatically." Rule-based workload is associated with actions or processes that are defined by specific, often codified, procedures such as aircraft configuration changes and radio navigation. This type of task often involves retrieval of memorized procedures for dealing with specific situations. Knowledge-based workload occurs in situations where it is necessary for the operator to select which rules apply. Such a task is generally the largest contributor to cognitive workload in the cockpit. Knowledge-based behavior is applicable in unusual situations or emergencies that require judgement.

Although these cognitive distinctions between tasks appear to be clear cut, the boundaries can be vague. The difference between skill-based and rule-based tasks, for example, may simply be the level of training of the pilot. As the pilot gains experience, tasks that had formerly required thought become automatic. The difference between knowledge-based and skill-based tasks is dependent on the size of the information database that the pilot needs to access. For knowledge-based tasks, the pilot has to rely on all of his experience in order to evaluate what actions might be appropriate. Rule-based tasks require the recall of just one set of relevant procedures, but these may have to be selectively retrieved from a larger information base, similar to a knowledge-base. Even though these distinctions are informal, they are helpful in establishing a general task hierarchy.

2.2 Past Approaches to Cockpit Design

The selection of a design methodology is necessarily a function of the purpose of the design and the available technology. As technology has advanced, cockpit designers have chosen to address increasingly cognitive issues in the pilot task hierarchy. This trend is illustrated by the following discussion of three methodologies for cockpit design: human factors engineering, control theory models, and expert systems.

2.2.1 *Traditional Human Factors Engineering*

Historically, this was the first approach taken towards a systematic evaluation of cockpit design in terms of its suitability for the human operator. This methodology tries to empirically match physical characteristics of control and input devices with the body's sensory and motor systems. The approach is aimed specifically at producing guidelines for engineers to determine which types of manual control devices are appropriate for given tasks. It has been used to design and evaluate instrumentation that involves visual, auditory, or tactile feedback to the pilot. The goal is to reduce the amount of effort, physical and mental, involved in processing this feedback so as to reduce pilot error and ease strain. Such improvements are also likely to result in systems that are easier to learn to use. The human factors methodology achieves its practical goal and is suitable for some issues even today.

The applicability of traditional human factors engineering to the cognitive domain, however, is limited. The approach does not provide any insight about the cognitive processes underlying the use of control devices and takes into account only the most basic, or overlearned, cognitive processes. Color and task compatibility is one such issue: for example, the association between green with 'go' and red with 'stop.' This color and task correspondence is so highly learned that it is difficult for an operator to override. However, this phenomena is on a lower cognitive level than even skill-based functioning. Certainly, this approach is not suitable for complex mental tasks involving rule-based or knowledge-based workload.

2.2.2 Control Theory Models

The control theory approach to cockpit design issues is characterized by mathematical models of pilot performance on skill-based tasks. The "human-in-the-loop" is represented as an inner feedback loop which incorporates neuro-muscular characteristics but assumes that cognitive processing is negligible. That is, selection and execution of control responses take place with little or no need for cognitive processing. The two most common models of performance are the crossover model and the optimal control model. These and other models are reviewed by Gerlach (1977). Such models have been quite successful in offering designers a quantitative way of incorporating human performance into the design of the aircraft control systems such as simple position or altitude holding autopilots. Recently, control theory models have been used to describe tracking task performance using active and passive side stick controllers by Hossman and van der Vaart (1987). They are obviously inappropriate for tasks that require higher levels of processing, such as navigation.

2.2.3 Expert Systems

Expert systems are specially designed software packages that use production rules to process information and make inferences and decisions. The rules are generated from a detailed analysis of the heuristics that human experts use to evaluate situations. The goal is to help the pilot by pre-processing the raw data through software which prioritizes information and suggests alternative courses of actions. Expert systems are currently being developed for tasks such as fault diagnosis (Remington and Palmer, 1987), malfunction handling (Georgeff and Lansky, 1986), and route planning (Sexton, et al, 1987).

Expert systems are clearly applicable to the domain of rule-based behavior. They will eventually be indispensable for vehicles such as the space shuttle since they are capable of handling extremely large databases of information. Entire operations manuals and detailed system diagrams could be accessible to the program. The "Pathfinder" expert system which is being developed by Lockheed, for example, has a proposed database that is much larger than that used by the current FMC. The table below compares the information stored in each (taken from Sexton, et al., 1987).

Table 2.1 Proposed Database of the Lockheed Pathfinder System

Present FMC's	Additional Data Required
Navigational Aids	Federal Aviation Regulations
Airfields	Weather
Company Routes	Company Rules
Performance	Obstacles (Altitude Constraints)
Fuel	Company Priorities
Status	Special Use Airspace
	Noise Abatement Areas
	Slot Times

Pilots are currently responsible for obtaining, storing and retrieving the additional information that the Pathfinder system will eventually incorporate.

The potential for the use of expert systems on advanced aircraft is great. As systems like Pathfinder store more and more information, and process it with more and more complex and "intelligent" rules, they will be dealing more with knowledge-based behavior. They will begin to implement "judgement." As noted in Chapter 1, though, designers are responsible for deciding how much automation is too much. The ultimate possibility of flying a pilotless aircraft is technologically feasible, but will take many years, at best, to become a reality due to social and political factors.

2.3 Cognitive Aspects of the Clearance Amendment Task

The clearance amendment task is clearly knowledge-based. Pilots must rely on experience with their vehicle, their familiarity with the area, their knowledge of the traffic environment, and many other factors in order to determine the acceptability of a clearance. That is, the pilot must have a clear mental picture of their situation; this is known as situational awareness. There is no precise definition of the term situational awareness, nor is there any formal or objective (or even subjective) measure of it. The loss of situational awareness, though, can eventually cause the pilot to become disoriented about the position and state of his vehicle, leading to obvious problems.

In order to understand situational awareness more thoroughly, the psychological literature on spatial orientation was reviewed. The study of navigation issues in experimental psychology is a young field, and therefore, studies have focused around the broad issues of representation, storage, manipulation, and retrieval of spatial information concerning relative (and absolute) locations of landmarks or objects. This research has been conducted in non-aviation environments, but is generalizable since navigation of an aircraft involves the same types of processing for selection of routes with waypoints as "landmarks." Relevant findings from this body of research are presented below.

2.3.1 Cognitive Maps

The mental representation of spatial relations is known as a cognitive map. The properties of such maps have been explored by several researchers and some fundamental attributes are now accepted. In 1982, Levine et al. explicitly stated these properties as three intuitive axioms:

> Axiom 1: From a sequence of movements in space, one is able to construct a representation (e.g. a picture) of the path.
>
> Axiom 2: From a picture of a path, one can move appropriately among the points of the path itself.
>
> Axiom 3: After learning a sequence of connected points, humans behave as though the information has been place into a simultaneous system. (Principle of Equiavailability)

The third axiom above makes two important predictions. First, it implies that once a cognitive map has been formed, the subject can compute new routes, even shortcuts through the environment. Secondly, it predicts that new and old path segments are equally accessible, again illustrating the picture-like nature of cognitive maps. Both of these predictions have been supported by experimental findings.

2.3.2 *Formation and Orientation of Cognitive Maps*

Given that cognitive maps are picture-like representations, a host of issues concerning their orientation are raised. For example, are maps stored in several orientations, or just one? If there is only one map, how can people re-orient themselves to the same environment from a different view? If there is only one map, from which perspective is it drawn? How is it that experienced pilots tend to view maps north up, no matter what direction they are travelling along, while novices tend to turn the map in alignment with their heading? Levine et al. began to address the orientation issue with three principles, summarized below:

> The Two-point Theorem: Two pieces of information, either two points or a point and a direction are necessary in order to relate terrain to a map.
>
> The Alignment Principle: For maximum ease of use, the map should be turned to parallel the terrain.

> Forward-Up Equivalence: The orientation of a vertical map is psychologically equivalent to that of a horizontal map produced by a simple lay-down (90° forward rotation) transformation.

There is little to argue about the two-point theorem, a mathematical fact, and forward-up equivalence, an intuitive concept.

The alignment principle, though intuitively acceptable, may be influenced by several factors, such as familiarity with the environment, or the way in which the cognitive map was formed. The reason for this is the phenomena of mental rotation. Mental rotations are a well established and readily identifiable effect, seen as a linear relationship between the angle of rotation and the amount of time taken to complete the rotation. The idea is simply that if the mind completes a rotation by calculating all intermediate stages, the amount of time for the rotations should be proportional to the angle of rotation. If, however, intermediate stages were not computed (perhaps several rotated images are stored separately), the amount of time to access a rotated version would not vary linearly with angle of rotation.

Hintzman et al. (1981) studied orientation in cognitive maps in several experiments which varied the method by which the cognitive map was created. Some maps were visual (i.e. drawn on a CRT), while others were mentally created (i.e. imagined). They obtained mental rotation in some tasks, but not in others. Their results were inconclusive though, since they were unable to predict which conditions would yield mental rotation. Nonetheless, mental rotation was often used to imagine cognitive maps from different orientations. Experienced pilots probably use it regularly while navigating and with practice become more comfortable reading maps north up, regardless of their heading.

Evans and Pezdek (1980) studied knowledge of real world spatial information by testing two groups of subjects on their knowledge of the spatial relations between buildings on a college campus. One group, students from the college, had learned the campus through direct interaction, that is, by walking around. A second group of students, attending another college, was asked to learn the campus of the first college by studying a map of the area. These groups differed significantly in that students that learned the campus by walking around had no preferred orientation for visualizing the area, while the other students were obviously using mental rotation to align the task with the well-learned north up orientation. This demonstrates that the way that people first encode a cognitive map affects the way in which information is retrieved.

2.3.3 *Conclusions of Cognitive Evaluation*

There are two main conclusions to be drawn from the analysis of the clearance amendment task. The first conclusion is that the notion of cognitive maps would support the idea of graphical clearance amendment delivery. It is reasonable to assume that the pilot stores his route in some form of a cognitive map, so it appears that it would be desirable to send him route amendments in a form more compatible with this internal representation. The second conclusion is that although there is no directly applicable information available from the experimental psychology literature, that approach to studying spatial orientation has resulted in interesting and useful findings about underlying mental processes. These findings encourage a comprehensive cognitive evaluation of the task, including a directly applicable experiment.

2.4 User Centered Design Methodology

Norman (1986) first proposed a user centered approach for design of human-computer interfaces. We have chosen to implement this methodology for the clearance amendment task as an alternative to past cockpit design approaches. The approach which he terms "cognitive engineering" promotes the use of existing models of cognition to evaluate and design systems in a manner analogous to traditional engineering methods. The foundation of a user centered analysis is the evaluation of users' needs and preferences. This objective was accomplished by conducting a survey on cockpit automation which is discussed in detail in Chapter 3. The results of the survey analysis were then incorporated into the design of the experimental simulation which is presented in Chapter 4. The clearance amendment process is representative of a class of flight deck tasks that may benefit from user centered analysis. The approach will hopefully provide a systematic method of studying an issue that has heretofore eluded objective analysis.

3 Chapter 3: Survey on Cockpit Automation

This chapter discusses the development of the survey on cockpit automation as well as its findings. First, the Boeing flight path management system is reviewed briefly to illustrate the components and generic structure of such systems. Next, the specific purposes of the survey are stated. The survey was primarily designed to assess the general and specific needs and preferences of pilots who have experience on currently available flight path management systems. Following this, the structure of the survey is overviewed and results of the survey are presented. (A sample survey is included in Appendix A.) Finally, recommendations and conclusions are made upon the basis of these findings.

3.1 Flight Path Management System Overview

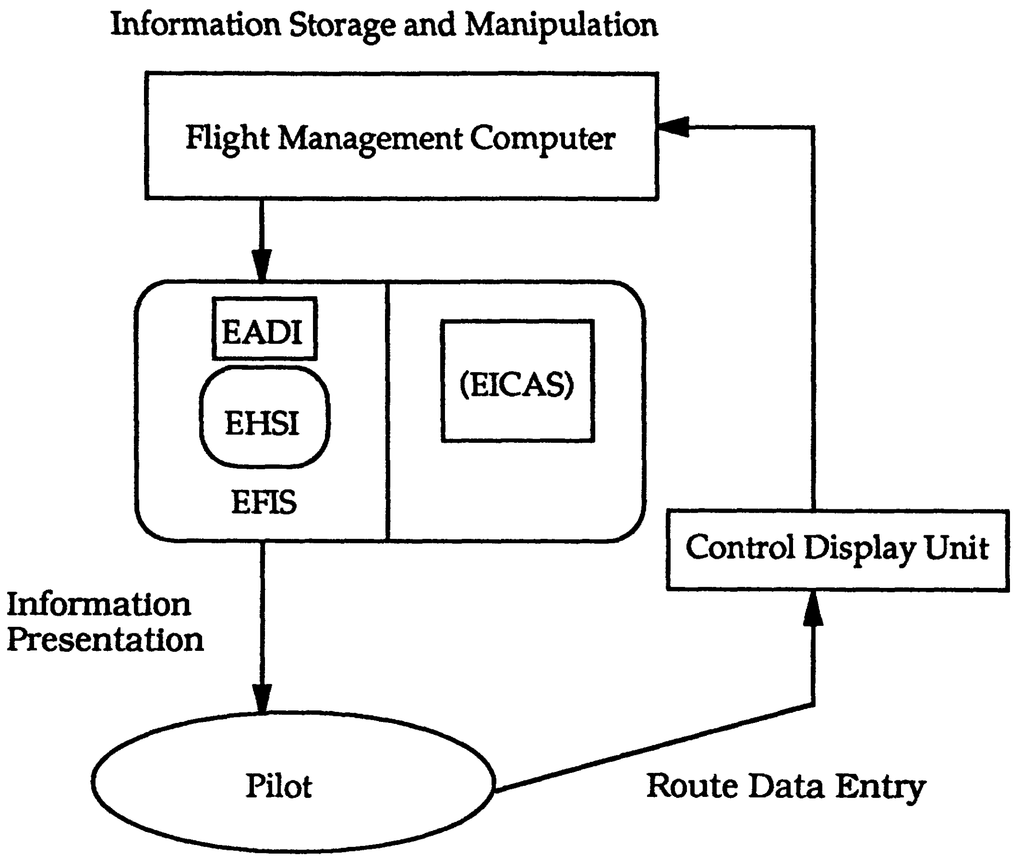
A schematic diagram of the flight path management system is shown in Figure 3.1. As indicated, the pilot enters route data and other information into the FMC via the CDU. This step takes place pre-flight during ground operations. The FMC stores and manages this information all through the flight. It obtains real time data, such as current winds and temperature, from other on-board computers and incorporates this data into its calculations of statistics such as fuel burn and estimated times of arrival. The pilot can access information from the FMC via the Electronic Flight Instrumentation System (EFIS) which consists of an Electronic Horizontal Situation Indicator (EHSI) and an

Figure 3.1. Schematic Diagram of the Flight Path Management System

The pilot uses the CDU as an interface to the FMC. The FMC calculates and stores information, displaying it to the pilot through the EFIS.

Definition of Terms

EFIS: Electronic Flight Instrumentation System
EHSI: Electronic Horizontal Situation Indicator
EADI: Electronic Attitude Director Indicator
EICAS: Engine Indication and Crew Alerting System



Electronic Attitude Director Indicator (EADI). The EADI is similar in form to traditional attitude director indicators. The electronic presentation of engine data through the Engine Indication and Crew Alerting System (EICAS) shown in Figure 3.1 is not present on all EFIS-equipped aircraft.

As seen in Figure 3.2, the EHSI is much more versatile than traditional horizontal situation indicators. It has four basic display modes that the pilot can select from: Plan, Map, VOR and ILS. Of these modes, the VOR and ILS are traditional in format, but Map mode and Plan mode are not. The Map mode, illustrated in detail in Figure 3.2, offers a graphical presentation of the aircraft's route and progress along it. The Plan mode aids in route planning and offers a similar but static "north-up" display of the entire active route. In the Map mode, which is sometimes known as the "moving map", the path moves in relation to a fixed aircraft symbol so that it appears that the aircraft is moving along the route. This is a graphical, inside-out (pilot's eye view), of the route. Navigational aids, weather, and route information are all presented pictorially.

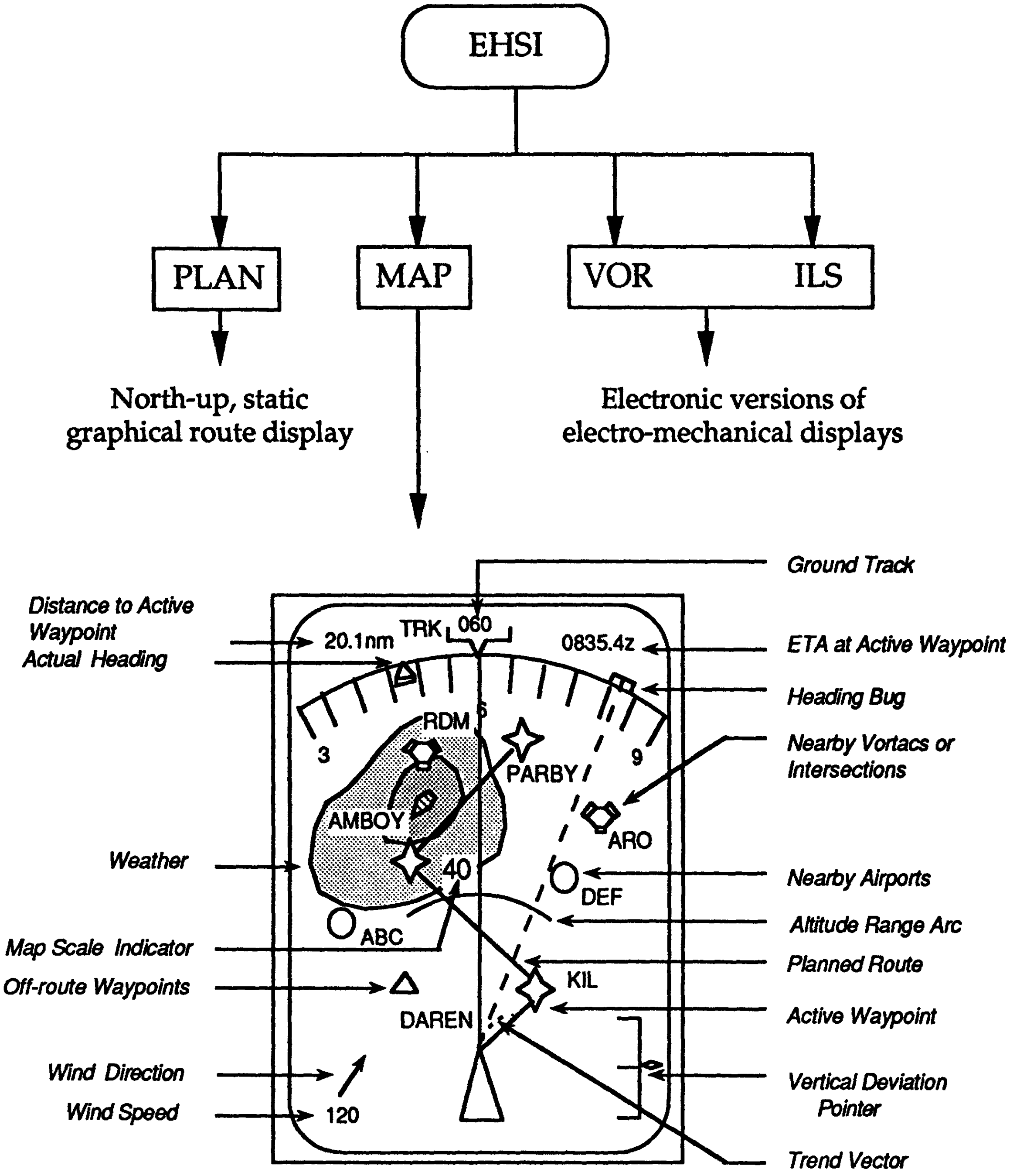
3.2 Survey Goals

In accordance with the user centered methodology, the survey's primary goal was to assess the needs and preferences of an existing population of flight path management system users. These needs and preferences were evaluated with regard to the four systems listed below:

(1) the flight path management system overall
(2) EHSI Modes
(3) the Map mode display
(4) the flight path management system as related to the clearance amendment process

Figure 3.2. Electronic Horizontal Situation Indicator Modes

The four basic modes of the EHSI are Plan mode, Map mode, VOR mode, and ILS mode. Each discrete item of information on the moving map mode is shown here in detail.



In chosing these systems, two hypotheses were made which the results were expected to validate. First, pilots were expected to by and large prefer to fly automated aircraft. Second, in selecting the map mode for detailed analysis it was expected that this display would be the mode of choice for the majority of pilots. Although these hypotheses were formulated prior to the survey itself, every effort was made to phrase the questions neutrally in order to prevent experimenter expectations from biasing the results.

3.3 Survey Structure

A prerequisite to the analysis of needs is an understanding of background characteristics of the population. Therefore, the first section of the survey obtained information such as age, extent of transport aircraft experience, experience with computers, and educational background. These factors may contribute to the acceptance of and general attitudes toward aircraft automation. The second section asked pilots for an overall evaluation of the flight management computer which they currently operate. The third survey section focused on the information presented on the EHSI in each of the four display modes described above and in the map mode in particular. Using a technique similar to that of Lee (1988), a set of diagrams of a generic moving map display with each discrete piece of information tagged (see Figure 3.2) were presented. Pilots evaluated the relative need for each information element on the diagram for each of six phases of flight. (A generic display was chosen so that the survey would be applicable to a wider pool of pilots.) The fourth section dealt with ATC-initiated clearance amendments. It was anticipated that clearance amendments given in already high workload periods, i.e. departure and arrival, would greatly add to the workload, so this section was directed at the frequency of occurrence of such amendments and the workload associated with their execution. The majority of questions in the survey were forced choice but many free-response items were also included.

3.4 Survey Results

The survey's results are presented in the same order as the survey itself. First, group characteristics of the respondents are examined. On the basis of these characteristics, it was decided to separate the population into four groups by flight experience with the FMC. It was seen that pilot's do prefer to fly automated aircraft, validating the first of our hypotheses. An analysis of the use of EHSI modes also bears out our second hypothesis that the moving map mode is commonly used. A closer look at the need for information on the map display is then presented, employing various measures of information load. Relative differences in workload between FMC equipped aircraft and non-FMC equipped aircraft were also assessed. The use of the FMC for ATC clearance amendments is then addressed. Finally, pilot comments on the system are discussed.

3.4.1 Group Characteristics

The survey was distributed to 250 pilots of Boeing 737-300, 767 and 747-400 aircraft through United Airlines.[1] Of these, 46 were returned and analyzed. The level of automation of the three types of aircraft are quite similar in terms of the operation of the FMC, the only significant difference being the presentation of engine instruments. In fact, the survey data analysis showed

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[1] The 747-400 pilots had simulator experience only.

that the single significant difference in the way that these groups responded to the questions could be explained by the differences in the types of routes that are assigned to the three types of aircraft, rather than by fundamental differences in their use of the FMC.

The 46 respondents were divided into four groups on the basis of their flight experience with the FMC. This criteria was chosen because it was quantifiable and because it was expected that attitudes toward the system would change with expertise and familiarity. Table 3.1 shows the group characteristics for each of these quartiles.

The groups did not vary significantly on any background criteria other than their experience with the FMC. It appears from Table 3.1 that pilots with more FMC experience are older and this would in fact confirm company policies of training the most senior pilots for these modern aircraft. This trend is not significant in our sample, however. The number of total flight hours experience for each of the groups did not differ significantly as well.

3.4.2 *Attitudes Toward Automation*

Figure 3.3 confirms our first hypothesis (see Section 3.2) about acceptance of automation. The majority of pilots (82%) prefer to fly automated aircraft. Pilots were also asked to briefly explain their preference; these responses are listed in Table 3.2. There are clearly many issues involved with pilot attitudes toward automation.

Three of the issues noted in Table 3.2 were examined in further detail: capabilities, ease, and workload. Pilots were uniformly quite satisfied with the capabilities, power, and flexibility of the flight path management system.

Figure 3.3. Acceptance of Automation

Overall, pilots expressed a decided preference for the automated flight path management system, although there were complaints of boredom during long flights. Experience with the FMC was not a significant factor in this preference.

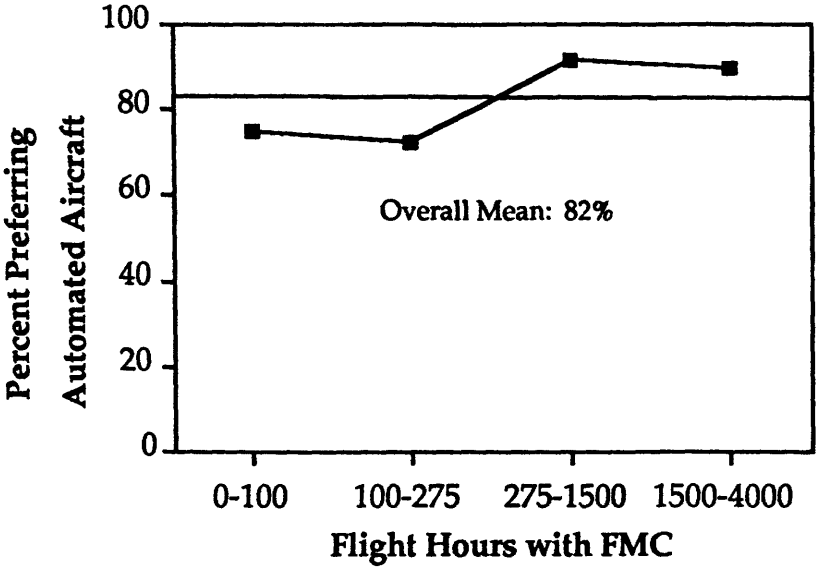

Figure 3.4. Flight Path Management System Ease of Use

Experience with the FMC significantly affected pilots ratings for ease of use. Pilots with more than 275 flight hours of experience rated the system significantly easier to use than those with fewer hours.

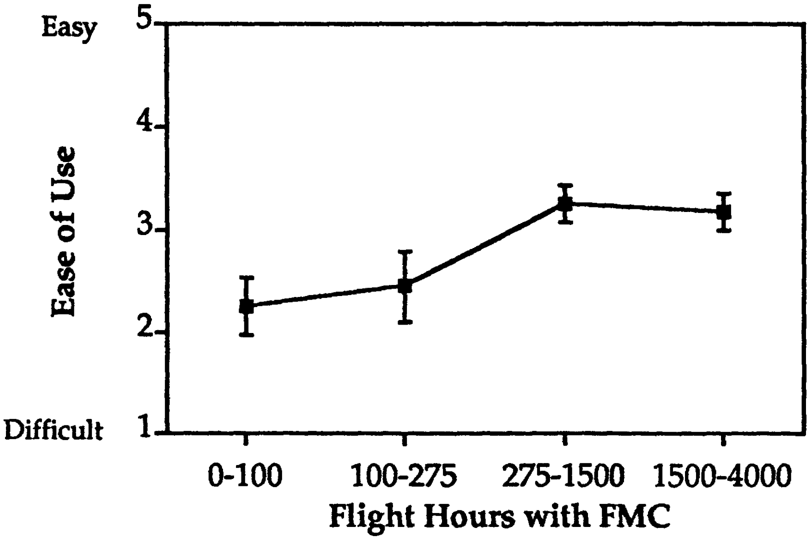

Table 3.1

Group	Flight Hours with FMC	N	Age (yrs) (mean ± S.D.)	Total Flight Hours (mean ± S.D.)	Flight Hours with FMC (mean ± S.D.)
1	0-100	12	43 ± 7	4170 ± 3760	50 ± 36
2	101-275	11	46 ± 7	8650 ± 5350	220 ± 40
3	276-1500	12	47 ± 6	7030 ± 4670	790 ± 400
4	1501-4000	11	50 ± 5	12000 ± 4600	2310 ± 650

Table 3.2

Prefer Aircraft with FMC	Prefer Aircraft without FMC
Capabilities, Precision and Efficiency of FMC	More job satisfaction flying old technology
Ease of operation	Inexperience with system (more difficult to operate)
Lower workload	Higher workload at critical times
Prefer the (larger) amount of information available (cluttered displays)	Too much information presented
Prefer the visual presentation of information (Better awareness; especially with Map display)	Prefer raw information
Interesting to fly modern equipment	Boring on long flights
Safety	Too much head down time (disturbs instrument scan)
Choice of automation levels	Prefer to have a flight engineer

The average rating was 2.37 on a five point scale where 1 indicated "very satisfied" and 5 indicated "very unsatisfied." Ease of use, however, varied significantly with experience with the FMC, as seen in Figure 3.4. Pilots with fewer than 275 hours of experience with the FMC rated it significantly more difficult to use than those with larger amounts of experience ($p \ll 0.01$). The change in workload between aircraft with an FMC and those without was rated by pilots separately for each of six phases of flight.[2] These ratings are plotted in Figure 3.5. On the whole, workload is reduced by the FMC. This effect is most noticeable during the cruise phase of flight. The amount of workload is not reduced during ground operations since more planning is necessary at this stage in order to use the automation system.

3.4.3 Use of EHSI Modes

The use of EHSI modes was evaluated by presenting pilots with a table. The four modes (Map, Plan, VOR, ILS) were listed in separate rows, and each column was one of the six phases of flight (see Appendix A). Pilots indicated whether they used a particular mode (more than 10% of the time) in a particular phase of flight by checking the appropriate cell. These responses were distributed as shown in Figure 3.6. These plots are not an indication of the actual amount of time spent on a particular mode during the indicated phases of flight; they are only the percentage of pilots that specified that they used that mode at all during that phase.

It is clear from Figure 3.6 that almost all pilots use the map mode during all phases of flight, confirming our second hypothesis (see Section 3.2). The plan mode is used most often during ground operations, as expected, but it is also used significantly during cruise. The ILS and VOR modes are used by a relatively small portion of pilots. It should be noted that use of these two

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[2] The six phases of flight were defined within the survey as:
1) Ground Operations: Dispatch, Pre-Start, Taxi
2) Departure: Takeoff, Lift-off to Top of Climb
3) Cruise
4) Descent: Top of Descent to Approach Control Contact
5) Terminal Area: Approach Control Contact to Final Approach Fix
6) Final Approach: Final Approach Fix to Runway Threshold

Figure 3.5. Automation-related Workload Changes

Ratings of flight deck workload of an FMC equipped aircraft relative to an aircraft without an FMC are plotted. The workload is significantly reduced by the FMC in all phases other than ground operations. [Ground Operations (GND), Departure (DEP), Cruise (CRZ), Descent (DES), Terminal Area (TA), and Final Approach (FIN)]

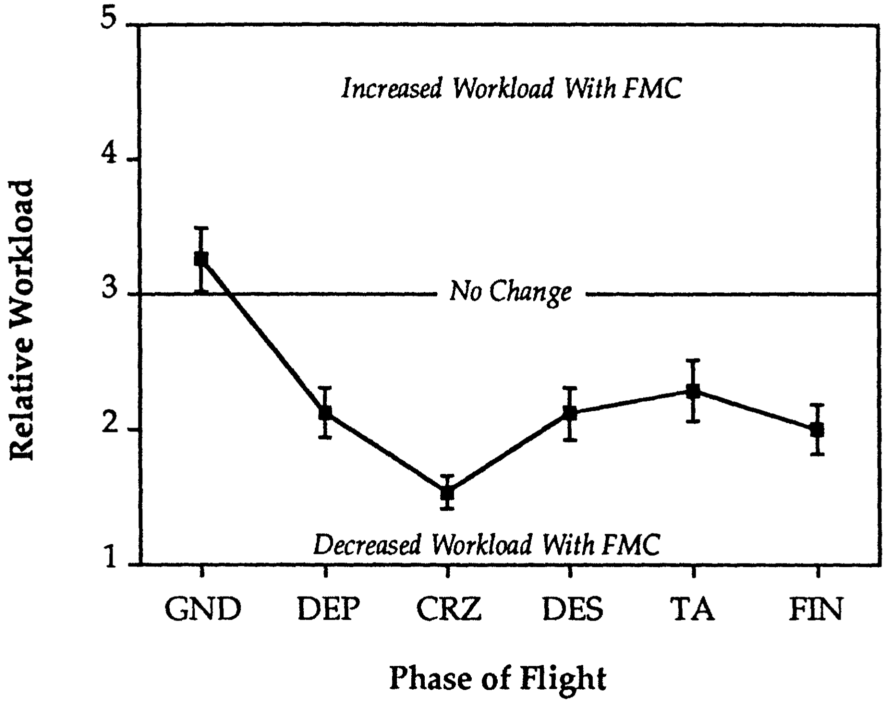
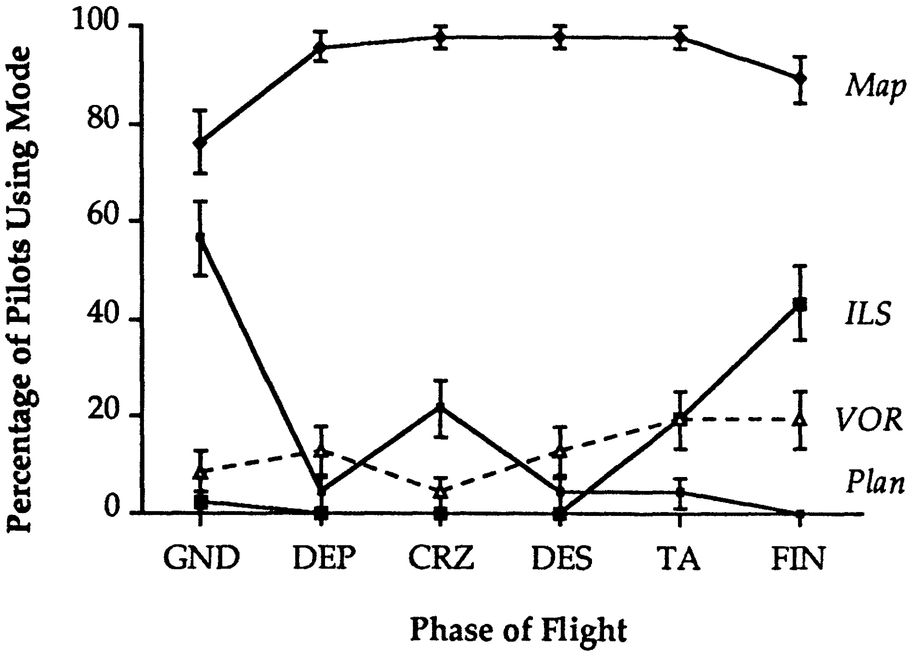


Figure 3.6. Use of EHSI Modes

The percentage of pilots using each mode is plotted by phase of flight. Their favorite is clearly the map mode.



modes is not required, as all of the raw flight path deviation data are available on either the the map mode or the attitude indicator. There is a moderate correlation between use of the ILS and VOR modes; this is to be expected if there is a subset of pilots that prefers to fly with traditional display formats.

3.4.4 Use of Information from the Moving Map Display

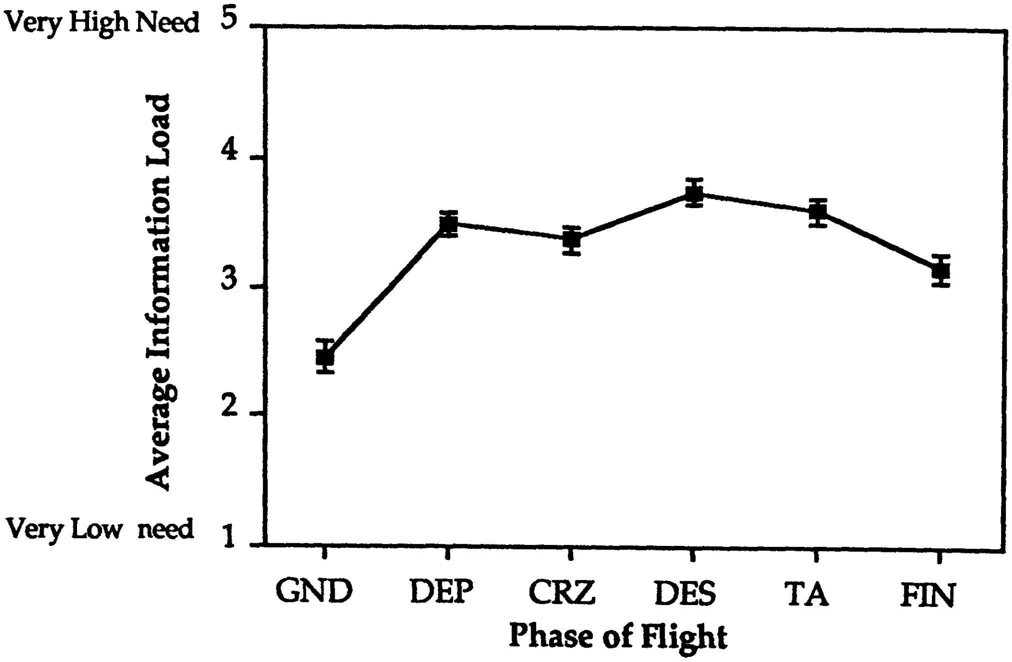
As noted in Section 3.3, the use of information from the map display was assessed through a series of diagrams of the display with each discrete item tagged. Six diagrams were presented, one for each phase of flight. The need for each item of information (during the indicated phase of flight) was rated on a scale from 1 (very low need) to 5 (very high need). The data from these diagrams were analyzed in two ways. First, two methods of computing a measure of information load for each flight phase were evaluated. Secondly, specific information elements were examined upon the basis of their average importance across all phases of flight.

Information Load

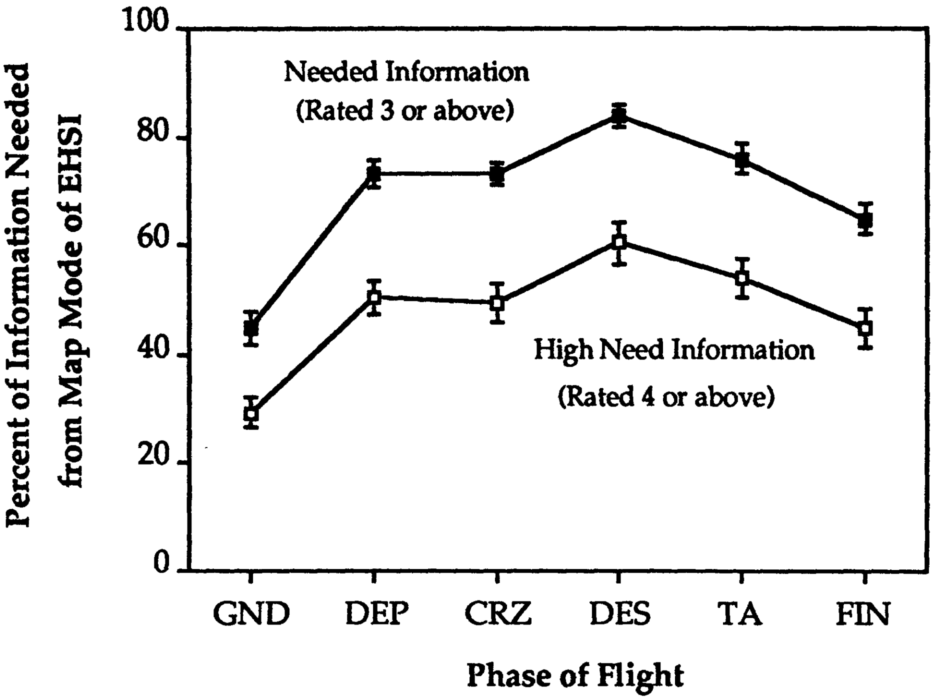
The first measure of information load from the map display is simply the average of the ratings across all items in each phase of flight. This measure is plotted in Figure 3.7a. The information load is lowest for the ground operations phase and highest for the descent phase. Information load does not differ significantly for the departure, cruise and terminal area phases, although the trend is that the load in the terminal area is higher than the load in departure and cruise. The load during final approach is lower than all other phases, other than ground operations.

Figure 3.7. Information Load by Phase of Flight

a) An average information load was calculated by averaging the ratings of need for all seventeen discrete items on the moving map display.



b) Not all items of information are actually shown during all phases of flight. To eliminate the effect of inconsistencies in dealing with this issue, the number of items actually rated as "needed" was tabulated. Slight differences were found in the significance levels of the two plots shown below.



A second measure of information load was developed to eliminate a slight problem with the first measure. The problem arose from the generic map displays. Technically, certain information elements do not appear in all phases, but our diagrams did not indicate this. Pilots dealt with this matter inconsistently; some gave low need ratings to items that were in fact not present on the displays, while others did not rate them. The second measure of information load thus set a criterion level. The number of items rated above this level were tabulated and divided by the total number of items on each diagram, yielding a percentage information used from the map display. This measure is plotted for two criteria levels in Figure 3.7b. The implications of this measure are generally the same as those of the first, although the differences are somewhat more obvious. Slight differences were found in the levels of difference with the two criteria.

Importance of Information Elements

When averaged across the phases of flight, the most important pieces of information were (in order): weather, active waypoint, planned route and commanded heading. The next level of importance was given to the actual heading, the scale indicator, wind speed and wind direction. The least important items were the off-route waypoints, vertical deviation pointer and trend vector. Although these items had low ratings overall, it should be noted that they may have had high ratings for certain phases of flight.

3.4.5 Use of the FMC for ATC Initiated Clearance Amendments

Arrivals and departures are the busiest phases of flight for pilots as there are several tasks that require their attention. Procedures for arrival and departure are typically quite complex (requiring head down time reading charts) and the pilot must also be aware of aircraft configuration changes and traffic. Adding to all these factors is time pressure; arrivals and departures are conducted as quickly as possible to increase the air traffic flow through airports. It is easy to believe that reprogramming the FMC for such clearance amendments would exacerbate the situation.

This expectation was confirmed by pilot comments in the survey. One pilot, for example, gave two ratings for the question on the change in workload with and without the FMC for the terminal area. He gave a "decreased workload" rating labeled "when programmed ahead of time" and an "increased workload" rating labeled "with last minute changes." Another pilot in fact wrote "The FMC reduces the cruise workload, where you have lots of time anyhow. On departures and arrival it increases the workload and creates more 'heads inside' time." Anticipating this problem, United Airlines actually prohibits the reprogramming of the FMC at altitudes below 10,000 feet. Delta Airlines makes a similar recommendation to its pilots.

Frequency and Workload of ATC Clearance Amendments

Two questions on the survey specifically addressed the frequency of this problem. One asked pilots to estimate the frequency of clearance amendments during arrival, the other during departure. The distribution of these responses for both these situations is given in Figure 3.8. These values are distributed around an estimate of 20-30%, indicating that a significant fraction of arrivals and departures have clearance amendments.

The workload under the circumstances of a clearance amendment in the terminal area was rated separately. The exact wording of the question was:

How often do you find that entering a clearance amendment into the CDU while in the terminal area is a high workload situation? The responses, shown in Figure 3.9, indicate that there is cause for concern with clearance amendments issued in the terminal area.

Pilot Evaluation of ATC Clearances

A series of questions were aimed at understanding what factors pilots consider when evaluating ATC clearances or initiating clearances. The issues that arose are listed below:

1) Weather/Safety
2) Passenger comfort/ride quality
3) Fuel economy
4) Aircraft performance and capability (weight constraints)
5) Effect on arrival times
6) Completeness/Correctness of the clearance

On a free-response question asking which type of clearance information was most likely to be misunderstood, pilots raised a number of issues such as the clarity and speed of the controller's speech, the length of the message, and their expectations about the clearance. Several mentioned that names of fixes are sometimes misunderstood, particularly if the area is unfamiliar. Numbers, such as aircraft identifiers, or altitude restrictions were often confused. Also, it is difficult to keep track of the order of changes with lengthy clearances. On the whole, however, pilots indicated that they rejected only 5-10% percent of clearances. Pilots also reported that they were unable to execute clearances that they had accepted about 5-10% of the time.

Figure 3.8. Estimated Frequency of Clearance Amendments

Pilots were asked to approximate on what percent of their arrivals and departures they received at least one clearance amendment. Responses indicate that this situation occurs relatively frequently.

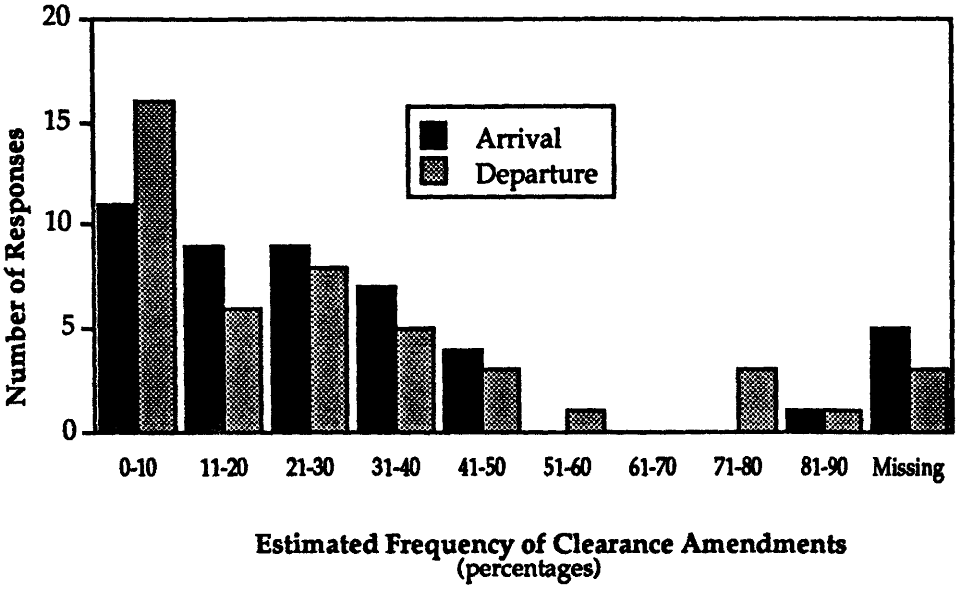
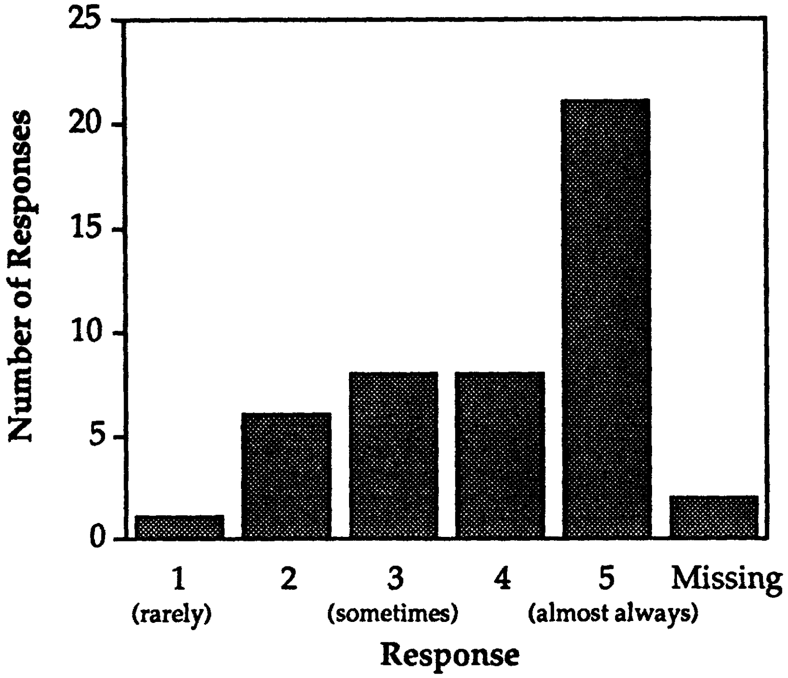


Figure 3.9. Workload Associated with Clearance Amendments in the Terminal Area

Pilots were asked to indicate how often clearance amendments in the terminal area were high workload situations. Responses show that such amendments often cause high workload.



Pilot Evaluation of Proposed Methods of Clearance Amendment Delivery

The two methods of clearance amendment delivery described in Section 1.4 were also proposed within the survey in order to obtain pilot reactions and suggestions. Pilots were asked to assess the desirability of these methods, and to note any concerns or problems that they could foresee. Overall, the graphical method was preferred to the textual method, but there were advantages and disadvantages for both. These points are discussed below.

Textual Clearance Delivery

On the positive side of text delivery, pilots pointed out that this method would require them to verify and review the entire clearance prior to entering it. They also preferred the redundancy of the text method, saying that it would bring the pilot into the loop more. However, there were several concerns with this process as well. Verifiability, head down time during high workload periods, and the high workload anticipated for understanding a written clearance were the primary issues. The necessity for appropriate alerting procedures was also pointed out. Secondary issues with the text method concerned poor wording and long amendments (display space is currently limited). There was also some concern about information loss since the current system has a 'party line' character whereby pilots can form a more complete mental picture of the traffic around themselves.

Graphical Clearance Delivery

The graphical delivery method generally received a more favorable response. Lower workload and a better awareness of the route change, were seen as the primary advantages for this method. As one pilot stated, this method "seems simpler and more descriptive of the change to be made." Verifiability and removal of the pilot from the loop were the big concerns. One pilot doubted that "the FAA will ever accept it. How do we as pilots confirm that this clearance is really for us?" Other issues that were brought up included a desire for both text and voice backup. Some pilots also noted that this method was more suitable for lateral navigation, and that there would be a problem displaying clearance amendments that affect route segments beyond the scale range of the map display (320 nautical miles).

3.4.6 Miscellaneous Pilot Comments

Throughout the survey, pilots mentioned the desire for some basic improvements in the FMC system. The first and foremost request was for a faster computer. Secondly, some pilots were in favor of a head up display presentation of flight parameters. A more flexible CDU, allowing voice or touch screen input, was also requested. One proposed the idea of a color coded CDU screen. There was also a desire for more easily accessible information about the last waypoint crossed. Finally, some pilots suggested that the location of the CDU be changed for better access to the keyboard. The use of a standard qwerty keyboard was also brought up.

3.5 Survey Conclusions

The survey on cockpit automation confirmed many expectations about the use of the flight path management system. First, pilots do prefer to fly with automation systems, but there are several issues to consider when evaluating these systems. Second, the moving map display of the EHSI is used by most pilots for all phases of flight. The information load from this display varies considerably across these phases. Finally, ATC clearance amendments given in high workload phases of flight are seen to greatly aggravate such situations. This problem is addressed further by the experimental simulation that is discussed in Chapters 4 and 5.

4 Chapter Four: Development of Experiment

The second phase of our study consisted of developing a simulation of the current Boeing 757/767 EFIS and CDU, and using this apparatus to experimentally assess quantitative and qualitative pilot responses to the three clearance amendment delivery methods discussed in Chapter 1. This chapter will concentrate on the development and design of our experiment. There were three primary objectives for this experiment. First, a quantitative analysis of the effect of the different modes of communication was desired. Second, the benefits and drawbacks of each mode needed to be assessed, taking into account their effect on pilot workload. The NASA Task Load Index was used to assess workload (Hart and Staveland, in press). Finally, valuable pilot opinions on the acceptability and ramifications of each mode were desired. Our time-based model of the task is presented below and each mode is compared in terms of this model. The methodology is then presented, including a description of the apparatus, software, task and procedure. Finally, the experimental design is detailed.

4.1 A Breakdown of the Clearance Amendment Process

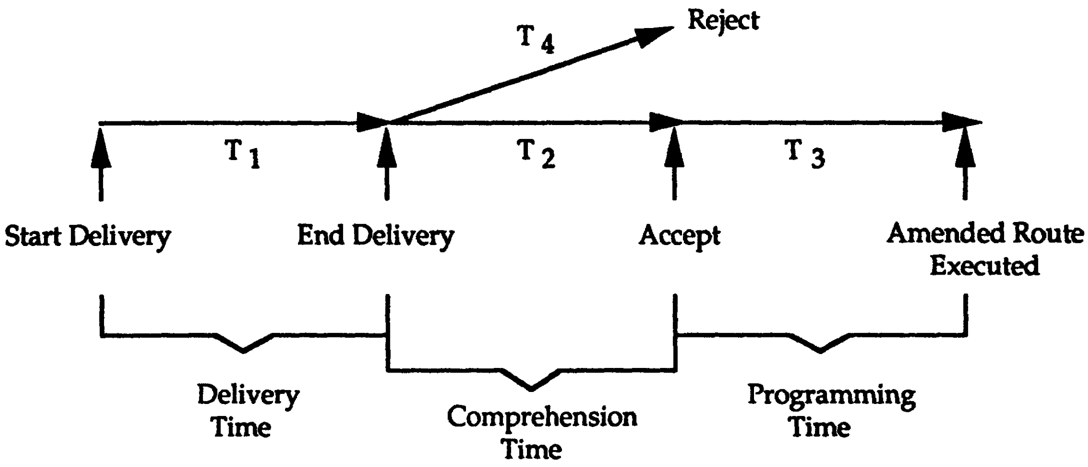
The psychological literature presented in Section 2.3 proposed theories about the mental processes the pilots use for navigation. However, this literature does not directly lead to a model of the clearance amendment process which could be used to quantitatively analyze the differences arising from each mode of communication. A time-based breakdown of the communication task was chosen for this study. This variable was employed since it is generally accepted that the amount of mental processing required for a task is reflected by the amount of time it takes to accomplish the task. Although some lower level mental processes have been modelled with parallel processing, higher level functioning is primarily serial. In terms of the route amendment task, this simply means that it should take longer for a pilot to understand and execute a complicated clearance than to understand and execute a simple clearance.

Based upon current voice communication procedures, the clearance amendment process has been modelled in time steps as shown in Figure 4.1. The delivery time is the time the controller actually spends reading the amendment to the pilot. During this period, the pilot begins to comprehend the change, but he is mainly occupied with the task of copying the new clearance into written notes so that he has a more permanent record of it. After the initial delivery, the pilot is expected to read the clearance back to the controller. Clarifications, if necessary, are made at this point. Once the readback is completed correctly, the pilot has implicitly indicated that he will abide by the amendment to his routing.

The actual amount of time the pilot spends comprehending the amendment begins at the start of the delivery and ends at the beginning of the correct readback. Our measure of comprehension time, however, begins when the controller has completed his initial delivery, and ends when the readback is completed correctly. In using this measure, it has been assumed that, to a first order, the pilot readback time is equal to the controller delivery time (see Figure 4.2). This measure was used since, in actual practice, the readback often occurs in pieces, with clarification messages interspersed between portions of the correct readback. When this occurs, it is much easier to identify the end of clarifications than to identify the time at which the entire

Figure 4.1: A Time Analysis of the Clearance Amendment Process

Each step in the current procedures for the clearance amendment process takes a finite amount of time to complete. We use this timeline as the generic model for our description of the effects of the three communication methods.

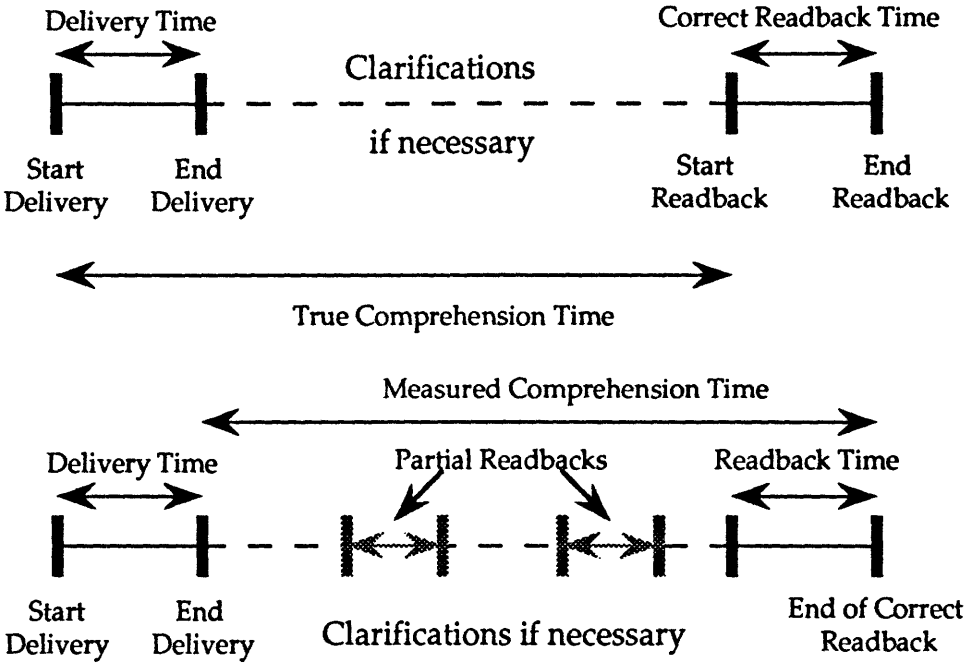


Total time to complete an acceptable amendment: $T_1 + T_2 + T_3$

Total time to complete an unacceptable amendment: $T_1 + T_4$

Figure 4.2: Explanation of Comprehension Time Measurement.

To a first order, the pilot readback time is presumed to approximate the controller delivery time. So, our measured comprehension time is approximately the same as the true time.



amendment is correctly understood. It is also assumed that the sum of the partial readback times is approximately equivalent to the time to readback the clearance all at once.

Once the changes have been accepted, pilots of automated aircraft have the option of programming these changes into the CDU (so that the autopilot will fly the new routing), or flying the amended route manually. For the purposes of our experiment, pilots were asked to program the CDU for all amendments.[3] Programming time was measured from the time after the clearance was accepted to the time when all necessary changes had been executed.

The time line of events discussed above applies to acceptable clearances. In the event of a clearance amendment that was unacceptable, a time to reject was coded. This time was measured from the end of the controller delivery to the beginning of the pilot transmission in which he identified the problem with the clearance. Amendments might be unacceptable for a number of reasons. For example, if an amendment were to place their path through an area of thunderstorm activity, pilots would find it unacceptable and request a different routing.

4.2 Comparison of Modes of Communication

Each mode of communication clearly requires the pilot to allocate his mental resources differently. This re-allocation depends upon the specific procedures

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[3] It is recognized, though, that in actual practice, it is recommended (or required) by some airlines that the CDU *not* be re-programmed under the high workload conditions associated with low altitudes (for example, below 10000 feet).

required for these modes. In the verbal mode, subjects were asked to use standard methods of communication. For the text mode, the text of the message was displayed on the CDU screen when it was called up by the pilot (see Figure 4.3a). This text was written out with only minor, standard, abbreviations.[4] The identifier was given, followed by the changes to the route. For example, the clearance might read: "Iris[5] 354, after Drako intersection, RNAV direct Cager intersection, direct Deepe intersection. Cross Deepe at 9000 ft., 250 kts." In the graphical mode, the text of the amendment appeared exactly as with the text mode, and the route modifications were also automatically entered, appearing on the EHSI as shown in Figure 4.3b. The pilot has only to ascertain the acceptability of the clearance and execute the changes, without any programming for this mode.

The verbal communication model can now be applied to the other two modes of communication. Figures 4.4 illustrates how the model applies for acceptable clearances. Figure 4.5 applies the model to unacceptable clearances. Note that for the text and graphical cases, the "readback" procedure was automated as well as the delivery. That is, pilots were asked to hit a "wilco" (or "will comply") key, rather than to read the text of the clearance to the controller. The comprehension time for text and graphical clearances, therefore, was measured as the time between when the clearance was called up, and when pilots indicated they would comply with it. This measure can be compared directly

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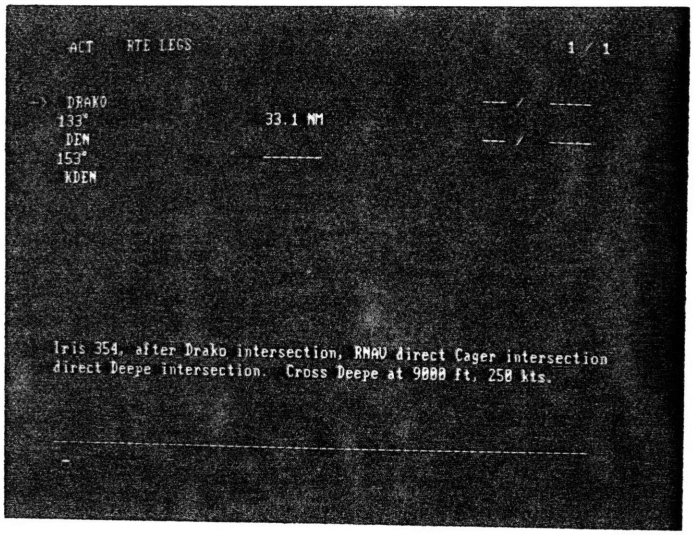
[4] The abbreviations used were: 'V' for Victor, 'ft' for feet, 'kts' for knots, 'VOR' for a particular type of navigational aid, and 'RNAV' for inertial navigation.

[5] A fictional airline name was used, as pilots were highly trained to hear only their own airline identifiers.

Figure 4.3. Modes of Clearance Amendment Delivery

a) Text Mode. The clearance amendment appears as a written message on the CDU screen as shown below.



```
   ACT    RTE LEGS                                         1 / 1

-> DRAKO                                              --- /  -----
  133°                    33.1 NM
   DEN                                                --- /  -----
  153°                    -------
   KDEN



  Iris 354, after Drako intersection, RNAV direct Cager intersection
  direct Deepe intersection.  Cross Deepe at 9000 ft, 250 kts.

  ------------------------------------------------------------------
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b) Graphical Mode. The clearance appears as a text message and as a graphical message. The graphical information is a dashed line on the map display which represents the proposed routing.

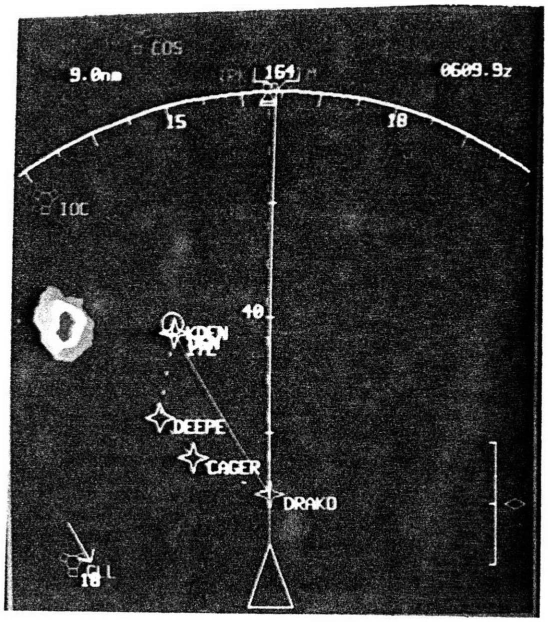
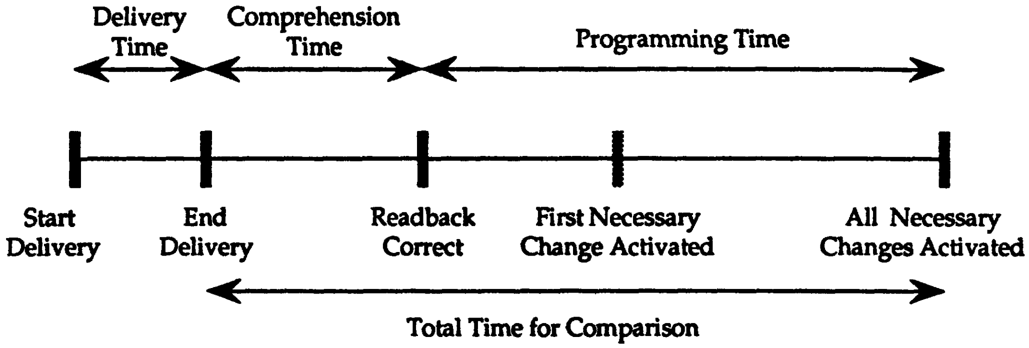
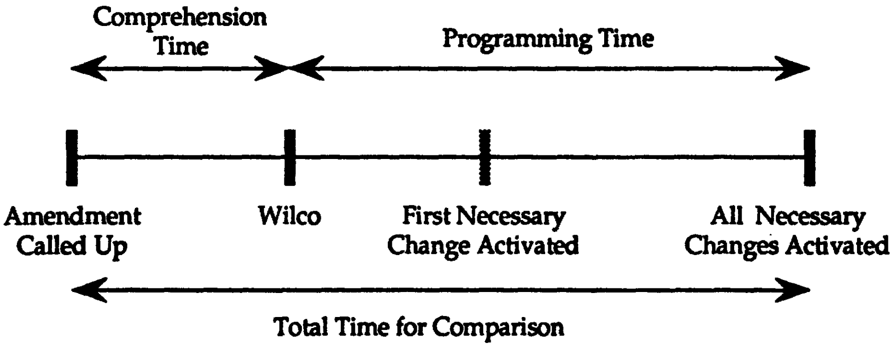


Figure 4.4 Time line for clearance amendment process in each mode of communication for acceptable clearances. Shaded bars represent optional actions.

a) Verbal Mode



b) Textual Mode



c) Graphical Mode

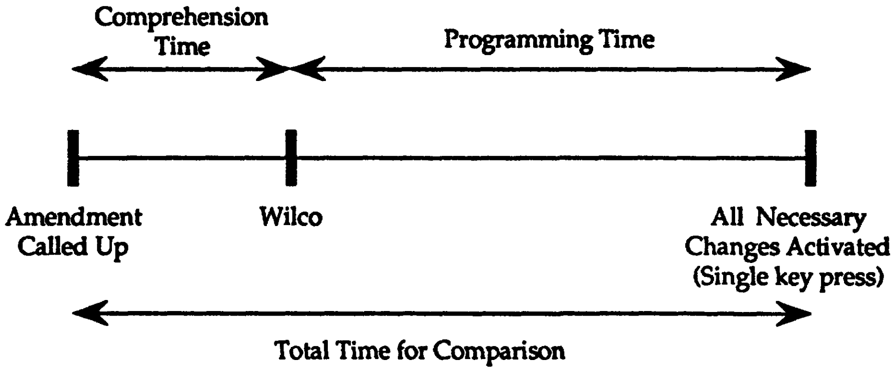
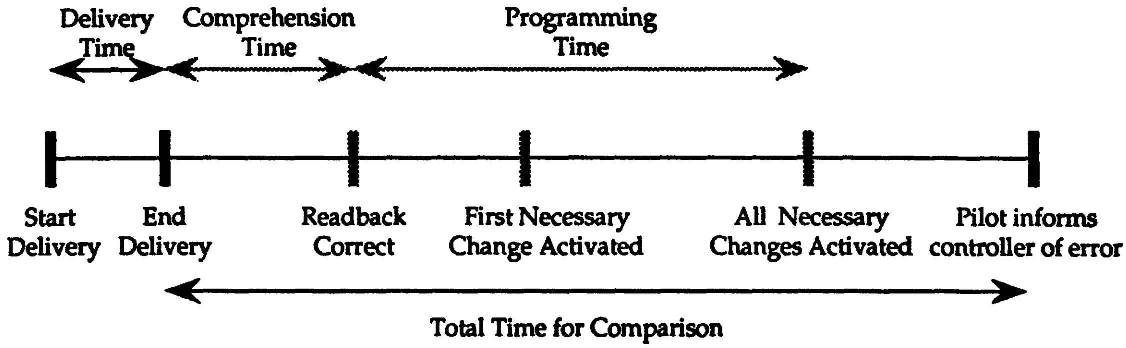
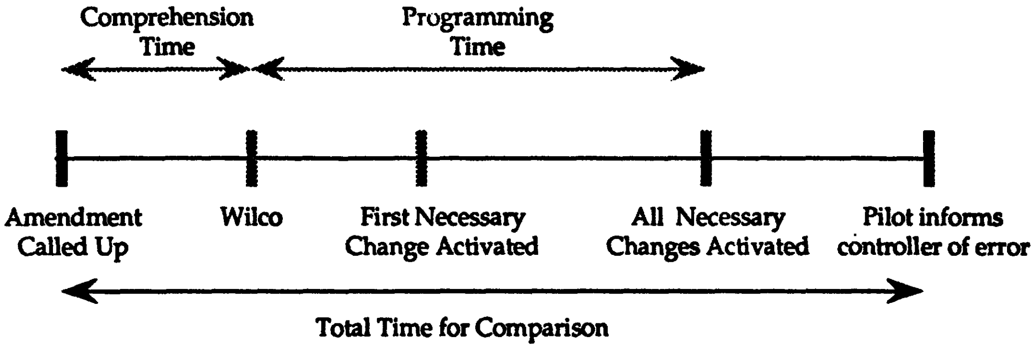


Figure 4.5 Time line for clearance amendment process in each mode of communication for unacceptable clearances. Shaded bars and arrows represent optional actions.

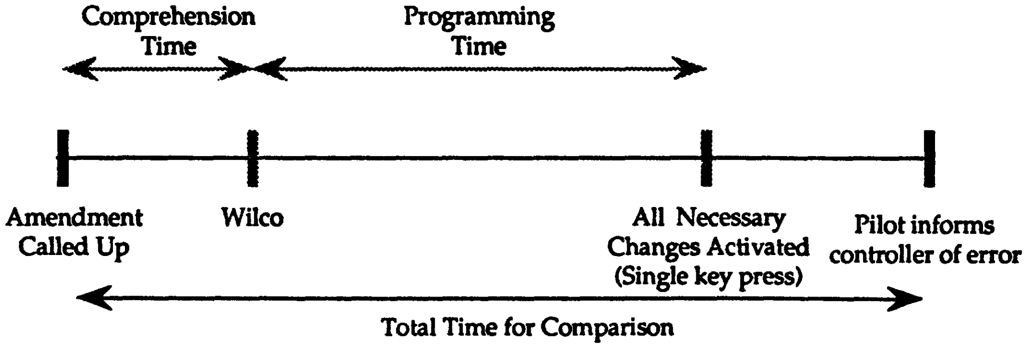
a) Verbal Mode



b) Textual Mode



c) Graphical Mode



with the verbal measure, since a correct readback indicates essentially the same action: the intent to comply with the new routing. In the graphical mode, the amended route is automatically programmed into the CDU, so that a single execute activates all modifications. In the event that the pilot forgot to hit the "wilco" key, the first action he took on the CDU that indicated he had begun the programming was taken as an indication that he had accepted the clearance.

Each mode of communication has strengths and weaknesses. The best mode for a task is likely to depend upon the information being transmitted. Each mode also affects the pilot's mental processes differently. These effects are summarized in Table 4.1.[6] Note that for the verbal and text modes, pilots are responsible for converting a procedural or literal description of the amendment into an image of the route changes. In the graphical mode, however, they are presented directly with the image.

The characteristics listed here are delivery time, decay time, and type of processing required. Each of these aspects is assessed from the pilot's point of view. Delivery time is finite in the verbal case since the pilot must listen to the controller for a length of time. In the text and graphical mode, the pilot simply calls up the amendment (when it is available) and all the information appears at once. Voice communications also have a decay time since the information is initially loaded into short-term memory which fades rapidly. As mentioned earlier, the usual procedure is to transcribe the

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[6] Some of these characteristics could be varied by the specifics of the procedures involved. This table evaluates them on the basis of the procedures employed in our simulation.

Table 4.1

Summary of Mode Characteristics

Mode	Mental Representation	Characteristics
Verbal current procedures	literal → image	finite delivery time rapid decay of information serial processing for comprehension
Textual text of amendment displayed on CDU	literal → image	instant delivery no decay of information serial processing for comprehension
Graphical text of amendment displayed on CDU and route modifications are loaded automatically	image	instant delivery pilot controls decay time parallel processing for comprehension

clearance as the controller reads it. With textual delivery, however, the text of the message could be displayed at the pilot's discretion, so it does not decay. The pilot controls the time for which the graphical amendment is displayed, since the graphical display is present until the modified route is activated (at which time the previous route is erased).

The major result expected from our experimental comparison is a primary effect of the mode of delivery on the total time to complete the amendment process. The total time, as seen in the figures above, is the sum of the delivery, comprehension, and programming times. It is also expected that the graphical mode will be easier to comprehend since it is more compatible with the internal representation and since pictorial information can be assessed at a glance (in parallel), while verbal and textual information must be processed serially. The textual clearances may also yield a faster comprehension time than verbal clearances, since they remove the need for many types of clarifications. Workload ratings should provide support for the graphical clearances for the same reasons given above. The effects of these modes on situational awareness, however, are unpredictable. Graphical clearances might improve awareness if they are used properly, but automatic reprogramming might also promote boredom and/or a false sense of security.

4.3 Methodology

In our experiment, professional airline pilots were asked to fly the simulation through nine scenarios, three in each mode of communication. The pilot had an EFIS, CDU and autopilot available to him. This equipment was sufficient to simulate flight in instrument weather conditions. The Air Traffic Control facility was set up in a nearby separate room. Communications were conducted via push-to-talk buttons and headsets which were connected through phone lines.

Each scenario was divided into two phases. The simulation always began with the pilot in the lower altitude airway structure in the terminal area of Denver's Stapleton airport. As the experiment progressed, the flight's clearance was amended several times and pilot performance was recorded. The results of this phase are discussed in this document. The second part of each scenario was the approach into Denver. A separate study concerning the delivery of windshear and microburst alerts during approach was conducted in this phase. The results of that study are in preparation by other authors.

4.3.1 *Subjects*

The subjects for this experiment were obtained through the approval of the Air Line Pilots Association. Six Boston area, professional Boeing 757/767 pilots participated without compensation in one five to six hour session. Further information about the subjects is presented in Section 5.1 which presents the data from a preliminary questionnaire that all subjects completed.

4.3.2 *Apparatus*

A relatively good fidelity simulation facility of the EFIS, CDU and autopilot head was developed by students at MIT within hardware and time limits. Only the features necessary to perform the necessary tasks were simulated. The system emulates the Boeing 757/767 EFIS and CDU as documented in the Operations Manual. When the manual was not specific enough pilots of the Boeing 757/767 were consulted. Nonetheless, some of the simulation's performance was based solely on our best estimates of the performance of the actual system. The cockpit room facilities are shown in Figure 4.6; each of the components is described below.

Electronic Flight Instrumentation System (EFIS)

A Silicon Graphics IRIS 2400 Turbo graphics workstation was used to simulate the EFIS. Our EFIS displayed the EADI, EHSI, and annunciations of autopilot settings (see Figures 4.7). In the upper left hand corner of the screen is the attitude indicator (detailed in Figure 4.7a). To its left is a speed indicator (knots of indicated air speed), and to its immediate right, a mean sea level altitude indicator. To the right of the altitude tape is a vertical speed indicator. This arrangement of displays is similar to that of the Boeing 747-400 aircraft. The

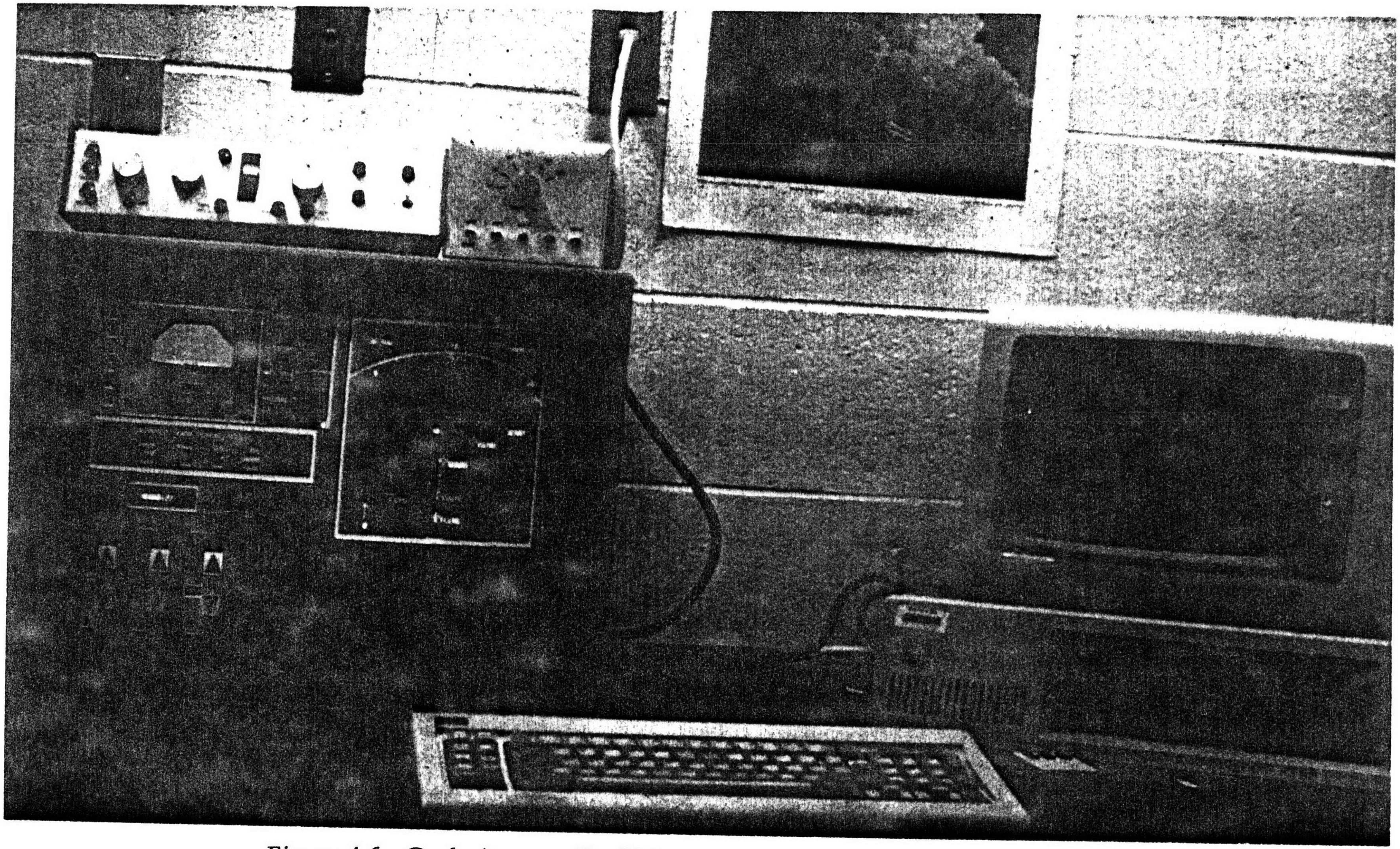


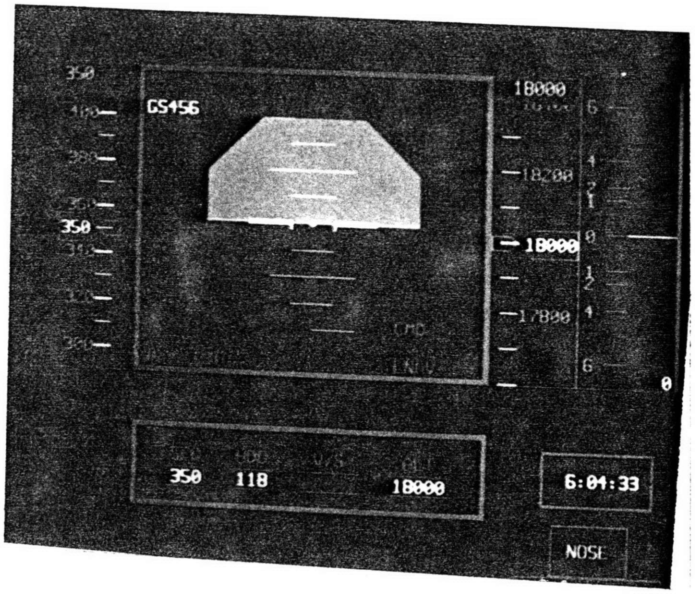
Figure 4.6. Cockpit room Facilities

The large computer screen on the left served as the EFIS. Autopilot controls were placed above this screen. The IBM on the right served as the CDU.

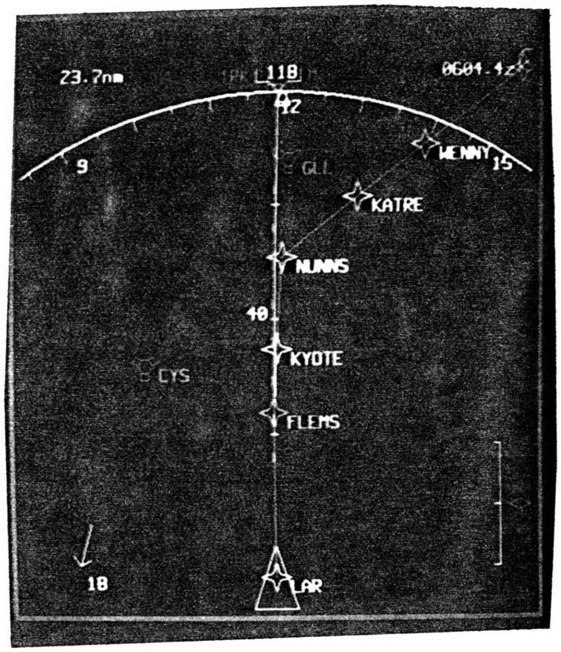
Figure 4.7. The Simulation EFIS Display

The main components of the EFIS screen were the attitude indicator and the moving map display. These are shown in detail in 4.7a and 4.7b. The arrangement of these displays is seen in 4.7c. The lower left corner of the screen shows the side task meters (see section 4.3.3). For the experiment, only one meter was present. The message box mentioned in Section 4.3.3 appeared directly below the map display.

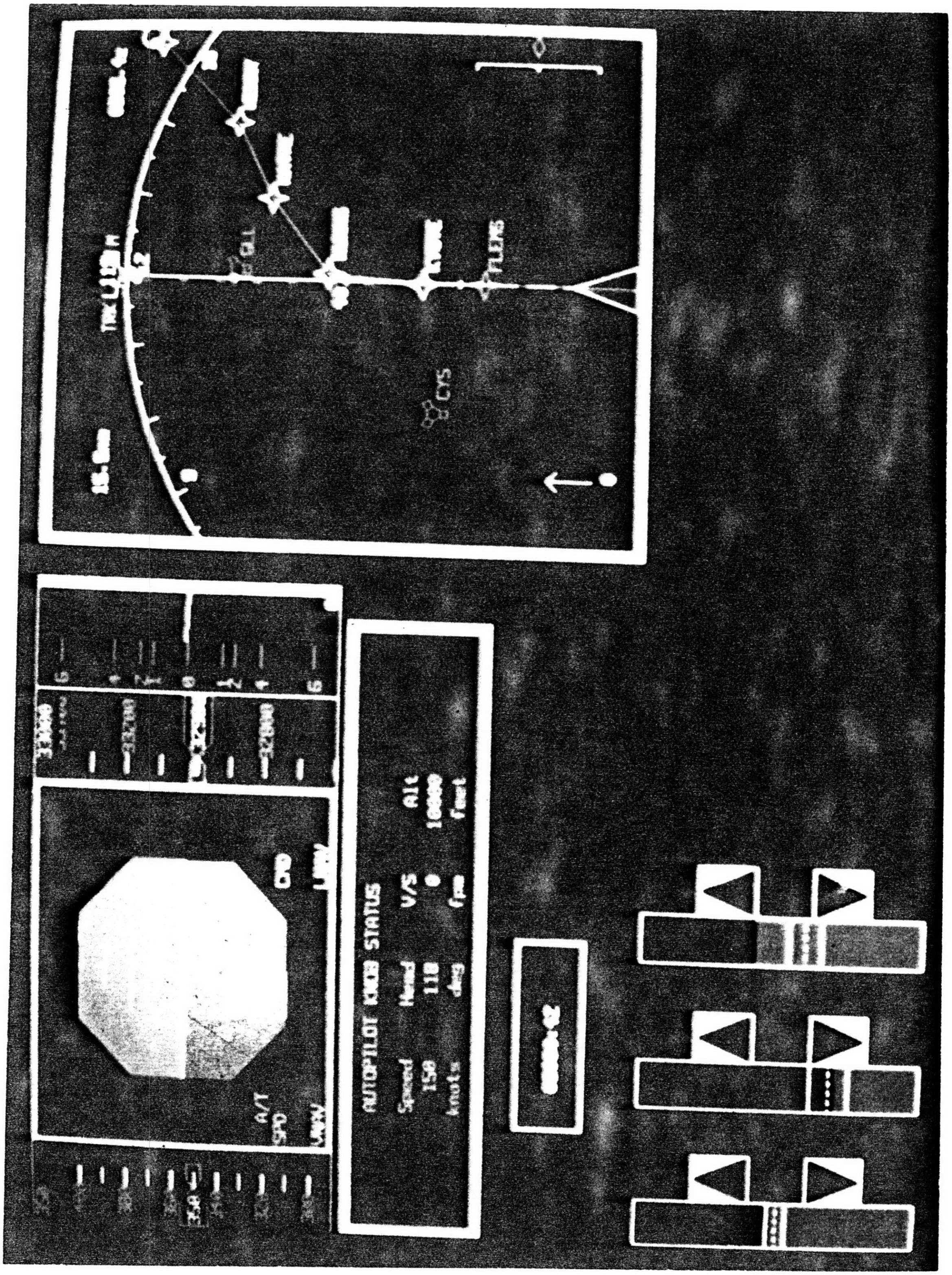
a) Electronic Attitude Indicator



b) Moving Map Diisplay



c) EFIS Screen



moving map display is in the upper right corner of the EFIS screen. This display was carefully designed to closely emulate the actual moving map; its interpretation was discussed in Chapter 3. A control box for the settings of the map display was also constructed and placed above the EFIS display. This box allowed the pilot to set the range of the map. It also allowed him to control which types of information (navigation aids, airports or intersections) were displayed. Indicators for flaps and landing gear were also drawn on the EFIS screen (not shown in Figure 4.7). A side task display and message text window were presented on the EFIS as well. These are discussed in Section 4.3.3.

Autopilot

The autopilot controls (shown in Figure 4.6 on top of the EFIS) allowed the pilot to fly the aircraft without using the CDU. The autopilot is able to fly the vehicle at various levels, so there are several modes of operation. The most commonly used mode is LNAV, or the lateral navigation mode. When LNAV is armed, the autopilot will fly along the route shown on the map display. In conjunction with LNAV is VNAV, or the vertical navigation, mode. When VNAV is activated, the autopilot flies the climbs and descents that are programmed on the CDU. Both LNAV and VNAV are armed for much of the flight time.

Other modes of the autopilot ask it to control specific parameters. Our autopilot was able to fly on speed select mode, heading hold, heading select, altitude hold, or altitude capture (also known "flight level change"). In the modes designated as "select," the pilot commanded the parameter. For example, in the heading select mode, he could set the heading to 100 degrees, and the aircraft would turn to fly at that heading. In the "hold" modes, the autopilot would stabilize the parameter at its current value. Altitude capture is a "select" mode for altitude. The annunciations of the commanded parameters were displayed on the EFIS underneath the attitude indicator (rather than next to the controls) due to hardware limitations.

As our CDU was not designed to handle landings, pilots were asked to use the ILS mode of the EHSI and the autopilot to fly approaches. Three modes were incorporated into the autopilot for this purpose. In the approach mode of the EHSI, shown in Figure 4.8, there are separate displays of the deviation from the glideslope laterally and vertically.[7] In localizer mode, the autopilot aligns the aircraft with the runway laterally. In approach mode, the autopilot automatically flies the specific descents for the approach into the armed runway. A "go around" mode was also present since our scenarios contained severe weather alerts on final approach. This mode was selected when the pilot wished to discontinue the landing.

Control Display Unit (CDU)

The Boeing CDU is a complete environment for programming all flight path management functions. Its software structure is based on hierarchical menus that serve different functions. At the top level, and index screen (or "page") lists all menus below it. The actual system contains several pages with different functions, such as initialization, takeoff, climb, descent, arrival, departure and many others. Obviously, many of these features were

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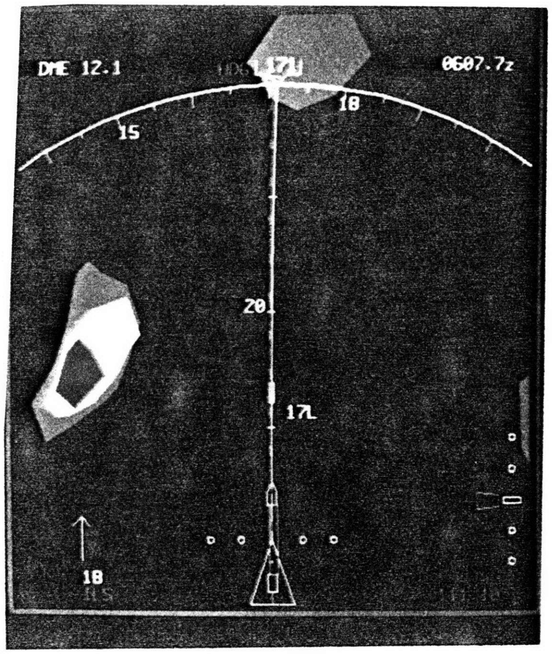
[7] The glideslope in this sense is a fairly narrow radio beam aimed at a three degree angle from the ground. The planes instruments lock on and follow this signal down to the runway. Such a procedure is known as a precision approach, since the glideslope angle is precisely three degrees.

Figure 4.8. Approach Mode of the EHSI

In this mode, waypoints in the area are not displayed. Horizontal and vertical deviation indicators are seen at the aircraft symbol and to its right respectively. These indicators represent the deviation of the aircraft from the runway centerline.



unnecessary for this experiment. Our CDU simulation contains only four pages which can be used to alter routes and runways.

There is a great disparity between the hardware of our system and the actual system. The real system has an alphabetical keyboard and its method of screen line selection involves specialized hardware. There is a vertical column of buttons on either side of the screen next to each line. These buttons are used to select lines for modifications. Our simulation of the CDU (shown in Figure 4.9) is written for an IBM XT using a qwerty keyboard, so it could not reproduce the line selection procedure. Instead, the one step line select procedure was converted into a two step procedure within the software. First, an arrow pointer displayed on the left side of the screen was positioned at the desired line by using standard arrow keys. To actually select the line, the return key, labeled ENTER, was pressed. This two step procedure consistently replaced every occurrence of the line select procedure.

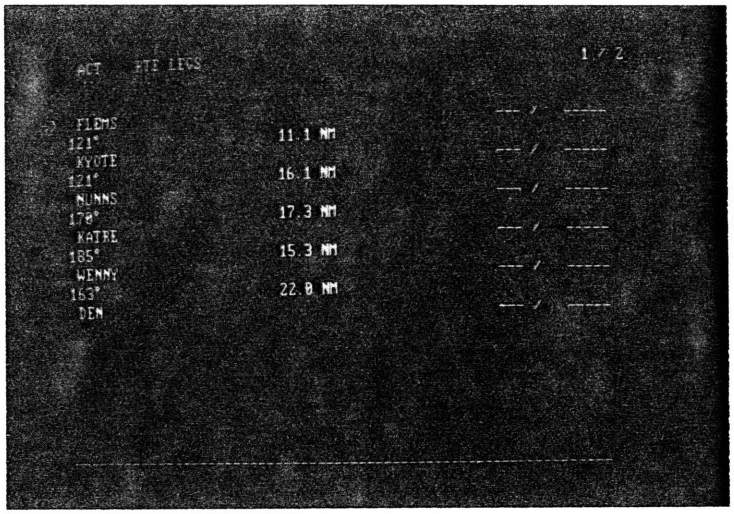
There were three types of modifications that could be made from our CDU. First, a "Direct" page allowed the pilot to change his active waypoint. Second, waypoints could be inserted and deleted on the "Legs" page. This page could also be used to enter altitude and speed constraints on waypoints for the VNAV autopilot mode. Finally, the active landing runway could be modified from the "RTE" (route) page. Whenever unactivated modifications were displayed, the blinking word "EXECUTE?" would appear in the lower right corner of the screen (see Figure 4.9b). The CDU also served as the display screen for the text of amendments in the graphical and textual modes as noted in Section 4.2

Figure 4.9. The Simulation CDU

The CDU was simulated by an IBM XT. Its keyboard was completely different from the actual CDU, so color coded labels were placed over the special function keys.

a) Active Route Displayed

Note the arrow on the left side of the display. This pointer indicated which line would be selected when the ENTER key was pressed. Headings and distances between waypoints were displayed on each line.



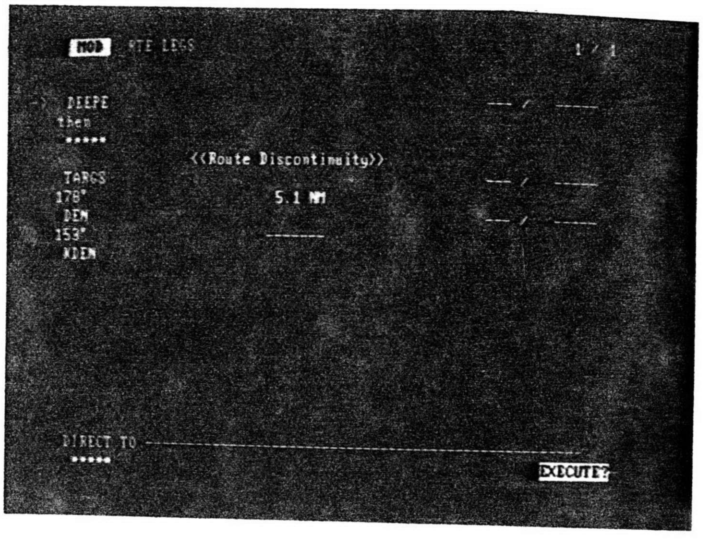
```
  ACT   RTE LEGS                                1 / 2

                                      --- /  -----
->  FLEMS
 121°              11.1 NM            --- /  -----
    KYOTE
 121°              16.1 NM            --- /  -----
    NUNNS
 170°              17.3 NM            --- /  -----
    KATRE
 185°              15.3 NM            --- /  -----
    WENNY
 163°              22.0 NM            --- /  -----
    DEN

 ------------------------------------------------
```

b) Modified Route Displayed

Route discontinuities appear on the CDU when a waypoint has been inserted. The EXECUTE? in the lower right corner flashed on and off when modifications were displayed.



```
  MOD  RTE LEGS                                 1 / 1

->  DEEPE                             --- /  -----
 then
 *****
              <<Route Discontinuity>>
    TARGS                             --- /  -----
 178°              5.1 NM
    DEN                               --- /  -----
 153°              ------
    KDEN



 DIRECT TO ----------------------------------------
 *****
                                          EXECUTE?
```

Software

The software for the EFIS was written in the C programming language in a UNIX environment. Software for the IBM was written in Turbo Pascal version 4.0. In the aircraft, these systems would both be controlled by the FMC. Here, each of these computers had their own versions of the necessary information. Serial communications were therefore set up for the IRIS and IBM. This communication was primarily from the IBM to the IRIS. Autopilot data, for example, was first sent to the IBM which passed it on to the IRIS. The IRIS sent the IBM information about the currently active waypoint. Both computers were also used to collect and store data. The IRIS recorded all control inputs to the autopilot, and all communication packets from the IBM. With this information, it is possible to reproduce and play back a video of the each run. The IBM stored the time of each key press the pilot made to program the CDU. It also recorded the amount of time that the pilot and controller mikes were open. This data could be processed and coded to reveal the time information for our time-based model.

Air Traffic Control

The air traffic controller as mentioned before was in a nearby but separate location. The controller was aware of the pilot's position through a video camera which was focused on the EFIS. Thus, both the pilot and controller were looking at the same information. This video signal was also recorded for analysis. Audio communications were achieved through headsets connected via phone lines. A tape recorder was also placed on this line so that the controller/pilot communications were recorded. Each had a push-to-talk button that activated the phone lines. (These were the button presses recorded by the IBM in order to calculate the duration of each message.) The role of the controller was played by two students who were very familiar with the project.

4.3.3 Task and Procedure

As noted earlier, subjects were asked to fly a total of nine scenarios in the Denver area. The first part of the scenarios required the use of the CDU to comply with clearance amendments initiated by ATC. Subjects were told to evaluate and deal with these amendments as they would under normal circumstances as far as possible. They were told that the frequency of amendments would be much greater than normal and that there would be weather in all the scenarios, but they were not told that some of the amendments were designed to be unacceptable. The procedures for each method of amendment delivery were clearly explained to the subjects.

The experimental procedure lasted approximately five to six hours. First, subjects were asked to sign an informed consent form and fill out a preliminary questionnaire on their flight experience. This questionnaire was a modified version of the background section of the survey. Subjects were then given an overview of the experiment, after which they completed a Sources of Workload evaluation (a part of the NASA Task Load Index workload rating scale). Following this preliminary procedure, the subject was oriented to our simulation. The CDU was explained first in terms of its differences from the actual system which they were familiar with. Next, the EFIS and autopilot system was explained.

Once the subject was somewhat familiar with the systems, he completed a practice session. One amendment was given in each mode during this session. He was also asked to perform a side task when not occupied with flying the aircraft. The side task represented random distractions in the cockpit with a bar meter-like device in which the meter level would drift off at random from the desired tolerance (see Figure 4.7c). The pilot had to bring the meter level back to the desired value by using a mouse input device and clicking on the appropriate (up or down) screen "buttons." It was emphasized that the primary task was to fly the aircraft. After the practice session, subjects were asked to give separate workload ratings for the clearance amendments and the approach phase. Subjects were then given a few moments to familiarize themselves with the Denver area. All necessary charts were provided.

The experimental scenarios were run in blocks of three per mode of communication. Each scenario began with the presentation of the initial routing with which the pilot familiarized himself. This initial routing was presented in a message box on the EFIS display and on a sheet of paper. Subjects were reminded of the procedures each time a new mode block of scenarios was begun. Each scenario was followed by workload ratings as for the practice session. Through a set of preliminary subject tests, it was decided to have an experimenter present at all times in the cockpit room. The differences between our CDU and the actual system were substantial enough for ours to be difficult for some pilots to learn, so this experimenter would assist the pilot with programming tasks if necessary. The learning process associated with our CDU was not being examined.

4.4 Design

This experiment was designed on the basis of randomized blocks of trials. Each group of three scenarios was considered as a "block" of trials. Each scenario had three planned routing amendments, each of which is considered a trial. So, subjects received a total of nine amendments in each mode. One of the three amendments in each scenario was designed to be unacceptable for some reason. With these stipulations in mind, nine scenarios were planned. The controller was given a script for each scenario. A sample script is given in Figure 4.10a and a map of the airspace is provided in Figure 4.10b. Note that the script provides the controller with the text of the clearance and location cue as to when it should be given.

A Latin-square design was used to randomize the scenario blocks in order to counterbalance order effects. This design is diagramed in Figure 4.11. Hence, each scenario was eventually conducted in all modes with different pilots. Five types of bad clearances were given:

1) path crossing through dangerous weather soon
2) path crossing through dangerous weather later
3) clearance to the wrong airport (Colorado Springs, rather than Denver)
4) clearance for approach from an invalid initial approach fix
5) a crossing restriction at a waypoint that is not on the new route

Unfortunately, there were not enough trials for each of these types for statistical analysis.

Figure 4.10a. Sample ATC Scenario Script

Scenario scripts like this one were created for nine scenarios. Note that a location cue is given for each amendment. The text of the amendment is read by the controller in the verbal condition. This text appears on the CDU screen in the text and graphical conditions.

Initial Clearance:

Iris 354, cleared to Denver Stapleton via V4. Expect radar vectors to ILS DME-1 approach RWY 17L.

Start Conditions:

at Libel at 18000 ft, 300 kts. Ground Track 155° M

Amendment #1: (13 nm before Cager)
(acceptable)

Iris 354, turn left heading 100, when able proceed direct to Thurman VOR, V148 to Kiowa VOR, V19 to Denver. Expect ILS approach RWY 35R.

Amendment #2: (approx. 10 nm before Thurman)
(unacceptable due to weather)

Iris 354, proceed direct Kiowa VOR, direct Denver.

Amendment #3: (When requested or 35 nm to Kiowa)
(acceptable)

Iris 354, proceed RNAV direct Byers intersection, direct Kiowa, direct Sedal intersection. Cross Kiowa at 17000 feet.

Clear for approach: (20 nm from Sedal)

Iris 354, after Sedal cleared for ILS approach RWY 35R. Cross Sedal intersection at 10000 ft, 250 kts.

Handoff outside Gandi:

Iris 354, contact tower.

Identify after Gandi:

Iris 354, this is Denver tower. Cleared to land RWY 35R. Winds 050 at 15

Figure 4.10b. Low Altitude Chart of the Denver Area

This chart of the Denver air space accompanies the scenario script in 4.10a. The path that the pilot proceeds along is clearly indicated. The cross-hatched area represents an area of thunderstorm activity.

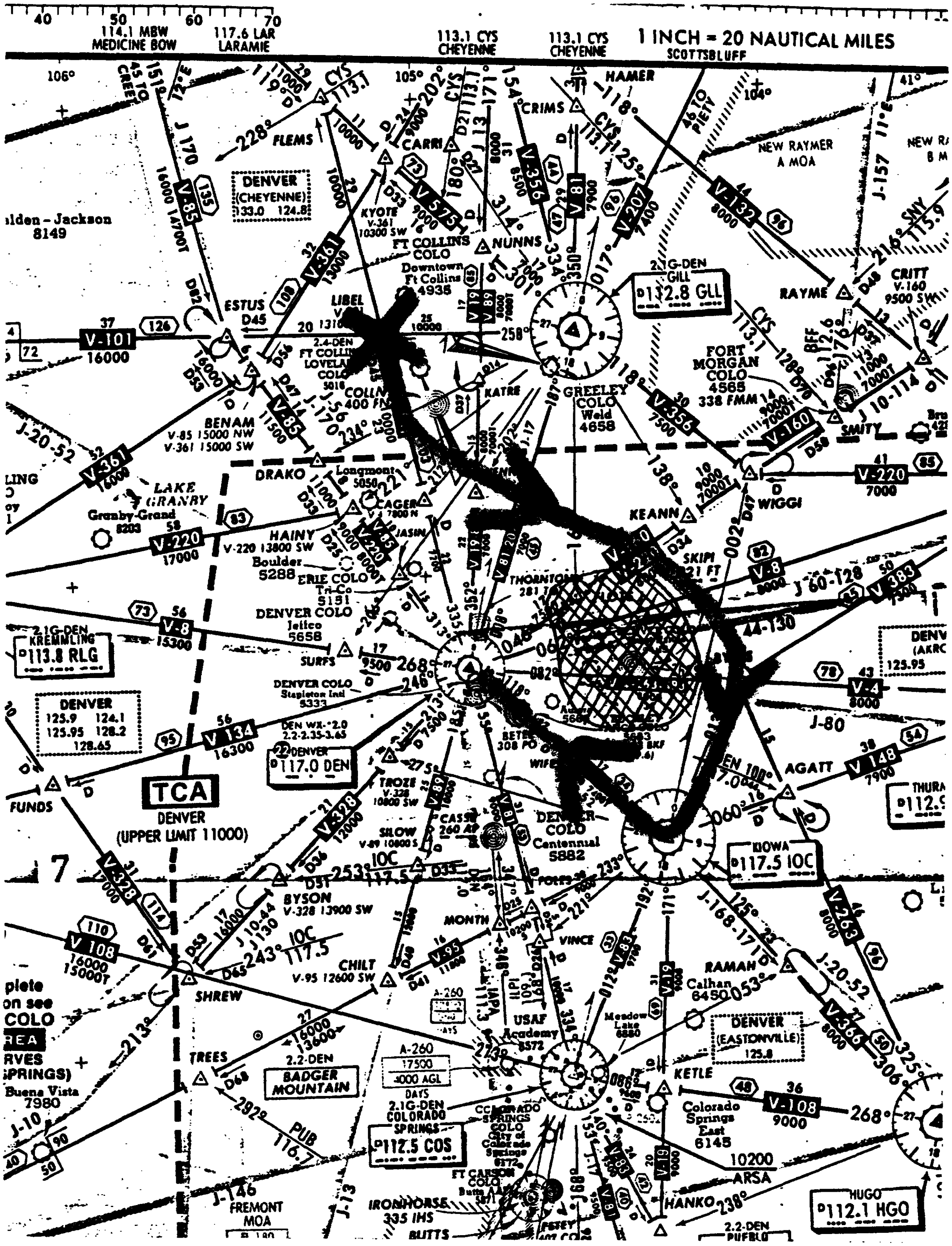


Figure 4.11. Latin Square Randomized Block Design

Each of the cells contains a letter representing on of the three sets of scenarios that were presented as a group. This type of design counterbalances the experiment for learning effects.

		Mode of Delivery		
		Verbal	Text	Graphical
Pilot Group	1	A	B	C
	2	C	C	B
	3	B	A	A

5 Chapter 5: Results of Experiment

The results of the experiment detailed in Chapter 4 are presented and discussed in this chapter. First, the background information obtained from the preliminary questionnaires is presented. Following this, quantitative results of the time analysis, workload ratings, and detection of unacceptable clearances are presented. Each mode is evaluated in terms of the time model. Finally, the qualitative results, pilot comments and individual differences, are discussed. The conclusions of the experiment are then reviewed.

5.1 Subject Characteristics

The subjects, all male, ranged in age from 30 to 59 years, with a mean of 47 years. Four of the six were captains on their aircraft, and the other two were first officers. Their total flight experience ranged from 5500 to 21000 flight hours. Their experience with the FMC ranged from 300 to 4200 hours. Note that all of these pilots would have fallen into the "more experienced" category of our survey data. None of the pilots had extensive computer experience, and all rated their typing skills on the low end of the scale. Four of the pilots were far-sighted and wore bifocal glasses; the other two had uncorrected vision. None of the subjects were highly familiar with the Denver area.

5.2 Quantitative Results

Part of the goal of this research was to quantify pilot performance on each of the three modes of communication. This section contains analyses of time data, workload ratings, and situational awareness. Unfortunately, the small number of subjects and trials prevented statistical significance in almost all cases. Two methods of normalizing the data within subjects proved unsuccessful in eliminating between subject differences.[8] Nonetheless, data averaged across subjects is presented in order to gain an overall picture of the results.

5.2.1 Time Analyses

In coding the raw data from the CDU, and through observations, it was noted that the pilots often used a particular strategy to cope with time critical route amendments. They would begin programming by entering the immediately necessary changes and executing them. Once the autopilot was proceeding correctly along the immediate route, pilots were able to evaluate and enter the remainder of the clearance amendment with less time pressure. The conscious use of this strategy was confirmed in post-experimental interviews. In the graphs that are presented below, therefore, both the total time to accomplish all route amendments and the time to execute the first changes are plotted. Time analyses for performance on the clearance amendments were conducted separately for acceptable and unacceptable clearances.

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[8] In the first method, the data for each trial was divided by the mean of the responses from the acceptable, verbally delivered clearances. This yielded time data in terms of percentages of the baseline condition. In the second method, data was normalized using the z-transform. That is, the data was converted by subtracting the mean of the baseline condition and then dividing by the standard deviation of the baseline condition. This yielded negative values for quicker responses and positive values for slower responses. In both cases, the data was normalized within subjects. Neither of these methods resulted in subject independent variables however. These normalization problems occurred with both the time data and workload ratings.

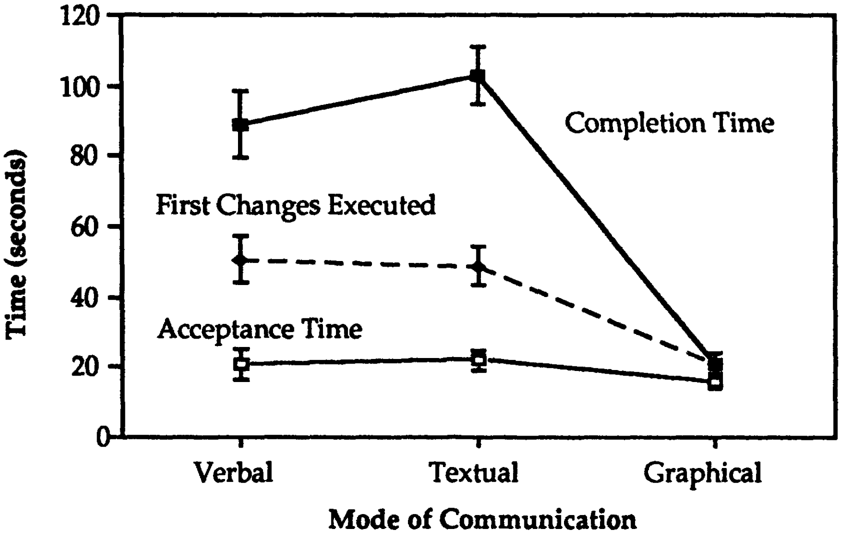
Acceptable Clearance Amendments

Figure 5.1 plots the time performance of the pilots for the acceptable amendments in our experiment by mode. In both Figures 5.1a and 5.1b, the time equals zero when the controller has finished delivering the amendment for the first time, or (for the text and graphical modes), when the amendment was called up. The times of three events are plotted: acceptance, execution of immediately necessary changes, and completion of the re-programming task. Figure 5.1b presents the same data as Figure 5.1a in a different format. Here, the time data has been plotted horizontally, so that this figure corresponds to the theoretical time lines given in Figure 4.3. These time lines are to scale, so that it is clear how much time each task consumes in each of the modes; they can be compared at a glance to reveal the same trends as Figure 5.1a.

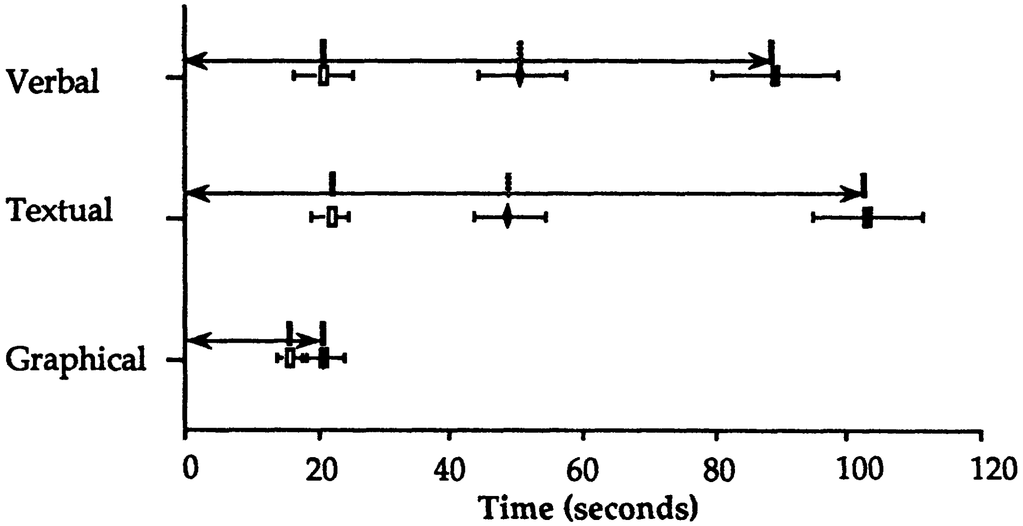
Our first hypothesis that the time for the entire amendment process is much smaller with the graphical mode of communication is clearly confirmed in both plots. This effect was also highly significant statistically ($p \ll 0.01$). The graphical mode execution time is shorter even when compared to the first execute time in the verbal and textual modes. There is no statistically significant difference between the events in the textual and verbal modes, although it appears that there is a tendency for the completion of the task to take somewhat longer in the textual mode. Our second hypothesis predicted that comprehension time would be less for the graphical mode since this mode presented information that was compatible with pre-existing mental representations of the route. This hypothesis was not confirmed statistically, although the trend was in the expected direction. It is interesting to note that the comprehension times for the verbal and textual modes did not differ.

Figure 5.1. Time Performance for Acceptable Clearance Amendments

a) The times to accomplish sub-tasks of the clearance amendment process are plotted. Note that the graphical mode of clearance delivery is much more time efficient than the other modes.



b) The data from figure 5.1a is presented in a time line format.



There is apparently no time benefit for comprehension with the clarity of written amendment messages.

Unacceptable Clearance Amendments

In the case of unacceptable clearance amendments, the time at which the amendment process was completed is considered to be the initiation of a pilot request that identifies the (intended) problem with the amendment. The detection times for these problem amendments occurred at various stages in the process. Sometimes the problem would be recognized the prior to accepting the amendment, but at other times not until much later. The data from these amendments is therefore analyzed separately for these two cases. Pilots were considered to be "initially aware" of the problem if they recognized it prior to acceptance. They were considered to be "finally aware" if they recognized the problem prior to the delivery of the next scheduled amendment.[9] If they were not initially aware of the problem, pilots most often completed processing the amendment in the same manner as an acceptable amendment. Complete misses of unacceptable amendments are discussed in Section 5.2.3.

Figure 5.2 presents data for the situation where the pilot was not initially aware of the problem, but did eventually detect it. As in Figure 5.1a, times for the acceptance, first execution, and completion of the task are plotted. Recall that here completion time is actually the detection time. Again, time is zero when

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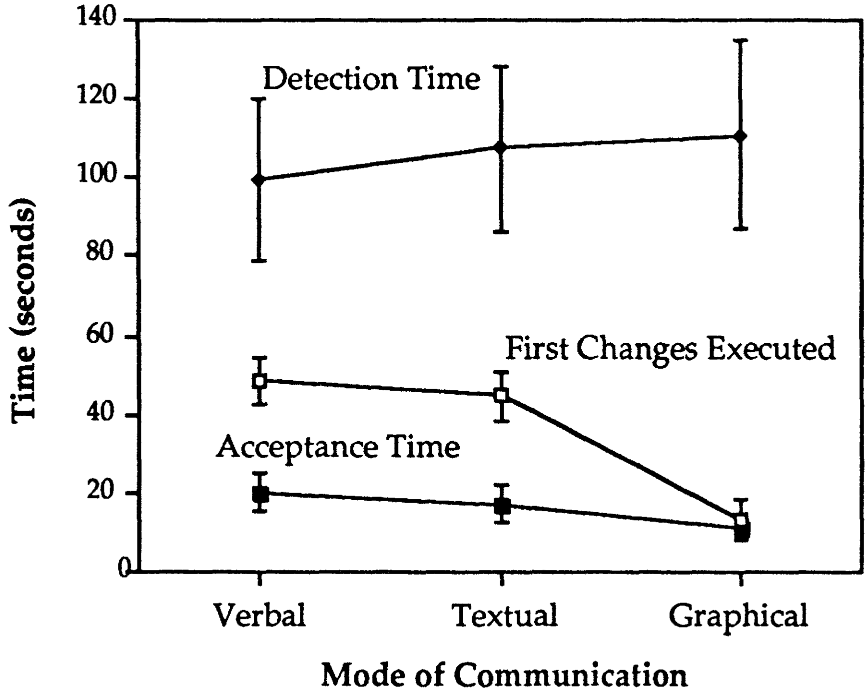
[9] Acceptable amendments that followed unacceptable amendments were delayed as much as possible. This delay was on the order of four to five minutes. By this time, pilots had thoroughly finished processing the bad amendment. There was only one case in which the pilot was apparently still considering a bad amendment when the following one was given.

Figure 5.2. Time Performance for Initially Undected Unacceptable Amendments

The time performance of pilots for the detection of unacceptable amendments is shown below. There is no apparent difference between detection times for the three modes.



the amendment has been delivered to the pilot. There is no difference between detection times for the three modes. It is suspected that detection times vary with the mode of amendment delivery *and* the specific problem with the amendment, but there were not enough trials to test this hypothesis.

Pilot performance on unacceptable clearances that were initially accepted is compared with performance on acceptable clearances in Figure 5.3. This figure shows that it took slightly longer to detect unacceptable clearances than it did to complete the execution of an acceptable clearance. The comprehension time (from zero to the acceptance) did not differ between unacceptable and acceptable clearance, and neither did the first execution times, so these are not shown in the figure.

Figure 5.4 compares the situation where pilots are initially aware of the problem to the situation where pilots become aware of the problem after accepting the amendment. This figure illustrates the time cost of initially accepting a clearance that is incorrect. It should be noted, though, that the frequency of unacceptable clearance amendments in the actual airspace environment is very low (as indicated by pilot reports in the survey data).

Conclusions of Time Analyses

On the whole, the graphical mode is seen to be the most efficient mode of communication in terms of the time required to initiate and complete the amendment process. Comprehension time was not significantly reduced by graphical communication in this data, but the trend is in the expected direction.Verbal and textual communication were seen to be about equal in terms of time efficiency, although textual appeared to be slightly worse.

Figure 5.3. Comparison of Acceptable and Unacceptable Amendments
This figures shows that it takes slightly longer to detect unacceptable amendments than it does to complete the updating process for an acceptable amendment.

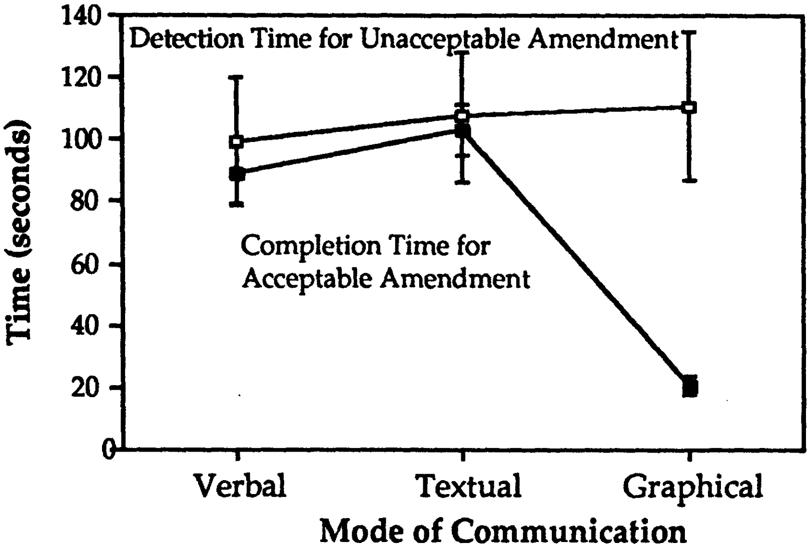
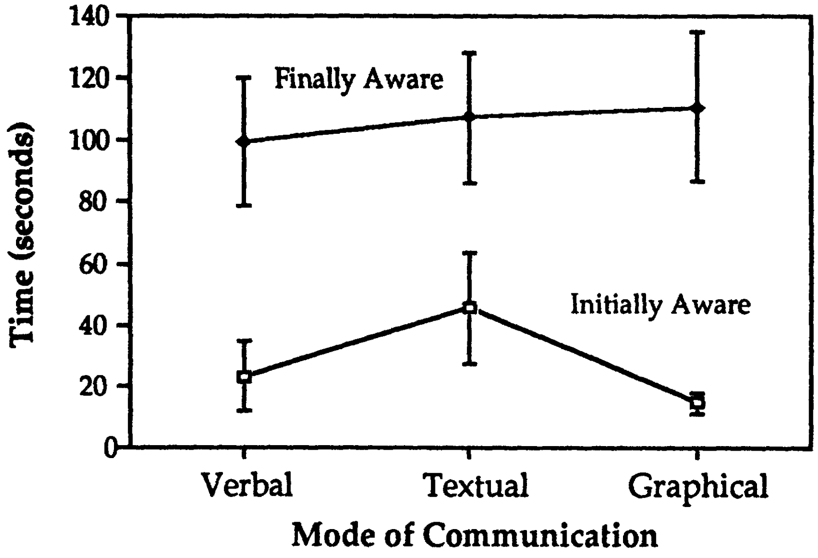


Figure 5.4. Detection Times
This figure illustrates the time penalty for not detecting unacceptable amendments prior to accepting them.



5.2.2 *Workload Ratings*

The NASA Task Load Index was used to assess workload for each of the modes. This scale divides workload into six components: mental demand, physical demand, temporal demand, effort, frustration and performance.[10] The overall workload rating is computed as a weighted average of the separate ratings on each of these scales.[11] The weights are obtained from the sources of workload evaluation which was completed during subject orientation. In this evaluation, the six components of workload are presented in pairs and the subject is asked to chose which of the two he feels is a more important contributor to workload for the flying task. The weights are simply the number of times a particular component was chosen to be a more important contributor to workload.

The overall workload ratings for each mode are plotted in Figure 5.5. Workload for the graphical mode was significantly lower ($p < 0.05$) than the workload for the verbal and textual modes. Figure 5.6 shows the ratings for each of the six sub-scales. There is a slight trend in these plots indicating that the textual mode has somewhat higher workload than the verbal mode, but

---

[10] Each component was rated on a ten centimeter horizontal line labeled at one end as "very low" and the other as "very high." The subject simply made a mark at the appropriate location. The distance from the very low (zero) end in millimeters was taken as the rating, so the ratings range from zero to one hundred.

[11] The performance rating is inverted by subtracting it from one hundred during the computation of this average. That is, a higher rating for performance is considered to lower the overall workload.

Figure 5.5. Overall Workload

Overall workload ratings were significantly lower for the graphical mode.

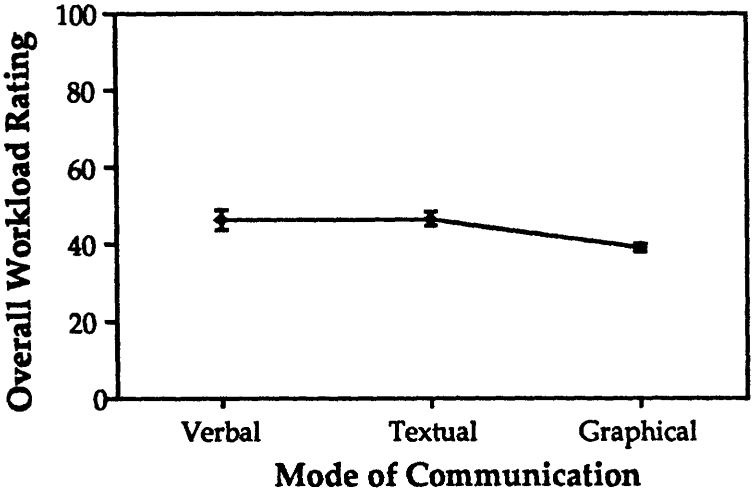
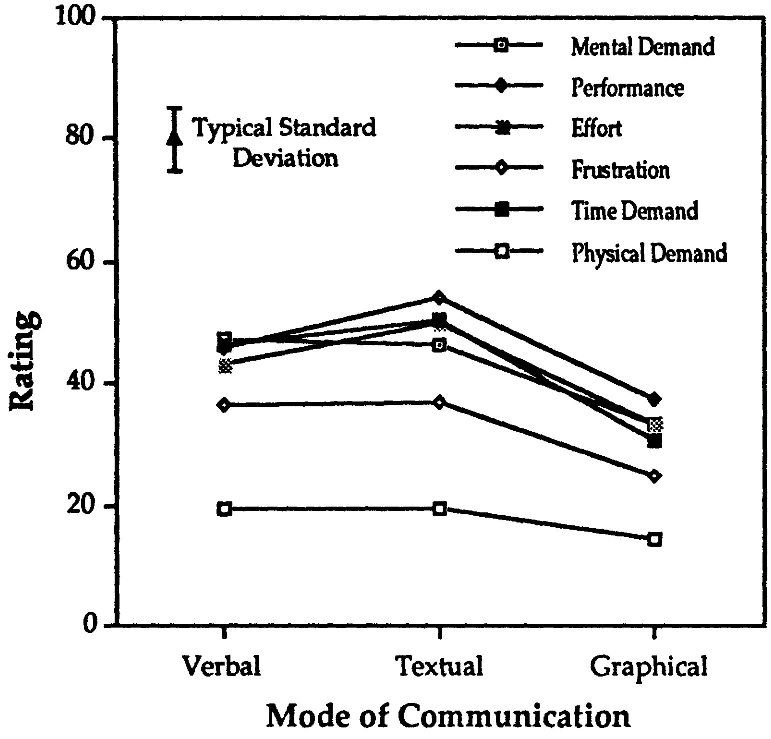


Figure 5.6. Components of Workload

The six components of workload reflected the overall trend that workload was lower for the graphical mode.



this trend is not statistically significant. It is unclear why the ratings of performance decreased for the graphical mode. Perhaps subjects felt that they had less influence on the completion of the task, or perhaps they simply misinterpreted the scale.[12] This trend again, though, was not significant.

5.2.3 Situational Awareness

There was no definitive measure of situational awareness employed in this experiment. One indication of awareness, however, is the detection of unacceptable amendments. Pilot performance on this task is presented in Tale 5.1, using the terminology explained previously. This table presents the number of times pilots caught bad amendments initially and finally, and the number of complete misses. It appears from this table that, on the whole, situational awareness was comparable between modes. An important conclusion from this is that situational awareness was not compromised in the textual or graphical modes relative to the level for the verbal mode.

Table 5.1 Detection of Unacceptable Amendments

Mode	Initially Aware	Finally Aware	Never Aware (Miss)
Verbal	4	14	1
Textual	5	12	3
Graphical	7	10	4

---

[12] Some subjects did not seem to realize that performance was a reversed scale. When they felt that workload was high, they simply rated all the scales on the high end, apparently without discrimination.

5.3 Qualitative Results

The qualitative results of this experiment were obtained through a structured post-experimental interview with the subject and through direct observation. In the interview, the subjects were asked to evaluate each of the modes. Several issues concerning the graphical mode in particular were also discussed. An overview of pilot comments are presented below, along with a summary of the individual differences that were observed.

5.3.1 Pilot Comments

In their evaluation of each modes, pilots overwhelmingly preferred the graphical mode of communication. When asked to rate each mode on a scale from one to ten (ten being the most desirable), the average rating for the graphical mode was 9.0. The textual mode was rated 5.33 on the average and the verbal, 5.25. Although the ratings for the textual and verbal modes were similar when averaged across all subjects, there were noticeable differences between subjects. Some rated the textual mode as substantially better than the verbal, but others rated the two exactly oppositely. On the one hand, pilots were pleased with the clarity of identifiers and numerical information with the text display. At the same time, all indicated that they were very comfortable with standard procedures in which they ask the controller for clarifications. So, some did not feel that the textual advantages were significant.

Several issues specific to the graphical mode of delivery also arose in the discussion with subjects. The first concern was that the workload level of this mode might be so low that the task would become boring, possibly leading to complacency. The consensus was that this method was not boring at all during the simulation, but some felt that it could become dull if they were more accustomed to it. For the session, they all felt it was quite novel.

Another concern was the loss of the "party line" atmosphere. That is, with the current system, pilots are able to listen to controller conversations with other aircraft in the area. They often use this information to create a mental picture of the traffic situation and to keep ahead of what amendments the controller is likely to give them in the near future. The graphical mode of delivery, however, is aircraft selective and this information would be lost. The feeling on this issue was that en route, the loss would not be great. Pilot tend to pay attention to the party line conversations much more in the terminal area. In that situation, some pilots would feel a loss of information with the graphical mode of delivery.

A similar issue concerns information that pilots obtain through the tone and tenor of the controller's voice delivery. Often, a sense of immediacy is better created through verbal communications. For this reason, and others, pilots definitely wanted voice backup for all graphical (or textual) communications. Finally, pilots themselves brought up the point that graphical communications would lower the workload for pilots, but were likely to increase the workload for controllers.

5.3.2 Individual Differences

The within subject effects that were so difficult to eliminate for the statistical analyses were most likely due to actual differences between subjects. For the quantitative results, it was necessary to examine all the data on average, since there were no specific characteristics which would immediately categorize the subjects into a small number of groups. The two main factors that appeared to affect pilot responses, styles and age, are discussed below.

Pilot Styles

Even with the small number of subjects in this study, style differences among the pilots were evident. One major difference was the pilot's working style with the controller. Some were quick to initiate requests that they felt were in their interests, while others had a more "wait-and-see" attitude. Some also indicated that they expected to receive amendments while in the terminal area. If they became aware of an impending problem, they would not react to it immediately since they expected that their clearance would be amended before they had to confront the problem.

Another difference in pilot styles was how comfortable they felt with the technology. Some feel very comfortable with the CDU, and used it in innovative ways. For example, they would occasionally enter a modification to go direct to a waypoint (and then cancel it) simply to *locate* the waypoint on the map mode display. This eliminates the need to search through complicated charts. One pilots even noted that in the aircraft, he would use the CDU data entry line as a general notepad to copy down the clearance amendment as it was delivered, rather than copying it with pencil and paper. This use of the CDU was not actually observed with our version, presumably as the subjects were not as comfortable with it.

In the graphical mode of delivery, it was evident that pilots trusted the method to different extents. Some pilots always checked the charts prior to accepting the amendment to be sure that the graphical display was indeed a correct display of the textual information. Others simply accepted the graphical amendment without ever checking the charts. Still others would accept the amendment and then check the charts. One pilot observed that pilots' map reading skills in general deteriorated after long time use of the map mode display. It is evidently common for pilots not to examine their paper charts at all.

Age Differences

Two qualitative effects of age were apparent in this study. First, it appeared that older pilots were more uncomfortable with our simulation of the CDU than younger ones. In the interviews, pilots also indicated that captains in training for the Boeing 757/767 qualification generally had a more difficult time learning the system than co-pilots. It was informally observed that the older pilots had a more literal knowledge of the functioning of the CDU. These pilots had a difficult time converting the single step line select procedure into our two step procedure. Those that adjusted to the simulation more easily seemed to have a more fundamental understanding of the conceptual structure on which the CDU functions were based.

The second age related difference between pilots was visual correction. The older pilots wore bifocals. These pilots had a more difficult time reading the textual amendments on the CDU and the autopilot annunciations. More than one pilot confused 8's and 0's, for example. Although our CDU screen was not ideal, it is difficult to discount these errors as being hardware or display related. The number of active far-sighted pilots is likely to justify some special consideration.

5.4 Conclusions

Conclusions of this experimental simulation can be made at two levels. From a theoretical perspective, the time-based model of the clearance amendment process has been a valuable tool for the evaluation. It was necessary, though, to modify the model slightly to account for the parsing strategy of pilots. This technique involves separating the amendment into segments which are executed in-part if there is time pressure or all at once if there is not. The quantitative and qualitative results both indicate that the graphical mode of communication was superior to text and verbal communications. Their was a split decision about the relative superiority of the textual and verbal modes.

6 Chapter Six: Summary and Conclusions

As noted in Section 1.4, the general goal of this study was to develop and test a methodology to evaluate levels of cockpit automation. The user centered approach was selected after careful consideration of a variety of past approaches to cockpit design. On the basis of this methodology, a survey on cockpit automation and a simulation experiment were conducted to evaluate the clearance amendment process for advanced transport category aircraft. The results of these portions of the study are reviewed below. An evaluation of the simulation fidelity, overall conclusions, and suggestions for future research are then given.

6.1 Conclusions of Survey

The results of the survey confirmed that pilots appreciate and use the automation for flight path management. The moving map display presentation of their horizontal situation was especially preferred. This is to be expected from the premise of this research: computer interfaces that emulate mental representations of information will facilitate human processing. The survey also pointed out that the flight path management system greatly eases the task of flying a specified route, especially during cruise. The system can be cumbersome to use, however, during high workload phases of flight at low altitudes when there are other aircraft in the vicinity. This situation occurs frequently enough to warrant attention.

6.2 Conclusions of Simulation

An experimental simulation to compare two proposed methods of clearance amendment delivery, textual and graphical, with standard procedures was also developed and carried out. The proposed methods of delivery will soon be feasible through the use of the Mode S transponder which provides aircraft selective digital datalink. In the textual mode, the text of the amendment was displayed directly on the data entry computer screen. In the graphical mode, the text of the message was displayed *and* the alternate route was automatically loaded into the flight management computer, appearing as a dashed line on the moving map display and a modified route on the CDU.

Six active Boeing 757/767 pilots flew a computer simulation of the EFIS and CDU which simulated the standard and proposed methods of clearance amendment delivery. Their performance on the clearance amendment task was measured quantitatively in terms of the amount of time taken to accomplish sub-tasks. The original model partitioned the task into two steps: comprehension and programming time. Observations and analyses, however, suggested that a refined model should treat the execution of the immediately necessary changes as a distinct step from the remainder of the programming. The graphical mode was determined to be most efficient mode primarily as a result of the elimination of the programming time. The data also suggests that comprehension time may be shorter for the graphical mode since the route information is presented in a manner that is easily processed by humans.

Interviews with pilots on their evaluation of the modes of communication were particularly helpful. They overwhelmingly expressed an preference for the graphical mode in the simulation. There were differences of opinions on the relative strengths of the textual and verbal modes. Some preferred the textual mode for its clarity; others felt there was not much of an advantage over the voice procedures with which they are comfortable. There were some concerns expressed about issues such as boredom, and information loss with the graphical mode, but this simulation was not able to properly assess these issues.

6.3 Evaluation of Simulator Fidelity

On the whole, pilots were impressed with the fidelity of the computer simulation. They did feel that they were given the tools necessary to complete the tasks given to them, although they adjusted to the simulation of the CDU with varying degrees of success. (There was an observable learning effect.) Pilots were asked to deal with the clearance amendments in the simulation in their usual manner as far as possible, but many indicated that their expectations were different in the simulation from those in the aircraft. One factor was that they were the only aircraft in our simulation, so there was no chance for some types of controller errors, such as confusion between aircraft, that occur in the real environment. Also, the scenarios employed in this experiment had an extremely high frequency of unacceptable clearance amendments (33%, compared with pilot estimates of 5-10% in the true environment). At least one subject indicated that the side task meter *was* a good simulation of distractions in the cockpit. Finally, the pilots were amused to find that their past experience with simulators lead them to constantly expect mechanical failures, which were not a part of this simulation at all.

6.4 Conclusions

The user centered approach to studying the clearance amendment process has been shown to yield useful results in this study. In the original discussion of the proposed methods of clearance amendment delivery (Figure 1.1), it was noted that the methods were listed in order of increasing levels of automation: verbal, textual, and graphical. Through our evaluation of these levels, however, it has become clear that simply increasing the level of automation does not necessarily result in a "better" system. Rather, it is more necessary to evaluate user needs, preferences, and mental processes in designing automation systems for higher-level pilot tasks. Such a multi-faceted analysis results in a better understanding of the judicious use of automation.

6.5 Suggestions for Future Research

The first recommendation for future research is to test more subjects on the present experiment. This should improve the statistical validity of the results. It may also help to reveal characteristics that could be used to sort the subjects into groups such that the between subject differences would be negligible within these groups. Hopefully, there are a small number of groups that account for the various pilot styles that are encountered in the system.

Eventually, it will be useful to conduct a full-simulation of the proposed methods of clearance amendment delivery. This simulation should reveal higher order effects of the future procedures. Prior to this, however, an intermediate step might be wise. On the basis of more solid results from the experiment discussed in this document, it is likely that a higher fidelity simulation will be possible, without going to the full-simulation immediately.

Such an experiment could improve on each aspect of the simulation that has been conducted by using more realistic scenarios (perhaps with dummy aircraft in the area), more trials of each type of bad amendment, and a more refined simulation of the CDU.

Appendix A:

Survey on Cockpit Automation

Survey on
Advanced Cockpit Automation

The Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology is currently evaluating automation in transport category aircraft. As a first step, we are conducting a survey of pilot opinions regarding the current Flight Management Computer (FMC), Electronic Flight Instrumentation System (EFIS) and Control Display Unit (CDU). The information obtained will be used to help improve future designs of the FMC, EFIS, and CDU.

Please remember that this is only a survey of your *opinions.*

Participation in this survey is completely voluntary. It is not necessary to give your name at any point. You may decline to answer any of the questions in this survey, without prejudice. All information obtained from any individual survey will be kept confidential by the researchers at MIT.

For further information about this study, please feel free to contact :

Principal Investigator:

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Thank you for your time and cooperation.

I. Background Information

This background information will help us assess the amount and type of experience you have with aircraft equipped with automated navigation systems. All information will remain confidential.

AGE: ______________ SEX: M F

VISUAL CORRECTION?

1) None 2) Near-sighted 3) Far-sighted 4) Other ____________________

Transport Category Aircraft Flying Experience

Please list in order of *most recent* experience to *least recent* experience:

Aircraft Type	Position*	Approx. Flight Hours	FMC Type (if any)**

Approximate FMC Equipped Flight Hours Over the Last Year ____________________

Approximate Total Flight Hours Over the Last Year ____________________

Commonly Flown Routes

____

____

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[*] Captain, First Officer, Second Officer, or Instructor/Checkpilot

[**] FMC's may be of two types:
(1) AFMC: Automatic Flight Management Computer (EFIS only, no EICAS)
(2) FC2A: Fully Compliant Second Version Sub-Chapter A

Computer Experience (other than FMC Experience)

Please indicate your choice by circling the appropriate number.

As a PERSONAL/BUSINESS COMPUTER USER:

1	2	3	4	5
little or no experience				extensive experience

As a COMPUTER PROGRAMMER:

1	2	3	4	5
no programming experience				extensive programming experience

Miscellaneous Information

HIGHEST EDUCATION LEVEL

1) high school 2) some college 3) college degree 4) graduate work/degree

HIGHEST MATH LEVEL

1) arithmetic 2) algebra 3) calculus 4) beyond calculus

TYPING SKILL

1	2	3	4	5
unskilled typist				skilled typist

HOBBIES

____

____

II. General FMC Questions

The following questions pertain to general characteristics of the automated flight management system which consists of the Flight Management Computer (FMC), Electronic Flight Instrumentation System (EFIS), and Control Display Unit (CDU). *FMC equipped* aircraft are defined as those equipped with such a flight management system.

1) Which type of aircraft do you prefer to fly?

a) FMC equipped

b) Not FMC equipped

2) Briefly, what is the main reason for the preference you expressed in Question 1?

3) After flying **with** FMC equipped aircraft regularly, how difficult do you find it to adjust to flying **without** the FMC?

1	2	3	4	5	6
very easy				very difficult	no opinion

4) After flying **without** the FMC regularly, how difficult do you find it to adjust to flying **with** the FMC?

1	2	3	4	5	6
very easy				very difficult	no opinion

5) Overall, how easy is it to use the FMC?

1	2	3	4	5	6
very easy				very difficult	no opinion

Comments:

6) How satisfied are you with the capabilities, power and flexibility of the FMC for navigation?

1	2	3	4	5	6
very satisfied		satisfied		very unsatisfied	no opinion

Comments:

7) What changes would you make in the way that information is presented on the EFIS? Please explain.

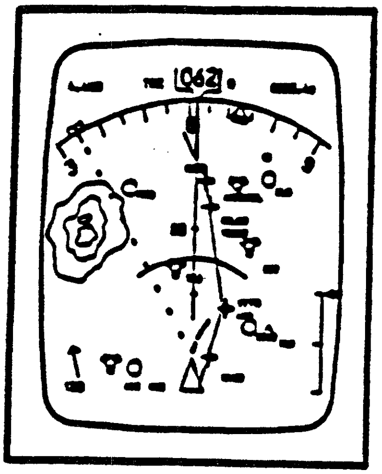
8) What would you like to change about the CDU data entry system? Please explain.

9) What, if any, specific capabilities would you like to see implemented on future designs of the FMC to make it more powerful? Are there any capabilities currently implemented that you seldom make use of?

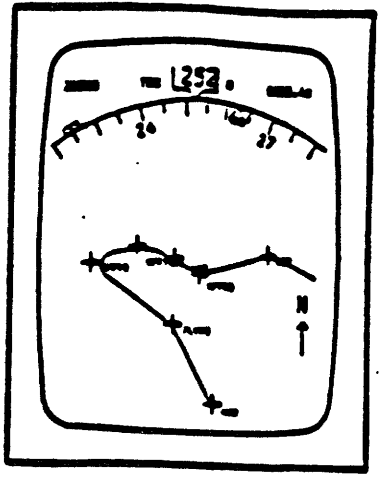
III. EHSI Questions

Each of the six EHSI modes on Boeing 757 and 767 aircraft is depicted below. Refer to these figures for the next set of questions.

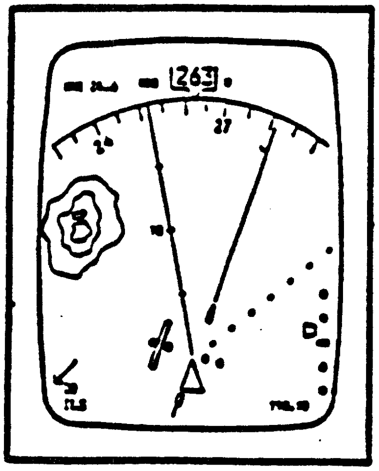
MAP MODE



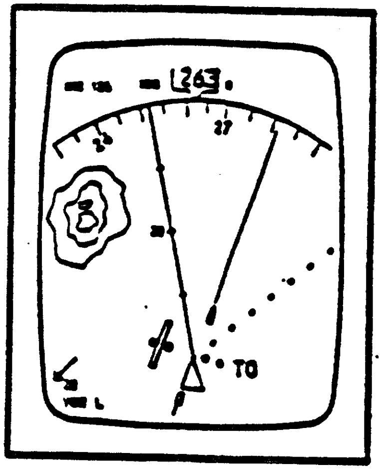
PLAN MODE



EXPANDED ILS MODE



EXPANDED VOR MODE



For the next set of questions, the phases of flight are defined as follows:

1) GROUND OPERATIONS: Dispatch, Pre-Start, Taxi
2) DEPARTURE: Takeoff, Lift-off to Top of Climb
3) CRUISE
4) DESCENT: Top of Descent to Approach Control Contact
5) TERMINAL AREA: Approach Control Contact to Final Approach Fix
6) FINAL APPROACH: Final Approach Fix to Runway Threshold

1) In the table below, place a check mark in the box if you use that EHSI display mode during that phase of flight more than approximately ten percent of the time, otherwise leave the box blank. Please refer to the figures on the previous page and the definitions given above.

☑ = Use this Mode more than approximately 10% of the time in this phase of flight

☐ = DO NOT Use this Mode more than approximately 10% of the time in this phase of flight (LEAVE BLANK)

EHSI Mode	Ground Operations	Departure	Cruise	Descent	Terminal Area	Final Approach
Map Mode						
Plan Mode						
ILS Mode						
VOR Mode						

2) For each of the EHSI modes listed below, please note what, if any, information you would consider valuable that is not currently displayed. Also indicate what, if any, information that is presented in that mode could be removed from the display. If you do not use a particular mode often, please note whether you feel that the mode itself is necessary or not.

Map Mode Information

Desired: ______________________________

Removable: ______________________________

Plan Mode Information

Desired: ____

Removable: ____

ILS Mode Information

Desired: ____

Removable: ____

VOR Mode Information

Desired: ____

Removable: ____

3) This question is designed to assess how you use the information on the moving map display during each phase of flight. Each of the next six pages has a generic representation of the moving map display in a different phase of flight.

Please rate each item of information on the following scale in the space provided below each label:

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Below each map, please rate how you feel the workload for navigation tasks differs between aircraft equipped with a FMC as compared to those without the FMC for each phase of flight using the following scale:

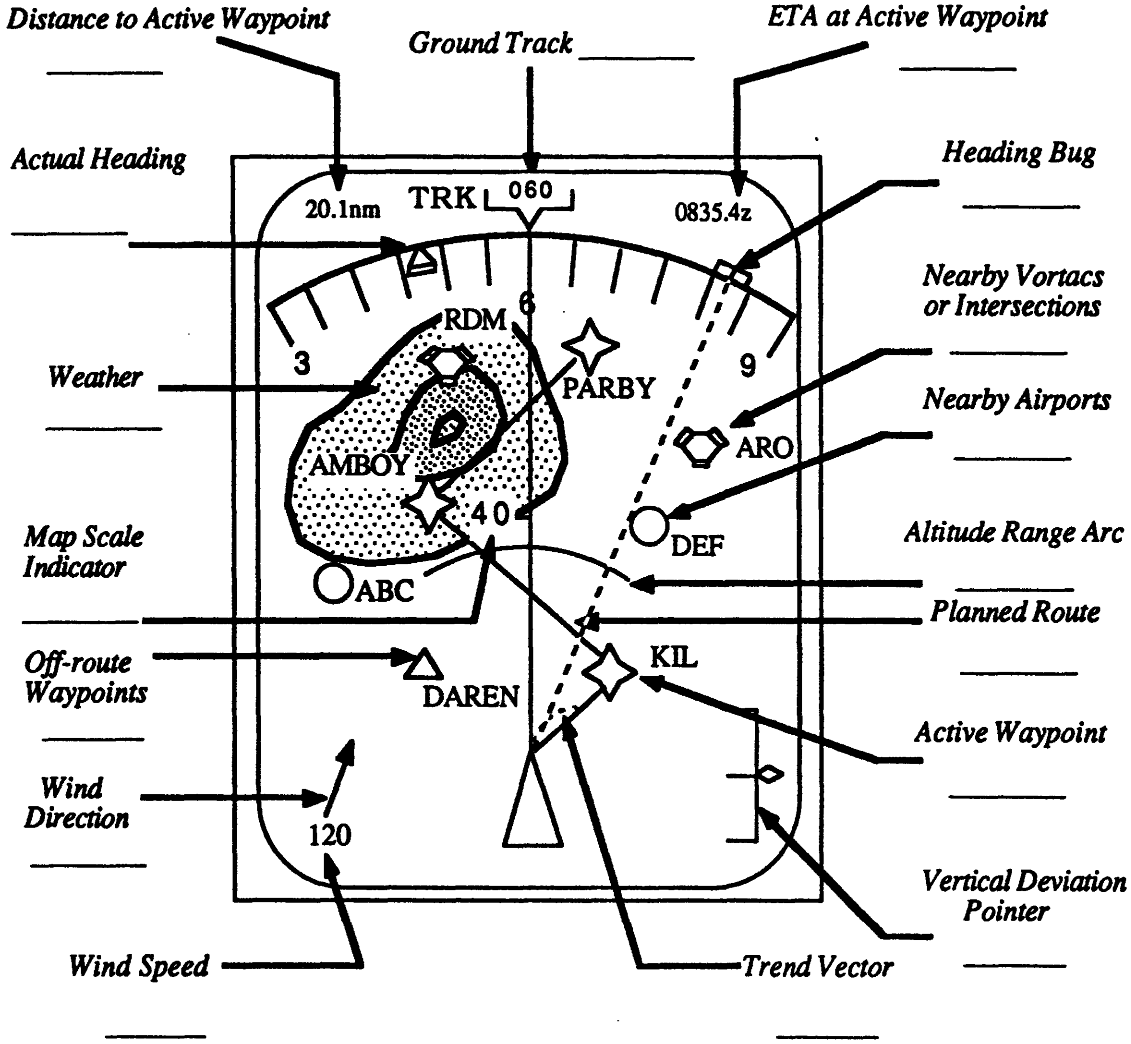
1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

GROUND OPERATIONS

Please rate each piece of information on how much you need it during **GROUND OPERATIONS.**

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Mark your rating in the space provided below each label.



CHANGE IN WORKLOAD

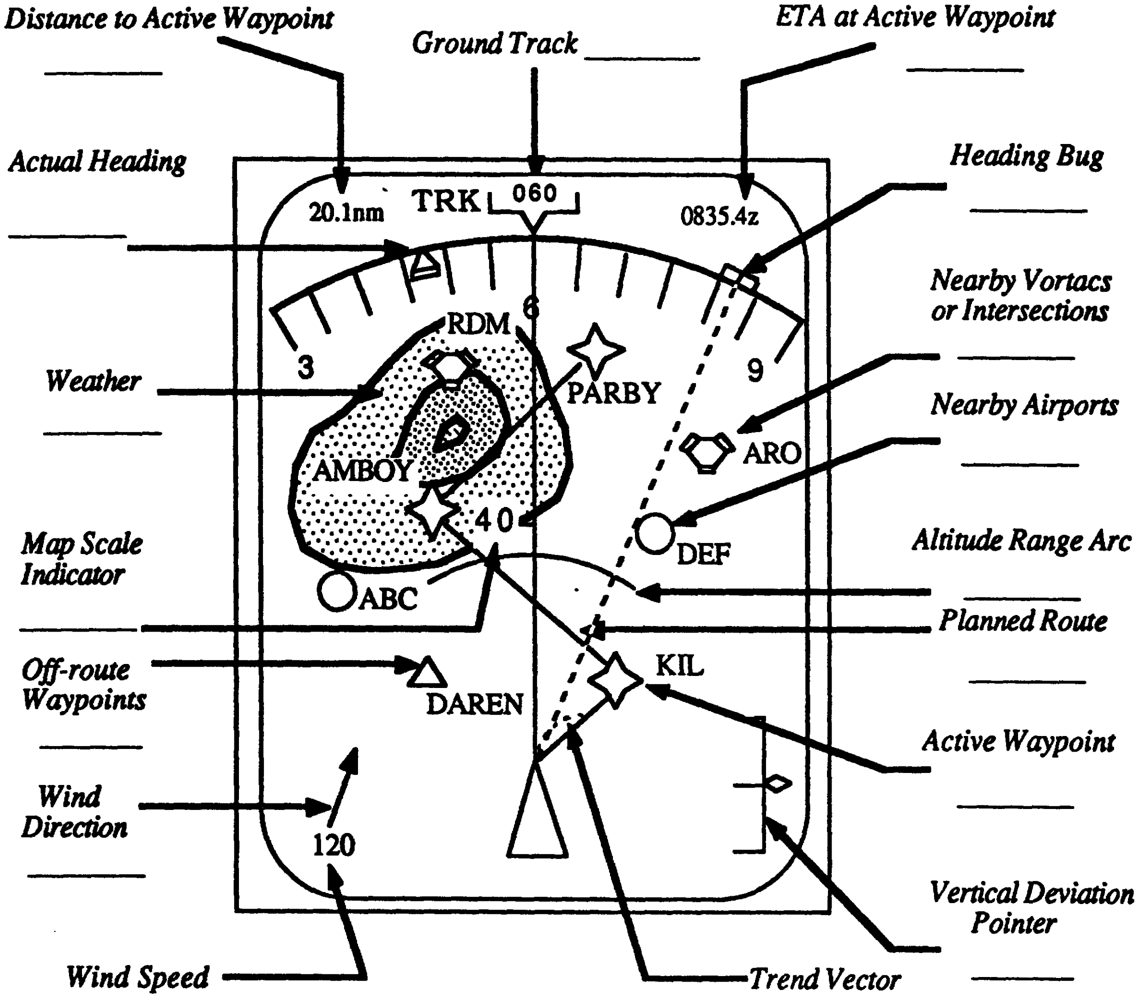
1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

DEPARTURE

Please rate each piece of information on how much you need it during **DEPARTURE.**

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Mark your rating in the space provided below each label.



Distance to Active Waypoint ______

Ground Track ______

ETA at Active Waypoint ______

Actual Heading ______

Heading Bug ______

Nearby Vortacs or Intersections ______

Weather ______

Nearby Airports ______

Map Scale Indicator ______

Altitude Range Arc ______

Planned Route ______

Off-route Waypoints ______

Active Waypoint ______

Wind Direction ______

Vertical Deviation Pointer ______

Wind Speed ______

Trend Vector ______

CHANGE IN WORKLOAD

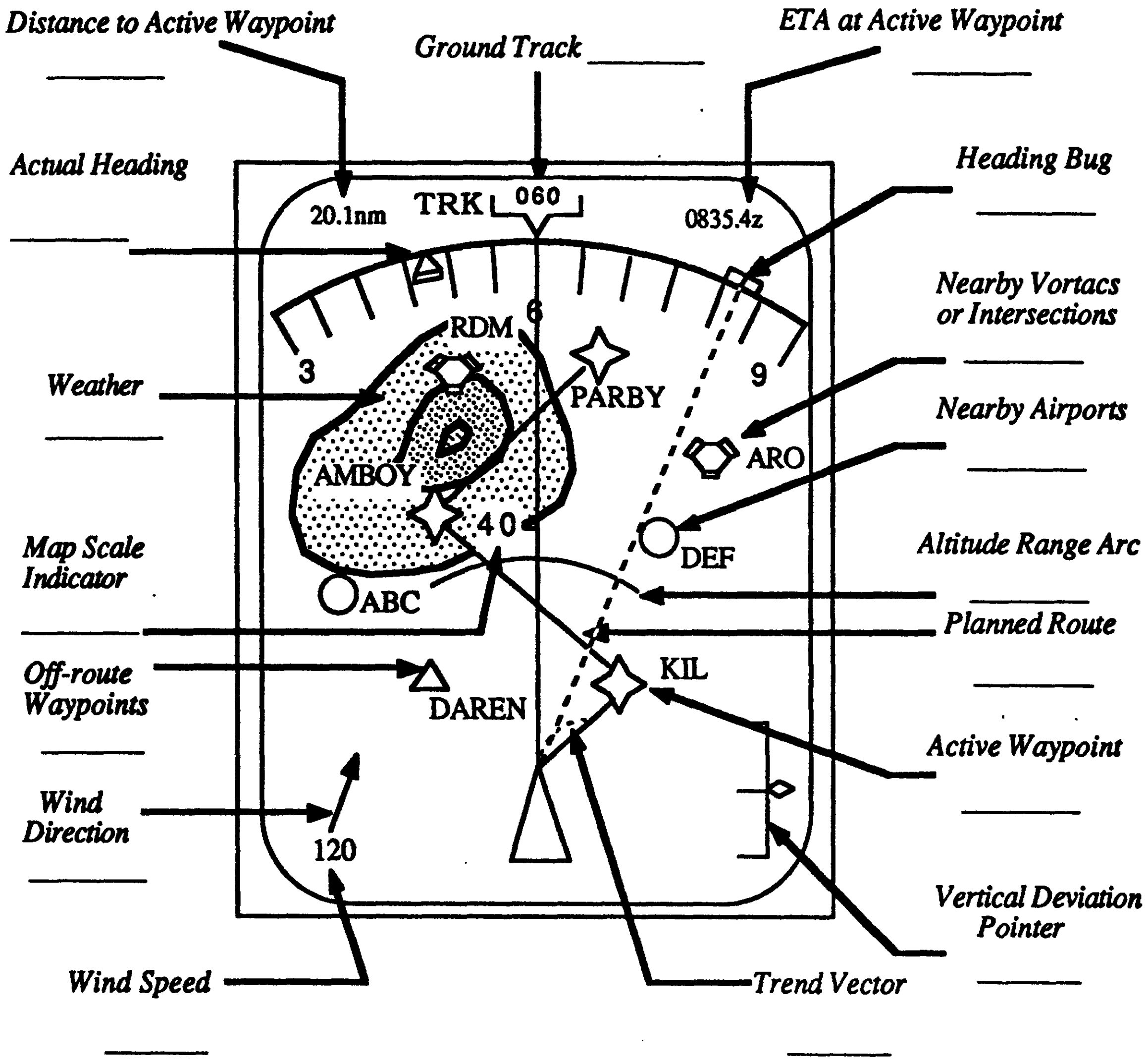
1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

CRUISE

Please rate each piece of information on how much you need it during **CRUISE.**

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Mark your rating in the space provided below each label.



CHANGE IN WORKLOAD

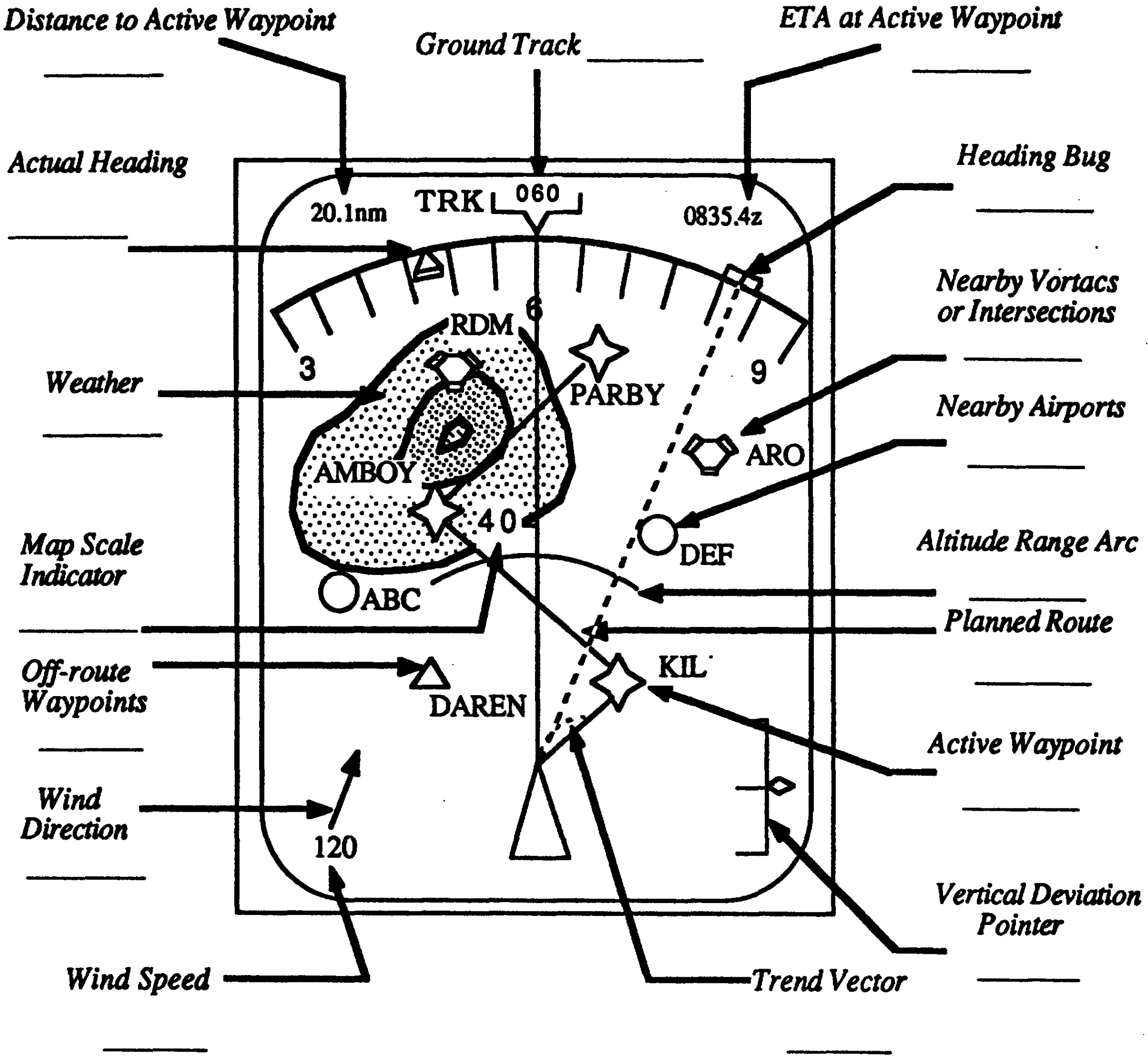
1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

DESCENT

Please rate each piece of information on how much you need it during **DESCENT.**

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Mark your rating in the space provided below each label.



CHANGE IN WORKLOAD

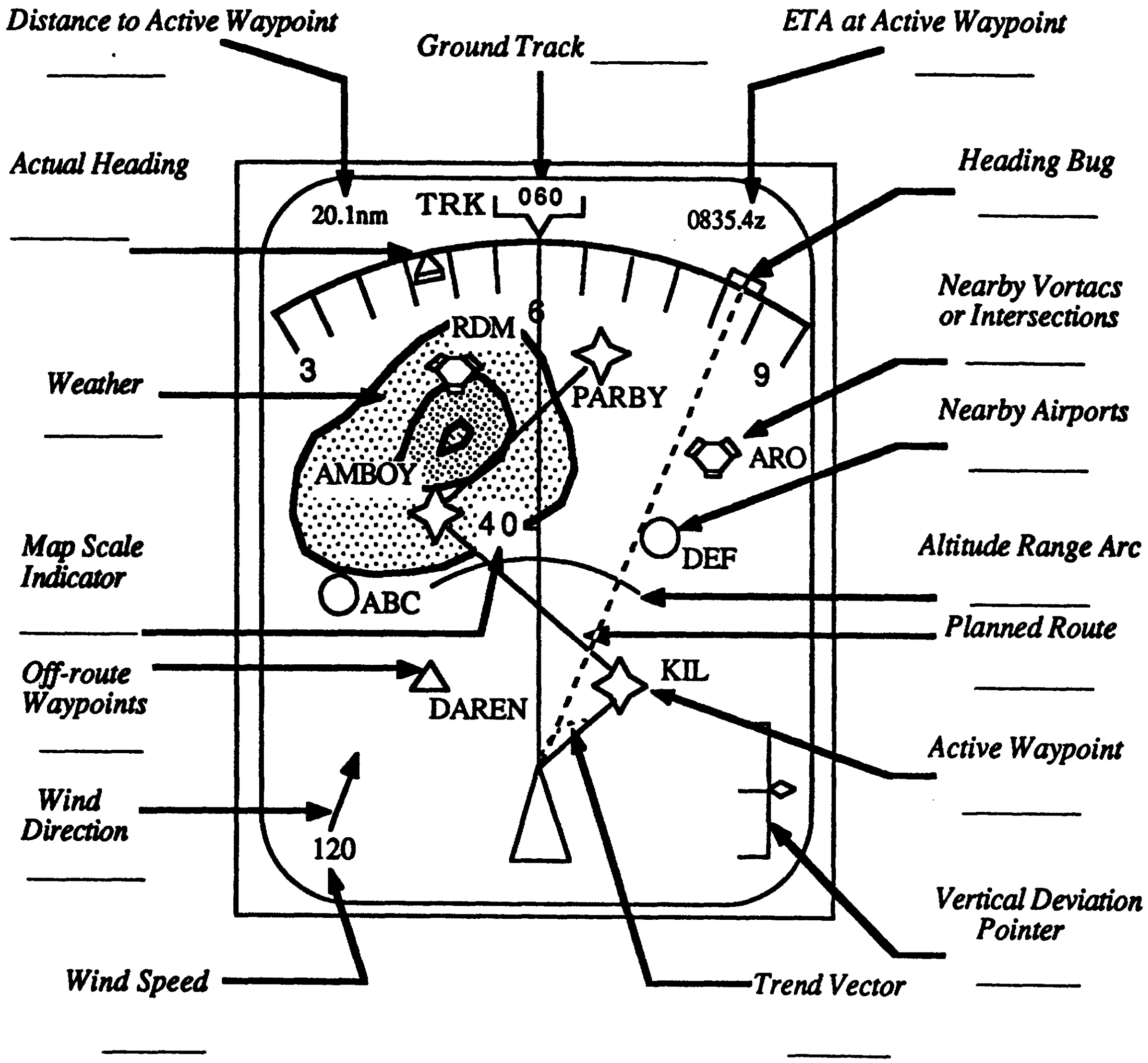
1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

TERMINAL AREA

Please rate each piece of information on how much you need it in the TERMINAL AREA.

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Mark your rating in the space provided below each label.



CHANGE IN WORKLOAD

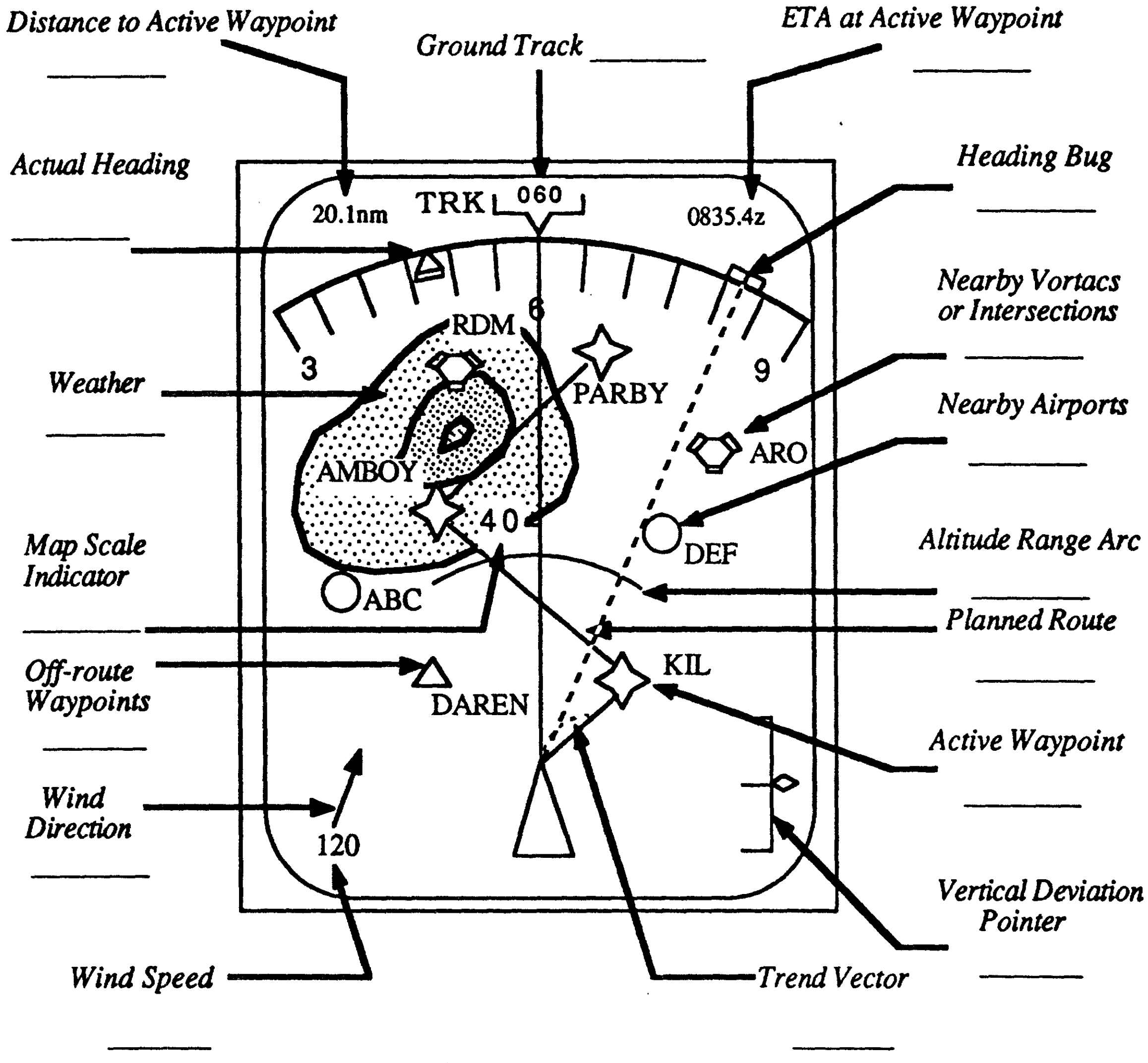
1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

FINAL APPROACH

Please rate each piece of information on how much you need it **FINAL APPROACH.**

1	2	3	4	5
very low need	low need	moderate need	high need	very high need

Mark your rating in the space provided below each label.



Distance to Active Waypoint ______

Ground Track ______

ETA at Active Waypoint ______

Actual Heading ______

Heading Bug ______

Nearby Vortacs or Intersections ______

Weather ______

Nearby Airports ______

Map Scale Indicator ______

Altitude Range Arc ______

Planned Route ______

Off-route Waypoints ______

Active Waypoint ______

Wind Direction ______

Vertical Deviation Pointer ______

Wind Speed ______

Trend Vector ______

CHANGE IN WORKLOAD

1	2	3	4	5
decreased workload with FMC		no change in workload		**increased** workload with FMC

IV. ATC Initiated Clearance Amendment Questions

The following questions concern the process of accepting (or rejecting) clearance amendments initiated by Air Traffic Control (ATC).

1) In *a* and *b* below, two proposed methods of clearance deliveries are described. (Assume that there is voice backup for both methods.) For each method, indicate whether you, as the user of the future system, feel that such a procedure would be desirable. Could you foresee any problems or concerns with the processes described?

a) *Text Format Clearance Delivery* A clearance amendment would show up as a textual message on the CDU. Once you have accepted it, you would be required to program it into the FMC through the CDU, as is the case today.

Desirability:

Remarks:

b) *Graphical Clearance Delivery* A clearance amendment would show up as a different color path on the moving map display, and pilots would simply be required to accept or reject the clearance with a single command. (The active route would also be displayed until the amendment was accepted, at which time the amended clearance would become the active route.) Thus, pilots would not have to re-program the Flight Management Computer using the CDU.

Desirability:

Remarks:

2) Please list the first three factors that come to mind that influence your decision to accept or reject a clearance amendment given by ATC.

a) ____

b) ____

c) ____

3) Approximately what percentage of time do you find that you cannot accept a clearance amendment? (Please give a specific percentage.)

____

4) Please list the three most common reasons why you reject clearance amendments.

a) ____

b) ____

c) ____

5) Approximately what percentage of time do you find that you are unable to execute a clearance that you had previously accepted? (Please give a specific percentage.)

____

6) From your experience, what kind of information is most easily *misunderstood* during a clearance delivery? Please explain.

7) While **departing** and still inside the terminal area, approximately what percentage of time are you required to enter at least one clearance amendment into the CDU?

a) 0% — 10 %
b) 11%— 20%
c) 21% — 30%
d) 31% — 40%
e) 41% — 50%
f) greater percentage
(please specify): __________

8) While **approaching** and still inside the terminal area, approximately what percentage of time are you required to enter at least one clearance amendment into the CDU ?

a) 0% — 10 %
b) 11%— 20%
c) 21% — 30%
d) 31% — 40%
e) 41% — 50%
f) greater percentage
(please specify): ______________

9) How often do you find that entering a clearance amendment into the CDU while in the terminal area is a high workload situation?

1	2	3	4	5
rarely		sometimes		almost always

10) What do you find to be the three most common reasons to initiate a request for an amendment?

a) ____

b) ____

c) ____

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