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Three Input Concepts for Flight Crew Interaction With Information Presented on a Large-Screen Electronic Cockpit Display

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Summary

A piloted simulation study has been conducted to compare three different input methods of interacting with a large-screen, multiwindow, "whole-flight-deck" (WFD) display for management of transport aircraft systems. One input method, the "thumball" concept, used a miniature trackball embedded in a conventional side-arm controller for cursor movement and numerical entry. The second method, the touch screen concept, provided data entry through a capacitive touch screen installed on the display surface. The third method, the voice concept, used a speech recognition system with input through a head-worn microphone.

No single input concept emerged as the most desirable method of interacting with the WFD display. Subjective results, however, indicated that the voice concept was the most preferred method of data entry and had the most potential for future applications, provided there are further advancements in voice recognition technology. On the other hand, the objective results indicated that, overall, the touch screen concept was the most effective input method. The quantitative results also showed significant differences between the time required to perform specific tasks and the input concept employed, with each concept providing the best performance relative to a specific task. These results suggest that a system combining all three input concepts might provide the most effective method of interaction.

Introduction

The rapidly increasing use of computer systems in the cockpit is providing an increase in information that can be displayed and managed within the limited flight deck environment and, as a consequence, more operational capability to the transport aircraft crew. Utilization of multiple (four to eight) small-screen color cathode ray tubes (CRT's) as multimode, multifunction indicators appears to be the current solution to consolidate and integrate this information. A potential alternative for future application is a large-screen, multiwindow, "whole-flight-deck" (WFD) display for the management of aircraft systems (refs. 1 to 3). A WFD display accommodates most aircraft information on one large CRT (ultimately to be replaced by one large, flat-panel display) in the pilot's primary head-down field of view. Figure 1 shows an example of a WFD display consisting of a primary flight display (PFD), a navigation display (ND), an automatic guidance and control unit (AGCU), a navigation control display unit (NCDU), engine displays, an advisory caution and warning system (ACAWS), and a subsystem display area. To effectively interact with such a display, pilots must be provided with user-friendly man-machine interface methods.

A piloted simulation study was conducted to compare three different input concepts as methods of interacting with a large-screen WFD display. The "thumball" concept used a miniature trackball embedded in a conventional side-arm controller; the touch screen concept used a capacitive touch screen installed on the CRT; and the voice concept utilized a voice recognition system installed in a personal computer and interfaced to the simulation computer.

A similar experiment was previously conducted that also compared three input concepts as methods of interacting with a WFD display (ref. 4). The present study was done as a follow-on to that work to compare one different input concept and improved implementations of the others.

This paper describes each of the three input concepts and the experimental design in detail. Objective data as well as subjective results, garnered from pilot questionnaires and discussions, are also presented.

Simulator Characteristics

Simulator Cockpit

This study was conducted in the Crew Station Systems Research Laboratory using the Advanced Display Evaluation Cockpit (fig. 2), a fixed-base, part-task research transport simulator outfitted with large CRT displays of the type which might be used on future transport aircraft (ref. 5, pp. 84 to 88). The equipment used consisted of the three study input devices, a 19-in. color raster CRT, a side-arm controller, and a throttle. Only the pilot side (left side) of the simulator cockpit was used for the study.

Aircraft Model

The aircraft model utilized for this study was a linear representation of the NASA Transport Systems Research Vehicle (TSRV), a specially instrumented Boeing 737-100 (ref. 5, pp. 77 to 83). The TSRV is a research aircraft that was modified to incorporate electronic displays and all-digital flight-control computers. The simulated aircraft was configured for low-speed level flight and was flown in the "manual electric" control mode; therefore, there was no attitude hold present. The aircraft model, implemented in FORTRAN, was hosted on a Digital Equipment Corporation VAX-11/780 minicomputer at an iteration rate of 15 Hz.

Graphics Display

The graphics display created for this experiment was a partial representation of a WFD display. A

WFD display is one in which most of the aircraft state information is located on one large CRT; thus the need for specialized dedicated instruments is eliminated. The large screen was partitioned into multiple display formats in various window areas. The relative sizes of these areas were under computer control to allow selected areas to expand or shrink as a function of events. The display for this study consisted of a partial primary flight display (PFD), engine displays, an advisory caution and warning system (ACAWS), a menu for displaying aircraft subsystems, and a menu for selecting symbology for presentation on a navigation display (fig. 3). There was also an area reserved below the PFD for displaying prompts to instruct the pilot which task to complete next.

The WFD display was produced on an Adage RDS-3000 programmable display generator using the Real-Time Animation Package (RAP). RAP is a high-level graphics programming language similar to the C language. This graphics software ran at an iteration rate of 2.5 Hz, six times slower than the aircraft model, primarily due to the inefficiency of the RAP language. As a result, there was a delay between the time an input was introduced into the system and the time the updated information was displayed on the screen. Although the graphics iteration rate was slower than that desired for real-time simulation, it was anticipated that this rate would have approximately the same effect on pilot performance with each input concept and hence would create little or no concept bias in this study.

In order to obtain the 2.5-Hz graphics iteration rate, a navigation display was not included in this WFD display. The PFD was also stripped of all unnecessary information in order to further reduce the time required to render the entire WFD display. The information remaining in the partial PFD consisted of an aircraft symbol, pitch indices, and heading, roll-angle, airspeed, and altitude numeric indicators. This information was all that was required to perform the basic flying task used in this study.

The ACAWS was located in a window directly beneath the engine displays. This area was event driven. When a warning or caution was introduced into the system, the engine displays were automatically reduced in size and the ACAWS area was enlarged to list the subsystems containing failures. Additionally, the menu used to display the aircraft subsystems was reordered, listing the subsystems with warnings at the top of the menu in red and those with cautions below in yellow (fig. 4).

The navigation symbology menu of reference 6 was used in this study. The menu is generally used to select various symbols for presentation on the navigation display. In this instance, the navigation display was not included as part of the WFD display; however, the menu was used to provide a typical input task for the evaluation of the input concepts.

Input Concepts

Input Tasks

In order to evaluate the usefulness of each input concept as a means of interfacing with the WFD display, each pilot was asked to perform several tasks. There were three basic types of tasks (table I), which are described as follows.

Task 1—Display a Subsystem

This task required changing the active menu (the menu that was in use at the time) from the navigation symbology menu to the subsystem menu and then selecting the indicated subsystem.

Task 2—Display the Subsystems Having a Warning and a Caution, and Clear Those Failures

This task required the subsystem having the warning to be displayed and the failure cleared. The same would then be done for the caution failure.

Task 3—Change the Reference Altitude by 1700 Ft

This task required engaging the numerical entry mode on the navigation symbology menu, changing the number to the indicated value, and then exiting the numerical entry mode.

Input Devices

Thumball

The thumball is a miniature trackball embedded in a conventional side-arm controller (fig. 5 and refs. 7 and 8). The trackball is rotated with the thumb to enable interaction with the WFD display. It is an input device that provides position information in both the horizontal and the vertical direction. Output magnitude is directly related to rotation speed.

The thumball concept utilized the thumball combined with a button and trigger located on the side-arm controller. With this system, the pilot was able to interact with all aircraft subsystems using one hand. Horizontal rotation of the thumball controlled the active menu designation, indicated by a magenta border surrounding the active menu, while vertical rotation of the thumball controlled the cursor within that menu. When the thumball was rotated to the right, the subsystem menu became active; when moved to the left, the navigation symbology menu became active. The cursor moved up or down through the active menu when the thumball was rotated up or down. A quick rotation caused the cursor to move two positions, while a slower rotation moved the cursor one position at a time. Both menus had a cursor wraparound feature which allowed the cursor to move from the topmost menu item to the bottommost item and vice versa.

Task 1, displaying a subsystem, required a maximum of five inputs with the thumball system. First, the pilot changed the active menu from the navigation symbology menu to the subsystem menu by rotating the thumball to the right. Next, the cursor was moved three menu locations to the desired menu item. The item was then selected by pulling the trigger. During task 2, subsystem failure, the cursor was initially positioned next to the warning item at the start of the task by the ACAWS. As a result, cursor movement was not necessary. The trigger was pulled to display the subsystem containing the warning. The warning was then cleared by pressing the right button on the control stick. The same steps were conducted for the subsystem containing the caution (a total of four inputs). The pilot changed the reference altitude value for task 3 by moving the cursor three menu locations and then engaging the numerical entry mode by pulling the trigger. The pilot then changed the reference altitude by rotating the thumball up to increment and down to decrement the value. A slow movement of the ball changed the number by 100; a quick movement changed it by 1000. After the pilot obtained the desired value, he exited the enter-number mode by pulling the trigger (a minimum of nine inputs).

Touch Screen

The touch screen system utilized a 19-in. capacitive touch screen that required skin contact directly with the surface of the screen for activation to occur (refs. 9 and 10). This concept operated in an intuitive manner. All that was necessary to activate a menu was to touch within the menu itself. To convey precisely which menu item was being chosen, the background color of an item changed when its touch zone was being pressed. As long as pressure was applied to the screen, nothing was activated. A menu item was selected when the finger was released from the screen. Performing a selection by this method helped prevent inadvertent selection of an undesired item. Note that cursor moves were not required for the touch screen concept. A direct selection of the proper item was possible.

A subsystem was displayed for task 1 by the pilot touching the required item in the subsystem menu and exiting from the screen. To complete task 2, the subsystem containing the warning was displayed by the pilot selecting the appropriate menu item. At that time, a "delete" option would be listed in the ACAWS area (fig. 6). The warning would then be cleared through selection of this option. This process was repeated for the subsystem containing the caution. The pilot changed the reference altitude value (task 3) by selecting the numerical menu item in the navigation symbology menu. As a result, arrows were displayed at the bottom of the navigation symbology menu (fig. 7). Pressing the thicker arrows changed the number by 1000, while pressing the thin arrows resulted in change by 100. The numerical value was continually altered while pressure was placed on an arrow. After the proper value was obtained, the enter-number mode was exited by selecting the numerical menu item again.

Voice

The voice concept utilized a speaker-dependent template-matching voice recognition system with input through a head-worn microphone (refs. 11 to 14). The voice system was operated in a "connected-speech" recognition mode that enabled the system to recognize phrases embedded within a spoken sentence. Because of the delay caused by the graphics iteration rate, it was necessary for the pilot to pause after each phrase; therefore, recognition was more comparable to isolated word mode. When a spoken phrase was acknowledged by the system, a code associated with that phrase was sent to the host computer. It was necessary to train the system for each subject individually for the vocabulary used for the simulation. The following list is the 34-phrase vocabulary set used in this study:

GRP	HYDRAULICS	ZERO
NAVAIDS	ELECTRICAL	ONE
LOCAL AIRPORTS	ENVIRONMENT	TWO
WAYPOINT DATA	CHECKLIST	THREE
STRAIGHT VECTOR	SUBSYSTEM	FOUR
TREND VECTOR	DELETE	FIVE
RANGE ARC	ACAWS MENU	SIX
REFERENCE ALTITUDE	SELECT	SEVEN
SCAN MODE	CLEAR	EIGHT
SECONDARY ENGINE	EXIT	NINER
FUEL	ENTER	HUNDRED
		THOUSAND

The voice system operated in a manner similar to the touch screen system. To select a menu item, the subject first had to choose the item by speaking the vocabulary phrase for that item and then select the item by saying "select." When the item was chosen, the background color of that item was changed to notify the subject that the voice phrase was acknowledged by the computer. "Select" was used to engage the menu item. This two-step method of selection helped prevent accidental activation of an undesired item. As with the touch screen concept, cursor movements were not required since direct selection of the items was possible.

Task 1 required the pilot to display a subsystem by speaking the vocabulary phrase for the requested subsystem and then selecting the subsystem by saying "select." Subsystem failures for task 2 were cleared by the pilot speaking the phrase for the subsystem containing the warning, followed by "select." As the subsystem was being displayed, a delete option was listed in the ACAWS area, similar to the touch concept (fig. 6). The pilot would clear the warning by speaking "delete," followed by "select." The same would then be done for the subsystem containing the caution. For example, to clear a warning in the electrical subsystem and a caution in the environment subsystem, the inputs would be as follows: "electrical," "select," "delete," "select," "environment," "select," "delete," "select." For task 3, the pilot changed the reference altitude value by saying "reference altitude," followed by "select." A scratch-pad area was then displayed below the reference altitude number in the navigation symbology menu (fig. 8). The pilot entered the desired value into the scratch-pad area by speaking the individual digits followed by the phrase "thousand" or "hundred." For example, to enter the value 6300, the pilot would say "six," "three," "hundred." The reference altitude was then equated to the scratch-pad value by the pilot saying "enter." The scratch-pad area was utilized so the pilot could verify that the proper value was entered before activation took place.

Experiment Description

Experimental Design

A full-factorial design with four replications for each condition was used for this study. The factors of the experiment were pilots, input concepts, input tasks, and versions of the various input tasks (replicates).

Each pilot was given four versions of each of the three tasks while concentrating on flying the simulated aircraft (experimental tasks) and also while focusing on just the tasks themselves (training tasks). This setup resulted in a total of 24 tasks for every input concept. The versions within a task were designed to have the same number of cursor moves and selections, so each would take approximately the same amount of time to perform. The pilot was prompted to perform a particular task by a message displayed in the center of the screen.

Objective Performance Measures

Performance data were collected for each experimental task. The time to complete each task, from the moment the prompt was displayed until the task was completed, was recorded. The average altitude and airspeed during each experimental task were also obtained.

Experimental Conditions

Six U.S. Air Force EC-135 pilots and six U.S. Air Force C-21 pilots were used in this study. The EC-135 pilots had a cumulative total of 16 450 flying hours, with an 1100-hour minimum and a 4500-hour maximum flying time. The C-21 pilots had accumulated 6825 flying hours, with a 275-hour minimum and a 2600-hour maximum flying time. Each pilot was asked to perform 12 training tasks and then 12 experimental tasks with each input concept. Table II shows the sequence of input concepts given to each pilot. The same 12 tasks were given in each instance but in random orders. During the experimental tasks, predetermined time intervals were randomly maintained between tasks so the test subject would not learn to anticipate when the next trial would be given. For the experimental tasks, the pilot was asked to maintain straight and level flight during turbulent conditions at an altitude of 1500 ft, an airspeed of 130 knots, and a heading of 360°. The turbulence was introduced into the model by superimposing noise values, using normally distributed random numbers, on the control stick.

At the start of each session, the pilot was provided with training time to become familiar with the aircraft simulator. Prior to data collection for each input concept, the concept was demonstrated and the pilot was allowed to practice with it until he was comfortable with the operation. A sample prompt for every type of task was also furnished so the pilot would know what to expect when the data collection began. The training tasks were then given for a concept, followed by the experimental tasks for that same concept. The training tasks were used only for training, and this training allowed the pilot to become thoroughly familiar with the operation of the input concept for the various tasks.

Data collected during the experimental tasks were used in the analysis of the performance measures. Input errors were recorded, and those tasks that resulted in errors were repeated at the end of that session. A subjective questionnaire was given at the completion of data collection for each input concept. A final subjective questionnaire was also given at the completion of the session to get a comparative opinion. The questionnaires are shown in appendixes A and B.

Results and Discussion

Objective Results

Analysis of Performance Measures

Table III is a summary of the analyses of variance for the three performance measures recorded during the experimental tasks, with third-order and higher interactions pooled in the error term. Results were considered statistically significant at the 95-percent confidence level. The following sections discuss some of the significant sources of variation for the performance measures. The interactions that are not discussed were not considered to be contributing factors to the analysis of the data.

Input concepts. The task completion time and average airspeed measures identified significant variability among concepts. (See table IV.) The lowest mean completion time across all tasks was recorded when the touch screen was used. This is understandable since the system operated in such a straightforward manner. With this concept, the pilot only needed to press the desired item and exit from the screen for selection. The voice concept resulted in the longest mean completion time. This could be attributed to the fact that there was a time delay from the moment the pilot spoke a phrase to the moment the WFD display reacted to the input. Therefore, a pause was necessary between each phrase. Also, a phrase would have to be repeated occasionally because it was not recognized by the voice recognition system. The thumball concept resulted in a mean completion time slightly slower than that of the touch screen concept. Although this method enabled all input to be made with one hand from the side-arm controller, more time would occasionally be required to complete a task because the cursor was sometimes driven past the desired menu item and correction was necessary. This occurrence was caused by the slow graphics iteration rate as well as the rotation rate of the ball. These limitations are discussed in more detail in the *Subjective Results* section.

Since the pilot's hands were always on the controls with the voice or thumball concepts, it was expected that the average airspeed would deviate less when these systems were used. This expectation held true for the voice concept; however, the data did not indicate this occurrence for the thumball concept. The airspeed deviation for the tasks performed with the thumball concept may have been caused by inadvertent control stick inputs when rotating the thumball. The airspeed variation for the tasks performed with the touch screen concept may have also been caused by inadvertent control stick inputs when the pilot leaned forward to press the screen.

Tasks. The task factor was statistically significant for the performance measures of task completion time and average airspeed. Table V shows that selecting a subsystem was the quickest task across all input concepts, while changing the reference altitude was the most time-consuming. These results were expected since selecting a subsystem was the simplest task to perform and changing the reference altitude was the most complicated.

The mean airspeed during task 2, handling cautions and warnings, deviated from the means of the other two tasks, thus accounting for the significance of this interaction term. This occurrence could be attributed to the fact that two of the four versions of task 2 included an engine failure, which affected airspeed by shutting down engine 2. Although the mean airspeed during task 2 deviated from the others, it was nearer the designated airspeed of 130 knots.

Interaction of pilot and input concept. The interaction of pilot and input concept for task completion time is presented graphically in figure 9 and numerically in table VI. In general, all pilots performed best with the touch screen concept and worst with the voice concept. The first three pilots were an exception, with pilots 1 and 3 performing better with the thumball concept and pilot 2 performing best with the voice concept. Pilot acceptance or preference is one explanation as to why performance across pilots varied among concepts. Another reason may be the physical characteristics of the subjects. For example, a pilot with large fingers may not have been able to select items easily using the touch screen, or a pilot with a temporarily hoarse voice may have had trouble getting the voice recognition system to acknowledge his commands.

Interaction of input concept and task. Not unexpectedly, the completion time differences between the three input concepts varied with the task being performed, as indicated by the significance of the interaction of input concept and task. Figure 10 and table VII show that the touch screen concept was well suited for tasks which involved on-off operations, such as selecting a subsystem (task 1). The voice concept was best suited for entering a numerical value (task 3). Subsystem failures (task 2) were handled more effectively with the thumball concept since fewer steps were required and the hands remained on the controls.

Analysis of Input Error Data

An input error was recorded for a particular task if the pilot incorrectly completed the task as stated in the prompt. There were 16 errors noted for the 432 tasks given during data collection. Table VIII shows the number of errors by task and input concept.

The touch screen concept resulted in the most recorded input errors, particularly for entering the reference altitude. These errors were caused by the pilots exiting the enter-number mode when the improper value was entered for the reference altitude. The location of the input arrows on the screen along with the size of the touch zone for each arrow and the spacing between menu items may have contributed to the error rate. The pilots occasionally exited the enter-number mode prematurely by accidentally pressing the reference altitude number menu item. Also, the improper numerical value was sometimes accepted because the number would be incremented or decremented one additional unit after the pilot's finger was removed from an arrow. This was caused by the delay in the system. Touch screen errors also occurred when an incorrect subsystem was selected and when a caution was cleared before a warning.

The thumball method of entry resulted in pilot errors for selecting an incorrect subsystem and accepting an improper reference altitude. These errors could be attributed to the delay in the system and also to the rotation rate of the ball. These problems are discussed in more detail in the *Subjective Results* section.

Note that the voice method of data entry resulted in no errors. After becoming familiar with the vocabulary set, the pilots had no trouble providing the proper inputs for the tasks. When the system would not recognize an input command repeatedly, that task was reiterated but was not recorded as an error.

Any task that resulted in an error was deleted from the performance measure set and repeated at the end of that session to provide a complete data set of correctly performed tasks.

Subjective Results

This section discusses the comments obtained from the questionnaires shown in the appendixes and observations made during data collection. The comments are discussed in terms of input concept, with general comments following.

Thumball Concept

In general, the thumball method of input was the least preferred of the three systems. This can be largely attributed to the movement of the ball itself. Most pilots commented that the ball movement was too sensitive in both the vertical and the horizontal direction. This sensitivity resulted in accidental menu changes when the pilot's thumb moved over the ball or when the pilot moved the ball vertically at a rapid pace. It was particularly difficult for the pilots to distinguish between fine and coarse movements, where rotating the ball slowly was considered a fine input and rotating it quickly was a coarse input. The pilots suggested that more friction be added to the ball so that it would not be so easy to rotate or that detents be added so distinct fine or coarse positions could be located. Additionally, the thumball rotation values can be programmed per application and could help alleviate some of these problems. A faster graphics iteration rate could also improve performance.

The task of entering numerical data was considered fairly difficult and relates directly to the fine-coarse movement issue. For this experiment, a fine movement changed the altitude value by 100 and a coarse movement changed it by 1000. A suggestion was made to use a horizontal movement to change the numerical value by 1000 and to use a vertical movement to change the value by 100. Another possibility suggested was to change the 100 and 1000 values independently, instead of having the values change incrementally. Additionally, an occasional input reversal would be given when the pilot changed the value. For instance, the ball was sometimes rotated downward to increase the number, or vice versa. This could be attributed to the fact that pilots associate a forward (or upward) movement of the hand controller to command a pitch down, or a lowering of the nose of the aircraft, and a backward (downward) input to command a pitch up. Most pilots felt, however, that the direction of movement was appropriate and believed errors would not occur with more training with the system.

Pilots reacted positively to using one hand to provide all inputs necessary to interface with the aircraft systems. The hands were positioned in a normal flying arrangement and did not have to be removed from the controls during input. It was felt that the interaction with subsystem failures was particularly easy with this concept.

The thumball system as a whole was favorably noted as having more feedback than the other two methods. Something was always moving or changing on the screen. This was not so with the touch screen and voice systems. However, some pilots were concerned that moving a ball embedded in the control stick could interfere with flying the aircraft.

It was also thought that it may be difficult to operate the ball effectively during turbulent conditions.

Touch Screen Concept

The touch screen method of entry was well suited for tasks which involved on-off operations. It was felt that the task of selecting subsystems by touch was easy and straightforward. Pilots selected menu items by merely touching the desired item and releasing.

The location of the touch screen was a concern for most pilots. They did not feel it was wise to have to remove a hand from a control and reach forward to press the screen. This could result in erroneous control stick movements. It was suggested the touch screen be positioned near the throttles so it did not require the pilot to reach forward. Pilots also found that they were concentrating more on the interactive task and were neglecting their flying. They thought that in an actual flight environment too much time would be spent "inside" the cockpit instead of scanning the outside environment.

The pilots considered the touch screen method of entering numerical data to be fairly difficult. The location of the input arrows appeared to be the major contributing factor. The arrows were positioned at the extreme lower left corner of the screen. Pilots commented it was awkward to reach diagonally to press the arrows and suggested positioning them on the right side of the screen. It was also suggested that the arrows be displayed higher on the screen or that a pop-up menu be used so the arrows could be larger in size. Some pilots had difficulty locating the touch zone for the arrow. It was suggested that each arrow be displayed inside a rectangular area so there would be no question where the zone was located.

Other considerations when using a touch screen as an input device relate to the parallax problem. If a user's eye position is not in the same general vicinity as the designer's was when the touch zones were defined, it may appear that to select an item the user must press below-above or to the left-right of the item. One possible solution to the selection problem may be to provide a cross hair on the screen to show the location where the system recognizes a screen press. Also, touch zones should be designed large enough to accommodate fingers of all sizes and to account for turbulent conditions. Finally, the touch screen technology utilized is dependent on the application. For instance, Air Force pilots must wear gloves during various phases of flight. Therefore, a touch screen activated by capacitance could not be used because direct contact must be made with the skin.

Voice Concept

According to pilot discussions, the voice concept was, overall, considered the most preferred method of input of the three systems evaluated. Operation was very straightforward. Menu items were selected by verbally stating the desired item and then verbally selecting it. Entering numerical data was considered easier than with the other two methods. Since this implementation did not require physically reaching or moving a device, the hands were free for flying the aircraft and performing other pertinent tasks. It was also noted that it was not necessary to concentrate as much on the menus during the tasks. When a command was given, it was only necessary to glance at the menus to make sure the command was recognized.

A concern with the voice concept was the recognition capability of the speech recognition system. A concentrated effort by the pilot was sometimes necessary when pronouncing a phrase from the vocabulary set. Inflections in the voice pattern for a particular phrase had to remain consistent or the phrase may not have been recognized by the system. The voice recognition system seemed to be rather intolerant to variations in the voice pattern. As a result, phrases would occasionally have to be repeated to ensure acknowledgment. Certain phrases were more sensitive than others. Some of these sensitive phrases were "select," "delete," "enter," "six," and "hundred."

Pilots also commented that the response time for command acknowledgment was too slow. There was a delay between when a phrase was spoken and when a change occurred on the display screen. This was due to the difference between the iteration rates of the graphics program, the aircraft model, and the voice recognition system. The pilots would have preferred being able to enter commands in a normal speaking voice without having to pause between each phrase to ensure recognition.

As mentioned previously, menu items were selected with a two-step process. First, the phrase for the item itself was spoken; then the item was engaged by the pilot speaking the phrase "select." This was done in order to avoid inadvertent selection of an item. Some pilots felt this two-step process of selection was redundant and would have preferred engagement when the item phrase was spoken. When developing a voice system, care should be taken to utilize the most appropriate selection method for the specific application.

In general, the pilots felt that the voice method of input could be useful in a transport environment and was the most promising technology, assuming advancements are made in voice recognition technology. Concern with operation in a routine cockpit environment was expressed, however. Potential problems could arise from radio transmissions, noise from decompression, warning bells, or background cockpit conversation. Also, in emergency conditions, voice inflections would probably change dramatically. Voice patterns could also be altered when a pilot is ill with a cold or sore throat. Some of these concerns could be remedied by turning the voice system "on" or "off" when necessary. Also, if voice input is combined with other input methods, such as the touch screen or thumball, these systems could serve as backups for each other in the event of problems.

General Comments

Table IX shows that the pilots, in general, preferred the touch screen method of entry for selecting subsystems, the thumball method for handling system failures, and the voice method for entering the reference altitude. These comments conform with the performance data. (See fig. 10.) Each of the three concepts was considered a good candidate as an input method for a particular task. This could suggest, then, that a combination of input systems would be more suitable for providing inputs in a cockpit environment rather than one particular concept.

Concluding Remarks

No single input concept emerged as the most desirable method of interacting with the whole-flight-deck display. The objective results of this study indicated that the touch screen concept was, overall, the most effective interface. Operation was intuitively simplistic since the pilots selected items by merely touching the desired item and releasing. Subjectively, favorable reactions to aspects of all three input concepts were expressed; however, the voice concept was the most preferred method of data entry. The voice concept was also considered to have the most potential for future applications, provided there are further advancements in voice recognition technology. Pilots noted it was desirable to operate most aspects of the pilot interface verbally. This freed the hands for flying the aircraft and performing other pertinent tasks, thus reducing pilot work load.

The completion time differences between the three concepts varied with the task being performed. For the present implementations, the touch screen concept was well suited for tasks which involved on-off operations; entering a numerical value was best handled with the voice concept; and subsystem failures were handled most effectively with the thumball concept. This suggests, therefore, that a combination of input concepts might be the most effective method of providing system inputs in a cockpit environment rather than one particular concept.

It is recommended that this study be repeated in a simulator environment that can provide real-time iteration rates for the aircraft model and graphic displays. This will determine if the present iteration rates had any effect on the results of this study.

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Appendix A

Subjective Questionnaire for Individual Input Concepts

Check one of the following: Pilot # ______

Thumball ______
Touch Screen ______
Voice ______

For questions 1–4 answer with:

A – Strongly Disagree With Statement
B – Mildly Disagree With Statement
C – Neither Agree Nor Disagree
D – Mildly Agree With Statement
E – Strongly Agree With Statement

______ 1. Entering reference altitude was an easy task.

______ 2. Making changes (such as selecting subsystems, menus, etc.) was easy.

______ 3. This system could serve a useful purpose in the air transport environment.

______ 4. This system could reduce my workload while flying in a "high activity" flight environment.

5. List two or more things (such as characteristics, etc.) you liked about this input system.

____
____
____
____
____

6. List two or more things you did not like about this input system.

____
____
____
____
____

7. Other comments regarding this input system.

____
____
____
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____

Appendix B

Final Subjective Questionnaire

Pilot # ______

Please rank order the three systems under consideration for each situation as listed below. (Assume only transport operations.)

A = Thumball
B = Touch Screen
C = Voice

	Selecting Subsystems	Handling Failures	Entering Ref. Altitude
1st			
2nd			
3rd			

	Potential Usefulness In Transports	Routine Flight Conditions	Emergency Flight Conditions
1st			
2nd			
3rd			

COMMENTS: ______________________________

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13. *TI-Speech^{TM} Installation Guide.* TI Part No. 2223181-0001 (Revision A), Texas Instruments Inc., Dec. 1985.
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Table I. Description of Versions of Input Tasks

Task	Version	Description of task
1	1	Display electrical subsystem
1	2	Display fuel subsystem
1	3	Display secondary engine subsystem
1	4	Display environment subsystem
2	1	Handle engine warning, electrical caution
2	2	Handle fuel warning, engine caution
2	3	Handle electrical warning, environment caution
2	4	Handle environment warning, fuel caution
3	1	Change reference altitude by +1700 ft
3	2	Change reference altitude by −1700 ft
3	3	Change reference altitude by +1700 ft
3	4	Change reference altitude by −1700 ft

Table II. Sequence of Input Concepts Given to Each Pilot

Sequence of input concepts[a] for pilot—											
1	2	3	4	5	6	7	8	9	10	11	12
A	A	B	B	C	C	A	A	B	B	C	C
B	C	A	C	A	B	B	C	A	C	A	B
C	B	C	A	B	A	C	B	C	A	B	A

[a]Input concepts: A—thumball; B—touch screen; C—voice.

Table III. Summary of Analyses of Variance for Performance Measures

Factor (a)	Degrees of freedom	Significance[b] of performance measures of—		
		Time	Altitude	Airspeed
P	11	**	**	**
C	2	**	—	**
T	2	**	—	**
V	3	—	—	**
$P \times C$	22	**	—	**
$P \times T$	22	**	—	—
$P \times V$	33	—	—	—
$C \times T$	4	**	—	—
$C \times V$	6	—	—	—
$T \times V$	6	**	—	**
Error	320			

[a]Factors are as follows: P—pilot; C—concept; T—task; V—version.
[b]Significance shown as follows:
—not significant at levels considered;
*significant at 5-pecent level;
**significant at 1-percent level.

Table IV. Means and Standard Deviations for Statistically Significant Measures of Input Concept Factor Across all Tasks

Input concept	Task completion time, sec		Airspeed, knots	
	Mean	Standard deviation	Mean	Standard deviation
Thumball	11.72	8.85	133.46	7.88
Touch screen	10.39	6.40	132.62	8.10
Voice	13.79	7.16	130.69	9.85

Table V. Means and Standard Deviations for Statistically Significant Measures of Task Factor Across all Input Concepts

Task (a)	Task completion time, sec		Airspeed, knots	
	Mean	Standard deviation	Mean	Standard deviation
1	5.59	2.87	133.28	7.70
2	12.24	7.02	130.16	10.11
3	18.07	6.55	133.33	7.52

[a]Tasks are as follows:
1—display a subsystem.
2—handle a warning and caution.
3—change reference altitude.

Table VI. Means and Standard Deviations for Statistically Significant Measures of Interaction of Pilot and Input Concept

Pilot	Task completion time, sec, for—					
	Thumball concept		Touch screen concept		Voice concept	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	10.33	6.60	11.67	7.30	10.94	5.26
2	17.10	10.59	14.83	9.54	14.34	6.46
3	8.77	6.24	9.24	6.02	16.50	9.13
4	12.93	13.45	10.88	6.30	16.59	8.17
5	12.88	10.27	10.18	6.89	18.42	9.56
6	11.61	8.19	10.31	4.55	11.75	5.94
7	13.54	11.38	11.04	7.03	13.55	6.52
8	10.90	6.87	8.59	4.58	14.61	7.94
9	9.93	7.07	8.48	5.06	13.30	6.79
10	10.91	7.44	9.59	4.78	11.89	5.21
11	9.80	7.99	8.67	7.50	11.08	6.00
12	11.97	8.12	11.15	5.56	12.49	6.05

Table VII. Means and Standard Deviations for Statistically Significant Measures of Interaction of Input Concept and Task

Input concept	Task completion time, sec, for—					
	Task 1[a]		Task 2[a]		Task 3[a]	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Thumball	7.09	2.18	5.88	2.17	22.20	7.76
Touch screen	3.92	1.97	10.17	2.49	17.06	5.11
Voice	5.75	1.82	20.66	4.60	14.95	3.98

[a]Tasks are as follows:
1—display a subsystem.
2—handle a warning and caution.
3—change reference altitude.

Table VIII. Number of Input Errors Recorded During Data Collection

Task	Number of errors for—		
	Thumball concept	Touch screen concept	Voice concept
Display a subsystem	2	1	0
Handle a warning and caution	0	2	0
Change reference altitude	2	9	0

Table IX. Input Concept Preference of Pilots for Various Tasks

Preference	Display a subsystem	Handle a warning and caution	Change reference altitude
Most	Touch screen concept	Thumball concept	Voice concept
Least	Voice concept	Voice concept	Touch screen concept

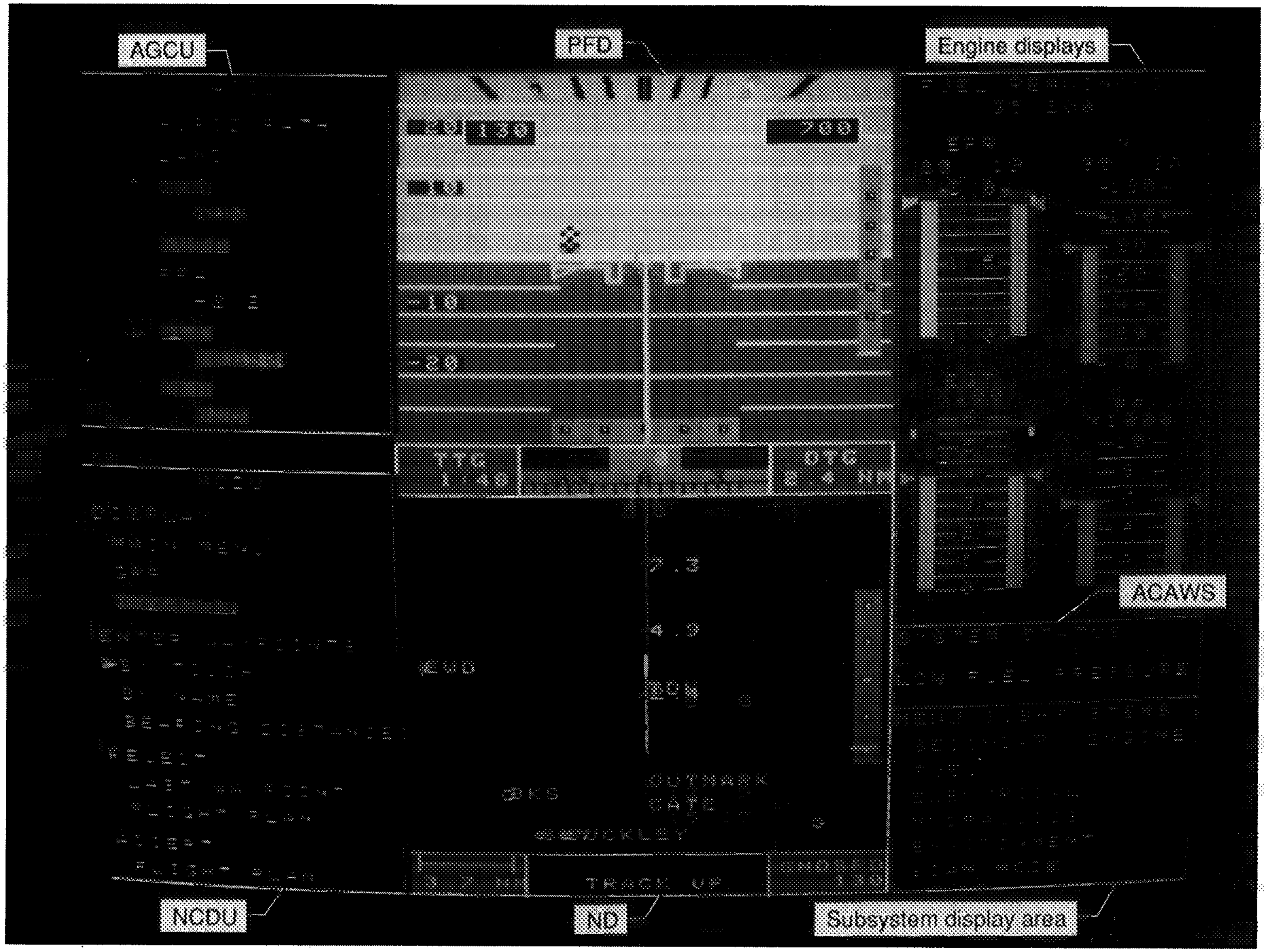

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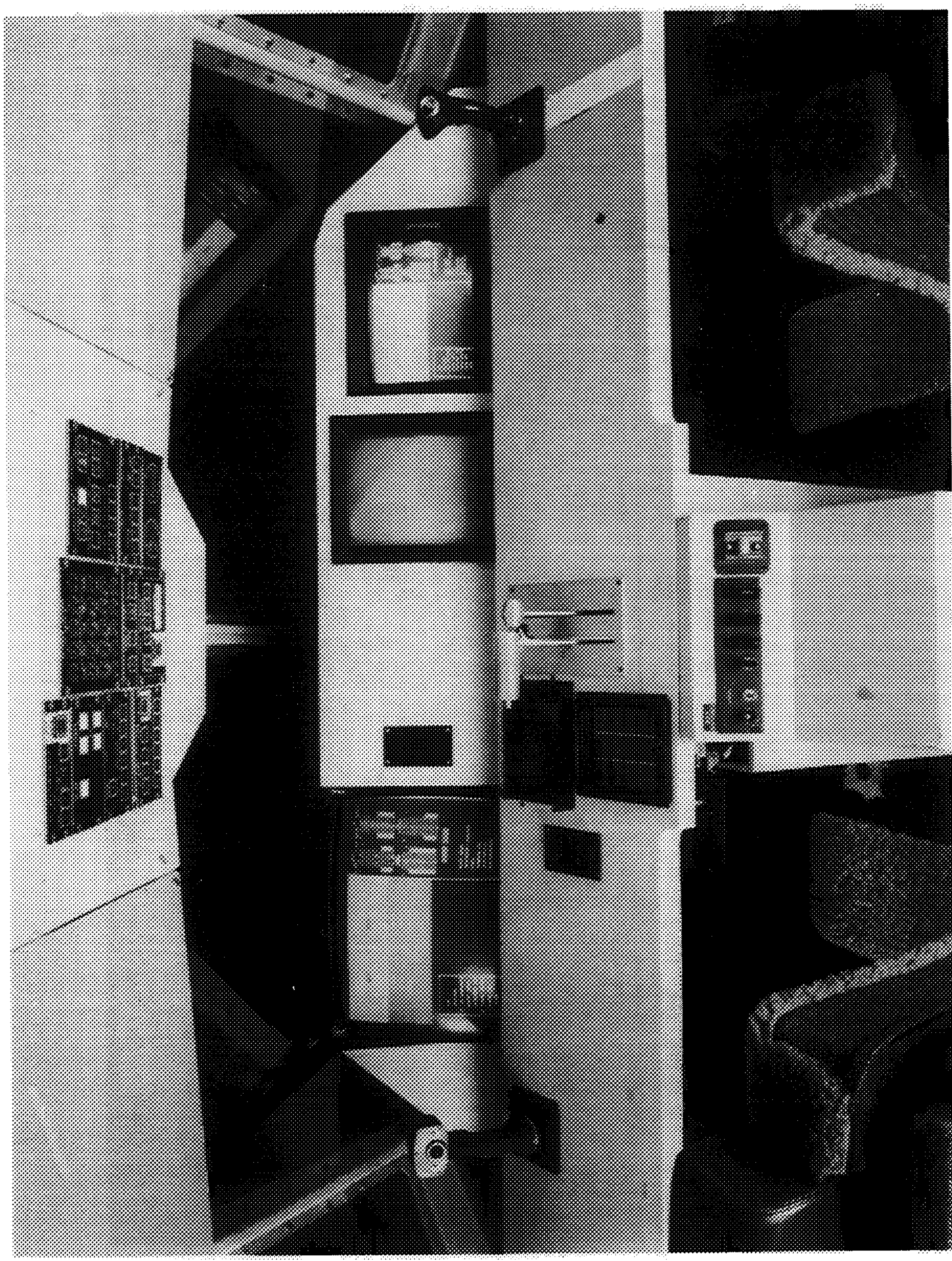
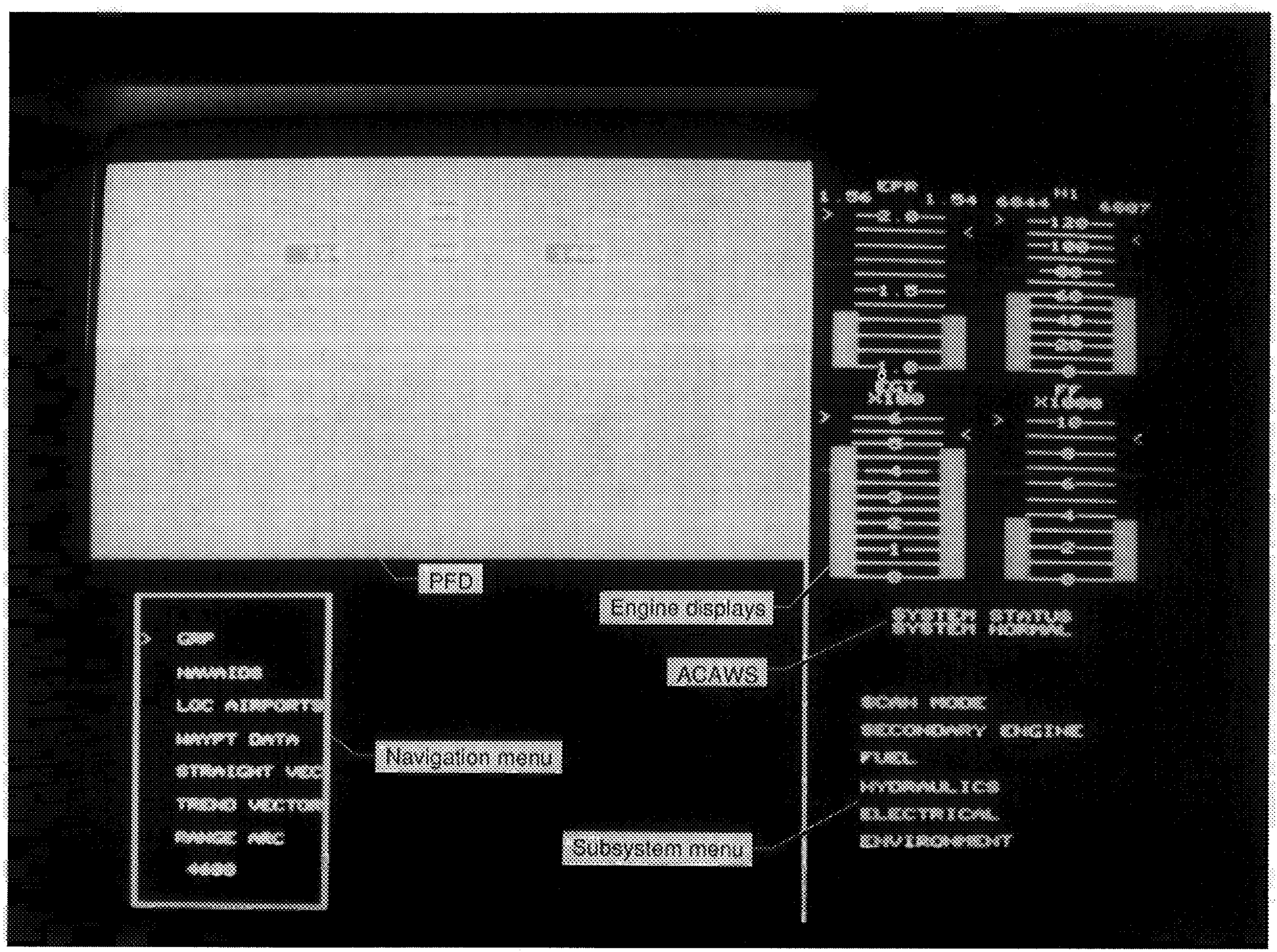
Figure 1. Whole-flight-deck display.



L-88-5396

Figure 2. Research simulator cockpit.



L-88-5378

Figure 3. Whole-flight-deck display used for present study.

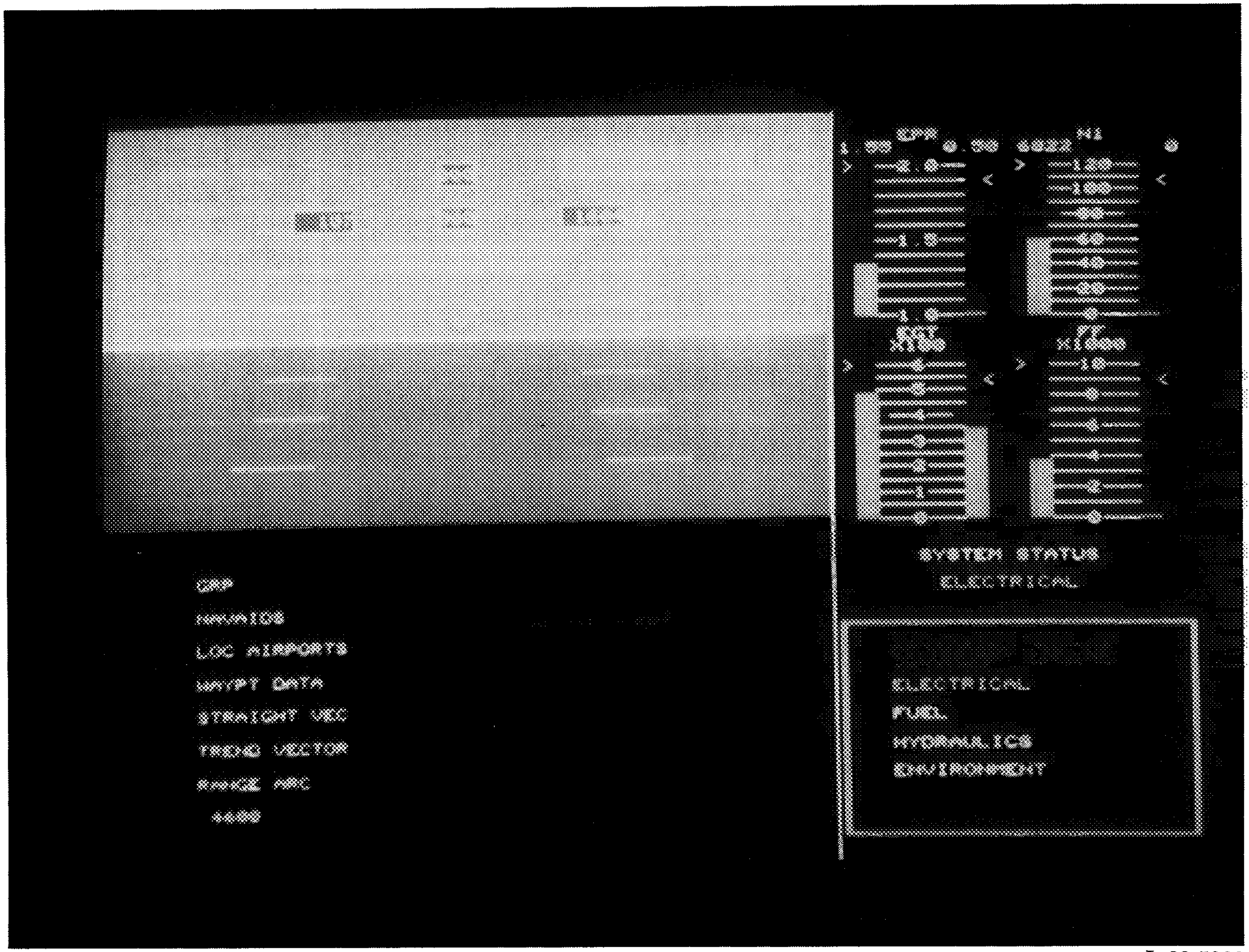


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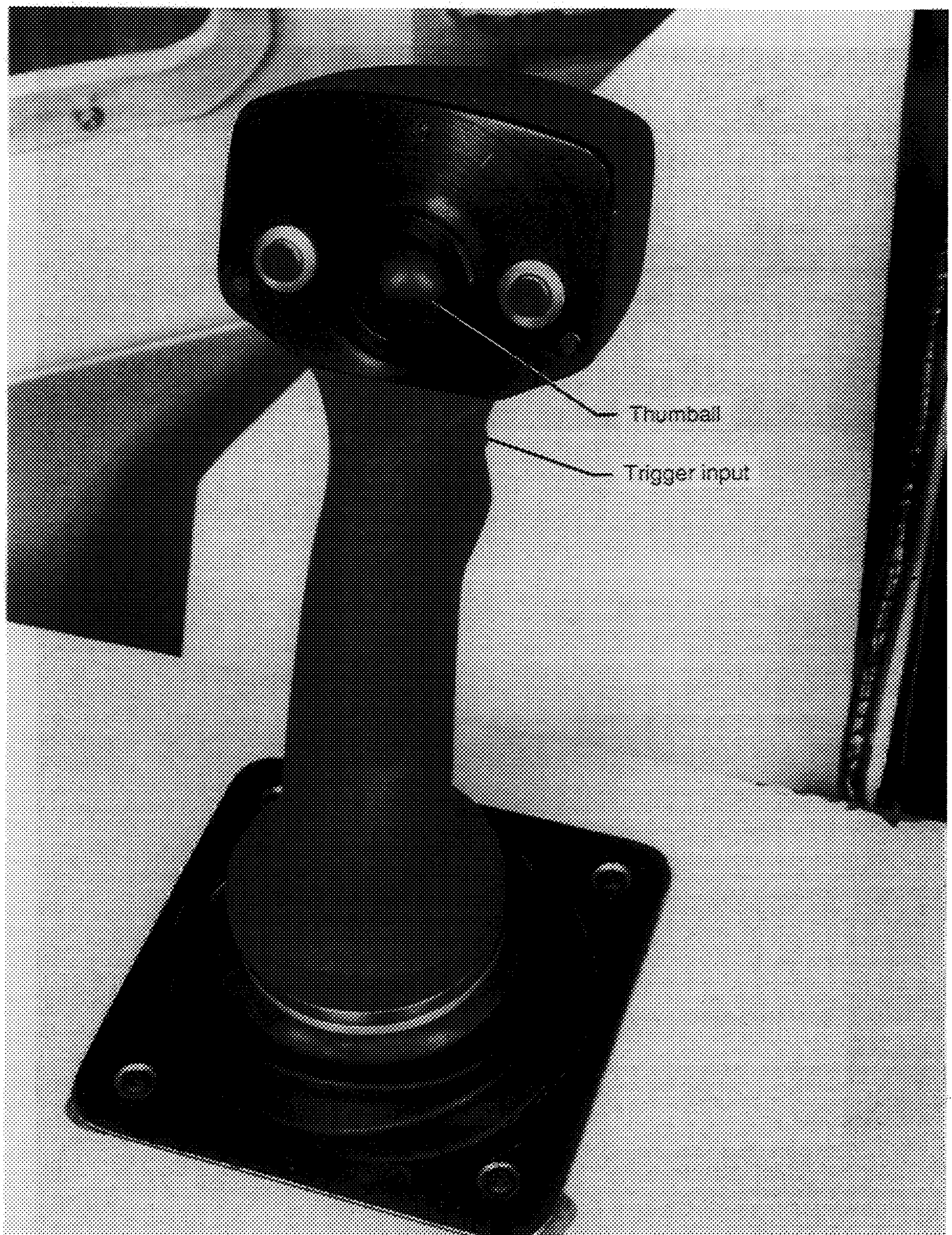
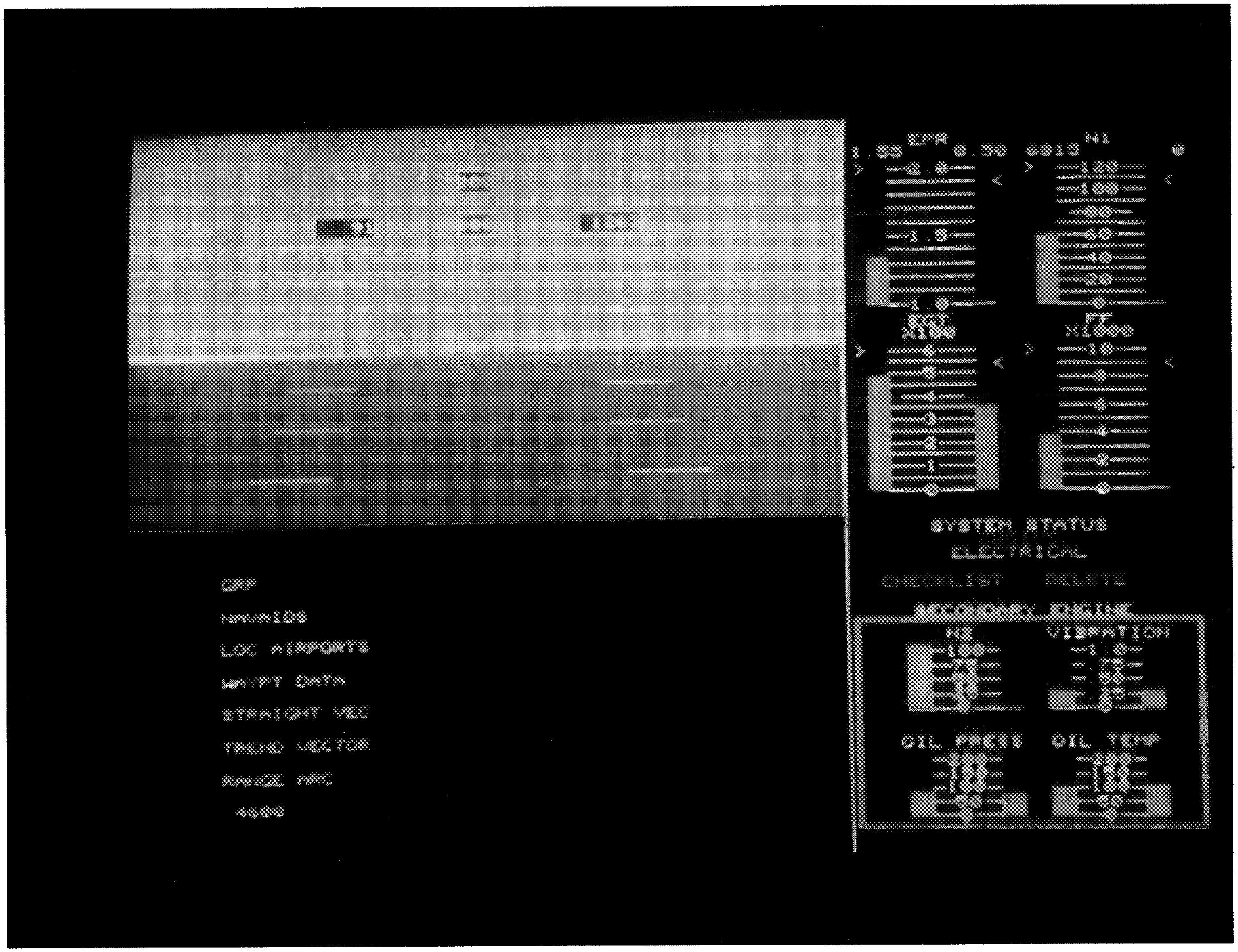
Figure 4. Whole-flight-deck display emphasizing advisory caution and warning system (ACAWS).



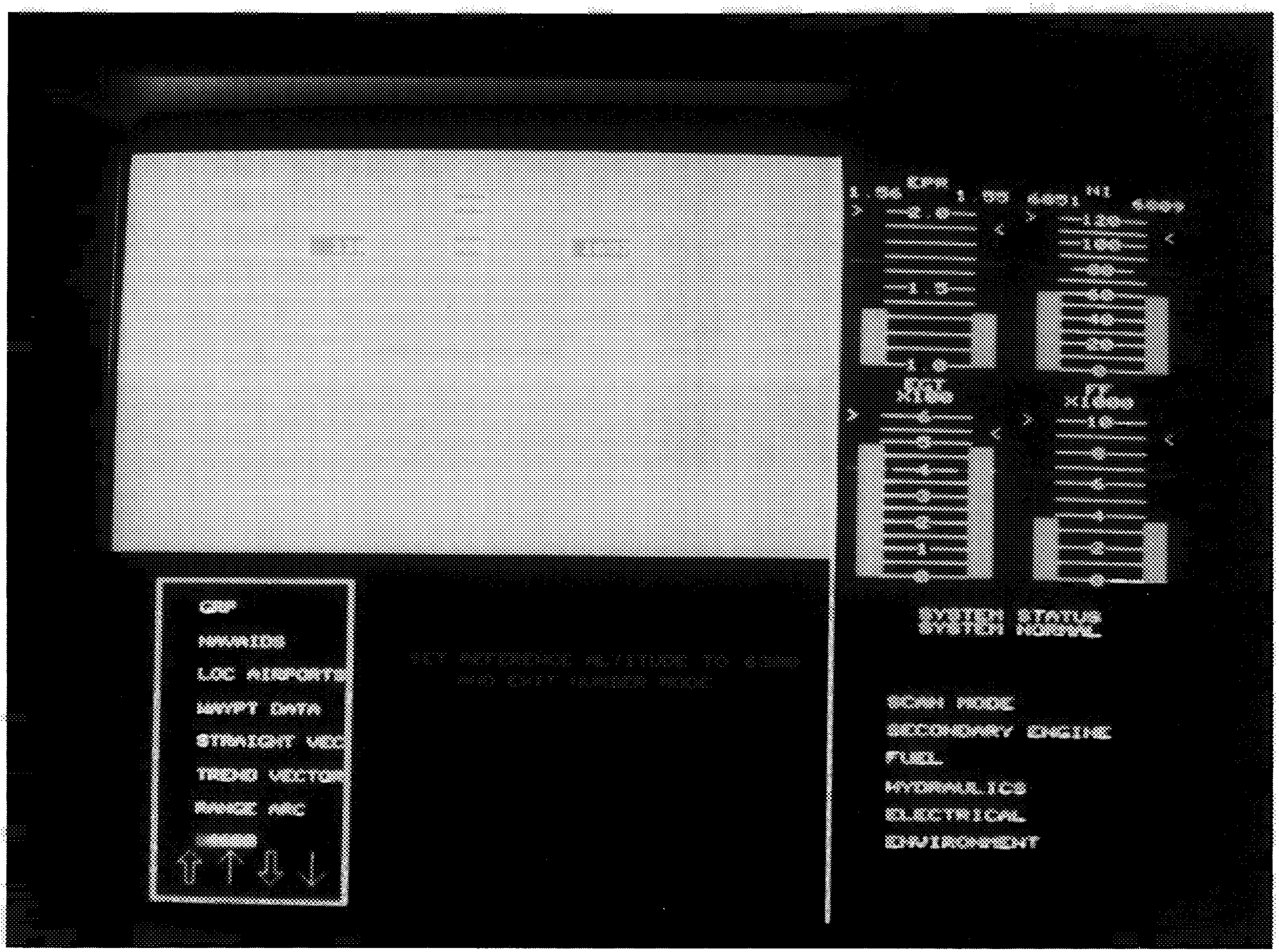
L-88-5395

Figure 5. Side-arm controller with thumball input device.



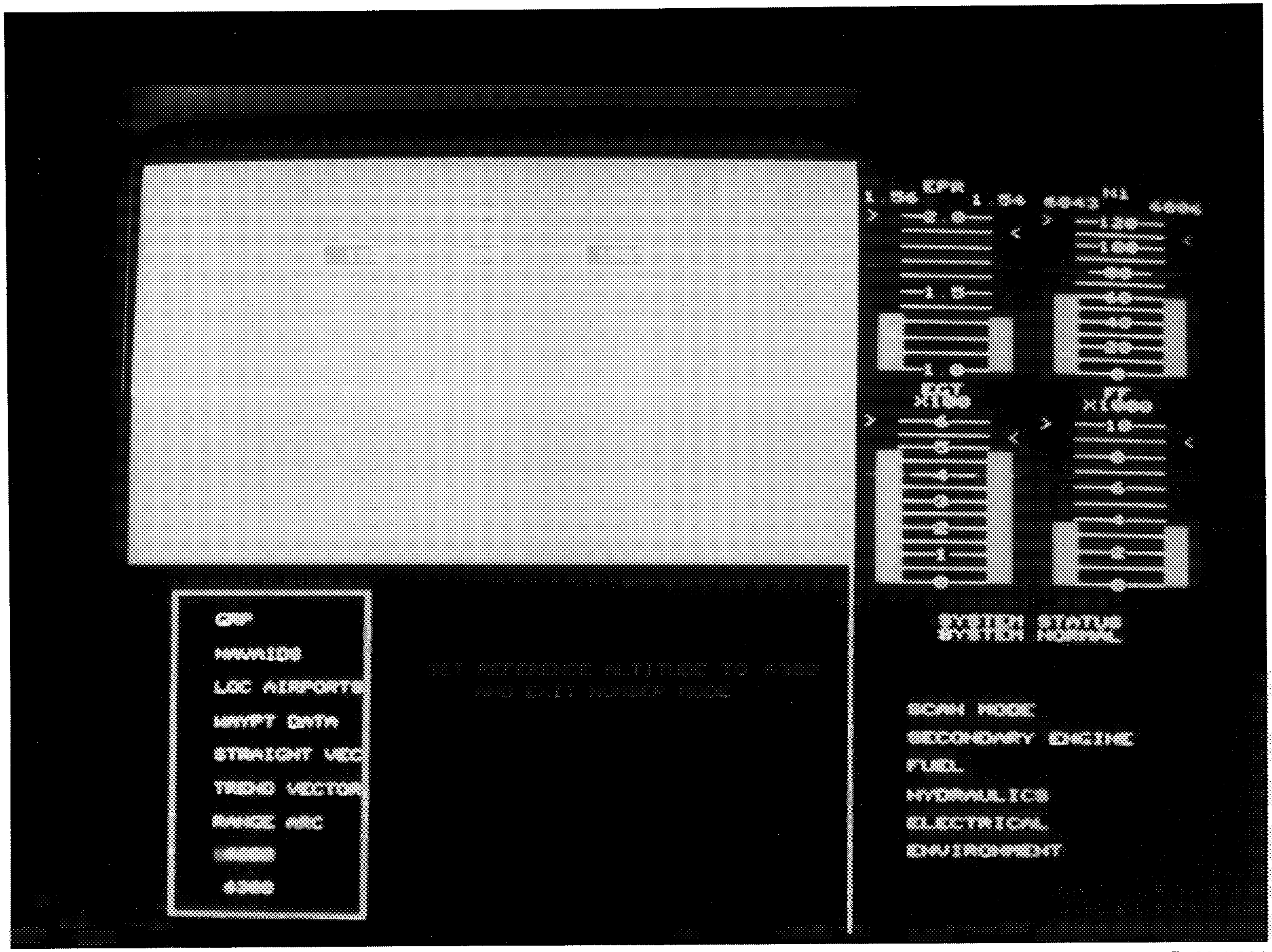
L-88-5391

Figure 6. Whole-flight-deck display featuring delete option for system failure for touch concept.



L-89-5389

Figure 7. Whole-flight-deck display showing method of numerical entry for touch concept.



L-89-5383

Figure 8. Whole-flight-deck display showing method of numerical entry for voice concept.

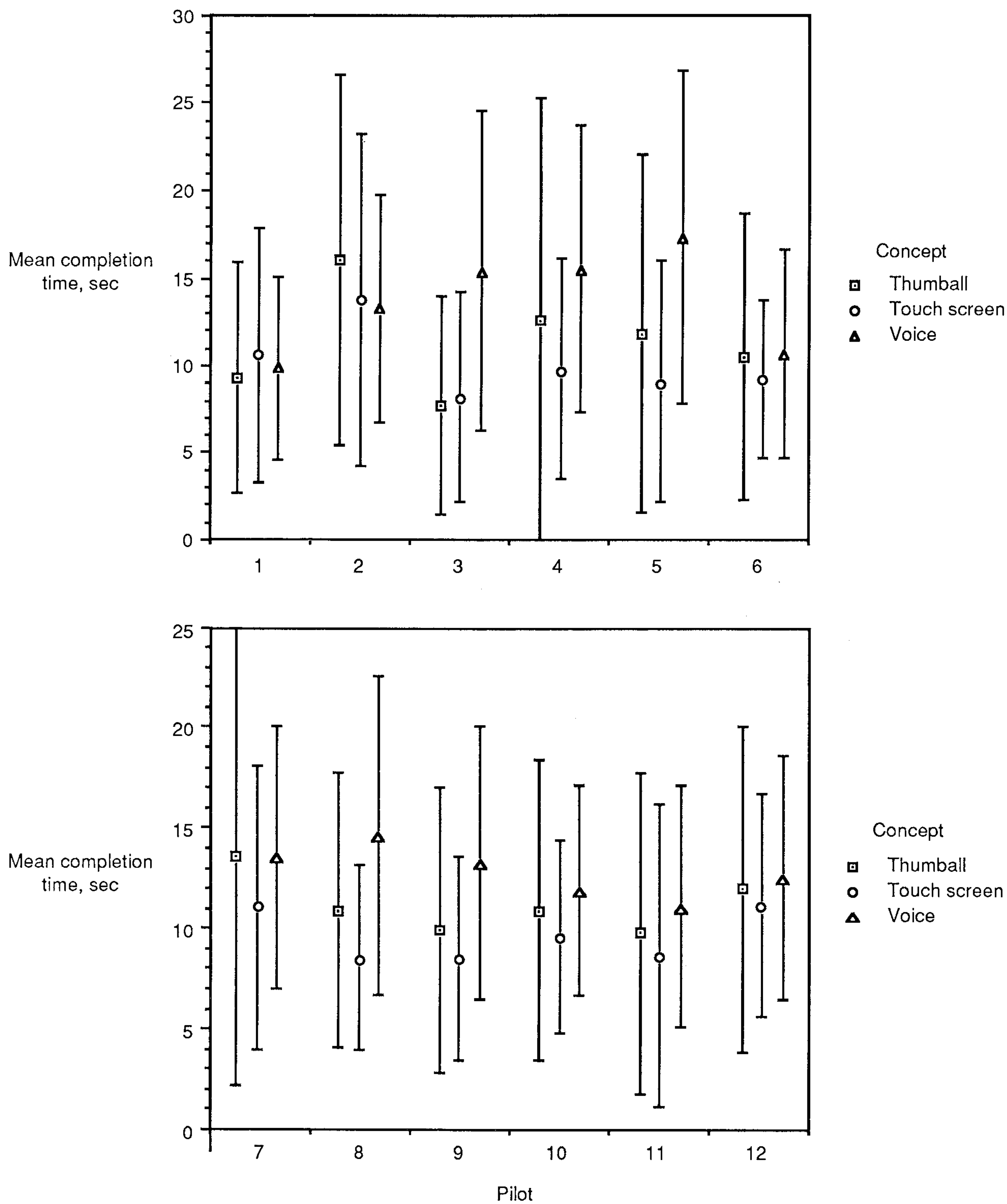


Figure 9. Mean completion times of various tasks for three input concepts for each pilot.

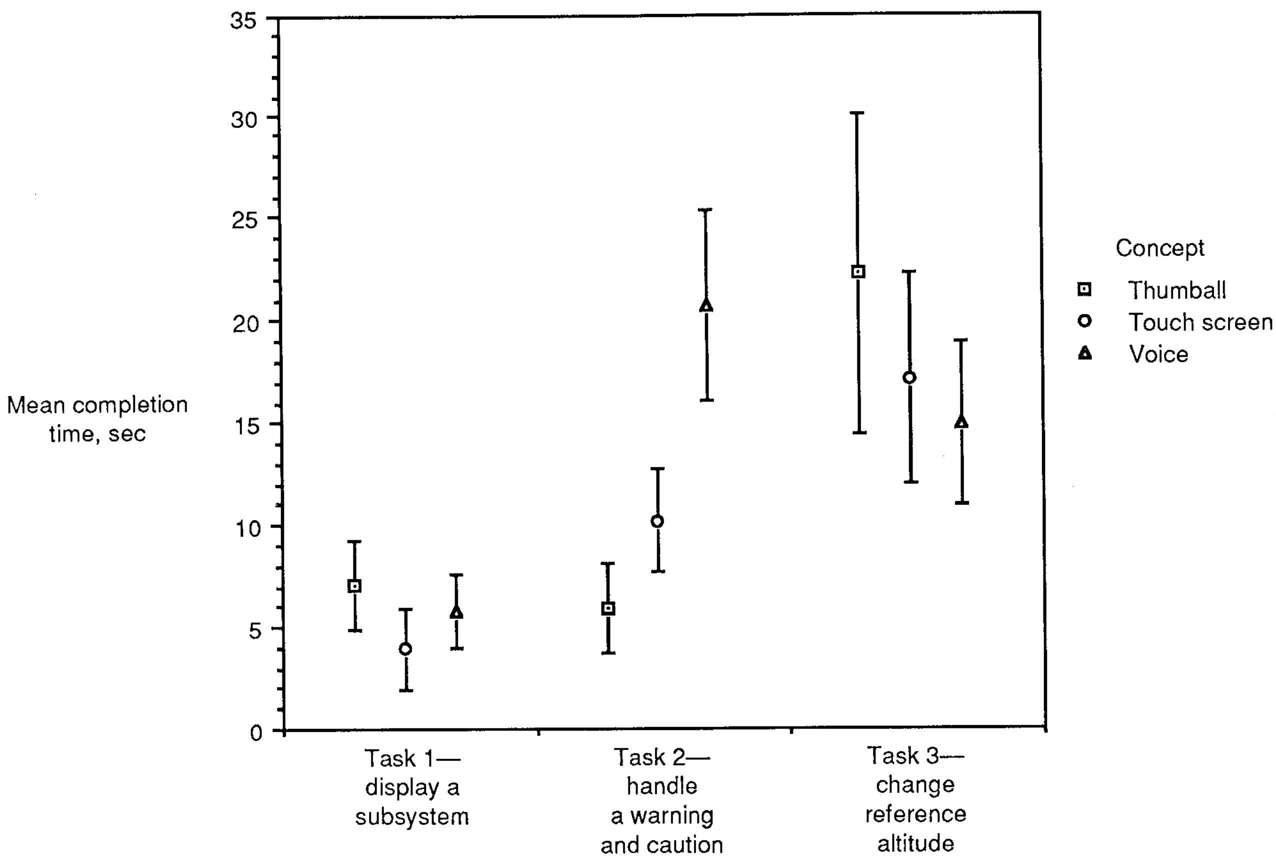


Figure 10. Mean completion times of each input concept for all pilots for each task.

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15. Supplementary Notes

16. Abstract

A piloted simulation study has been conducted to compare three different input methods of interacting with a large-screen, multiwindow, "whole-flight-deck" display for management of transport aircraft systems. The "thumball" concept used a miniature trackball embedded in a conventional side-arm controller. The touch screen concept provided data entry through a capacitive touch screen. The voice concept utilized a speech recognition system with input through a head-worn microphone. No single input concept emerged as the most desirable method of interacting with the display. Subjective results, however, indicated that the voice concept was the most preferred method of data entry and had the most potential for future applications. The objective results indicated that, overall, the touch screen concept was the most effective input method. There were also significant differences between the time required to perform specific tasks and the input concept employed, with each concept providing the best performance relative to a specific task. These results suggest that a system combining all three input concepts might provide the most effective method of interaction.

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