NASA/TP-2000-210284

Comparison of Pilots' Situational Awareness While Monitoring Autoland Approaches Using Conventional and Advanced Flight Display Formats

Lynda J. Kramer and Anthony M. Busquets
Langley Research Center, Hampton, Virginia

May 2000

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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SUMMARY

A research experiment was performed to assess situation awareness and workload of commercial airline pilots while monitoring simulated autoland operations with three advanced display concepts: two enhanced electronic flight information system (EFIS)-type display concepts and one totally synthetic, integrated pictorial display concept. All display concepts were presented on a heads-down, projection-based display system. In addition, the EFIS-type display concepts also incorporated a simulated monochrome head-up display (HUD) presented in an over-the-glareshield fashion. The basic instrument arrangement for the EFIS-type displays was a conventional T-arrangement of instruments with a Boeing 757 duplicate of a PFD over a ND. The three advanced display concepts incorporated visual enhancements consisting of a sensor-derived wireframe runway and iconic depictions of sensor-detected obstacles (other traffic) in different locations on the display media. The first enhanced EFIS-type display concept incorporated the sensor-based wireframe runway and icon obstacles into it's monochrome HUD; while, the second enhanced EFIS-type display concept incorporated the sensor-based information into it's primary flight display (PFD). The advanced pictorial display concept incorporated pathway-in-the-sky guidance and sensor-based wireframe runway and icon obstacles head-down in an integrated, large field of view (62-degree horizontal) display. Each of the enhanced visual and advanced pictorial display concepts was simulated under Instrument Meteorological Conditions (IMC). A conventional EFIS-based display concept utilizing a HUD without any sensor-based information provided an experimental control condition for the simulation. This conventional EFIS-based/HUD display concept was simulated under Visual Meteorological Conditions instead of IMC because the pilot had to visually detect the runway and other traffic without the aid of a sensor. Comparisons were made between the conventional EFIS-based/HUD concept and the advanced display concepts to ensure that the advanced concepts did not degrade a pilot's current level of SA or increase his or her workload during autoland operations. Using a fixed-base simulator, eight commercial airline pilots repeatedly flew complex microwave landing system (MLS)-type approaches to closely spaced parallel runways with extremely short final segments. Various scenarios, involving conflicting traffic situation assessments, main display failures, and navigation/autopilot system errors, were used to assess the pilots' situation awareness and workload during autoland approaches with the four display concepts. Situation awareness was operationally defined as the pilot's knowledge of ownship position relative to its desired flight route, the runway and other traffic as well as the pilot's comprehension of ownship systems information. From the results, for each scenario, the integrated pictorial display concept provided the pilots with statistically equivalent or substantially improved situational awareness over the other display concepts. Similarly, subjective results indicated a very strong preference for the integrated pictorial display concept over the two enhanced EFIS-type display concepts and the conventional EFIS-type display concept for all monitoring tasks (i.e., the approach, verifying the runway location, detecting ground runway incursions, monitoring autopilot functions, monitoring airborne traffic, etc.). All pilots indicated that the advanced pictorial, "pathway-in-the-sky" display concept afforded substantial improvements in situation awareness for detection and comprehension of an abnormal flight condition (e.g., conflicting traffic, loss of localizer signal, etc.) over the two enhanced EFIS-type display concepts. In addition to increased situation awareness, subjective rankings indicated that the pictorial concept offered reductions in overall pilot workload (in both mean ranking and spread) over the two enhanced EFIS-type display concepts. Out of the four display concepts flown, the pilots ranked the pictorial concept as the display that was easiest to use to maintain situational awareness, to monitor an autoland approach, to interpret information from the runway and obstacle detecting sensor systems, and to

make the decision to go around.

INTRODUCTION

Many research programs have been established by the government and industry to study aircraft cockpit technologies that may enable improved crew situation awareness, safety, operational efficiency and reduced crew workload during critical mission phases. (See ref. 1.) Several of these programs involve the use of "synthetic vision" to enhance transport operations under restricted-visibility conditions. Synthetic vision also provides the cornerstone technology for more advanced aircraft, such as a high-speed civil transport, that, because of the complex aerodynamic and economic requirements, may have limited forward visibility.

Numerous studies have been undertaken to assess the requirements (ref. 2) and to determine the performance (ref. 3) of various synthetic vision system concepts aimed at providing or enhancing some of the capabilities mentioned above. One such area of investigation involves the use of synthetic vision concepts to enhance crew situation awareness (SA) as a means of providing increased safety and advanced capabilities.

Initial investigations have been conducted on flight deck displays aimed at studying the spatial awareness component of situation awareness (refs. 4-6) and its effect on flight path control during the landing approach portion of the flight mission. (See ref. 7.) Results of these studies indicate that intelligently designed, enhanced flight display formats are able to increase situation awareness (at least some of its components) without incrementing pilot workload or degrading flight path control. A follow-on experiment was designed to assess the SA provided by enhanced display formats where the subjects task was focused on approach monitoring rather than flight path control.

This paper will focus on the aforementioned experiment whose objective was to assess pilots' situation awareness and workload while monitoring autoland operations, under Instrument Meteorological Conditions (IMC), utilizing three advanced display concepts: two enhanced electronic flight information system (EFIS)-type display concepts and one totally synthetic, integrated pictorial display concept. The hypothesis to be tested was that large-screen, pictorial displays offer enhanced performance and safety through increased situational awareness (without incrementing pilot workload) over conventional and advanced EFIS-type displays. Situation awareness was operationally defined as the pilot's knowledge of ownship position relative to its desired flight route, the runway and other traffic as well as the pilot's comprehension of ownship systems information. All display concepts were presented on a heads-down, projection-based display system. The EFIS-type display concepts also incorporated a simulated monochrome head-up display (HUD) presented in an over-the-glareshield fashion. The basic instrument arrangement for the EFIS-type displays was a conventional T-arrangement of instruments with a Boeing 757 duplicate of a PFD over a ND. The three advanced display concepts incorporated visual enhancements consisting of a sensor-derived wireframe runway and iconic depictions of sensor-detected obstacles (other traffic) in different locations on the display media. The first enhanced EFIS-type display concept incorporated the sensor-based wireframe runway and icon obstacles into it's monochrome HUD; while, the second enhanced EFIS-type display concept incorporated the sensor-based information into it's primary flight display (PFD). The advanced pictorial display concept incorporated pathway-in-the-sky guidance and sensor-based wireframe runway and icon obstacles head-down in an integrated, large field of view (62-degree horizontal) display. Further explanation of the display formats will follow in the Experiment Design section under the subheading Display Concepts. After being compared to each other, the three advanced display concepts were then compared to a conventional EFIS-based display concept utilizing a HUD without any sensor-derived information. The EFIS-based/HUD concept represented a conventional flight deck in today's fleet. Comparisons were made between the conventional EFIS-based/HUD concept and the advanced display concepts to ensure that the advanced concepts did not degrade a pilot's current level of SA or increase his or her workload during autoland operations. This conventional EFIS-based/HUD display concept was simulated under VMC instead of IMC because the pilot had to visually detect the runway and other traffic without the aid of a sensor. Various scenarios, involving conflicting traffic situation assessments (both on the ground and in the air), main display failures, and navigation/autopilot system errors, were used to assess the pilots' situation awareness and workload during autoland approaches with the four display concepts. The intent of these abnormal scenarios was to determine if significant differences exist between the display concepts that incorporate sensor-based wire-frame runway and icon obstacles (advanced display concepts) when measuring a pilot's situational awareness and workload under IMC, and then compare these display differences to a conventional EFIS-based/HUD display with no sensor-based information under VMC.

Situation Awareness Assessment Tools and Techniques

Finding techniques to assess situation awareness is a challenging task within itself. Several techniques have been suggested in the overall literature, each with its own advantages and drawbacks. Historically, the most common method used to assess situation awareness is by measuring traditional pilot/vehicle performance. However, there has been no established direct relationship between performance and awareness and, therefore, these measures should be supplemented by additional techniques. (See ref. 8.) Three additional techniques (ref. 9) that were used to assess situation awareness in this experiment were Anomalous Cues/Detection Time Techniques, Freezing/Probes and Subjective Methods. Brief descriptions of these techniques are presented below.

Anomalous Cues/Detection Time Technique

This technique requires setting up scenarios that introduce slowly developing problems that may require some subject interaction. The experimenter then measures the time it takes for the subject to detect the problem, as well as the time before any corrective action is taken.

Freezing/Probes

This method entails a direct approach in which the experimenter either interrupts a task or "freezes" the task and then proceeds to take some form of measurement. Usually, the experimenter asks the subject relevant questions (in effect, probing them) concerning the task the subject was performing. (See refs. 10-11.) Often questions are asked as to future events (based on what has transpired until the moment of "task freezing") that may provide greater insight as to the subject's awareness of the situation at that moment. In other words, the better the SA, the more accurately the subject will be able to predict the immediate future. In addition, after resuming the task, other measurements indicative of SA may be taken (such as time to restore to some predetermined condition). These methods require caution in that not only has the original task been corrupted, but also the probe results must rely on the subject's short-term memory.

Subjective Methods

Subjective methods mainly consist of questionnaire type evaluations where the subject, either verbally or by handwritten means, expresses personal opinions or feelings about the topic of situation awareness.

Mental Workload Assessment Measures

For the purposes of this paper, mental workload is defined as the amount of processing capability required by a person to perform a specific task. The supposition is that there are performance decrements when a task requires greater processing capability than is available within an individual. In other words, when mental workload is exceeded, performance declines. Two subjective measures, modified Cooper-Harper (C-H) ratings and questionnaire display rankings, were utilized in this experiment to assess the pilot's mental workload while monitoring autoland operations with each of the display concepts.

Modified Cooper-Harper Ratings

The modified C-H scale (fig. 1 and ref. 12) provides a subjective assessment of mental workload associated with perceptual, cognitive, and communications tasks. The modified C-H scale is typically administered to a subject after an experimental run or group of experimental runs is completed.

Subjective Methods

Subjective methods mainly consist of questionnaire type evaluations where the subject rates the level of mental effort required to accomplish a specific task.

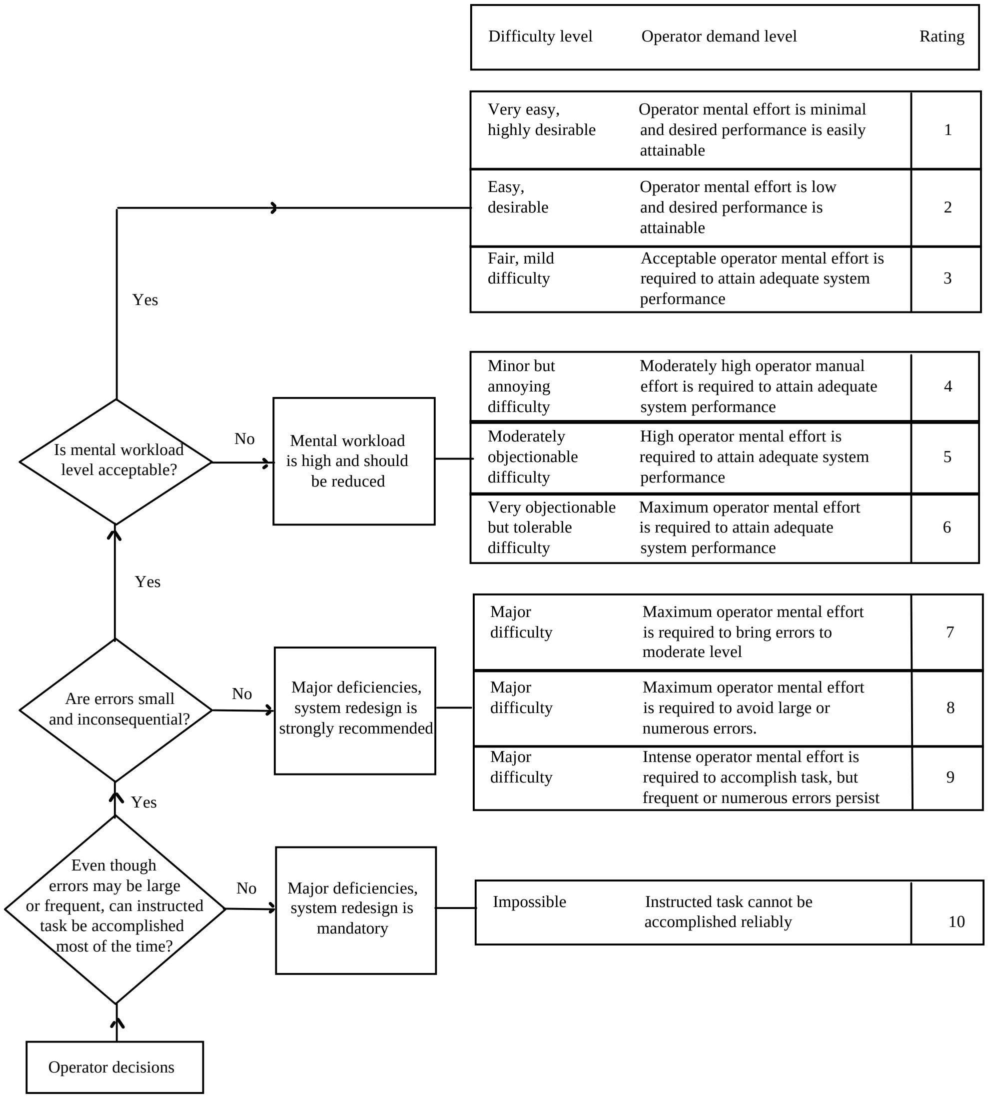


Figure 1. Modified Cooper-Harper scale for mental workload assessment.

ABBREVIATIONS

ADI	attitude direction indicator
AGL	above ground level
ANOVA	analysis of variance
AP	autopilot
C-H	Cooper-Harper
CH	Conventional HUD
CRT	cathode ray tube
DERP	design-eye reference point
EC	Embedded Conventional
EFIS	electronic flight information system
EH	Enhanced HUD
FD	flight director
FMS	flight management system
FOV	field of view
GPS	global positioning system
GS	glideslope
HUD	head-up display
ILS	instrument landing system
IMC	Instrument Meteorological Conditions
INS	inertial navigation system
LNAV	lateral navigation
LOC	localizer
MLS	microwave landing system
ND	navigation display
Nmi	nautical miles
OTW	out-the-window
PF	pilot flying
PFD	primary flight display
PNF	pilot not flying
PV	Pictorial Vision
RA	resolution advisory
SA	situation awareness
SAL	standard approach to landing
SNK	Student-Newman-Keuls
TA	traffic advisory
TCAS	Traffic Alert and Collision Avoidance System
TOGA	take-off/go-around
VISTAS	Visual Imaging Simulator For Transport Aircraft Systems
VMC	Visual Meteorological Conditions
VNAV	vertical navigation

METHODS

Subjects

Eight current line pilots with national commercial airlines, all with extensive glass-cockpit experience and familiarity with the Traffic Alert and Collision Avoidance System (TCAS), acted as subjects in the experiment. (See table 1.) Subjects were asked to complete a brief questionnaire describing their flight experience. The number of years flying commercial aircraft that subjects reported ranged from five to 17.5, with a mean of 11.6 years. Six of the eight subjects also had experience flying military aircraft, with a mean of 10.3 years. The total number of hours flying ranged from a low of 5,300 to a high of 11,000, with a mean of 8,338 hours flying. A summary of the flight experience of the pilots serving as subjects is given in table 1.

Table 1. Summary of pilot experience of subjects in Situation Awareness experiment.

Subject	Years Flying Commercial	Years Flying Military	Total Hours Flying
767 F/O	6	20	8000
767 F/O	14	--	8700
777 F/O	12	3	7500+
757 Captain	17.5	5	10250
737-300 Captain	17	--	11000
DC-9 F/O	5	13	5300
767 F/O	7	10	5500+
757/767 Captain	14	11	10450
Means	11.6 Years	10.3 Years	8338 Hours

Simulator Description

The Langley Research Center has developed a flexible, large-screen flight display research system, named the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS), which was utilized for this experiment. The workstation-based simulator is comprised of the following elements: visual system hardware, graphics generation hardware and software, aircraft mathematical model, and computer implementation. (See fig. 2.) The visual and interactive control elements of this flight display research tool have been integrated as a piloted workstation in order to explore the advantages and limitations of large-screen, pictorial, reconfigurable display concepts and associated interactive techniques.

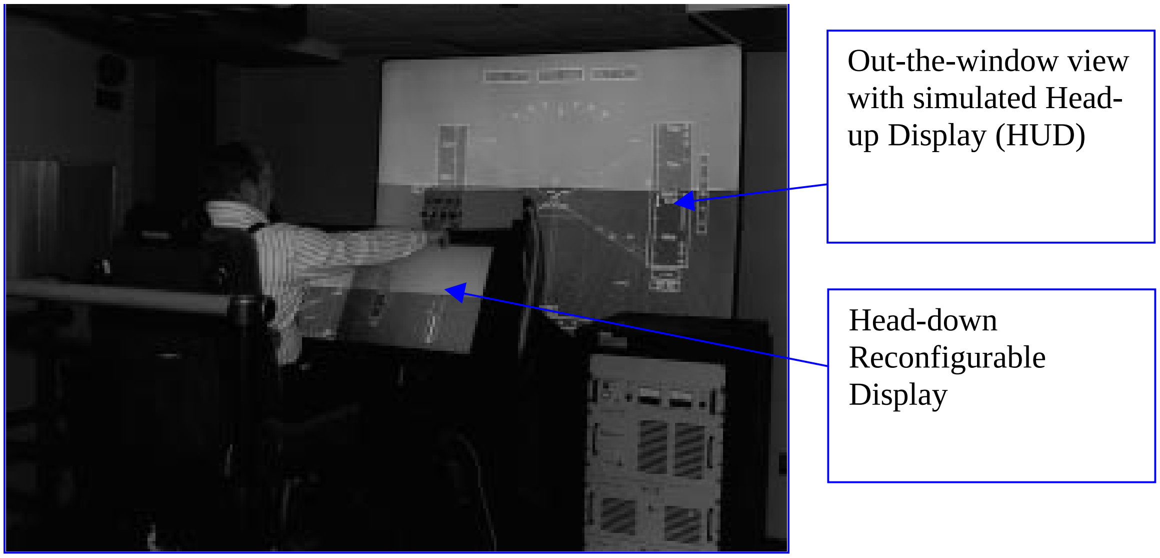


Figure 2. Visual Imaging Simulator for Transport Aircraft Systems.

Simulator Visual System

The core of the visual system is embodied in dual, full-color, high-resolution cathode ray tube (CRT) projectors that are configured to vary the projected display's aspect ratio by edge-matching and overlapping the images from each projector. Since each of the two projected images is 15 inches in height by 20 inches in width (standard 3:4 aspect ratio), a maximum 15 by 40-inch image can be achieved. Image resolutions up to 1280 x 1024 pixels in a 60-Hertz progressive scan format can be obtained (per projector). The images are generated by dual graphics display generators operating in conjunction, utilizing the same visual database in order to produce a single, large-screen, integrated picture (combined by the projection system onto the rear-projection screen that serves as the simulated aircraft's main instrument panel). Given that the design-eye reference point (DERP) for transport cockpit applications is typically around 28 inches, the full 40-inch wide display provides a maximum 71-degree horizontal field of view (FOV). The DERP is centered about the full 15-inch x 40-inch display. At the stated maximum resolution this yields approximately 1 minute 40 seconds of arc of horizontal angular visual resolution (about 36 pixels per degree) and approximately 1 minute 45 seconds of arc of vertical angular visual resolution (about 34 pixels per degree).

In addition, an out-the-window (OTW) representation of the real-world forward view (forward cockpit window) is simulated by a high-resolution projector and front projection screen combination. A 40-degree horizontal FOV is achieved by placing the 80-inch wide, curved projection screen 9.2 feet from the pilot eye reference point. The 1280 by 1024 pixel resolution projected image yields a 1 minute 52 second of arc of horizontal angular visual resolution (about 32 pixels per degree). HUD symbology is presented overlaying the OTW view and sized so that its subtended angular presentation corresponds to what it would be if it were an actual glareshield HUD.

Simulator Audio System

To add realism to the simulation, audio feedback and verbal cueing were provided by a desk-side computer with a sound system that allowed playback of digitized sounds (files) timed to external events. Audio feedback was provided in the form of aircraft sounds such as background engine noise and tire "chirps" on touchdown. A series of verbal announcements was utilized to represent various pilot flying (PF), pilot not flying (PNF) and tower communications on final approach such as landing clearances, instruments crosschecks, wind conditions, critical altitudes and flap settings. In addition to adding realism, the intent was to also assist in maintaining vigilance during the exhaustive set of repetitive approach trials.

Aircraft Mathematical Model and Computer Implementation

A simplified six-degree-of-freedom mathematical model of a transport aircraft with a 20-Hertz update rate was used in this study to provide the interaction between the pilot and the flight display formats. The linear transfer functions and gains were obtained empirically to represent a fixed-wing generic transport aircraft with rate command controls. Turbulence was used in the simulation to make it harder for the pilot to detect when a system error had been induced versus normal deviations from path due to wind gusts, as occurs in actual flight. The turbulence was introduced into the mathematical model through the addition of gust components to the body-axis longitudinal and lateral velocity variables. The level of turbulence was considered to be moderate by the participating pilots.

Cockpit Layout

The pilot workstation was configured as the pilot side of a generic transport, fixed-wing aircraft with the pilot’s seat designed to position the subjects so that their eyes were at the DERP. The workstation also accommodated the dual-head projection system and the rear-projection screen that simulated the instrument panel. Pitch and roll inputs to the aircraft mathematical model were provided in the workstation by a two-degree-of-freedom sidearm hand-controller with spring centering. A throttle lever that utilized a voltage-referenced potentiometer as the signal source provided throttle inputs. Typical self-centering rudder pedals provided yaw inputs.

The display screen (instrument panel) was tilted so that the center of the screen's display surface was set perpendicular to the pilot's line-of-sight. It's height was set so as to provide a 17-degree view over the top of the screen (line-of-sight from horizontal), which is typical of over-the-glareshield views in many aircraft.

Monitoring Task

The pilot’s task was to monitor, not control, autoland operations during a standard approach to landing (SAL) using the display concept available. The SAL was 6.0 nautical miles (Nmi) in length, consisting of a microwave landing system (MLS)-type approach (fig. 3) to closely-spaced parallel runways. The short final approach segment was only 1.7 Nmi in length. The SAL had a 20-knot headwind on base and turbulence throughout the entire approach. The turbulence was implemented in the simulation so that a crosswind gust component was present on each leg of the approach. On the SAL, the ownship began at 150 knots, 2150 feet above ground level (AGL) altitude, and landed at 130 knots. Autothrottles and the autoflight system were engaged throughout the duration of the SAL. The simulation began with the ownship in vertical navigation (VNAV) and lateral navigation (LNAV) modes with glideslope (GS) and localizer (LOC) armed. Typically, a pilot would manually arm the GS and LOC modes but for the purposes of this simulation these modes were automatically armed. The GS and LOC modes were captured about 50 seconds into the run. The total run time for the SAL was approximately 2 minutes and 55 seconds. The SAL used a 3-degree glideslope on base and final with a 4.5-degree glideslope in the turn to final. Ownship flare initiation began at 75 feet AGL altitude and the SAL ended at a threshold crossover altitude of 50 feet AGL. Other traffic was always present on the SAL in the form of an aircraft landing on the parallel runway 18 seconds before the ownship, runway traffic holding short on the approach end of the active runway, and crossing traffic on the ownship's base leg (at 90-degree angles). The crossing traffic was initially ahead and at the ownship's same altitude but then initiated a climb at a point in the simulation to prevent it from causing a TCAS Traffic Advisory (TA).

Eleven separate experimental scenarios, utilizing the same SAL procedure, were designed for the data collection sessions. The first of these eleven scenarios was a normal run in which no anomalous situations occurred during the SAL. The remaining 10 scenarios employed the SA assessment techniques referred to in the Introduction to generate an anomalous situation during the SAL. These 10 scenarios include a Flight Director Conflict with Autopilot Scenario, Flight Director Conflict with Raw Data Scenario, Aircraft Incursion on Final Scenario, Flag Take-off/Go-around (TOGA) Scenario, two Navigation System Error Scenarios, three Blanking Scenarios and a Probe Approach Scenario. All of the awareness scenarios involving abnormal situations in the investigation were completed well before a 50-foot threshold crossover altitude was obtained.

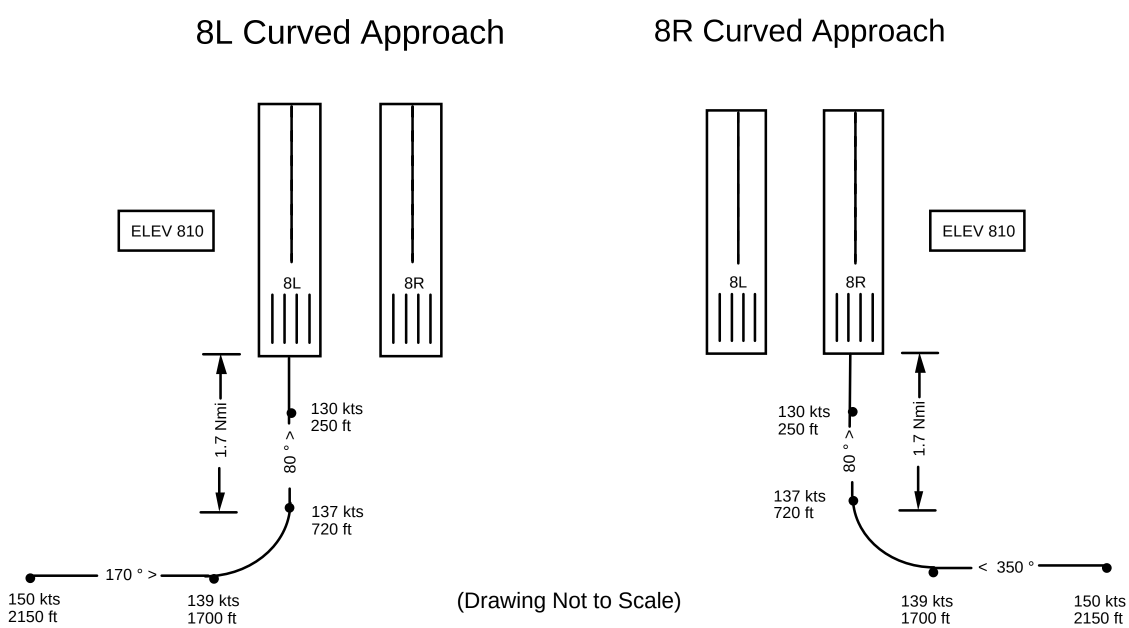


Figure 3. SAL Approach Plate for Runway 8L and Runway 8R.

Scenarios Based on Situation Awareness Assessment Techniques

The techniques chosen for this experiment were based upon their success in measuring situational awareness in a previous study (ref. 7) and their ability to generate suitable scenarios in the context of transport approach and landing operations. The pilot's basic, or standard, task was monitoring (not controlling) an approach to landing pattern designed for this experiment. Being a monitoring task, the traditional lateral and vertical RMS errors, as well as control input data, were not recorded during the basic task. However, pilot button presses indicating abnormalities/uneasiness with the autoland operations were recorded. The pilot could push two buttons (located next to his right hand) throughout the duration of a run. The first button was labeled 'CONCERNED' and was to be pressed if the pilot detected an abnormality while monitoring the autoland procedure. The second button was labeled 'TOGA' indicating that the pilot would disconnect the autopilot and fly manually; thus terminating the run. If the TOGA button was not pressed, the run ended upon crossing over the runway threshold.

As mentioned previously, all of the abnormal scenarios were implemented within the standard approach to landing procedure. Six scenarios were developed in order to utilize the anomalous cues/detection time technique. In addition to the slowly developing system anomalies, these scenarios included crossing traffic situations that sometimes caused TCAS alerts. Two types of probe techniques were also employed. The first technique interrupted the SAL procedure by blanking the displays and then introduced a new task - flying with a backup instrument (only the ADI, or attitude direction indicator, portion from the EFIS PFD). The blanking scenarios were unique in this experiment because this is the only time the pilot manually controlled the aircraft instead of monitoring its autoland operations. The supposition to be tested was that a superior display format would allow the pilot to think ahead of the airplane and thus be able to continue flying based on retained information. This scenario was thus formulated as a "Think-Ahead" awareness tool. The other probe technique also used the SAL procedure but generated three abnormal events in succession on the display. After the third event occurred, the display blanked to black and relevant questions about spatial orientation, instrument readings and traffic awareness were then verbally presented. Finally, numerous subjective questionnaires were administered in which the subject evaluated the display concepts subjectively by answering relevant questions and by ranking the display concept based upon the perception of the situation awareness afforded. Unsolicited subject comments were also recorded throughout the trials.

Anomalous Cues/Detection Time Scenarios

In the experiment, six scenarios (described below) can be categorized under this SA assessment technique. For each display concept encountered by the pilot, a base leg TCAS TA was embedded within two of the anomalous cues/detection time scenarios. The scenarios utilized for the embedded TCAS TA were the Flag TOGA scenario, the Runway Incursion on Final scenario, the Autopilot Oscillation scenario and the Navigation System Error scenario. (See table 3 in the Procedures section-Organization of Trials.) So, in addition to the slowly developing system anomalies, these four scenarios included crossing traffic situations that sometimes caused TCAS alerts.

Flight Director Conflict with Autopilot Scenario

The basic approach pattern (to the left parallel runway, 8L) always included another aircraft flying a SAL to the right runway. The other aircraft landing on Runway 8R landed 18 seconds ahead of the ownship. Crossing traffic in front of the ownship on base and runway traffic holding short of the active runway were also present for this scenario. The intent of this scenario was to implement a slow bias into the simulation so that the autopilot was not correctly following the flight director (fig. 4). This bias was implemented by incrementing a sinusoidal offset with time to the roll command (fig. 5) which is output from the flight director and used as input to the autopilot. The bias was slowly diverging (37 seconds) with a limited amount of offset (188.5 feet off path). The bias started at 15 seconds into the run and the run ended either upon a TOGA press by the pilot or upon crossing the runway threshold. Each pilot was exposed to this scenario once per display concept.

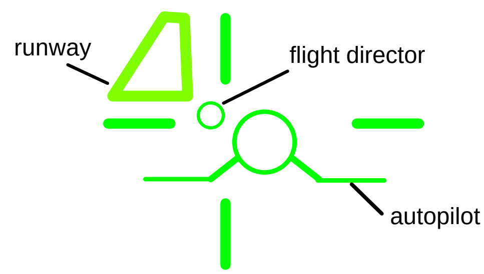


Figure 4. Guidance for FD conflict with AP Scenario.

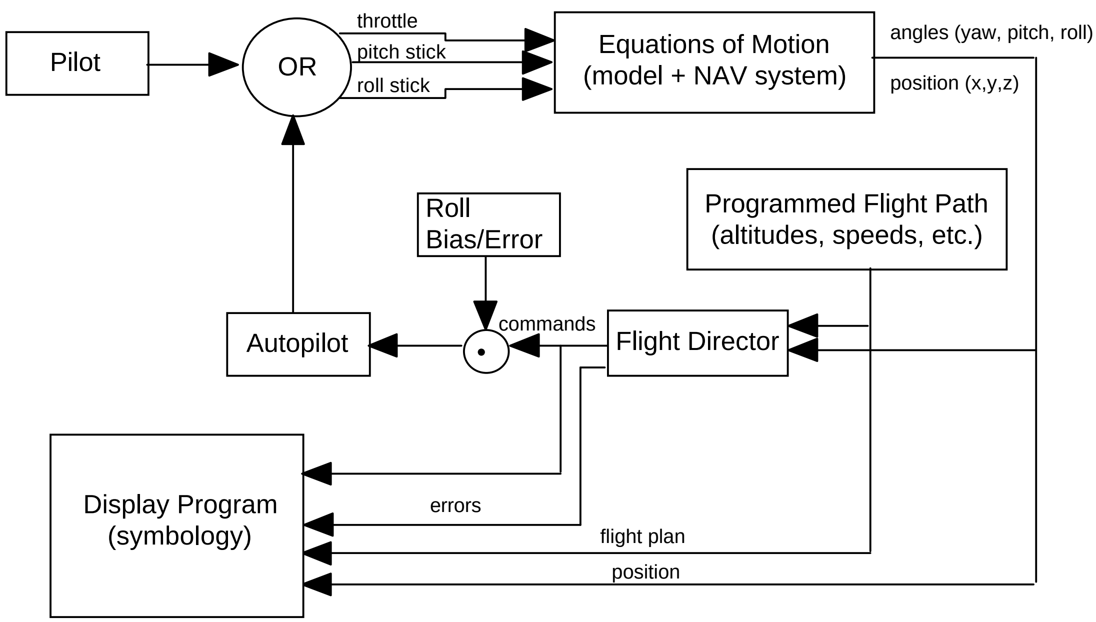


Figure 5. System Schematic of Bias Error in Flight Director Conflict with Autopilot.

Flight Director Conflict with Raw Data Scenario

The basic approach pattern (to the right parallel runway, 8R) always included another aircraft flying a SAL to the left runway and landing 18 seconds ahead of the ownship. Crossing traffic in front of the ownship on base and runway traffic holding short of the active runway were also present for this scenario. The aim of this scenario was to implement a slow bias into the simulation so that the autopilot was correctly following the flight director but the flight director was not correcting back to the appropriate path (raw data-derived). (See fig. 6.) The bias was implemented by incrementing a sinusoidal offset with time and adding this term to the lateral error input to the flight director (fig. 7). The bias was slowly diverging (35 seconds) with a limited amount of offset (477 feet lateral error). The bias started at 15 seconds into the run and the run ended either upon a TOGA press by the pilot or upon crossing the runway threshold. Each pilot experienced this scenario once per display concept.

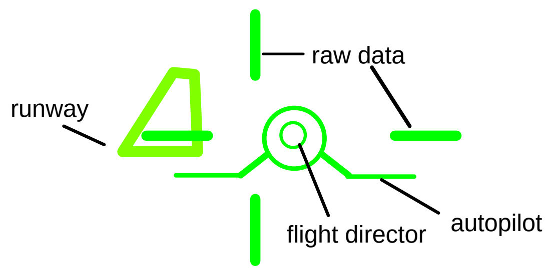


Figure 6. Guidance for Flight Director Conflict with Raw Data Scenario.

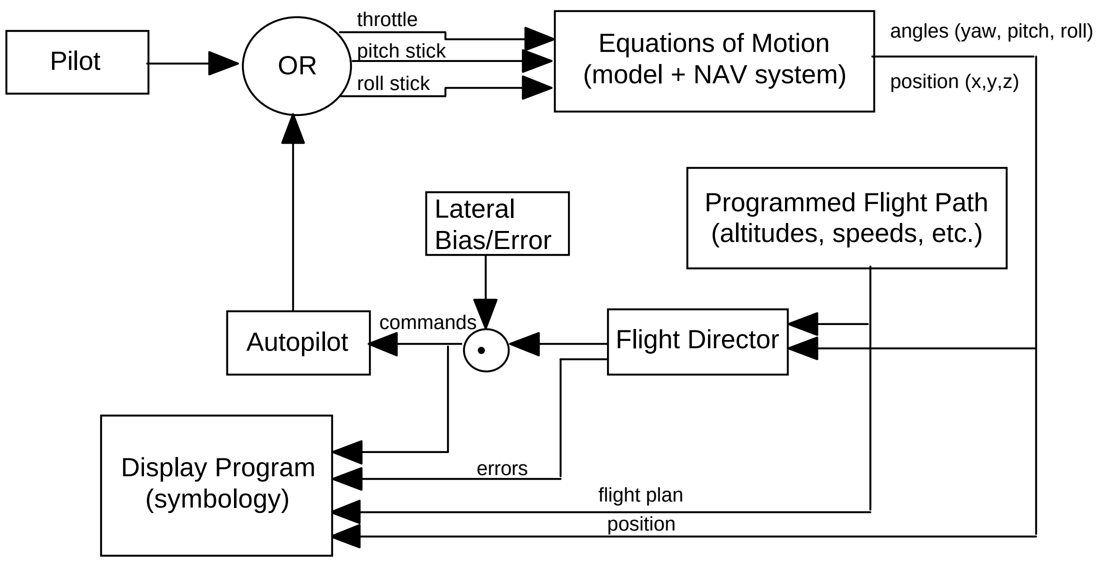


Figure 7. System Schematic of Bias Error in Flight Director Conflict with Raw Data.

Aircraft Incursion on Final Scenario

The basic approach pattern (either to runway 8R or 8L) always included another aircraft flying a SAL to the runway parallel to the active runway and landing 18 seconds ahead of the ownship. Crossing traffic was found on the base leg of the ownship's SAL. The purpose of this scenario was to have ground traffic, that normally holds short, pull onto the approach end of the active runway during the ownship's landing. Each pilot saw two replicates of this scenario (1 to runway 8R; 1 to runway 8L) for each display concept.

Flag TOGA Scenario

The basic approach pattern (either to runway 8R or 8L) always included another aircraft flying a SAL to the runway parallel to the active runway and landing 18 seconds ahead of the ownship. Crossing traffic in front of the ownship on base and runway traffic holding short of the active runway were also present for this scenario. The intent of this scenario was to simulate a flight situation on final approach where the pilot would automatically be forced to disconnect the autopilot and fly a go-around approach. For this scenario a fault was generated by the loss of the localizer signal at 650 feet AGL altitude. The fault created a mandatory TOGA situation typically indicated by a warning flag on the PFD. When the localizer failed, the autopilot continued following the glideslope guidance (vertical path and descent rate). The autopilot followed the lateral inertial track since it no longer had a valid localizer signal. Indications on the display of a localizer failure included displaying PFD and navigation display (ND) warning flags, removal of localizer raw data, removal of flight director commanded vertical bars, and drawing amber lines on the PFD mode enunciator. For the advanced pictorial display concept, there was no vertical flight director bar so the Flight Director circle remained centered laterally. Each pilot experienced two replicates of this scenario (1 to runway 8R; 1 to runway 8L) per display concept.

Autopilot Oscillation Scenario

The basic approach pattern (either to runway 8R or 8L) always included another aircraft flying a SAL to the runway parallel to the active runway and landing 18 seconds ahead of the ownship. Crossing traffic in front of the ownship on base and runway traffic holding short of the active runway were also present for this scenario. The purpose of this scenario was to build three full glideslope oscillations starting at an altitude of 580 feet AGL and increasing linearly to a maximum deviation of 1 dot error at threshold crossover. Each pilot was exposed to this scenario two times (1 to runway 8R; 1 to runway 8L) per display concept.

Navigation System Error Scenario

The basic approach pattern (either to runway 8R or 8L) always included another aircraft flying a SAL to the runway parallel to the active runway and landing 18 seconds ahead of the ownship. Crossing traffic in front of the ownship on base and runway traffic holding short of the active runway were also present for this scenario. The aim of this scenario was to generate a navigation system error between the autopilot and the onboard sensor on final approach. The onboard sensor was implemented to simulate a device that could detect runway edges and obstacles (including traffic) regardless of weather conditions. To accomplish this position conflict, a lateral position error was introduced into the inertial navigation system/global positioning system (INS/GPS) position information. (See fig. 8.) For this scenario, there was a disagreement between where the autopilot “saw” the runway and where the sensor “saw” the runway (fig. 9). The disagreement of the two systems from runway centerlines could be a small one (75 feet) or a large one (300 feet). Each pilot was exposed to one large disagreement and one small disagreement between the navigation system and the sensor system for each display concept. These two runs were flown to opposite runways.

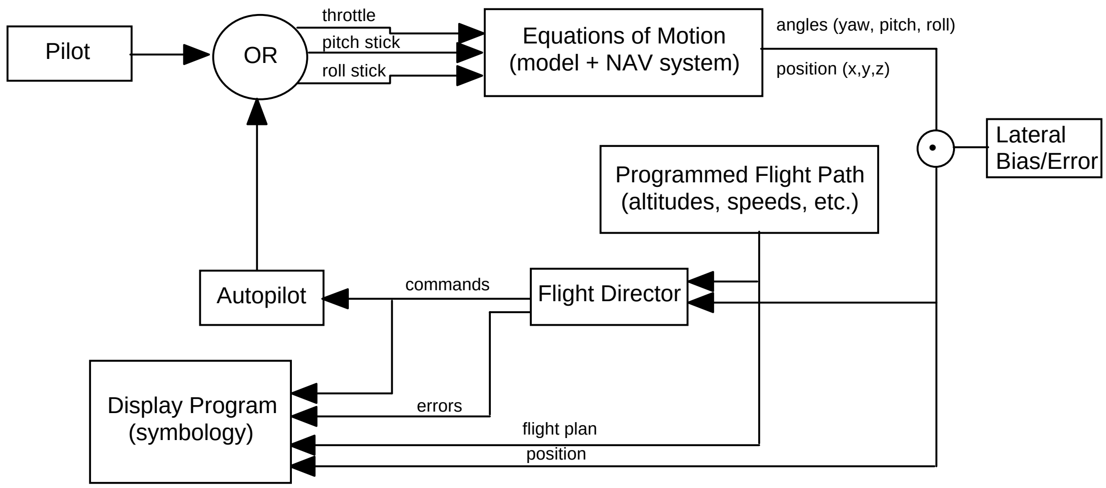


Figure 8. System Schematic of Bias Error in Navigation System.

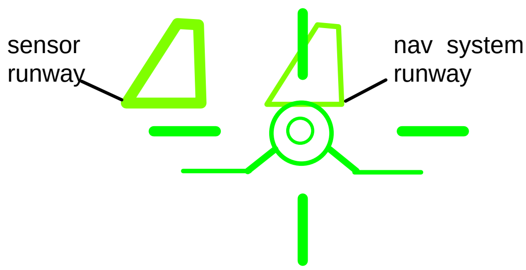


Figure 9. Guidance for Navigation System Error Scenario.

Freezing/Probes Scenarios

In the experiment, four scenarios (described below) can be categorized under this SA assessment technique.

Blanking Scenarios

Three different blanking scenarios exposed each of the eight pilots to incidents of simulated display system failure (by blanking the display screens) for each display concept. The pilot's sole source of information with which to begin flying the ownship in these blanking scenarios was a backup instrument (the ADI portion from the EFIS primary flight display). Prior to the experiment, a flight path visualization tool was developed to evaluate the amount of time subjects tended to stay within 1-dot glideslope and 1/2-dot localizer errors after display screen blanking. The average time was empirically determined to be approximately 20 seconds for the blanking scenarios' setup and spatial configuration, i.e. banking, descending turns. Therefore, tracking data was collected for twenty seconds of backup instrument flying (data collection started at blanking: either 3 seconds before path turn initiation, 3 seconds before path turn rollout initiation or 2 seconds after a crossing traffic conflict is generated, as discussed in the following blanking scenario descriptions).

Blanking Scenario one emulated a display system failure just before the turn to final (three seconds before turn initiation). Similarly, Blanking Scenario two occurred just before rollout on final (about three seconds before rollout initiation). The simulated display system failure in Blanking Scenario three occurred two seconds after a TCAS Resolution Advisory (RA) appeared while on base leg of the SAL. The RA was generated by the crossing base leg traffic not climbing fast enough. The commanded TCAS maneuver generated by the RA was a descent between 500 to 1500 feet per minute which was displayed on the vertical speed indicator by turning it green in the allowable zone and red in the forbidden zone. Each pilot saw two replicates of each blanking scenario for each display concept.

Probe Approach Scenario

The probe technique of freezing the task during execution and conducting an extensive quiz to assess subject awareness was implemented within the SAL procedure. Prior to the screen freezing and subsequent blanking, three events were generated in succession on the display. First, a lateral bias was introduced into the system as the ownship approached the turn to final causing a flight director conflict with the autopilot (event 1). The lateral bias became large enough to generate a TCAS TA on final approach with another aircraft landing on the runway parallel to the active runway (event 2). Two seconds after the TA appeared the aircraft lost it's glideslope signal (event 3) causing a TOGA warning flag to appear in the PFD and ND. Similar to the localizer failure scenario, the loss of the glideslope caused an amber line to be drawn through the PFD mode enunciator and removal of the affected raw data deviation bar and flight director command bar (horizontal). When the glideslope failed, the autopilot followed the vertical inertial track but continued to follow localizer guidance (lateral path). For the advanced pictorial display concept, the flight director is a circle, not command bars, so the flight director circle remained pinned vertically where the failure occurred. Four seconds after the glideslope failure (86 seconds into the run), the screen blanked and the subject was given the probe questionnaire. Each pilot received only one probe scenario across the four display concepts encountered during the two days of testing. Therefore, for the entire research experiment, only 8 probe scenarios were administered (one per evaluation pilot).

Experiment Design

Independent Variables

Hypothesis

Large-screen, pictorial displays offer enhanced performance and safety through increased situational awareness (without incrementing pilot workload) over conventional and advanced EFIS-type displays as measured by increases in detection times and decreases in reaction times to developing system anomalies and traffic conflict situations.

Display Concepts

This experiment attempted to assess pilots' SA and workload while monitoring autoland operations utilizing three advanced display concepts incorporating sensor-based wire-frame runway and icon obstacles, as well as a conventional EFIS-based display concept for baseline comparisons.

The baseline EFIS display, which also incorporated a simulated monochrome (green) HUD presented on the simulated OTW view, used no sensor-based information and was simulated under VMC. (See fig. 10.) The EFIS+HUD baseline display concept will hereinafter be referred to as the Conventional HUD (CH) display concept. The basic instrument arrangement (for the CH concept and first two advanced display concepts) was a conventional T-arrangement of instruments with a B-757 duplicate of a PFD over a ND (See fig. 11.) To the left of the PFD was a typical airspeed indicator dial and to the right were typical altitude, vertical speed, and turn coordinator instruments arranged over one another in that order. Non-standard (but used also in the first two advanced display concepts) was a power indicator that integrated engine and ambient information to display actual power (including engine spool-up) in percent thrust. (See ref. 13.) Also presented on the power indicator were power commanded by the throttle setting and power desired by the Flight Management System (FMS) for flying the programmed approach.

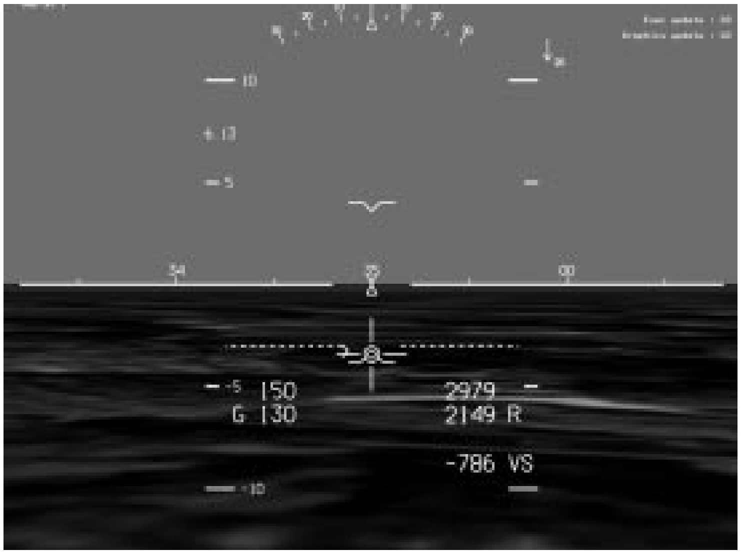


Figure 10. Out-the-window HUD symbology used in Conventional HUD display concept.

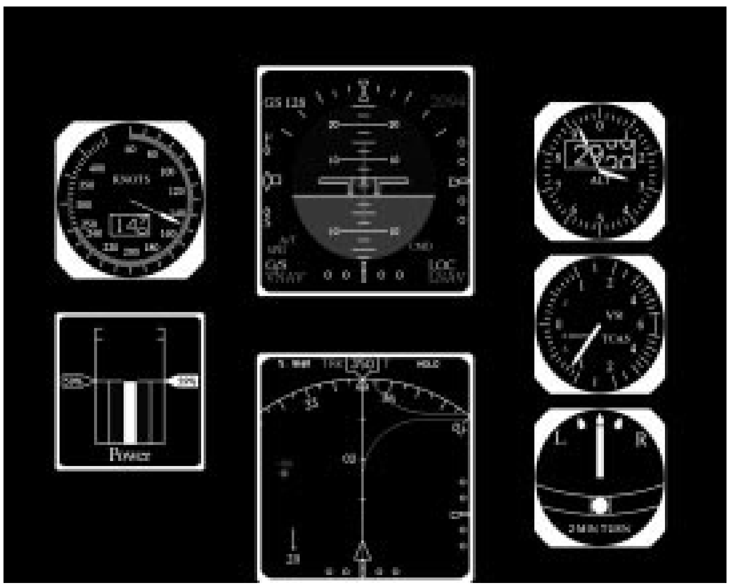


Figure 11. Basic EFIS instrument arrangement.

The HUD symbology (fig. 10) included digital altitude, groundspeed, airspeed and vertical airspeed readings, pitch and roll scales (in degrees), wind direction and speed, and a horizontal heading tape. Both groundtrack and heading markers were present on the horizontal heading tape. The central HUD symbology consisted of a flight path symbol, flight director, localizer/glideslope raw error lines, and pitch attitude symbol. At 300 feet radio altitude, a symbolic runway (dashed green outline) appeared on the HUD and was overlaid on the runway as perceived on the simulated OTW forward view. The symbolic runway location depiction can be thought of as being derived from INS/GPS position information. The HUD was attitude-centered and had a 40° horizontal FOV.

The first advanced display concept (hereinafter referred to as the Enhanced HUD (EH) display concept) incorporated a sensor-derived runway depiction and icon obstacles (other traffic) into the Conventional HUD display concept and was simulated under IMC. (See fig. 12.) The sensor-derived runway was depicted as a solid green outline on the monochrome HUD; while the HUD symbolic runway was depicted as a dashed green outline. Also displayed on the HUD were the sensor-based icon obstacles that used the same shapes and symbology as the TCAS objects shown on the ND. Similar to the OTW HUD, the sensor horizontal FOV was 40 degrees. As mentioned in the description of the CH display concept, the basic head-down instrument arrangement for the EH display concept was a conventional T-arrangement of instruments with a B-757 duplicate of a PFD over a ND. (See fig. 11.)

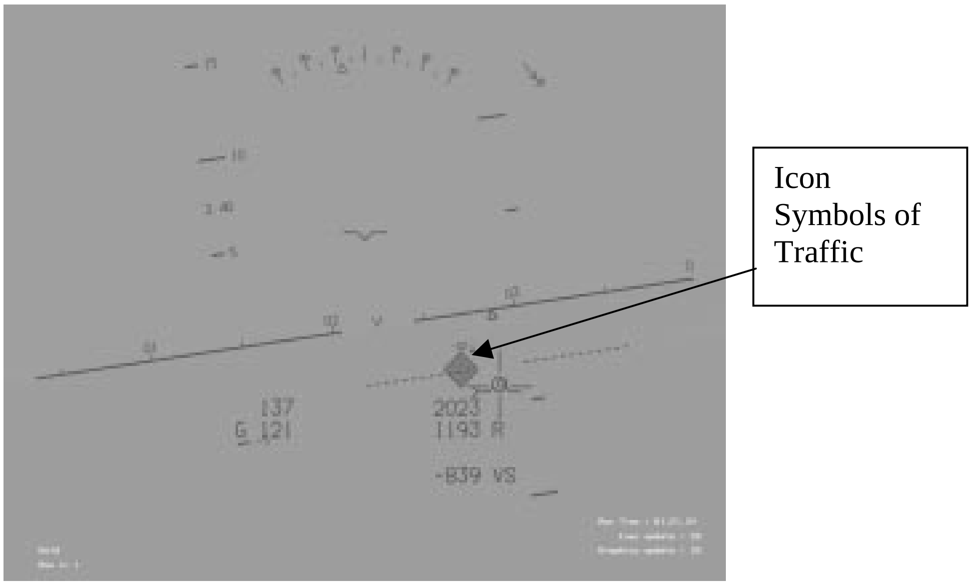


Figure 12. Enhanced HUD display concept.

The second advanced display concept (hereinafter referred to as the Embedded Conventional (EC) display concept) embedded the sensor-based runway and icon obstacles into the EFIS PFD instead of on the OTW HUD. Hence, the 40° FOV of the sensor was "minified" because it was represented in the smaller area of the PFD as opposed to the actual 40° FOV of the HUD. For the EC display concept, there was no out-the-window view because the HUD was removed, but the HUD symbology for the flight path symbol, flight director and pitch attitude symbol were embedded into the PFD. (See fig. 13.) Within the PFD, the sensor runway was displayed as a solid magenta outline and any sensor icon obstacles were displayed with their appropriate TCAS color and shape. Similar to the EH display concept, the symbolic runway appeared as a dashed white outline in the PFD at 300 feet radio altitude. A perspective runway, displayed as a solid green rectangle, was also seen in the compressed 40° FOV of the PFD.

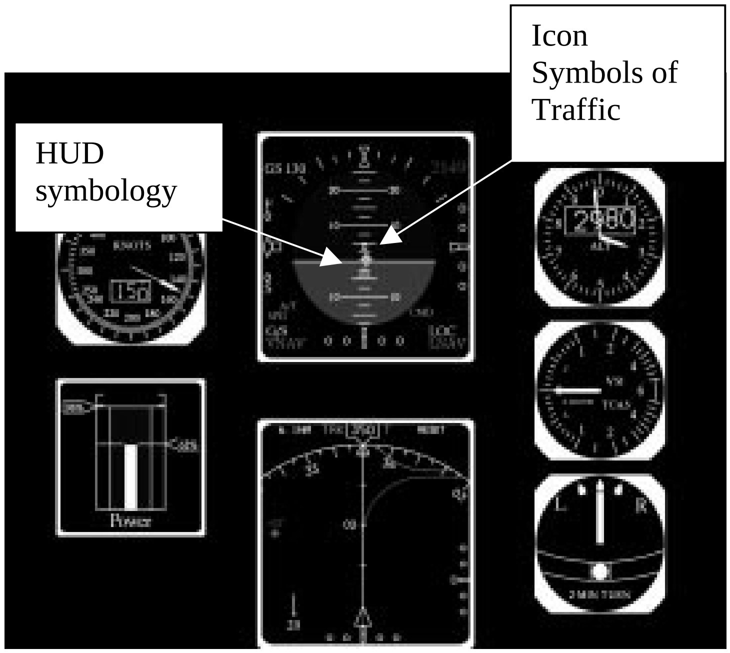


Figure 13. Embedded Conventional display concept.

The third advanced display concept (hereinafter referred to as the Pictorial Vision (PV) display concept) presented the pilot with a head-down, integrated pictorial display format that combined a computer-generated OTW view with overlaid HUD symbology. (See fig. 14.) The PV display concept had a 62° horizontal FOV as compared to the 40° FOV of the other three display concepts being examined. The OTW portion of the display consisted of a pathway-based approach tunnel, depicted by magenta dashed lines that represented the corners of the tunnel "box". The bottom of the tunnel was further marked by a magenta bar, spaced at approximately 1/10th nautical mile intervals, that also incorporated a vertical post to provide a relative (above ground) altitude cue. The tunnel's width and height corresponded to fractions of lateral and vertical instrument landing system (ILS) beam errors (1/2 dot right/left and 1 dot above/below tunnel centerline, respectively). The HUD symbology included airspeed and altitude vertical tapes, roll and pitch scales (in degrees), as well as a horizontal heading tape. All of the tapes incorporated Flight Management System (FMS) command "bugs." A vertical speed indicator was integrated onto the altitude tape as a growing/shrinking barber pole with a digital vertical speed tag (whose position on the altitude scale would denote the altitude to be attained in one minute based on current vertical speed). Similar to the CH display concept, the central HUD symbology for the PV concept consisted of a flight path symbol, flight director, localizer/glideslope raw error lines, and pitch attitude symbol. The display was attitude-centered with rate command control, although the pilots attempted to monitor the flight path vector. A "smoked-glass" (see-through) navigation display (fig. 15) was presented on the left side of the pictorial display, basically duplicating the EFIS ND. Thus, the see-through ND provided horizontal situation display information by depicting traffic within the OTW display FOV (delineated by the acute lines about the ownship centerline) as well as traffic outside the FOV.

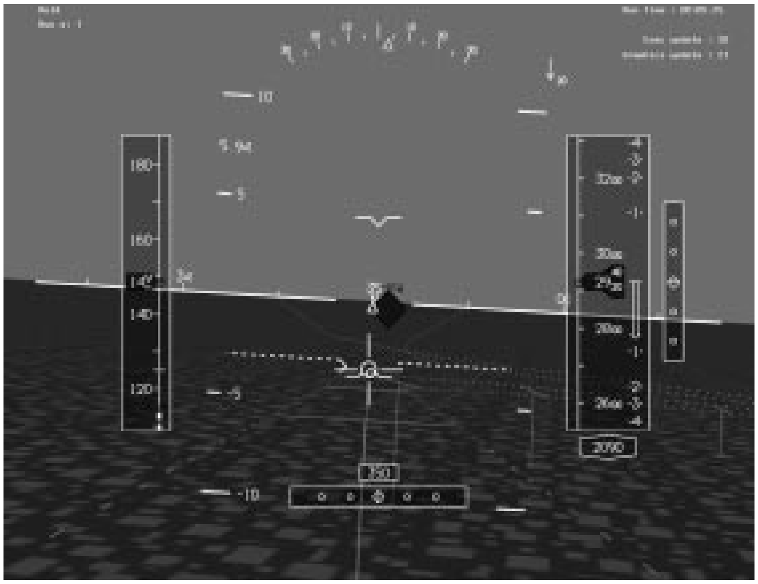


Figure 14. Partial view of the Pictorial Vision display concept’s computer-generated out-the-window view overlaid with HUD symbology.

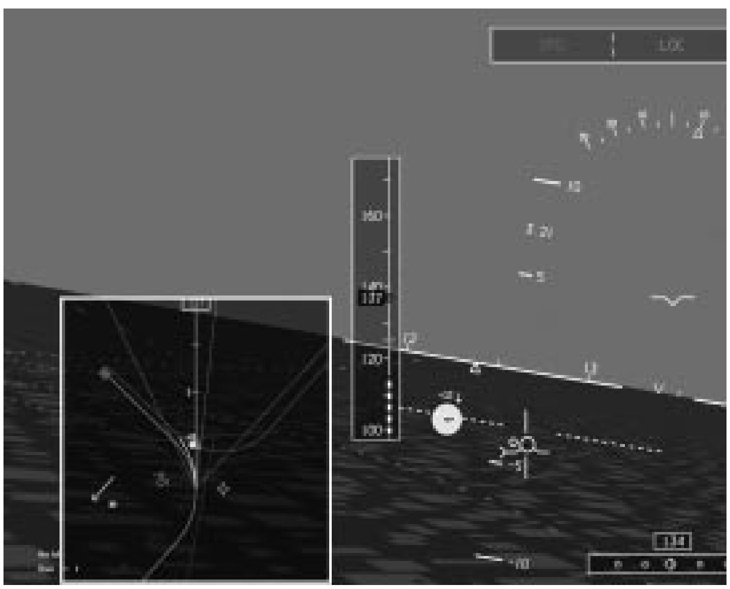


Figure 15. See-through navigation display on Pictorial Vision display concept.

In order to evaluate spatial awareness, scenarios were constructed that required the use of TCAS II-like implementations. All four display concepts incorporated TCAS symbology, but the implementation differed with respect to the display placement of the TCAS information. The CH, EH and EC displays incorporated TCAS symbols on the ND, along with relative altitude tags and vertical direction arrows (if climbing or descending). The meaning of the symbology itself is defined, for purposes of this experiment, in table 2. In actual field service, the TCAS advisory algorithms have changed and their implementation have become more sophisticated since the inception of this experiment. For all displays, the TCAS escape guidance command to either Climb or Descend was implemented on the Vertical Speed Indicator (VSI) in the form of a color-coded command bar. The pilot responded by keeping the VSI needle (or arrow) in the green-colored portion of the indicator (and out of the red). When this was achieved, the pilot was following the TCAS escape guidance command at an appropriate vertical rate. Warnings and commands were strictly visual (no audible alerts). The EH and EC displays also incorporated the TCAS symbology on the HUD thus providing a visual cue for relative traffic position OTW. For the PV display, TCAS symbology with the appropriate warning-color and shape-coding was implemented on the see-through ND and on the computer-generated traffic in the OTW scene. For all four display concepts, the TCAS advisories were turned off below 500 feet above ground level (AGL) altitude, although unfilled blue square symbols were used to represent other traffic on the displays, and their positional information continued to update.

Table 2. TCAS II Symbology

Symbol[a]	Definition
◇ Unfilled blue diamond	Other Traffic: > 7000 foot relative altitude or > 7 Nmi range at closest point of approach (CPA)._ Nonthreatening
◆ Solid blue diamond	Proximity Traffic: Within 1200 foot relative altitude and < 6 Nmi range at CPA. Nonthreatening
● Solid yellow circle	Traffic Advisory: Within 1200 foot relative altitude, <.2 Nmi range at CPA, and time to CPA • 45 seconds.
■ Solid red square	Resolution Advisory: Estimated miss distance • 750 ft, <.1 Nmi range at CPA, and time to CPA • 30 seconds.

[a]The actual display has these symbols in color; for purposes of this report, the symbols are in black and white.

Dependent Measures

All of the scenarios involving abnormal situations were implemented within the standard approach to landing procedure. SAL's with no abnormal situations developing (hereinafter referred to as Normal Runs) were randomly distributed in the test run sequence to lessen the pilot's expectancy of abnormal events occurring within each run. Therefore, no performance metrics were utilized for the Normal Runs.

The intent of these abnormal scenarios was to determine if significant differences exist between the display concepts that incorporate sensor-based wire-frame runway and icon obstacles (Enhanced HUD, Embedded Conventional, Pictorial Vision) when measuring a pilot’s situational awareness under IMC, and then compare these display differences to a conventional flight display (Conventional HUD) with no sensor-based information under VMC.

Metrics for the Anomalous Cues/Detection Time Scenarios

In each of these scenarios, the objective performance metrics were the time to detect and time to react to an anomalous situation. Detection time was recorded when the pilot pressed the ‘CONCERNED’ button and reaction time was recorded when the pilot pressed the ‘TOGA’ button. An additional metric for five of the six anomalous cue/detection time scenarios was the time difference between the CONCERNED and TOGA button presses. The one excluded scenario was the Flag TOGA scenario because it was assumed that detection and reaction occurred simultaneously since the pilot was required to immediately execute a TOGA. For those anomalous cue/detection time scenarios with an embedded TCAS TA on base leg, a second objective performance metric was the time to detect the Traffic Advisory indicated by a pilot ‘CONCERNED’ button press.

Metrics for the Freezing/Probe Scenarios

Blanking Scenarios

These are the only scenarios where the pilot was required to take control of the airplane and continue flying the approach. After blanking all displays (simulating display system failure), the pilot continued flying the approach solely utilizing the back-up instrument for approximately 20 seconds for each scenario. At blanking, the turbulence was turned off but the wind remained on so that the airplane maintained it’s inertial track until the pilot provided manual control input. This was done in order to maintain initial conditions for each of the display conditions for this scenario. For each blanking scenario, the objective performance measures were:

– vertical (altitude) path error rms, mean, and standard deviation
– lateral path error rms, mean, and standard deviation
– distance from path rms, mean, and standard deviation

Probe Scenario

After being exposed to the Probe scenario, the pilot was immediately asked a series of questions about the pilot’s situation awareness the moment the screen blanked. No objective performance metrics were utilized for the Probe Scenario.

Metrics for the Subjective Methods

Six questionnaires (one for each display concept, one comparing the three display concepts flown in IMC, and one for the probe scenario) were administered to each pilot during this simulation experiment. (See the right hand portion of table 3.)

As shown in table 3, each pilot was asked to complete a questionnaire at the end of the data-gathering runs for each display concept which dealt with the general evaluation (e.g., advantages, disadvantages, ease of detecting abnormal fight situations, etc.) of that particular display concept. (See appendix C.) Immediately after the Probe scenario was encountered, the researcher asked each pilot a series of questions (appendix C) about the pilot's spatial awareness the moment the screen blanked. The researcher recorded the pilot's verbal comments on a questionnaire (appendix D). After completing all the runs for each display concept, the probe questionnaire, and the individual display concept questionnaires, the pilots completed a final questionnaire that involved detailed comparisons of the three display concepts (EH, EC, and PV) flown in IMC. (See appendices C and D.)

Another method of subjective assessment of the individual displays was given in the form of modified Cooper-Harper (C-H) ratings for mental workload assessment. (See fig. 1 and ref. 14.) After the data-gathering runs for each display, each pilot issued a modified C-H rating for monitoring autoland approaches with that particular display concept.

Procedure

The experiment encompassed a total of two eight-hour days with scheduled rest periods. On the first day, after being briefed on the purpose of the experiment, the details of each Display Concept, and the various Scenarios to be encountered, the pilot spent about forty minutes going through familiarization training on VISTAS to learn about it's handling characteristics of the airplane model. The Conventional HUD display concept was used for the simulator familiarization. The pilots were then thoroughly trained with the standard approach to landing procedure, and then were thoroughly exposed to each abnormal Scenario (except the Probe scenario), for each Display Concept. The second day was the data collection session.

Organization of Trials

The four Display Concepts (CH, EH, EC, and PV) were randomly blocked across pilots, and the experimental scenarios were randomized within each Display Concept block. (See table 3.) Due to its intrusive nature as a SA assessment technique, the Probe scenario was always the last run in the Display Concept block in which it appeared. Pilots flew all 11 scenarios (some with replicates) for each display concept. If a scenario was flown to both runway 8L and 8R, these runs were considered replicates since the paths were mirror reflections of each other. For example, in table 3, the symbols A_3 and A_4 are considered replicates of each other because each refers to the same experimental run of an aircraft incursion on final approach, flown to parallel runways. Varying the approach paths by using parallel runways helped minimize pilot complacency and expectancy. Within each Display Concept block, two TCAS TA's were embedded within some of the anomalous cue/detection time scenarios. So, in addition to detecting the TA, the pilot was still required to detect and avoid an anomalous flight condition during the autoland approach. Therefore, these runs with an embedded TA were considered identical to the same runs without the embedded TA (same basic scenario) for the purposes of detecting and reacting to an anomalous condition. For example in table 3, the symbols A_3 (without embedded TA) and T_3 (with embedded TA) represent the same experimental run of the aircraft incursion on final approach to Runway 8L. The TA was for detection purposes only and did not affect the rest of the run. Table 3 presents an outline of a typical session, the details of which varied from pilot to pilot.

Table 3. Typical Pilot Session.

Display Concept	Approach Conditions[a]	Questionnaires		
		Individual Display	Final	Probe
EH	$A_1,N_1,T_8,A_4,A_{9b},N_1,A_5,A_7,B_2,A_2,N_2,B_1,N_2,A_6,T_3,B_3,A_{10a}$	✔		
PV	$N_1,A_8,T_6,A_1,B_1,A_2,A_{10a},A_4,N_2,A_{9b},A_5,B_3,N_2,N_1,B_2,T_7,A_3$	✔		
EC	$A_4,N_2,A_1,B_2,A_{9a},N_1,A_7,T_5,B_3,A_8,N_2,A_3,A_2,A_6,B_1,N_1,T_{10b}$,P	✔		✔
CH	$B_2,T_{9a},A_8,A_3,A_5,N_1,A_1,T_4,A_6,N_1,B_3,A_7,A_{10b},N_2,B_1,A_2,N_2$	✔	✔	

[a]Conditions:

$N_{1,2}$ signifies a standard approach (Normal Run) to either Runway 8L or 8R
A_1 signifies a flight director conflict with autopilot while on approach to Runway 8L
A_2 signifies a flight director conflict with raw data while on approach to Runway 8R
$A_{3,4}$ signifies a aircraft incursion on final approach to either Runway 8L or 8R
$A_{5,6}$ signifies a Flag TOGA (localizer failure) while on approach to either Runway 8L or 8R
$A_{7,8}$ signifies an autopilot oscillation while on approach to either Runway 8L or 8R
$A_{9a,9b}$ signifies a small navigation system error (75 feet) while on approach to either Runway 8L or 8R
$A_{10a,10b}$ signifies a large navigation system error (300 feet) while on approach to either Runway 8L or 8R
$B_{1,2,3}$ signifies the three blanking scenarios
$T_{3,4}$ signifies an embedded TA in aircraft incursion on final scenario to either Runway 8L or 8R
$T_{5,6}$ signifies an embedded TA in Flag TOGA while on approach to either Runway 8L or 8R
$T_{7,8}$ signifies an embedded TA in autopilot oscillation while on approach to either Runway 8L or 8R
$T_{9a,9b}$ signifies an embedded TA in small navigation system error while on approach to Runway 8L or 8R
$T_{10a,10b}$ signifies an embedded TA in large navigation system error while on approach to Runway 8L or 8R
P signifies probe on final approach

EXPERIMENTAL RESULTS AND DISCUSSION

All of the scenarios under investigation (excluding the Probe scenario) were designed as full-factorial, within-subjects experiments, with Display Concept and Replicates (where applicable) as the factors. The data collected in the experiments were analyzed using repeated measures analyses of variance (ANOVA) for each metric. Since extensive pilot variability is expected, the repeated measures design was chosen because in this experimental design each individual acts as his or her own control eliminating any post-treatment effects attributed to individual characteristics. The particular repeated measures design used was a randomized block design, with each individual designated as a “block”. (See ref. 15.) Student-Newman-Keuls (SNK) tests (at a 5-percent significance level) of individual means were performed at various stages in the analyses.

Objective Data Analyses

Anomalous Cues/Detection Time Scenarios

The intent of the anomalous cues/detection time scenarios was to determine if significant differences exist between the advanced display concepts that incorporate sensor-based wire-frame runway and icon obstacles (Enhanced HUD, Embedded Conventional, Pictorial Vision) when measuring a pilot’s situational awareness under IMC. These displays were then compared to a conventional EFIS display concept (Conventional HUD) with no sensor-based information under VMC. The meteorological conditions were established for the display concepts according to the scenarios as discussed in the Introduction. The scenarios developed for this simulation experiment required the pilot to detect anomalous situations with the ownship with respect to traffic and the runway position. Since the pilot had no sensor-derived information in the conventional EFIS display concept, he had to detect traffic and the runway visually. Hence, this concept was simulated under VMC instead of IMC. Table 4 lists the repeated measures ANOVA analyses performed for the anomalous cues/detection time scenarios. In each of these scenarios, the performance metrics were the times to detect and react to an anomalous situation by pressing the ‘CONCERNED’ button and the ‘TOGA’ button, respectively. Pilot detection time (in the form a CONCERNED button press) of a TCAS Traffic Advisory was also a performance metric in four of these scenarios. Additional analyses were performed on the time difference between the CONCERNED and TOGA presses for five of the anomalous cues/detection time scenarios. The one excluded scenario was the Flag TOGA scenario because it was assumed that detection and reaction occurred simultaneously since the pilot was required to immediately execute a TOGA. Only those scenarios with significant statistical differences between factors will be discussed in the remainder of this section. A complete summary of the ANOVA analyses performed for the anomalous cues/detection time scenarios are listed in appendix A.

Table 4. List of ANOVA analyses performed.

Anomalous Cue/Detection Time Scenario	CONCERNED press (detection time)	TOGA press (reaction time)	Time difference between CONCERNED and TOGA presses	TCAS Traffic Advisory Press (detection time)
Flight Director Conflict with Autopilot	✔	✔	✔	
Flight Director Conflict with Raw Data	✔	✔	✔	
Aircraft Incursion on Final	✔	✔	✔	✔
Flag TOGA		✔		✔
Autopilot Oscillation	✔	✔	✔	✔
Navigation System Error (small)	✔	✔	✔	✔
Navigation System Error (large)	✔	✔	✔	✔

Flag TOGA scenario

Significance of the sphericity test ($p < 0.05$) on one of the main factors, displays, indicated that the repeated measures ANOVA results should not be accepted. Sphericity is a form of deviation from the assumption of homogeneity of variance to which repeated measures designs are especially sensitive. (See ref. 15.) Investigation of the objective data showed that 6 out of 7 outliers for the TOGA button press reaction time could be attributed to one pilot. This one subject's reaction times were increasing the likelihood of unequal variances. A repeated measures ANOVA (appendix A.14), excluding this particular pilot, showed marginally significant differences among the main factor displays ($F(3,18) = 2.77$, $p < .072$), but not in the other main factor, replications, or in the interaction between these two factors. Post hoc analysis using SNK test with significance level .05 showed no significant differences between the three sensor-based display concepts. However, the Embedded Conventional display concept did show differences when compared to the performance obtained with the Conventional HUD display concept (no sensor information present). Figure 16 graphically presents the results of the Flag TOGA scenario. The mean TOGA press time (or pilot reaction time to an anomalous situation) for the EC display was 1.9 seconds sooner (corresponding to 23 ft relative altitude difference) than the CH concept.

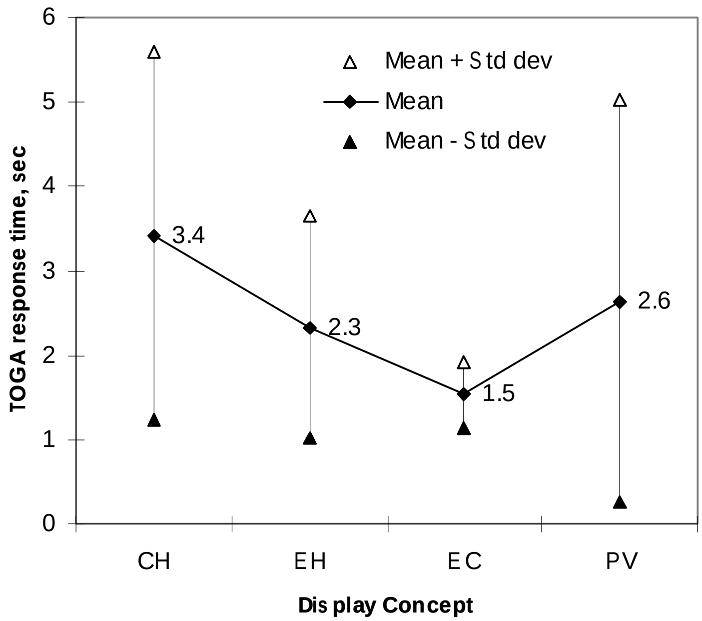


Figure 16. Flag TOGA scenario mean TOGA press times per display concept.

For this scenario, the indication of a localizer failure appeared both in the PFD and the ND for the CH, EH, and EC display concepts. The inference from these results is that the pilot's reaction time was quicker with the EC display concept probably because his visual scan (attention) was not divided between the head-up and head-down displays or across a wider field of view like it was with the other display concepts. The pilots may also have been visually distracted by the VMC scene found only in the CH display concept, resulting in display differences between that and the IMC EC display concept. Although marginally significant, the display differences in the Flag TOGA scenario would not be critical in real-world flight operations, having a relative altitude difference of only 23 feet.

Autopilot Oscillation scenario

Repeated measures ANOVA analyses (appendix A.15-A.16) on CONCERN and TOGA button press detection and reaction times with displays and replications as independent variables showed a highly significant main effect for displays ($F(3,21) = 7.95$, $p < .001$ and $F(3,21) = 17.80$, $p < .000$, respectively), but no significant main effect for replications or interaction effects between the two main factors present. Post hoc comparisons of the means (using the SNK technique) for both the CONCERN and TOGA button press times showed no differences between the EH, PV or CH display concepts but there was a difference between these concepts and the EC display concept. Figures 17 and 18 graphically present the results for the displays factor for the CONCERN press (pilot detection time) and the TOGA press (pilot reaction time), respectively. The pilots exhibited an (averaged) increased response mean time of 3.6 seconds for the CONCERN press and 5.2 seconds for the TOGA press with the Embedded Conventional display concept as compared to the other three display concepts.

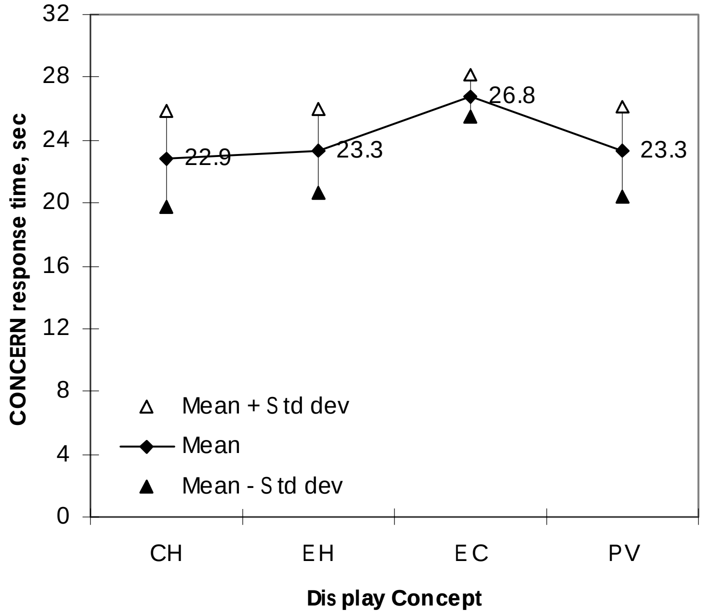


Figure 17. Autopilot oscillation scenario mean CONCERN press times per display concept.

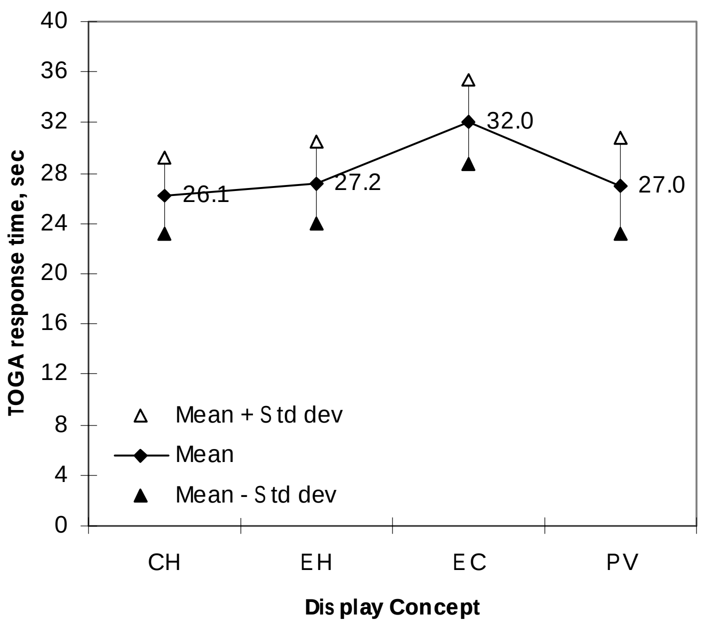


Figure 18. Autopilot oscillation scenario mean TOGA press times per display concept.

The autopilot oscillations began at 580 feet AGL altitude on final approach, reaching a 1 dot deviation in glideslope at threshold. The inference from these results is that the pilots were able to detect autopilot oscillations more readily (by an average of 3.6 seconds) with the CH, EH, and PV display concepts as compared to the EC concept. The head-down PV concept had a 62° horizontal FOV; while the head-up view of the CH and EH concepts had a 40° horizontal FOV. The EC concept's "minified" PFD display (compressed 40° horizontal FOV) probably caused the increased pilot detection time of the autopilot oscillations; thus, decreasing pilot recovery initiation by an average of 5.2 seconds (corresponding to 60 ft relative altitude difference) with the EC display when compared to the CH, EH, and PV displays. Small deviations from path are less apparent in the compressed 40° horizontal FOV of the EC concept. These display differences are significant, both statistically and in real-world flight operations, during the landing phase of flight where critical flight decisions are heavily constrained by time.

Navigation System Error (small)

Repeated measures ANOVA analyses (appendix A.18 – A.19) on the CONCERN button press time (pilot detection time) ($F(3,21) = 24.17$, $p < .000$) and the TOGA button press time (pilot reaction time) ($F(3,21) = 14.51$, $p < .000$) showed highly significant differences among the displays factor. Figures 19 and 20 graphically present the results of the Navigation System Error Scenario with the 75 foot discrepancy between sensor and inertial-referenced runway centerlines. For this scenario, the lateral position error was implemented at the beginning of the run so the CONCERN and TOGA button press time measurements began at this point as well. Post hoc analysis of the CONCERN press time means (using the SNK test at a significance level of .05) showed no differences between the PV and EC displays and no differences between the CH and EH displays, but differences were noted between these two groups. The mean CONCERN press time (or pilot detection time) for the PV display was 5 seconds sooner than the EC concept and 30 seconds sooner than the EH and CH concepts. These time differences correspond to a relative altitude difference of approximately 68 feet between the PV and EC concepts and 373 feet between the PV and EH/CH concepts for recognizing the small navigation system error. Post HOC comparisons of the TOGA press time means showed significant differences between the Pictorial Vision Concept and the other three concepts (CH, EH, and EC), but no differences between the latter three concepts. The mean TOGA press time (or pilot reaction time) for the PV display was 12 seconds sooner (corresponding to 146 ft relative altitude difference) than the EC concept and 23 seconds sooner (corresponding to 274 ft relative altitude difference) than the EH and CH concepts.

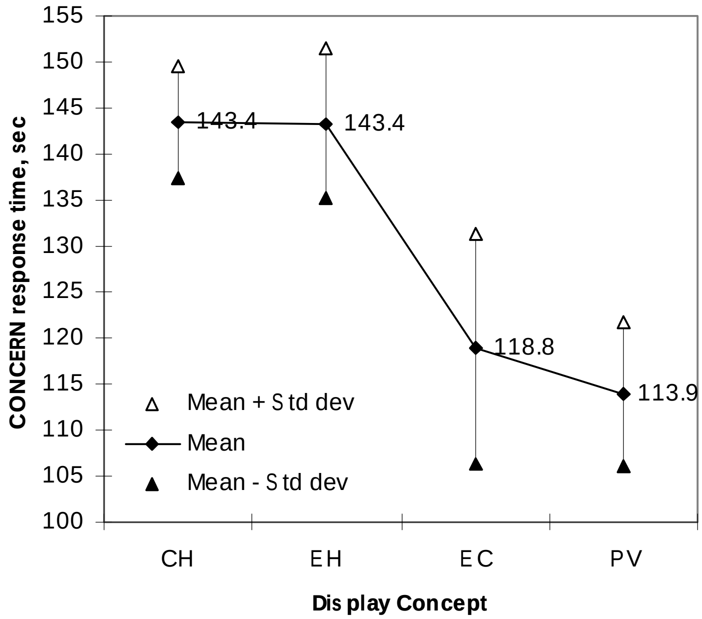


Figure 19. Small navigation system error scenario mean CONCERN press times per display concept.

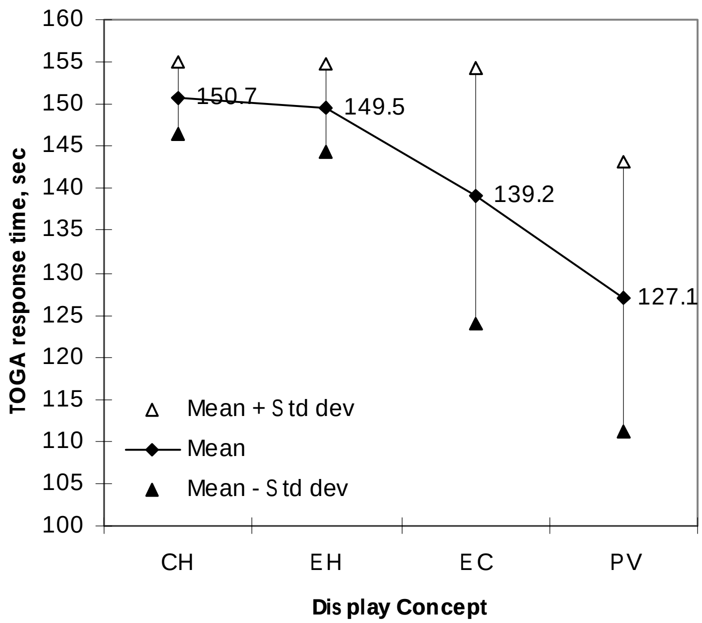


Figure 20. Small navigation system error scenario mean TOGA press times per display concept.

The inference from these results is that the Pictorial Vision display concept provided the pilots with better awareness of erroneous navigation system information than did the other display concepts. The 62° horizontal FOV of the PV display (as compared to the 40° horizontal FOV of the EH and EC displays) probably enabled pilot detection of the abnormal flight condition earlier and at higher altitudes (a 30-second-earlier detection time translates into 373 ft of altitude separation), indicating increased pilot awareness of the situation. Pilot reaction time (in the form of a TOGA press) to discontinue autoland approaches was considerably better with the Pictorial Vision display concept over the other three concepts (a 23-second earlier reaction translates into 124 ft of altitude separation), again indicating increased pilot situation awareness probably due to the larger FOV of the PV display concept.

Navigation System Error (large)

Graphical inspection of the data showed one outlier (3-σ away from the grand mean) for the CONCERN press (pilot detection) time, resulting in unequal display variances. Removal of this outlier in the CONCERN press data reduced the affected display's variance by a factor of four. (See fig. 21.) A repeated measures ANOVA analysis (appendix A.22) (excluding the pilot with the outlier) on the CONCERN button press detection time showed a highly significant main effect for displays ($F(3,18) = 14.85$, $p < .000$). Significance of the sphericity test ($p > 0.05$) on the main factor, displays, indicated that the repeated measures ANOVA results should be accepted. Figure 22 graphically presents the results of the Navigation System Error Scenario with the 300 foot discrepancy between sensor and inertial-referenced runway centerlines. For this scenario, the lateral position error was implemented at the beginning of the run so the CONCERN and TOGA button press time measurements began at this point as well. Post hoc comparisons of the CONCERN time means using SNK test at a 5-percent significance level showed no differences between the EC and PV concepts or the CH and EH concepts; however, differences were noted between these two groups. The mean CONCERN press time (pilot detection time) for the EC/PV displays was 13 seconds sooner than the CH/EH displays, resulting in a 169 feet relative altitude separation between the two groups.

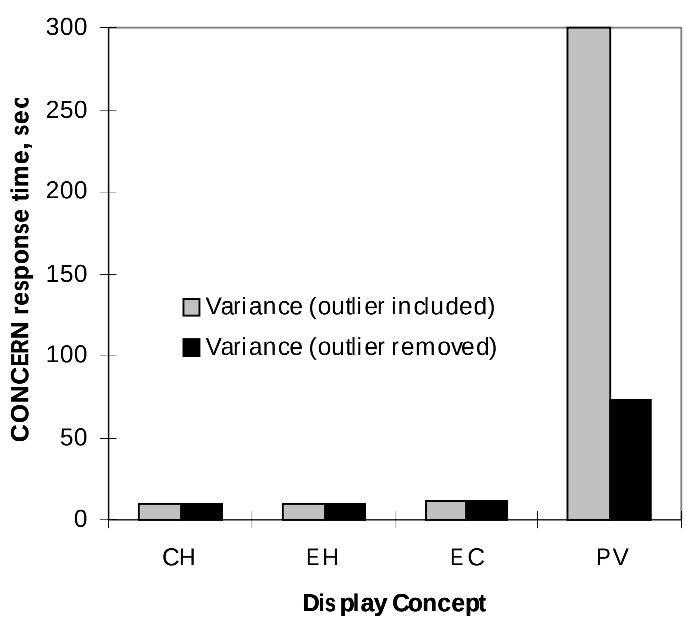


Figure 21. Large navigation system error scenario CONCERN press display variances with and without inclusion of an outlier.

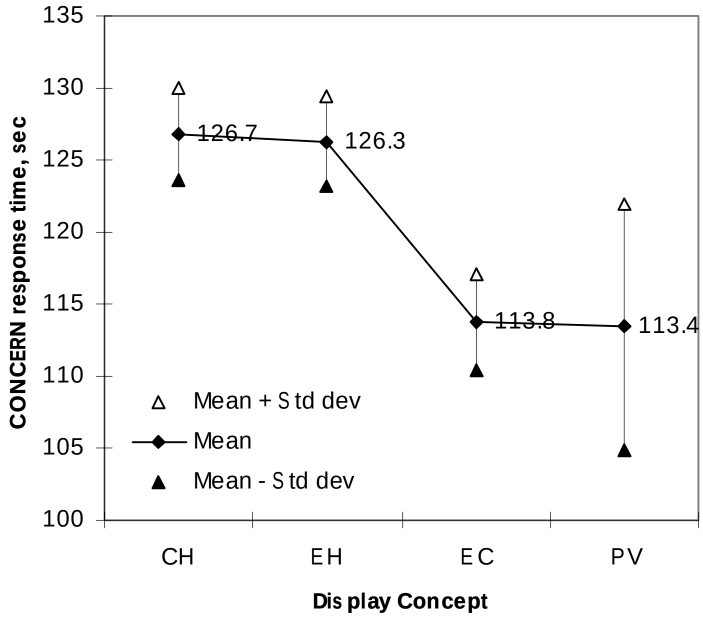


Figure 22. Large navigation system error scenario mean CONCERN press times per display concept.

The inference from these results is that the Pictorial Vision and Embedded Conventional display concepts provided the pilots with better awareness of inaccurate navigation system information than did the Conventional HUD and Enhanced HUD display concepts. The head-down-only scan of the PV/EC displays (as opposed to the dual head-down/head-up scan with the CH/EH displays) probably enabled pilot detection of the abnormal flight condition earlier and at higher altitudes (a 13-second-earlier detection time translates into 169 ft of altitude separation), indicating increased pilot awareness of the situation. The magenta runway outline for the sensor in the multi-colored PV/EC displays probably helped improve pilot detection time with these displays as compared to the green outlines of the sensor and inertial-based runways in the monochrome CH/EH displays.

Freezing/Probes Scenarios

Blanking Scenarios

These are the only scenarios where the pilot was required to take control of the airplane and continue flying the approach. The blanking/back-up instrument time was approximately 20 seconds for each scenario. At blanking, the turbulence was turned off but the wind remained on so that the plane maintained it's inertial track until the pilot provided manual control input. This was done in order to maintain initial conditions for each of the display conditions for this scenario. For each blanking scenario, a repeated measures ANOVA on displays (only factor present) was performed for the following performance measures:

– vertical (altitude) path error rms, mean, and standard deviation
– lateral path error rms, mean, and standard deviation
– distance from path rms, mean, and standard deviation

No differences (at the .01 significance level) were found among the four display concepts in the 27 repeated measures ANOVA analyses that were performed. (See appendix B.) Trends that were seen in the data are discussed in the remainder of this section. Lateral and vertical rms path errors, collapsed across blanking scenarios and pilots, showed that the sensor-based display concepts offered performance improvements over the Conventional HUD display concept. For Blanking Scenario 1 (blanks before turn to final), although not statistically significant, improvement in lateral and vertical rms path errors was observed in the sensor-based displays. (See fig. 23.) For Blanking Scenario 2 (blanks before roll-out on final), the vertical rms path errors remained relatively small and constant across the four displays; while the Embedded Conventional display had lower lateral RMS path errors as compared to the other three displays. (See fig. 24.) All eight pilots correctly initiated the commanded TCAS maneuver (descent) for Blanking Scenario 3 (blanks after TCAS resolution advisory on base) when using the three display concepts utilizing sensor information. One pilot incorrectly initiated the commanded TCAS maneuver while flying the Conventional HUD display concept; while the other seven pilots initiated the correct response for the CH display concept.

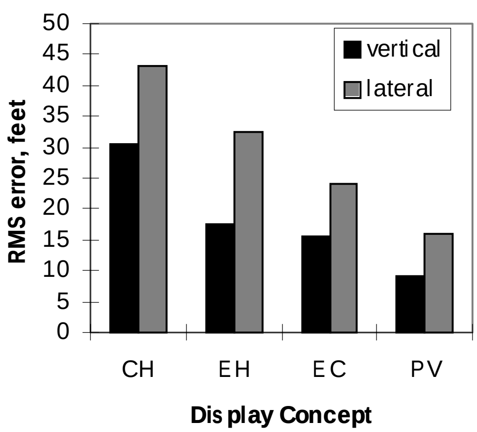


Figure 23. Blanking scenario one–vertical and lateral rms path errors per display concept.

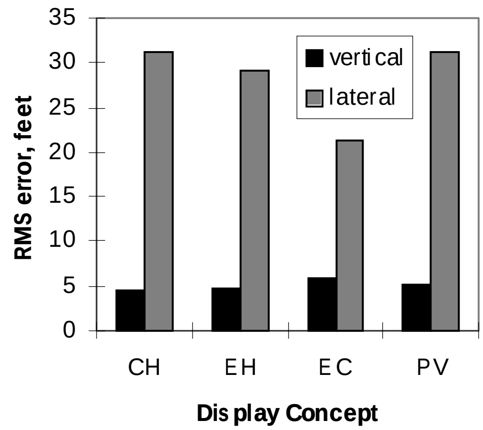


Figure 24. Blanking scenario two–vertical and lateral rms path errors per display concept.

The blanking scenarios yielded no relevant information about spatial awareness differences between the display concepts being examined. This type of SA assessment technique, under this experiment design, does not appear to provide a useful measure of pilots' situation awareness when comparing display concepts that incorporate sensor-based wire-frame runway and icon obstacles (Enhanced HUD, Embedded Conventional, Pictorial Vision) under IMC with a Conventional HUD display concept under VMC during autoland approaches.

Probe Scenario

For each Display Concept, the probe scenario occurred twice. Each pilot experienced the Probe scenario only once during the data collection runs. Figure 25 graphically shows the results for the small sampling of pilots in the Probe scenario. When using the EC display all three abnormal flight conditions (Flight Director (FD) Conflict with Autopilot (AP), TCAS Traffic Advisory, and Loss of Glideslope) were detected and correctly identified for 5/6 occurrences. With the remaining three display concepts, the pilots detected and correctly identified 4/6 occurrences of the abnormal flight conditions. The Conventional HUD concept had one pilot missing the FD conflict with AP and the other pilot missing the TA. The Enhanced HUD concept had one pilot correctly identifying all 3 abnormal flight conditions and the other pilot missing the TA and the FD conflict with AP. The Pictorial Vision concept had both pilots missing the FD conflict with AP. No pilot missed the loss of glideslope flight condition.

It is suggestive from these results that the EC concept provided somewhat better situational awareness than the other three displays. The greater number of detections with the EC concept was probably attained because the pilot's visual scan was contained in a smaller, centrally-located area with this concept as compared with the other three display concepts.

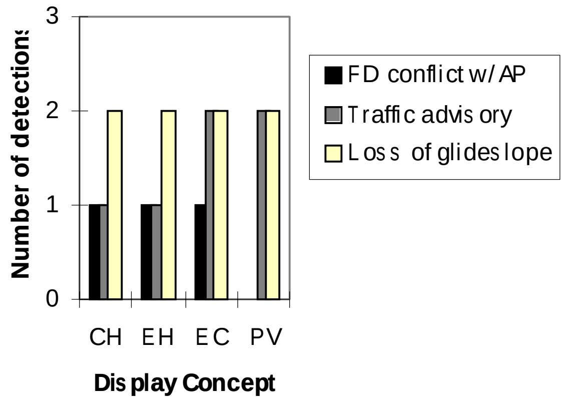


Figure 25. Probe scenario number of detections of abnormal flight conditions per display concept.

Subjective Data Analyses

Six questionnaires (one for each display concept, one comparing the three display concepts flown in IMC, and one for the probe scenario) were administered to each pilot during this simulation experiment. (See the right hand portion of table 3 in the Procedures section-Organization of Trials. Also reference appendices C and D.) In addition to the display-specific questions, the pilots were asked to assign a modified C-H rating after being exposed to a block of scenarios for a specific display concept.

Display Questionnaire Ratings

A repeated measures ANOVA analyses on the modified C-H operator ratings showed a highly significant effect ($F(3,21) = 4.964$, $p < .009$) for the factor displays. Post hoc analysis of the modified C-H ratings using SNK test with significance level .05 showed differences between the PV display concept and the other three display concepts (CH, EH and EC). The PV display concept had a lower operator demand level and difficulty level than the other three displays. No significant differences were seen between the means of CH, EH, and EC display concepts. Figure 26 graphically shows the mean modified C-H ratings for each display concept. The PV display concept had a mean modified C-H rating of 1.625 which indicated a “easy, desirable” difficulty level to the pilot. A modified C-H rating in this range indicates that the “operator mental effort is low and desired performance is adequate.” The mean modified C-H ratings for the remaining three display concepts indicated a “fair, mildly” difficulty level to the pilot and that “acceptable operator mental effort is required to attain adequate system performance” by the pilot.

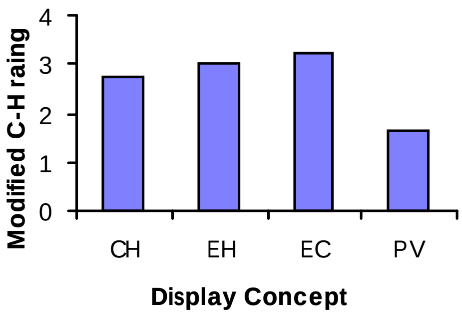


Figure 26. Modified Cooper-Harper mean ratings for each display concept.

Individual Display Concept Questionnaire

A series of repeated measures ANOVAs were performed on the pilot responses to individual display questionnaire inquires about the following (See appendix D):

1. encountering the anomalous cues/detection time scenarios
2. monitoring an autoland approach
3. pilot workload in monitoring autopilot functions, airborne traffic and airport surface traffic
4. ease of making the decision to go around
5. ease of maintaining situational awareness

The anomalous cues/detection time scenarios encountered by each pilot are as follows:

1. Flight Director conflict with Autopilot
2. Flight Director conflict with Raw Data
3. Aircraft Incursion on Final
4. Flag TOGA (localizer failure)
5. Autopilot Oscillation
6. Navigation System Error - small (75 feet)/large (300 feet)

For each anomalous cues/detection time scenario, the pilots rated the Pictorial Vision concept as the easiest display concept among the three displays flown in IMC to detect and understand the unusual flight condition. The pilots ranked the Enhanced HUD system second of the three displays flown in IMC for ease of detecting and understanding all the anomalous cues/detection time scenarios, except for two instances. The Embedded Conventional concept was ranked second for ease in understanding what was wrong in the scenario in which the Flight Director and the Flight Director Raw Data are in conflict and for ease in understanding what was wrong in the scenario in which a Failure Flag (loss of localizer signal) occurred. No statistical differences between the means of the PV concept and the EH concept were found in any of the anomalous cues/detection time scenarios except in the scenario of recognizing an aircraft runway incursion. For this scenario, pilot opinion inferred that the Pictorial Vision concept was very easy in recognizing an aircraft incursion; while, the Enhanced HUD concept neither aided nor hindered the recognition of an aircraft incursion. The pilots ranked the Embedded Conventional concept last among the three displays flown in IMC for ease of detecting and understanding all of the anomalous cues/detection time scenarios, except for the two conditions noted above. This low ranking can probably be attributed to the difficulty of recognizing an abnormal condition in the EC's compressed 40° field of view as presented in the PFD as compared to the 40° FOV found in the EH's out-the-world scene or the 62° FOV found in the PV's synthetic scene.

Out of the four display concepts flown, the pilots ranked the Pictorial Vision concept as the display that was easiest to use to maintain situational awareness, to monitor an autoland approach, to interpret information from the runway and obstacle detecting sensor systems, and to make the decision to go around. The PV concept was also the pilot preference among the fours displays evaluated for ease of monitoring autopilot functions, airborne traffic and airport surface traffic.

Final Questionnaire

After completing all the runs for each Display Concept, the probe questionnaire, and the individual display concept questionnaires, the pilots completed a final questionnaire that involved detailed comparisons of the three display concepts (EH, EC, and PV) flown in IMC. Similar to the subjective results found for the individual display questionnaires, the Pictorial Vision concept was significantly preferred over the Enhanced HUD and the Embedded Conventional display concepts when considering all monitoring tasks (i.e., the approach, verifying the location of the runway, detecting ground runway incursions, etc.). For each anomalous cues/detection time scenario, the Pictorial Vision concept had the highest pilot ranking among the three display concepts flown in IMC for ease of detecting and understanding the unusual flight condition. The pilots rated the Enhanced HUD concept second and the Embedded Conventional concept third of the three displays for ease of detecting and understanding the anomalous cues/detection time scenarios. The EC's low ranking can probably be attributed to the difficulty of recognizing an abnormal flight condition in this concept's "minified FOV" PFD display.

Figure 27 shows the results of comparative rank ordering (of the display concepts flown in IMC) by the pilots for several categories on a scale of 1 (the least desirable display) to 10 (the most desirable display). For each category, the mean, maximum, and minimum pilot rankings (not plus or minus the standard deviations) for all experiment scenarios are presented. The pilots ranked each display's effectiveness for allowing the pilot to monitor all flight tasks, maintain situation awareness and monitor an autoland in restricted visibility conditions, for reducing their overall workload, and for presenting them sensor-based information. Based on subjective rankings, the PV display concept offered considerable improvements in situation awareness and reductions in overall pilot workload (in both mean ranking and spread) over the EH and EC display concepts. The pilot preference for the PV display concept over the other two display concepts may have been influenced by the reduced scan-time and larger field of view associated with this display. When using the Pictorial Vision concept, the pilots scan time was not divided between the Head-up and Head-down displays like it was in the Enhanced HUD concept, and the pilots had a much larger FOV (62° as compared to a compressed 40°) to determine unusual flight conditions than they did with the Embedded Conventional concept.

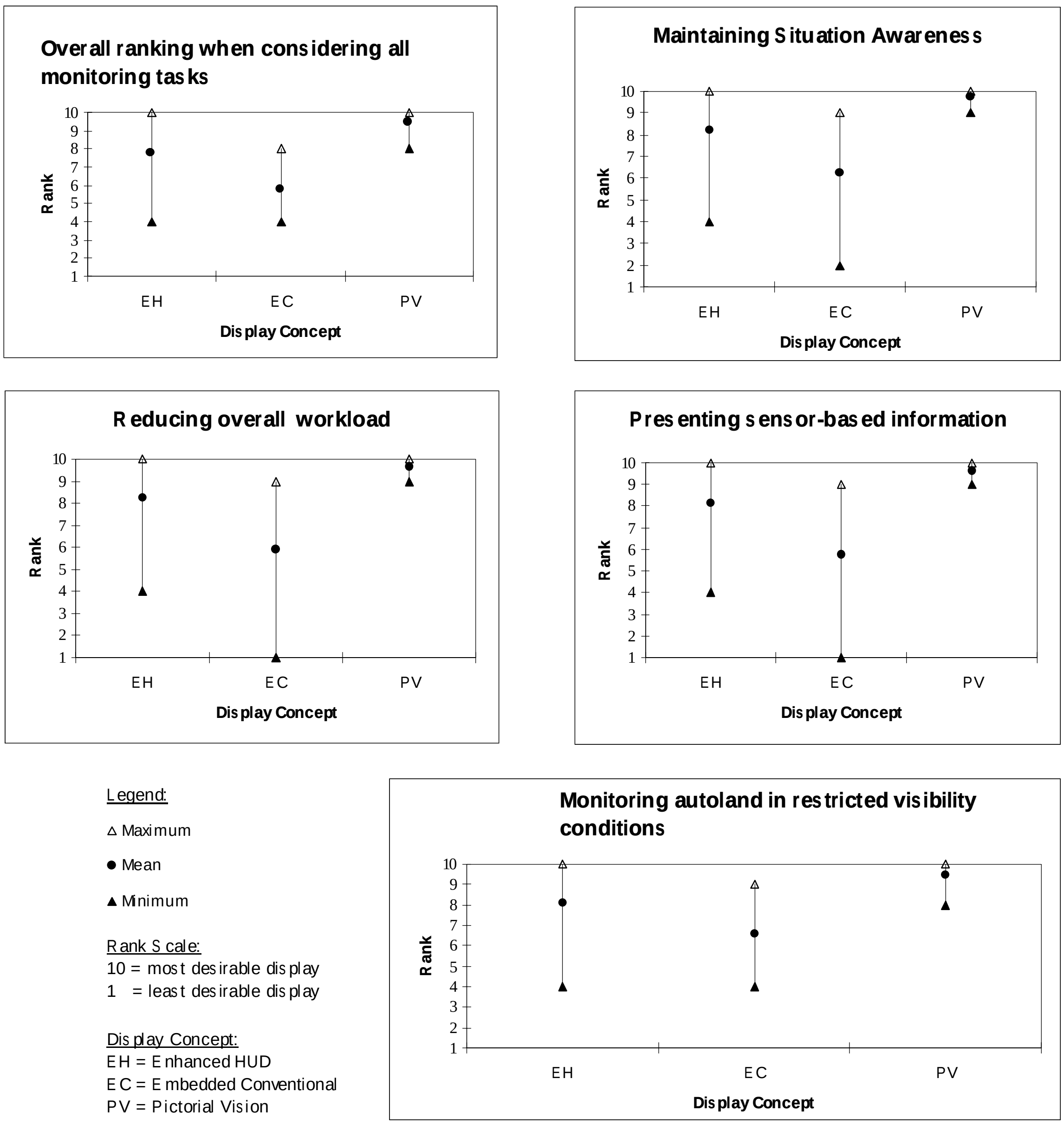


Figure 27. Comparative rank ordering by pilots for five categories.

Probe Questionnaire

Several pilots commented that the intrusive SA assessment technique of the Probe scenario helped them remain vigilant while monitoring the autoland operations. After encountering this "surprise" scenario, the pilots commented that they were expecting more "surprises" which encouraged them to remain alert. However, no significant display differences were noted.

Pilot Comments

In addition to the questionnaire results, pilots were also give the opportunity to provide comments on the questionnaires about the display concepts. Some of the more notable comments are the following:

> "What appears to be complete situational awareness. The field of view is very good and traffic alerts and resolutions are noticed very quickly. It almost gives a three dimensional effect. The pathway presents a fulltime unconscious evaluation of LOC and G/S performance which reduces the amount of crosschecking required of the raw data. This reduction in workload really pays off when unexpected problems arise which demand additional attention. One can allocate that additional time while still subconsciously monitoring the approach. " [comments on advanced pictorial display concept]

> "When comparing all three systems PV [advanced pictorial display concept] was only system that would make a CAT IIIc a comfortable approach."

> "The sensor information is a must for any future aircraft instrumentation for increased flight safety first and restricted visibility conditions approaches and landings."

> "Overall SA was greatly improved over conventional systems. Easier to monitor not only flight progress, but the complete flight environment. I believe this alone lends itself to a safer operation for both the user aircraft and airspace it's operating in." [comments on advanced pictorial display concept]

CONCLUDING REMARKS

A simulation study was conducted using eight commercial airline pilots, repeatedly flying MLS-type autoland approaches to closely spaced parallel runways, to assess pilots' situation awareness and workload while monitoring autoland operations utilizing three advanced display concepts. These concepts incorporated sensor-based wire-frame runway and icon obstacles and were flown under Instrument Meteorological Conditions. A conventional EFIS-based display concept utilizing a HUD without any sensor-based information provided an experimental control condition for the simulation. This conventional EFIS-based/HUD display concept was simulated under Visual Meteorological Conditions instead of IMC because the pilot had to visually detect the runway and other traffic without the aid of a sensor. Comparisons were made between the conventional EFIS-based/HUD concept and the advanced display concepts to ensure that the advanced concepts did not degrade a pilot's current level of SA or increase his or her workload during autoland operations. Various situational awareness measurement techniques, involving conflicting traffic situation assessments, main display failures, and conflicting position information, were used to assess the pilots' situation awareness with the different display concepts, both objectively and subjectively. The situation awareness tools utilized in the experiment proved to be most effective in the assessment (with the exception of the Blanking Scenarios), in that the results were consistent across and within the objective and subjective measures. Two subjective measures, modified Cooper-Harper (C-H) ratings and questionnaire display rankings, were utilized in this experiment to assess the pilot's mental workload while monitoring autoland operations with each of the display concepts.

Objective data analyses for the Navigation System Error scenarios revealed that better situation awareness performance (quicker recognition and understanding of inaccurate navigation system information) was achieved with the Pictorial Vision display concept as compared to the other display concepts (Conventional HUD, Enhanced HUD and Embedded Conventional). Analyses of the data for the Autopilot Oscillations Scenario showed a dramatic reduction in situational awareness (significant both statistically and operationally) when using the Embedded Conventional display concept during landing. No significant differences existed among the other three display concepts for the Autopilot Oscillations scenario. The objective data analysis for the FLAG TOGA (loss of localizer signal) scenario yielded no significant differences between the three sensor-based displays, but there were differences noted between the Embedded Conventional and the Conventional HUD display concepts. Although statistically significant, these differences are not operationally significant for a transport aircraft.

A summary of the numerous subjective results indicate a very strong preference for the Pictorial Vision display concept over the Enhanced HUD and Embedded Conventional display concepts when considering all monitoring tasks (i.e., the approach, verifying the runway location, detecting ground runway incursions, monitoring autopilot functions, monitoring airborne traffic, etc.). The major subjective results of the study showed that substantial improvements in situation awareness for detecting and understanding an abnormal flight condition (e.g., conflicting traffic, loss of localizer signal, etc.) were provided by the integrated pictorial concept (Pictorial Vision) when compared to the other two advanced sensor display concepts (Enhanced HUD and Embedded Conventional). In addition to increased situation awareness, subjective rankings indicated that the pictorial concept offered reductions in overall pilot workload (in both mean ranking and spread) over the two advanced sensor display concepts. Data analyses on modified C-H ratings of mental workload showed that the Pictorial Vision concept had a lower operator demand level and difficulty level than the other three display concepts. Out of the four display concepts flown, the pilots ranked the Pictorial Vision concept as the display that was easiest to use to maintain situational awareness, to monitor an autoland approach, to interpret information from the runway and obstacle detecting sensor systems, and to make the decision to go around.

Both objective and subjective results indicate that an integrated pictorial display has shown significant promise for providing improved situational awareness, without increments in pilot workload, during autoland operations and should therefore be further studied with regard to potential corresponding safety benefits. This type of format is expected to provide the cornerstone for an effective synthetic vision system, a system which is believed to be an enabling technology for solving restricted visibility problems associated with advanced subsonic and future high speed civil transports.

Appendix A

Repeated Measures ANOVA Summary Tables for Anomalous Cues/Detection Time Scenarios

A.1 ANOVA Summary Table For CONCERN Press Time For Flight Director Conflict With Autopilot

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	588.44	7	84.06		
DISPLAY	102.59	3	34.20	1.46	.253
SUBJECT BY DISPLAY	490.20	21	23.34		
TOTAL	1181.23	31			

A.2 ANOVA Summary Table For TOGA Press Time For Flight Director Conflict With Autopilot

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	39223.45	7	5603.35		
DISPLAY	273.05	3	91.02	1.73	.192
SUBJECT BY DISPLAY	1105.72	21	52.65		
TOTAL	40602.22	31			

A.3 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Flight Director Conflict With Autopilot

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	31175.18	7	4453.60		
DISPLAY	254.22	3	84.74	1.43	.261
SUBJECT BY DISPLAY	1240.88	21	59.09		
TOTAL	32670.28	31			

A.4 ANOVA Summary Table For CONCERN Press Time For Flight Director Conflict With Raw Data

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	658.48	7	94.07		
DISPLAY	45.19	3	15.06	1.09	.377
SUBJECT BY DISPLAY	291.22	21	13.87		
TOTAL	994.89	31			

A.5ANOVA Summary Table For TOGA Press Time For Flight Director Conflict With Raw Data

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	34541.07	7	4934.44		
DISPLAY	37.63	3	12.54	.26	.852
SUBJECT BY DISPLAY	1007.01	21	47.95		
TOTAL	35585.71	31			

A.6 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Flight Director Conflict With Raw Data

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	31357.58	7	4479.65		
DISPLAY	90.06	3	30.02	.78	.517
SUBJECT BY DISPLAY	805.78	21	38.37		
TOTAL	32253.42	31			

A.7 ANOVA Summary Table For CONCERN Press Time For Aircraft Incursion On Final (8L)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	461.69	7	65.96		
DISPLAY	425.47	3	141.82	2.13	.126
SUBJECT BY DISPLAY	1395.67	21	66.46		
TOTAL	2282.83	31			

A.8 ANOVA Summary Table For TOGA Press Time For Aircraft Incursion On Final (8L)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	14.94	7	2.13		
DISPLAY	.34	3	.11	.18	.911
SUBJECT BY DISPLAY	13.57	21	.65		
TOTAL	28.85	31			

A.9 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Aircraft Incursion On Final (8L)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	488.03	7	69.72		
DISPLAY	444.10	3	148.03	2.29	.108
SUBJECT BY DISPLAY	1356.96	21	64.62		
TOTAL	2289.09	31			

A.10 ANOVA Summary Table For CONCERN Press Time For Aircraft Incursion On Final (8R)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	26.55	7	3.79		
DISPLAY	12.68	3	4.23	2.14	.125
SUBJECT BY DISPLAY	41.40	21	1.97		
TOTAL	80.63	31			

A.11 ANOVA Summary Table For TOGA Press Time For Aircraft Incursion On Final (8R)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	12.68	7	1.81		
DISPLAY	.53	3	.18	.29	.831
SUBJECT BY DISPLAY	12.78	21	.61		
TOTAL	25.99	31			

A.12 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Aircraft Incursion On Final (8R)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	28.99	7	4.14		
DISPLAY	8.99	3	3.00	1.58	.224
SUBJECT BY DISPLAY	39.82	21	1.90		
TOTAL	77.80	31			

A.13 ANOVA Summary Table For TOGA Press Time For Flag TOGA

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	926.56	7	132.37		
DISPLAY	152.45	3	50.82	1.84	.170
SUBJECT BY DISPLAY	578.60	21	27.55		
REP	10.97	1	10.97	1.45	.267
SUBJECT BY REP	52.93	7	7.56		
DISPLAY BY REP	62.98	3	20.99	2.41	.095
SUBJECT BY DISPLAY BY REP	182.58	21	8.69		
TOTAL	1967.07	63			

A.14 ANOVA Summary Table For TOGA Press Time For Flag TOGA (excluding Pilot 4)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	16.56	6	2.76		
DISPLAY	25.49	3	8.50	2.77	.072
SUBJECT BY DISPLAY	55.28	18	3.07		
REP	1.66	1	1.66	.37	.564
SUBJECT BY REP	26.75	6	4.46		
DISPLAY BY REP	14.23	3	4.74	1.86	.173
SUBJECT BY DISPLAY BY REP	45.94	18	2.55		
TOTAL	185.91	55			

A.15 ANOVA Summary Table For CONCERN Press Time For Autopilot Oscillation

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	115.66	7	16.52		
DISPLAY	161.68	3	53.89	7.95	.001
SUBJECT BY DISPLAY	142.39	21	6.78		
REP	4.98	1	4.98	1.38	.278
SUBJECT BY REP	25.25	7	3.61		
DISPLAY BY REP	9.50	3	3.17	.65	.591
SUBJECT BY DISPLAY BY REP	102.21	21	4.87		
TOTAL	561.67	63			

A.16 ANOVA Summary Table For TOGA Press Time For Autopilot Oscillation

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	465.33	7	66.48		
DISPLAY	339.90	3	113.30	17.80	.000
SUBJECT BY DISPLAY	133.67	21	6.37		
REP	3.71	1	3.71	2.64	.148
SUBJECT BY REP	9.84	7	1.41		
DISPLAY BY REP	13.59	3	4.53	1.69	.201
SUBJECT BY DISPLAY BY REP	56.45	21	2.69		
TOTAL	1022.49	63			

A.17 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Autopilot Oscillation

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECT	340.42	7	48.63		
DISPLAY	33.69	3	11.23	1.73	.192
SUBJECT BY DISPLAY	136.56	21	6.50		
REP	17.27	1	17.27	6.29	.041
SUBJECT BY REP	19.24	7	2.75		
DISPLAY BY REP	9.14	3	3.05	.76	.528
SUBJECT BY DISPLAY BY REP	83.98	21	4.00		
TOTAL	640.30	63			

A.18 ANOVA Summary Table For CONCERN Press Time For Small Navigation System Error

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	526.25	7	75.18		
DISPLAY	5946.49	3	1982.16	24.17	.000
SUBJECT BY DISPLAY	1722.08	21	82.00		
TOTAL	8194.82	31			

A.19 ANOVA Summary Table For TOGA Press Time For Small Navigation System Error

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	2334.55	7	333.51		
DISPLAY	2900.81	3	966.94	14.51	.000
SUBJECT BY DISPLAY	1399.87	21	66.66		
TOTAL	6635.23	31			

A.20 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Small Navigation System Error

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	1553.70	7	221.96		
DISPLAY	1016.58	3	338.86	3.97	.022
SUBJECT BY DISPLAY	1791.55	21	85.31		
TOTAL	4361.83	31			

A.21 ANOVA Summary Table For CONCERN Press Time For Large Navigation System Error

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	576.26	7	82.32		
DISPLAY	934.11	3	311.37	3.76	.026
SUBJECT BY DISPLAY	1737.21	21	82.72		
TOTAL	3247.58	31			

A.22 ANOVA Summary Table For CONCERN Press Time For Large Navigation System Error (excluding pilot 8)

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	187.23	6	31.21		
DISPLAY	1144.00	3	381.33	14.85	.000
SUBJECT BY DISPLAY	462.32	18	25.68		
TOTAL	1793.55	27			

A.23 ANOVA Summary Table For TOGA Press Time For Large Navigation System Error

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	2056.94	7	293.85		
DISPLAY	857.25	3	285.75	2.35	.102
SUBJECT BY DISPLAY	2553.53	21	121.60		
TOTAL	5467.72	31			

A.24 ANOVA Summary Table For Time Difference Between CONCERN And TOGA Presses For Large Navigation System Error

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	2065.16	7	295.02		
DISPLAY	190.44	3	63.48	1.63	.214
SUBJECT BY DISPLAY	820.16	21	39.06		
TOTAL	3075.76	31			

A.25 ANOVA Summary Table For CONCERN Press Time For Embedded TCAS Traffic Advisory

Source of Variation	SS	DF	MS	F	Sig of F
SUBJECTS	2.20	7	.314		
DISPLAY	1.208	3	.403	1.062	.383
SUBJECT BY DISPLAY	7.958	21	.379		
TOTAL	11.366	63			

Appendix B

Repeated Measures ANOVA Summary Tables for Blanking Scenarios

B.1 ANOVA TABLE FOR VERTICAL RMS - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	679.05	7	97.01		
Display	1920.26	3	640.09	1.83	.174
Subject by display	7365.33	21	350.73		
Total	9964.64	31			

B.2 ANOVA TABLE FOR VERTICAL RMS - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	229.87	7	32.84		
Display	10.03	3	3.34	.07	.976
Subject by display	1026.11	21	48.86		
Total	1266.01	31			

B.3 ANOVA TABLE FOR VERTICAL RMS - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	15147.37	7	2163.91		
Display	1717.49	3	572.50	.23	.873
Subject by display	51707.57	21	2462.27		
Total	68572.43	31			

B.4 ANOVA TABLE FOR LATERAL RMS - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	8123.65	7	1160.52		
Display	3223.98	3	1074.66	.68	.573
Subject by display	33099.54	21	1576.17		
Total	44447.17	31			

B.5 ANOVA TABLE FOR LATERAL RMS - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1061.09	7	151.58		
Display	523.90	3	174.63	.13	.942
Subject by display	28359.21	21	1350.44		
Total	29944.20	31			

B.6 ANOVA TABLE FOR LATERAL RMS - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	38631.88	7	5518.84		
Display	3143.21	3	1047.74	.19	.905
Subject by display	118100.79	21	5623.85		
Total	159875.88	31			

B.7 ANOVA TABLE FOR DISTANCE FROM PATH RMS - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	7036.40	7	1005.20		
Display	5328.19	3	1776.06	.94	.439
Subject by display	39637.70	21	1887.51		
Total	52002.29	31			

B.8 ANOVA TABLE FOR DISTANCE FROM PATH RMS - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1096.47	7	156.64		
Display	472.32	3	157.44	.11	.952
Subject by display	29387.01	21	1399.38		
Total	30955.80	31			

B.9 ANOVA TABLE FOR DISTANCE FROM PATH RMS - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	50335.68	7	7190.81		
Display	3891.43	3	1297.14	.16	.920
Subject by display	166797.42	21	7942.73		
Total	221024.53	31			

B.10 ANOVA TABLE FOR VERTICAL MEAN - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	647.88	7	92.55		
Display	2741.23	3	913.74	2.04	.139
Subject by display	9410.65	21	448.13		
Total	12799.76	31			

B.11 ANOVA TABLE FOR VERTICAL MEAN - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	28.96	7	4.14		
Display	12.59	3	4.20	1.23	.324
Subject by display	71.74	21	3.42		
Total	113.29	31			

B.12 ANOVA TABLE FOR VERTICAL MEAN - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	8791.43	7	1255.92		
Display	767.31	3	255.77	.13	.944
Subject by display	42905.01	21	2043.10		
Total	52463.75	31			

B.13 ANOVA TABLE FOR LATERAL MEAN - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1783.96	7	254.85		
Display	2135.16	3	711.72	.90	.459
Subject by display	16652.94	21	793.00		
Total	20572.06	31			

B.14 ANOVA TABLE FOR LATERAL MEAN - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1645.20	7	235.03		
Display	703.26	3	234.42	.21	.889
Subject by display	23565.40	21	1122.16		
Total	25913.86	31			

B.15 ANOVA TABLE FOR LATERAL MEAN - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	12008.89	7	1715.56		
Display	1144.16	3	381.39	.14	.935
Subject by display	57376.21	21	2732.20		
Total	70529.26	31			

B.16 ANOVA TABLE FOR DISTANCE FROM PATH MEAN - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	2485.04	7	355.01		
Display	5644.98	3	1881.66	1.25	.318
Subject by display	31676.01	21	1508.38		
Total	39806.03	31			

B.17 ANOVA TABLE FOR DISTANCE FROM PATH MEAN - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1666.45	7	238.06		
Display	690.65	3	230.22	.20	.896
Subject by display	24349.46	21	1159.50		
Total	26706.56	31			

B.18 ANOVA TABLE FOR DISTANCE FROM PATH MEAN - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	21413.99	7	3059.14		
Display	2007.06	3	669.02	.13	.940
Subject by display	106126.26	21	5053.63		
Total	129547.31	31			

B.19 ANOVA TABLE FOR VERTICAL STD - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	166.93	7	23.85		
Display	119.21	3	39.74	2.02	.142
Subject by display	412.96	21	19.66		
Total	699.10	31			

B.20 ANOVA TABLE FOR VERTICAL STD - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	210.37	7	30.05		
Display	7.71	3	2.57	.06	.982
Subject by display	954.39	21	45.45		
Total	1172.47	31			

B.21 ANOVA TABLE FOR VERTICAL STD - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	7269.71	7	1038.53		
Display	919.07	3	306.36	.41	.747
Subject by display	15647.45	21	745.12		
Total	23836.23	31			

B.22 ANOVA TABLE FOR LATERAL STD - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	6245.88	7	892.27		
Display	1534.57	3	511.52	.58	.632
Subject by display	18401.93	21	876.28		
Total	26182.38	31			

B.23 ANOVA TABLE FOR LATERAL STD - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1267.63	7	181.09		
Display	288.58	3	96.19	.24	.864
Subject by display	8269.56	21	393.79		
Total	9825.77	31			

B.24 ANOVA TABLE FOR LATERAL STD - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	25179.60	7	3597.09		
Display	2238.64	3	746.21	.24	.869
Subject by display	65835.80	21	3135.04		
Total	93254.04	31			

B.25 ANOVA TABLE FOR DISTANCE FROM PATH STD - Blanking Scenario 1

Source of Variation	SS	DF	MS	F	Sig of F
Subject	5128.69	7	732.67		
Display	1106.86	3	368.95	.61	.613
Subject by display	12615.56	21	600.74		
Total	18851.11	31			

B.26 ANOVA TABLE FOR DISTANCE FROM PATH STD - Blanking Scenario 2

Source of Variation	SS	DF	MS	F	Sig of F
Subject	1429.35	7	204.19		
Display	319.94	3	106.65	.26	.854
Subject by display	8643.77	21	411.61		
Total	10393.06	31			

B.27 ANOVA TABLE FOR DISTANCE FROM PATH STD - Blanking Scenario 3

Source of Variation	SS	DF	MS	F	Sig of F
Subject	28123.42	7	4017.63		
Display	2330.82	3	776.94	.22	.879
Subject by display	72897.44	21	3471.31		
Total	103351.68	31			

Appendix C

Sample Questionnaires - Display, Probe, and Final

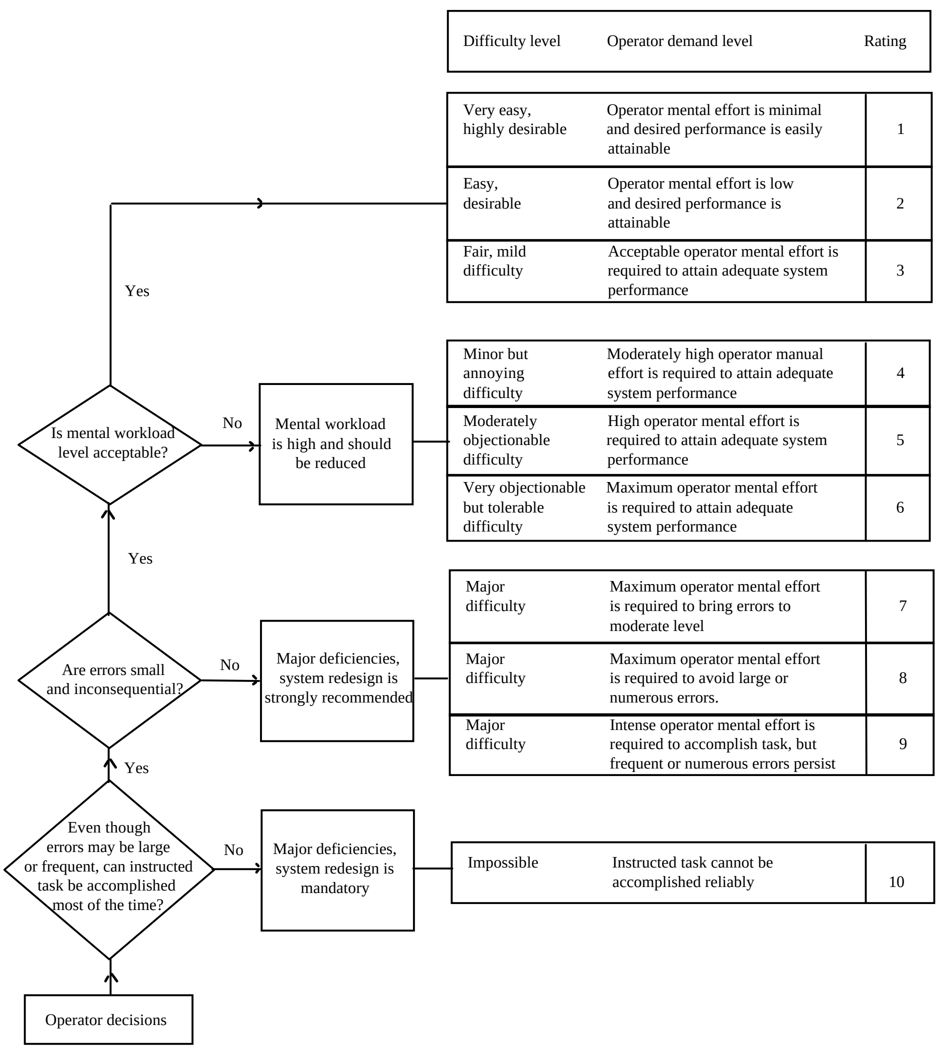
Name:______________
Date:______________

Display Evaluation

(check one)

_______ Conventional HUD (CH)
_______ Enhanced HUD (EH)
_______ Embedded Conventional (EC)
_______ Pictorial Vision (PV)

1. The display you have been monitoring is now to be evaluated over all of the experimental conditions encountered by using the modified Cooper-Harper rating scale shown below. In determining the Cooper-Harper operator rating for this display, it is important to start at the "operator decisions" block located at the lower left of the chart.



Cooper-Harper Rating ____________

2. In the previous question, you determined the Cooper-Harper operator rating number for this display. When you selected the Cooper-Harper rating number among the final group of three (with the exception of a Cooper-Harper rating of 10), what adjective description listed under "Difficulty Level/Operator Demand Level" influenced your decision? Please discuss. (Example: I selected a rating of 3 because the symbology layout provided ...)

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In using this display:

3. Evaluate the ease of monitoring an autoland approach.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

4. Evaluate the ease in interpreting the information from the runway and obstacle detecting sensor systems in this display concept.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

5. Evaluate the ease of recognizing an aircraft runway incursion.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

6. For the scenario in which the autopilot stops following the Flight Director commands, evaluate:

A. the ease in detecting that something was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

B. the ease in understanding what was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

7. For the scenario in which the Flight Director and the F/D Raw Data are in conflict, evaluate:

A. the ease in detecting that something was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

B. the ease in understanding what was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

8. For the scenario in which the autopilot (assume a navigational system error) and the sensor data were in conflict, evaluate:

A. the ease in detecting that something was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

B. the ease in understanding what was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

9. For the scenario in which an autopilot oscillation was encountered, evaluate:

A. the ease in detecting that something was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

B. the ease in understanding what was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

10. For the scenario in which a Failure Flag occurred, evaluate:

A. the ease in detecting that something was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

B. the ease in understanding what was wrong.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

11. Rate your overall "workload".

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

12. Rate your workload in monitoring only the autopilot functions, i.e. course errors, airspeed errors, etc.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

13. Rate your workload in monitoring only airborne traffic.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

14. Rate your workload in monitoring only airport surface traffic.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

15. Evaluate the ease of making the decision to go-around.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

16. Evaluate the ease of maintaining situation awareness. (Note: One could define situation awareness as "...the pilot has an integrated understanding of the factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions".

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

17. How would you assign crew role/duties in using this system?

____

____

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____

18 Please discuss the advantages of this display concept:

19. Please discuss the disadvantages of this display concept:

20. What improvements would you suggest for this display system?

21. Was there any symbology in this display that either appeared confusing or should be changed?

22. Suggestions/comments:

NAME:________________
DATE:________________

PROBE QUESTIONNAIRE

(check one)

_______ Conventional HUD (CH)
_______ Enhanced HUD (EH)
_______ Embedded Conventional (EC)
_______ Pictorial Vision (PV)

The experimenter will complete the probe questionnaire based upon the **verbal** comments obtained from the evaluation pilot. This shall be done **immediately** after the blanking of the screen.

Question:

1. At the moment the screen went blank, what was your overall situation?

____

____

____

____

____

____

2. Have the pilot indicate his/her position on the appropriate approach plate the instant the screen went blank.

3. At the moment the screen went blank, you were:

right of path _______
left of path _______
on path _______

4. At the moment the screen went blank, you were:

above the glideslope _______
below the glideslope _______
on the glideslope _______

5. PICTORIAL DISPLAY:

Have the pilot indicate his/her position with respect to the cross-sectional drawing of the pathway.

6. CONVENTIONAL AND PICTORIAL

   a. Your lateral error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units

   b. Your vertical error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units

7. Using the same approach plate in question two, have the pilot indicate the location of any target aircraft along with their TCAS symbology status.

8. Mention any other anomalies you may have detected.

____

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____

9. If this had been an actual flight situation, what would you have done? (prioritize)

____

____

____

____

____

____

10. Evaluate this display for ease of maintaining "spatial awareness" while monitoring the approach.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

11. Suggestions and/or comments concerning the probe scenario.

Name:________________
Date: ________________

Final Questionnaire

1. Based upon exposure to the three cockpit displays flown during this experiment in IMC conditions, please indicate your **OVERALL** relative ranking/grading of the displays by placing "EH", "EC" ,or "PV" at the appropriate location on the horizontal line shown below. In determining the overall evaluation, consider all monitoring tasks, i.e., the approach, verifying the location of the runway, detecting ground runway incursions, etc.

   where:

   "EH": indicates Enhanced HUD (IMC)

   "EC": indicates Embedded Conventional (HUD info in PD)

   "PV": indicates Pictorial Vision

EXAMPLE

```
                                    EH
                              PV    EC
|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
   1     2     3     4     5     6     7     8     9    10
least desirable                                  most desirable
display                                          display

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
   1     2     3     4     5     6     7     8     9    10
least desirable                                  most desirable
display                                          display
```

2. Discuss your rationale in determining the overall evaluation in item 1 above.

____

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(Continue on next page)

Rank/Grade the three displays flown in IMC conditions with respect to the following factors.

where:

"EH": indicates Enhanced HUD (IMC)

"EC": indicates Embedded Conventional (HUD info in PD)

"PV": indicates Pictorial Vision

3. improving flying safety

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display | most desirable display

4. monitoring an "autoland" in restricted visibility conditions

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display | most desirable display

5. monitoring other traffic

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

6. allowing you to think ahead of the aircraft

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

7. presenting sensor-based information

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

8. recognizing aircraft runway incursions

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

9. detecting a Flight Director and F/D Raw Data conflict.

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

10. understanding a Flight Director and F/D Raw Data conflict.

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

11. detecting the scenario where the autopilot stops following the F/D

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

12. understanding the scenario where the autopilot stops following the F/D

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

13. detecting an autopilot (assume a navigational system error) and sensor conflict.

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

14. understanding an autopilot (assume a navigational system error) and sensor conflict.

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

15. detecting an autopilot oscillation.

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

16. understanding an autopilot oscillation.

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

17. making the decision to go-around

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

18. reducing overall workload

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
1 2 3 4 5 6 7 8 9 10
least desirable display — most desirable display

19. maintaining situation awareness*

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

* Note: One could define situation awareness as "...the pilot has an integrated understanding of the factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions."

20. The Enhanced HUD (EH) system is a useful concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

21. The Embedded Conventional (EC) system is a useful concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

22. The Pictorial Vision (PV) system is a useful concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

23. I would feel comfortable flying with the sensor information presented in the Enhanced HUD (EH) concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

24. I would feel comfortable flying with the sensor information presented in the Embedded Conventional (EC) concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

25. I would feel comfortable flying with the sensor information presented in the Pictorial Vision (PV) concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

26. The sensor information is needed for landing in restricted visibility conditions.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

27. The sensor information could increase flight safety.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

28. Comments/suggestions concerning this experiment:

Appendix D

Captured Comments on Questionnaires

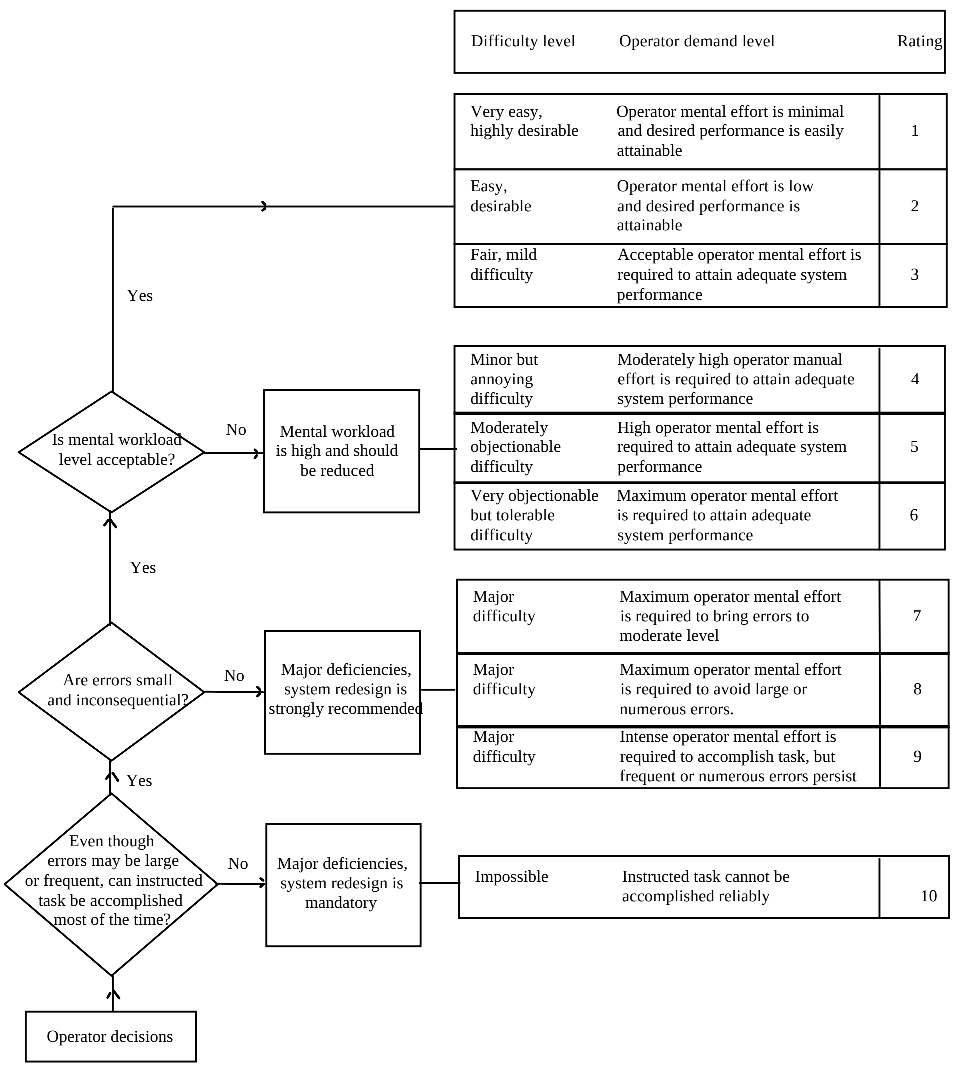
Pilot Comments on Individual Display Questionnaires

Display Evaluation

(check one)

__✔___ Conventional HUD (CH)
_______ Enhanced HUD (EH)
_______ Embedded Conventional (EC)
_______ Pictorial Vision (PV)

1. The display you have been monitoring is now to be evaluated over all of the experimental conditions encountered by using the modified Cooper-Harper rating scale shown below. In determining the Cooper-Harper operator rating for this display, it is important to start at the "operator decisions" block located at the lower left of the chart.



Cooper-Harper Rating ___Mean = 2.75___

2. In the previous question, you determined the Cooper-Harper operator rating number for this display. When you selected the Cooper-Harper rating number among the final group of three (with the exception of a Cooper-Harper rating of 10), what adjective description listed under "Difficulty Level/Operator Demand Level" influenced your decision? Please discuss. (Example: I selected a rating of 3 because the symbology layout provided ...)

Pilot 1: #2 - easy/desirable. Superb piece of equipment - I wish all a/c were equipped with the HUD.

Pilot 2: Rating 2. The VFR environment is easier than IFR. All cross checks are contained inside until the runway environment is in view. All symbols are easily identified.

Pilot 3: The symbology and overall display is easy to read. All required information is easily attainable using the HUD. The HUD itself is a good tool in that it allows the pilot to read required info while maintaining visual contact with the outside world.

Pilot 4: The major cues for loc/gs errors were the yellow flags on the ADI. I found myself crosschecking between the HUD and the EFIS instead of using only one area for all the cues. The EHSI gave me more field of view for TCAS traffic than on the HUD so once again I was crosschecking between the HUD and EFIS to get the big picture.

Pilot 5: Level 3 was selected because the two displays HUD and EFIS giving acceptable performance required more mental workload due to monitoring both displays. While mental effort was acceptable it did border on level 4 adjective annoying.

Pilot 6: Based on the fact that the symbology in both the HUD and EFIS displays are the same as the Enhanced HUD (EH) version, with the exception of the sensor generated images and being in sim VFR conditions, my written comments are the same as, and are reference the (EH) evaluation sheet. One slight difference is my scan pattern is divided 70% HUD/outside and 30% EFIS/inside the cockpit. In the EH, the scan was opposite - 30% HUD and 70 % EFIS.

Pilot 7: Selected 4, mental workload in interpretation between HUD outside and lower screens.

Pilot 8: I selected a rating of 2 because the symbology layout is compact while being clear and easily attainable. The biggest improvement to this display would be incorporation of sensor whereever possible.

17. How would you assign crew role/duties in using this system?

Pilot 1: PF: fly the a/c. PNF: monitor TCAS/warnings/comm/make callouts etc. As well as keep an outside traffic watch.

Pilot 2: Pilot Flying - Monitor LOC and GS and runway alignment and runway environment. Non-Flying Pilot - Monitor airspeed and make altitude callouts.

Pilot 3: PF - 75% HUD 25% cockpit instruments. PNF - 25% HUD 75% cockpit instruments.

Pilot 4: PNF accomplishes checklists. First pilot to notice anything abnormal calls out the abnormality. PF stays outside with HUD while PNF stays inside with EFIS.

Pilot 5: As done currently pilot flying. Pilot not flying with more emphasis on monitoring HUD display.

Pilot 6: Refer to EH eval.

Pilot 7: Crew duties could remain normal. Pilot flying outside with crosscheck, pilot not flying callouts crosscheck inside.

Pilot 8: Pilot flying would have full responsibility for the aircraft and approach to landing. PNF would be responsible for all checklists/call outs and traffic advisories - This is VMC conditions only.

18 Please discuss the advantages of this display concept:

Pilot 1: Helpful when the pilot is 'outside' the cockpit, that he can remain outside with all HUD info supplying the additional information.

Pilot 2: The display in cockpit is easy to understand and the HUD provides redundant info and the runway environment is in view.

Pilot 3: The ability to by looking outside while still obtaining required flight information.

Pilot 4: HUD symbology allows PF the opportunity to watch outside while presenting flight path data that he would otherwise have to obtain by looking inside. Gives him a faster reaction time to respond to the changing conditions.

Pilot 5: HUD display is relatively uncluttered and easy to see through. F/D a/p guidance easy to understand. Situational awareness ok not as good as pictorial display. EFIS display conventional and easy to use by itself, except for Flt/Dir lag on ADI. Both displays together cover most concerns. TCAS traffic and determining their relationship to aircraft was much easier than pictorial display. Also easier to determine their movement.

Pilot 6: Refer to EH eval.

Pilot 7: Keeps pilot flying outside with most needed info always available. Provide better time to make go around decision.

Pilot 8: The major advantage is the HUD display. Even in VMC conditions aircraft systems and navigation data is easier to read and interpret. This concept provides better quantity and quality data through the HUD.

19. Please discuss the disadvantages of this display concept:

Pilot 1: none.

Pilot 2: none.

Pilot 3: I think with HUDs in general a pilot could become too reliant on the system (HUD) and have a tendency to ignore his conventional instruments.

Pilot 4: Still requires some crosschecking between outside world and EFIS.

Pilot 5: Both displays require a Heads up and down approach to flying which requires more mental workload. In some instances 1 display is better than other for various parts of the approach (i.e., HUD is used more on short final). Concern some info such as loc/gs flags might be missed when using HUD. As there is a tendency to look through HUD possibly missing these indications on HUD as they don’t stand out as well.

Pilot 6: Refer to EH eval.

Pilot 7: Must crosscheck lower screen to confirm loss of Loc/GS. Also TCAS would only enter in with voice cautions or directives. The HUD wind vector arrow is in a different location (upper right) then the lower screen (lower lt.)

Pilot 8: Without the sensor data on the HUD crosschecking becomes slightly more difficult.

20. What improvements would you suggest for this display system?

Pilot 1: none.

Pilot 2: none.

Pilot 3: Possible moving airspeed, altitude off to each side in a vertical (tape) type format and maybe incorporate an ADA-slow/fast indicator.

Pilot 4: Have gs and loc flags flash yellow when displayed. On HUD, instead of simply removing LOC/GS FD CMD bars, change the color of inop bar to flashing red before removing it or go from | to OFF in red on HUD.

Pilot 5: Get rid of one system. Use the HUD and a nav display or the EFIS ADI/HSI not both. Too much "split screen" scanning which increases workload.

Pilot 6: Refer to EH eval.

Pilot 7: Put wind arrow center of HUD, bottom where it would be more likely taken into scan as runway came into view. Now can be compared with airspeed/gspeed for possible wind delta or shear (low level).

Pilot 8: None - sensor data incorporated on the HUD is displayed in another condition.

21. Was there any symbology in this display that either appeared confusing or should be changed?

Pilot 1: none.

Pilot 2: Change the size of the other aircraft in relation to their proximity to the aircraft (TCAS depiction).

Pilot 3: no comments given.

Pilot 4: Consider not displaying any airborne traffic on the HUD unless it is an alert or resolution. Display all traffic on EHSI for planning purposes.

Pilot 5: Altimeter and radar altimeter counters very difficult to read and interpret. Also get in way of HUD display when trying to see aircraft movement on airport.

Pilot 6: Refer to EH eval.

Pilot 7: Item 20.

Pilot 8: NO - all the symbology is easy to read, identify and interpret during normal and abnormal operations.

22. Suggestions/comments:

Pilot 1: Love that HUD!

Pilot 2: none.

Pilot 3: Keep up the good work.

Pilot 4: See above.

Pilot 5: Don't think this combination of flight displays will work seem too cumbersome to fly. Suggest pictorial with change of TCAS traffic display to this display's TCAS traffic symbology.

Pilot 6: Refer to EH eval.

Pilot 7: no comments given.

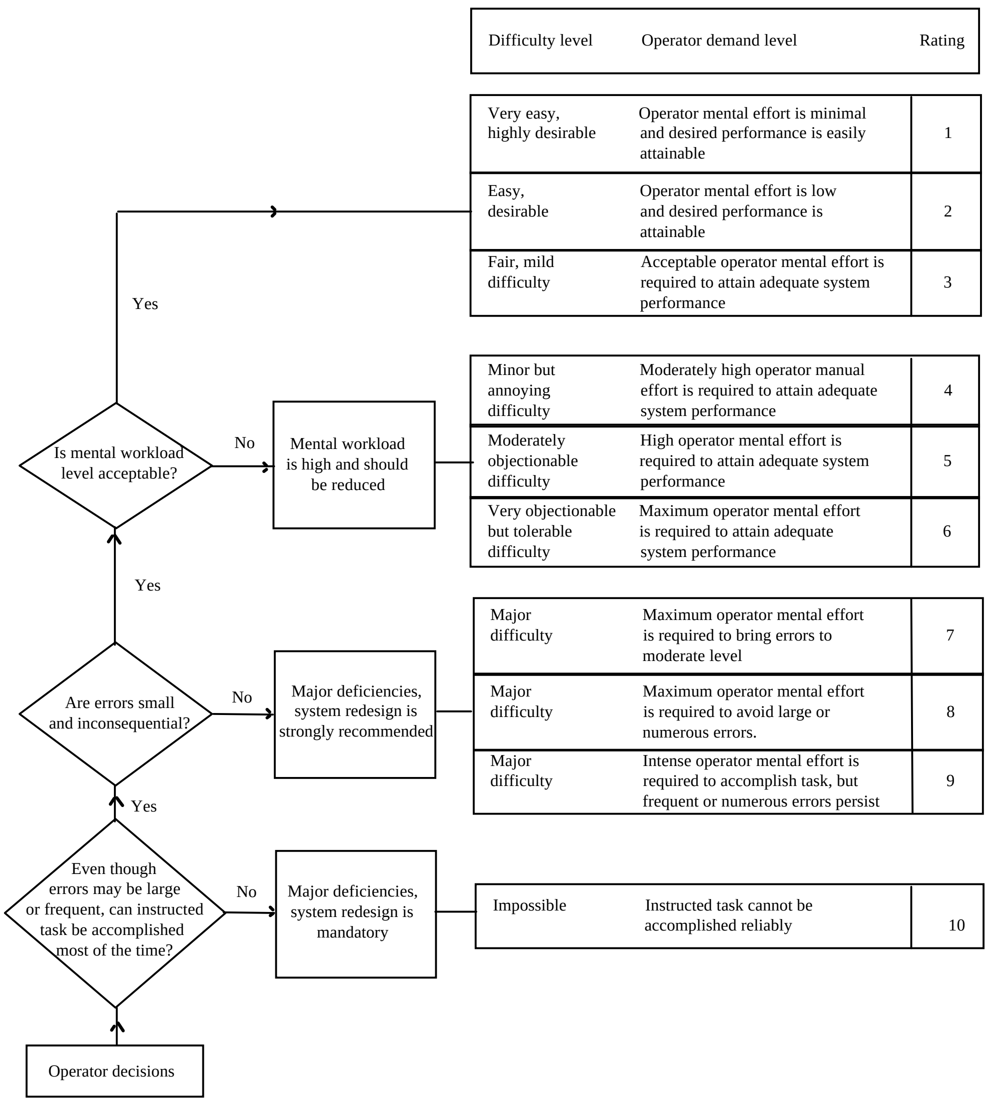
Pilot 8: Combine sensor data on **all** HUD equipment.

Display Evaluation

(check one)

________ Conventional HUD (CH)
__✔___ Enhanced HUD (EH)
________ Embedded Conventional (EC)
________ Pictorial Vision (PV)

1. The display you have been monitoring is now to be evaluated over all of the experimental conditions encountered by using the modified Cooper-Harper rating scale shown below. In determining the Cooper-Harper operator rating for this display, it is important to start at the "operator decisions" block located at the lower left of the chart.



Cooper-Harper Rating ___ Mean = 3.00___

2. In the previous question, you determined the Cooper-Harper operator rating number for this display. When you selected the Cooper-Harper rating number among the final group of three (with the exception of a Cooper-Harper rating of 10), what adjective description listed under "Difficulty Level/Operator Demand Level" influenced your decision? Please discuss. (Example: I selected a rating of 3 because the symbology layout provided ...)

Pilot 1: symbology layout provided a very comprehensive 'picture' and certainly aids the pilot in the critical approach and landing phase of flight.

Pilot 2: I selected 3 because the HUD display is adequate to complete the task. However there is a great deal of information on the display, some of which may be redundant thus causing unnecessary clutter.

Pilot 3: "2" symbology and info available is good and for the most part easy to read and understand.

Pilot 4: A narrow field of view for traffic within HUD. Singular color features, which require further confirmation and additional crosschecking. No confirmation on HUD for GS and Loc capture. Large distances of eye travel between HUD and EFIS.

Pilot 5: 3 level selected because performance was adequate mental effort while acceptable was close to 4 level due to the annoying task of looking up and down between HUD and EFIS.

Pilot 6: Because: (a) a cross check between the HUD and the EFIS display is used or desirable and (b) similar symbology having different meanings for flight and approach/navigational guidance is used in both the HUD and EFIS displays (i.e., Flt dir EFIS vs loc/gs HUD).

Pilot 7: Selection 4. Although EHUD provides for increased field of view crosscheck between HUD display and lower screens requires more effort.

Pilot 8: I selected a rating of 1 because the symbology of that display utilized the best aspects of all the displays including sensors. Even in heavy IMC situational awareness and traffic problems were easier to identify and deal with. Approach monitoring and possible runway incursions were very easy to recognize, as were instrumentation failures. IMC forces a better crosscheck.

17. How would you assign crew role/duties in using this system?

Pilot 1: P/F: in charge of "flying a/c". Pilot not flying: communication/monitoring instruments and proper callouts.

Pilot 2: Pilot Flying: Monitor LOC and GS within parameters - monitor runway environment. Non Flying Pilot - Monitor airspeed and altitude with call outs, monitor roll out on runway.

Pilot 3: PF 75% HUD 25% cockpit instruments. PNF 75% cockpit instruments 25% HUD.

Pilot 4: PF monitor HUD data. PNF monitor EFIS.

Pilot 5: Pilot flying outside on HUD with pilot not flying monitoring inside with particular attention to NAV display.

Pilot 6: PF- always monitor a/c approach and navigation parameters using EFIS display. PNF - monitors airborne and gnd traffic using HUD while looking outside for the runway environment. PF - could transition to the HUD at 1000 or 500 feet until landing.

Pilot 7: After turn to final pilot flying monitors only EHUD display . Pilot not flying callouts and lower screens.

Pilot 8: PNF must do nothing but monitor aircraft instruments and performance while pilot flying runs checklist and communications. The main reason is to maintain situational awareness in case of a total loss of aircraft power (i.e. standby instruments, only IMC).

18 Please discuss the advantages of this display concept:

Pilot 1: enhances total 'picture'...makes for a very comprehensive approach and landing. Gives me the added information needed to make timely decision, but doesn't give me too much which would clutter the instruments/HUD, etc.

Pilot 2: HUD display prepares the pilot for an easy transition to visual environment.

Pilot 3: PF - ability to obtain runway/airport visual cues sooner on an instrument approach while still monitoring flight information (loc, g/s, dh...).

Pilot 4: Provides PF with faster recognition of outside visual cues while maintaining some flight data.

Pilot 5: HUD gives a clear presentation (not too cluttered) on final approach segment with fairly easy flight path interpretation combining in with EFIS all info for monitoring is easily available for use.

Pilot 6: Love to have a HUD in all my aircraft. Increased SA and reduced workload by being able to stay focused outside looking for the runway environment while still viewing/following a/c flight performance through the HUD. (ie) no need to keep a cross check from inside the a/c to outside and back again. Reduced the possibility of inducing vertigo by eliminating head movements-therefore increases safety margins.

Pilot 7: Symbology using EHUD is easier to understand interpret. Also transition to outside during CAT II, or roll-out during CAT III is better.

Pilot 8: It incorporates sensors and all the best aspects of the other displays - HUD without the clutter.

19. Please discuss the disadvantages of this display concept:

Pilot 1: none.

Pilot 2: It is difficult to recognize a failure in the G.S. or LOC.

Pilot 3: Could become too reliant on HUD and not crosscheck enough with cockpit instruments.

Pilot 4: I can compute colors faster than symbols, therefore, having all symbols in monocolor slows down my decision making process.

Pilot 5: Difficult to determine movement of traffic on ground. HUD - depth of field with TCAS traffic a little difficult to determine. Constant looking up and down from EFIS to HUD. Annoying. Occasional fixation on one display due to task at hand. Watching TCAS traffic easiest on NAV display. Making turn easiest on NAV display. Final approach segment easiest on HUD and failure flags easiest to notice on ADI.

Pilot 6: none

Pilot 7: Difficult to maintain crosscheck from EHUD to lower screens. Also TCAS icons on EHUD have no change in color only a change in shape, making the TA/RA more difficult to notice (i.e., must continue to crosscheck lower screens).

Pilot 8: NONE - in several ways its cleaner and not as cluttered as the others yet all the information is still available.

20. What improvements would you suggest for this display system?

Pilot 1: none - I like what I see.

Pilot 2: A flashing LOC or GS sign in the event of failure should be displayed on the HUD screen.

Pilot 3: no comments given.

Pilot 4: Add color. Remove TCAS displays on HUD unless alert/resolution.

Pilot 5: Remove altitude counters, in way of ground traffic. Hard to read - go to tapes. Change ground traffic symbology. Difficult to tell whether ground traffic is moving or aircraft display is moving. Combine any useful ADI info to HUD and do away with ADI. Use HUD and NAV display.

Pilot 6: see #22 below. Go-around decision will always depend on the situation that exists at any given moment (scenario). The goal is to make this decision as early as possible and is always going to be a personal choice based on comfort, experience and directives.

Pilot 7: In addition to the problem with TCAS icons needing color. Perhaps having the loc bar on EHUD flash instead just going away when LOC is lost. This would be more likely to be seen quickly.

Pilot 8: Improve the TCAS symbology on the HUD.

21. Was there any symbology in this display that either appeared confusing or should be changed?

Pilot 1: no.

Pilot 2: The symbol for taxiing a/c should be closer to the actual size of the a/c relative to the taxiways and runway.

Pilot 3: The ground traffic symbology can be a little confusing and I think requires a little more attention than should be necessary.

Pilot 4: Add trend arrows to ground traffic. Flash LOC/GS upon capture. Flash LOC or GS before removing from HUD.

Pilot 5: See 20.

Pilot 6: Yes - loc/gs in HUD vs Flt Dir in the EFIS display same displayed symbology, different meanings.

Pilot 7: Item 20.

Pilot 8: The TCAS symbology on the HUD was not nearly as effective as the TCAS symbology on the HSI.

22.	Suggestions/comments:

Pilot 1: none as of now.

Pilot 2: The symbols for other a/c can become confusing with a lot of traffic (e.g. O'Hare). If the symbols could be made relatively larger or smaller depending on their distance and/or altitude would help in identifying developing problems.

Pilot 3: no comments given.

Pilot 4: Provide wider field of view.

Pilot 5: Combine HUD ADI NAV display too hard to scan. Whole display should be combined or condensed for easier interpretation.

Pilot 6: Sensor data vs Nav error - if error is not large, then it's hard to determine or even unable to determine until a confirmation exists at 300 feet when sensor blanking is switch off. Depending on the situation or approach - that could be much too late. A/P errors - again, should have redundant warnings for failure or when the a/p is unable to follow commanded guidance.

Pilot 7: Color was the drawback on EHUD. If color could be generated on screen all symbology would make more sense.

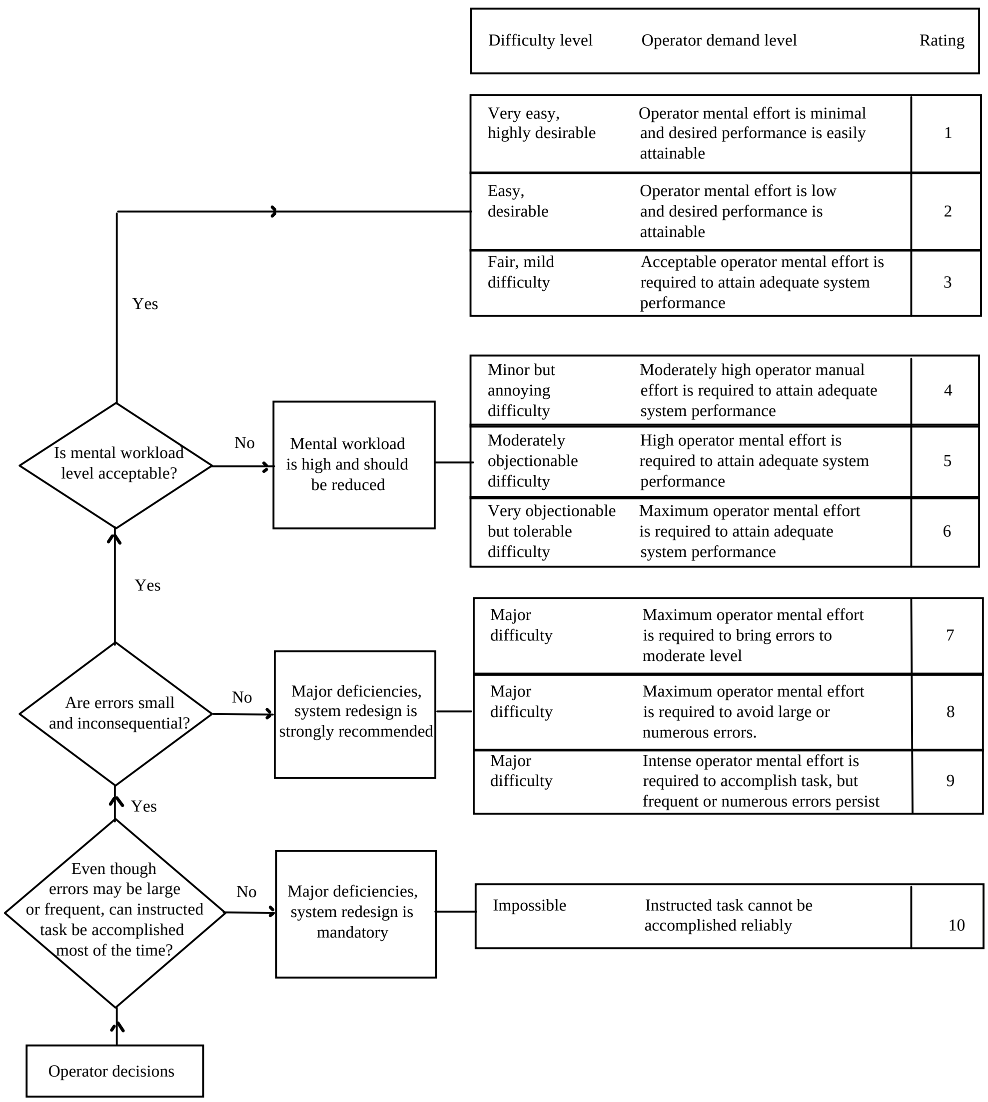
Pilot 8: All of the displays have pros and cons but the best combination would seem to be the HUD with sensors and bright clear graphics of heads down pictorial.

Display Evaluation

(check one)

_______ Conventional HUD (CH)
_______ Enhanced HUD (EH)
__✔___ Embedded Conventional (EC)
_______ Pictorial Vision (PV)

1. The display you have been monitoring is now to be evaluated over all of the experimental conditions encountered by using the modified Cooper-Harper rating scale shown below. In determining the Cooper-Harper operator rating for this display, it is important to start at the "operator decisions" block located at the lower left of the chart.



Cooper-Harper Rating ___ Mean =3.25___

2. In the previous question, you determined the Cooper-Harper operator rating number for this display. When you selected the Cooper-Harper rating number among the final group of three (with the exception of a Cooper-Harper rating of 10), what adjective description listed under "Difficulty Level/Operator Demand Level" influenced your decision? Please discuss. (Example: I selected a rating of 3 because the symbology layout provided ...)

Pilot 1: no comments given.

Pilot 2: I selected a 2 rating because all information was displayed on the ADI and HSI. This reduced the crosschecking. However the transition to the outside environment is more difficult.

Pilot 3: “3” overall the information that is required is easily attainable and the symbology is good so long as the pilot is adequately trained and shown some of the anomalies of the system.

Pilot 4: Provided fairly good situational awareness along with normal performance cues without a great amount of eye travel during the crosscheck.

Pilot 5: 3 is selected because some symbology such as ground aircraft made mental effort a bit more difficult than low. System display performance was ok for monitoring of an autoland approach but was a little more difficult than other displays.

Pilot 6: Embedded symbology in the PFD is incorrectly sized for nearly all flight conditions, increasing pilot workload, rather than reducing it. Too much effort. Therefore, time, is used at critical phases of flight determining safe flight conditions (with regard to airborne and ground traffic/symbology). With respect to system malfunctions and monitoring flight parameters, certain symbology needs to be enhanced or enlarged (i.e., flight director).

Pilot 7: Selected 6. Due to display on NAV screen. The combination of screen size and number of and size of symbology displayed creates a high mental workload. The aircraft TCAS “staple” symbol needs to be a relative size to runway symbol.

Pilot 8: I selected a rating of 2 because the symbology layout provided easy monitoring of all aircraft functions **except** the detection of aircraft runway incursions. All other system monitoring for CAT III approaches was somewhat easy. Detection and decision making for all major discrepancies was also somewhat easy.

17. How would you assign crew role/duties in using this system?

Pilot 1: PF: fly the a/c, make the decision regarding landing or go around, etc. PNF: monitor everything else, comm, make callouts, etc. Again, CAPT always makes the CAT 3 landings.

Pilot 2: Flying Pilot monitor LOC and GS a/c on ground. Non Flying Pilot monitor airspeed call out altitudes. Both pilots monitor runway alignment and compare IRS image to sensor image.

Pilot 3: PF 75% cockpit 25% outside. PNF 75% outside 25% cockpit.

Pilot 4: PF primary area of concern would be to monitor the PD while the primary area of concern for the PNF would be to monitor the ND and forecast possible traffic problems.

Pilot 5: Pilot flying and non pilot flying would have to be inside monitoring until the alert height when the pilot flying would look outside to determine a landing would be made while the nonflying pilot would continue to monitor progress through the displays.

Pilot 6: PF - needs to concentrate all his/her efforts monitoring/following flight guidance information because of its reduced size and potential obscuration by the larger traffic symbology. PNF - back up flight guidance monitoring and reconflicting traffic info/symbology.

Pilot 7: Assume CAT IIIB, it would appear that the pilot flying concerned only with control of aircraft "monitoring". Pilot not flying monitor traffic, TCAS, airport traffic, NAV deviations/errors.

Pilot 8: Copilot would fly the aircraft during the approach while the captain monitored the aircraft down to alert height where the decision to continue to land or go-around would be made on a CAT III approach.

18 Please discuss the advantages of this display concept:

Pilot 1: Great to have it all superimposed in one small area.

Pilot 2: All information is presented on the panel instruments. All necessary data is presented on the ADI and HSI.

Pilot 3: Valuable information for low visibility approaches.

Pilot 4: Nice tight area for crosschecking data. I really like the traffic alert/resolution display on the ADI. It gives very good trend data in the vertical plane.

Pilot 5: All info is closely grouped for an easy instrument scan. Transitions from inside to outside would only occur once unlike a combined HUD display, which would be a continuous inside/outside transition. F/d a/p info easy to interpret on ADI.

Pilot 6: Obvious advantage is having all the information pertaining to total SA combined into one place - changing from a flight instrument crosscheck to an instrument stare. Go-around decisions are more difficult for system problems due to the smaller symbology on the PFD. For ground traffic runway intrusions because symbology is too large and tends to obscure the runway and it's environment.

Pilot 7: Runway sensor information is an advantage. However, the methods used to display misalign of magenta rwy and tracking are way too small.

Pilot 8: All primary data is located on two primary instruments - ADI and HSI. Symbology colors are excellent - bright and easy to recognize and evaluate.

19. Please discuss the disadvantages of this display concept:

Pilot 1: Could possibly have too much info in the small area...but I think advantages outweigh the disadvantages.

Pilot 2: The obvious problem is the size of the display of the runway environment. As the FD and a/p line up with the runway symbol, the runway almost disappears. With added traffic ahead the display would be even more difficult to read.

Pilot 3: Some of the symbology occasionally becomes obscured and is difficult to read.

Pilot 4: Traffic, other than alerts and/or resolutions, clutter the ADI display.

Pilot 5: Surface traffic extremely hard to determine position until close to runway. TCAS traffic on ADI confusing transition to outside must be made at some point. Runway sensor vs data discrepancy hard to detect until close to ground.

Pilot 6: Disadvantages outweigh the advantages - too much of the wrong information (symbology, size) and the primary required information (symbology) is too small.

Pilot 7: Too much information in this display and of wrong relative size make it too hard to interpret.

Pilot 8: Runway symbology is too small and aircraft incursions are difficult to detect initially, especially on Runway 8L.

20. What improvements would you suggest for this display system?

Pilot 1: no comments given.

Pilot 2: A much larger ADI so as to increase the runway environment scale.

Pilot 3: Changes to some of the symbology (i.e., the ground traffic symbol and runway symbol (sensor and inertial)).

Pilot 4: Remove traffic symbols from the ADI unless the traffic is an alert or resolution. Keep all traffic display on the HSI (ND).

Pilot 5: Remove TCAS from ADI. Enlarge ADI to accept larger symbology.

Pilot 6: Increase the size of the flt. director and incorporate a loc/gs cross for that portion of the approach (PFD). Decrease size or remove from the PFD all airborne traffic info/symbology. Decrease or remove from the PFD all ground traffic symbology.

Pilot 7: If NAV display was a larger screen perhaps TCAS icons could be relative size. Surface airport traffic could be small diamond.

Pilot 8: Reduce TCAS symbology - leave the color the same. Increase runway and autopilot/flight director displays as much as possible. Delete turn and slip indicator.

21. Was there any symbology in this display that either appeared confusing or should be changed?

Pilot 1: no.

Pilot 2: Due to the scale there was some confusion as to whether a runway incursion was taking place.

Pilot 3: no comments given.

Pilot 4: The symbology for traffic on the ground was difficult to get used to. I would like to see a motion trend arrow inside the symbol. I would also add raw data to the flight path vector symbol.

Pilot 5: Traffic on ground. TCAS on ADI not very useful nor is there any depth of field. Seem to get in way of f/d a/p guidance. Discrepancy in runway from sensor data hard to discern from a distance.

Pilot 6: None that was confusing. See 20 above for changes.

Pilot 7: Ground traffic should only be displayed if it is possible conflict to a landing or takeoff aircraft.

Pilot 8: Only runway incursion problems associated with runway 8L.

22. Suggestions/comments:

Pilot 1: no comments given.

Pilot 2: The scale of the presentation is simply too small. If the display could be enlarged the presentation would be acceptable.

Pilot 3: Good idea to use the probe scenario. I think it could be very easy to get complacent doing the same runs. The test pilot needs to be awakened some times.

Pilot 4: no comments given.

Pilot 5: Not much different than current displays in use.

Pilot 6: The basic concept for this display is good. The amount and size and timing of displayed symbology need to be reworked.

Pilot 7: Items 17-21.

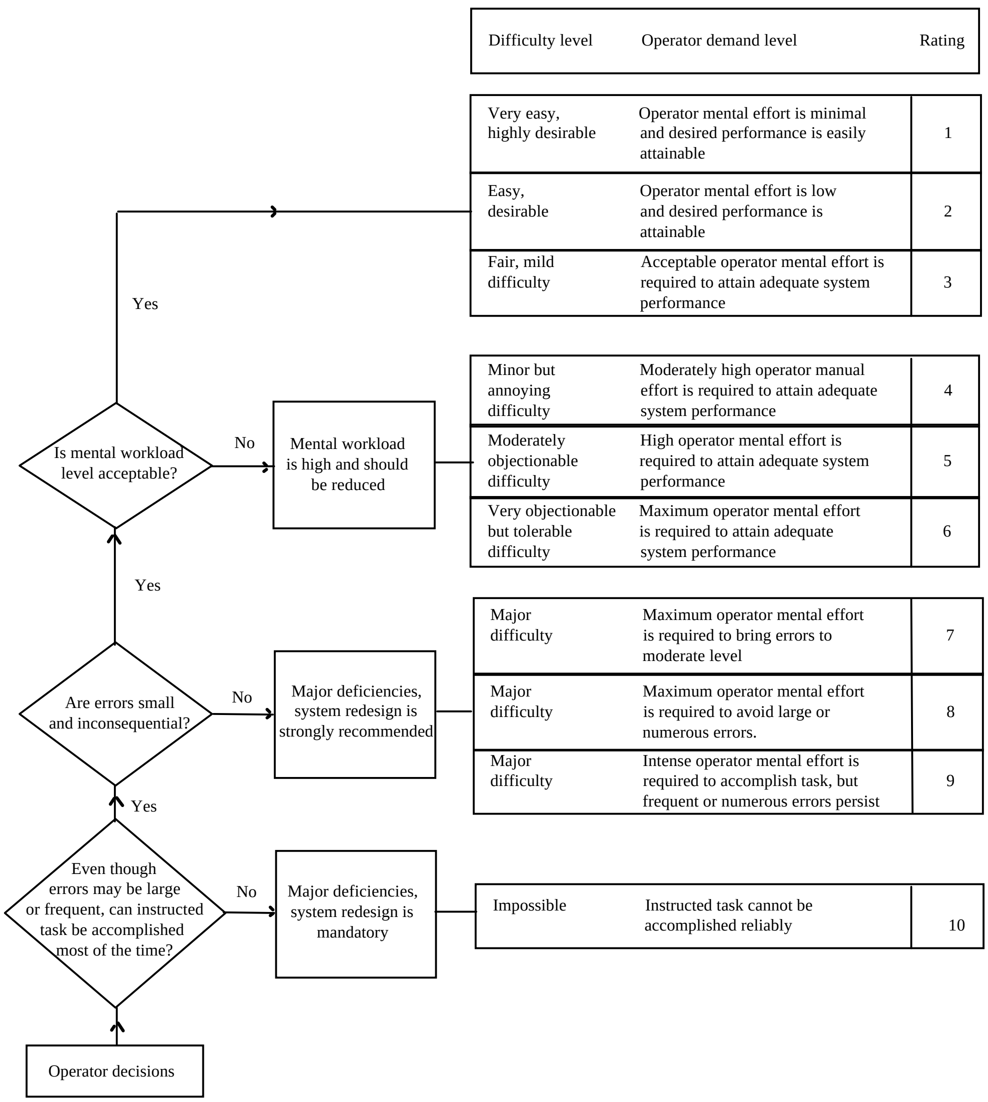
Pilot 8: This display concept could be easily incorporated into present Boeing 757/767 EFIS equipment and would enhance the present system by improving TCAS data and runway incursion possibilities during low visibility approaches.

Display Evaluation

(check one)

_______ Conventional HUD (CH)
_______ Enhanced HUD (EH)
_______ Embedded Conventional (EC)
__✔___ Pictorial Vision (PV)

1. The display you have been monitoring is now to be evaluated over all of the experimental conditions encountered by using the modified Cooper-Harper rating scale shown below. In determining the Cooper-Harper operator rating for this display, it is important to start at the "operator decisions" block located at the lower left of the chart.



Cooper-Harper Rating ___ Mean = 1.625___

2. In the previous question, you determined the Cooper-Harper operator rating number for this display. When you selected the Cooper-Harper rating number among the final group of three (with the exception of a Cooper-Harper rating of 10), what adjective description listed under "Difficulty Level/Operator Demand Level" influenced your decision? Please discuss. (Example: I selected a rating of 3 because the symbology layout provided ...)

Pilot 1: Pictorial vision display provided excellent symbology, which seemed relatively easy. I became more comfortable with it after numerous approaches.

Pilot 2: One rating was selected because the display was very close to reality. Very little translation was required; accurate situational awareness.

Pilot 3: "1" very easy and useful display decreases workload tremendously.

Pilot 4: What appears to be complete situational awareness. The field of view is very good and traffic alerts and resolutions are noticed very quickly. It almost gives a three dimensional effect. The pathway presents a fulltime unconscious evaluation of LOC and G/S performance which reduces the amount of crosschecking required of the raw data. This reduction in workload really pays off when unexpected problems arise which demand additional attention. One can allocate that additional time while still subconsciously monitoring the approach.

Pilot 5: Selected 2 because display provided attainable performance with a minimum of mental effort. While this display was close to a one rating the mental effort still required was more than a minimal effort.

Pilot 6: With the exception of a few minor design changes discussed at the end, I felt the display was very user friendly - Flight guidance was simple, easy to interpret and follow. Overall SA was greatly improved over conventional systems. Easier to monitor not only flight progress, but the complete flight environment. I believe this alone lends itself to a safer operation for both the user a/c and airspace it's operating in.

Pilot 7: Selected 1. Excellent display. Wide field of view provides less interpretation, and thus mental workload.

Pilot 8: I selected a rating of 2 because the symbology graphics were the best of any display. They are bright, clear and easy to read and react to . This display just needs to be reduced and brightened in the map screen as well as reduce the airspeed indicator and move it inside the left field screen boundary along with moving the glide path indicator inside the right field screen boundary.

17. How would you assign crew role/duties in using this system?

Pilot 1: P/F: fly the a/c, decision making (CAPT does the autoland at UNITED): PNF: comm/callouts/monitor autoland functions, etc.

Pilot 2: Pilot Flying - Monitor LOC and GS and runway environment. Pilot Not Flying - Monitor airspeed; call altitudes; monitor other traffic.

Pilot 3: PF 75% PV 25% outside. PNF 75% outside 25% PV.

Pilot 4: PF stay inside until ~ 100 feet then begin to combine inside and outside scans. PNF stay inside for entire approach and landing.

Pilot 5: Would still assign duties as done on current systems with a pilot flying and a pilot not flying who is backing up and monitoring the flying pilot who is in turn monitoring the aircraft.

Pilot 6: PF - Monitors a/c performance as it pertains to the approach (i.e., alt, as, loc, gs, a/p and flt direc.) PNF - monitors any airborne or gnd traffic. Primary concern should be airport/runway environment while crosschecking outside for a visual on the landing runway.

Pilot 7: Similar to current roles, i.e. Pilot flying - flying aircraft, pilot not flying - monitors makes callouts - calls deviations.

Pilot 8: Same as the HUD down without sensors in the VMC environment only. Crew duties always vary significantly based on VMC or IMC conditions.

18 Please discuss the advantages of this display concept:

Pilot 1: Total '3d' picture...very easy to get used to, felt more comfortable with it as we flew more approaches.

Pilot 2: This depicts a simulated VFR environment. Excellent situational awareness.

Pilot 3: Easy to read, nice to look at good and helpful information.

Pilot 4: It provides the big picture in one location. Reduces the amount of mental "picturing" of a situation.

Pilot 5: Easy to determine relative position to required flight path and any divergence from path. Easy to pickout TCAS traffic position. Failures are relatively easy to determine. Overall situational awareness is high with a minimum output of effort. It would be easy to monitor an autoland with this display in relation to today's monitored autoland approaches.

Pilot 6: "A picture is worth 1000 words." Less mental work (i.e., no need to read and interpret numerous analog instruments to build a mental picture.) Overall situational awareness of your entire flight environment is there in front of you. Eliminates guess work of where you are in the sky, where other traffic is in relationship to your a/c. Ease of use and monitoring allows for better multiple cockpit tasking. Provides increased safety because of the above listed items.

Pilot 7: This display provides "the big picture" allowing the pilot to consider all aspects of his current environment.

Pilot 8: The graphics displays are the best - very clear and bright, especially the TCAS information. I also like the ILS path display and the runway incursion examples.

19. Please discuss the disadvantages of this display concept:

Pilot 1: none.

Pilot 2: The only minor problem was the location of airspeed a little difficult to include in the scan.

Pilot 3: No engine indications.

Pilot 4: None noticed.

Pilot 5: Sometimes difficult to tell direction of TCAS traffic while turning. Pitch oscillations vs autopilot/f/d errors sometimes require a "trend" before determining that an error has occurred. Possible hypnotic effect caused by tunnel.

Pilot 6: Potential exists to have a very cluttered display in a high density traffic area. Numerous airborne and ground traffic being displayed could disrupt (PF) and unnecessarily increase workloads at critical flight times (i.e., takeoff and landings) as well as cover or blank critical flight displays.

Pilot 7: no comments given.

Pilot 8: Although I like the ILS path display it tends to make the screen very cluttered on the turn from base to final approach when your trying to identify runway location and possible ground traffic.

20. What improvements would you suggest for this display system?

Pilot 1: no comments given.

Pilot 2: Display airspeed in the area of the F/O and A/P.

Pilot 3: no comments given.

Pilot 4: Once capturing the LOC and GS have the raw data lines (outside of the FD) turn green and flash, then go steady. Conversely, if there is a failure of LOC/GS, turn that line red and flash it before removing the line.

Pilot 5: no comments given.

Pilot 6: Limits to when and how much information will have to be incorporated into the software so that condition of #19 will not affect the safe operation of the flight. Especially during critical phases of flight.

Pilot 7: The system could have a monitoring between the IRS runway symbol graphic, i.e. lat/long and magenta runway sensor position. When not in limits magenta runway symbol would flash - to better, faster interpretation.

Pilot 8: This is my favorite display however I would reduce and brighten the map screen. Also reduce and move the airspeed indicator inside the field screen and move the glide path on the right inside the altimeter.

21. Was there any symbology in this display that either appeared confusing or should be changed?

Pilot 1: No.

Pilot 2: No.

Pilot 3: DME readout should be relocated to a corner in the display.

Pilot 4: The TCAS symbology needs to be dynamically sized in relation to distance. Currently the traffic on the opposite runway, which is no threat, displays a large symbol and detracts from the flight data. Also, other traffic, which is of no threat, attracts attention when displayed on screen for short periods. Non-threat traffic displays on the ND are great and might be enough data.

Pilot 5: Size of TCAS traffic display. F/d annunciator on top of display was a little difficult to bring into overall scan. Required a look up, outside of the normal scan to gather the info.

Pilot 6: Yes - the DME is hard to locate. Suggest it be boxed and placed below the a/s scale on the left side of the display (similar to RA on the right). Loc and gs needles should be fixed and not attached to the flight director. Alt and a/s scales should not float - tied to the heading and cmd guidance boxes at the bottom and top of the display.

Pilot 7: The magenta dashed approach corridor symbology could be larger dashed lines. This would give a better indication of possible loc or gs error.

Pilot 8: Possibly change the color of the actual/real runway on the ILS display so they don't both use the same color. The final ILS path and runway outline are very similar when you first line up on final.

22. Suggestions/comments:

Pilot 1: no comments given.

Pilot 2: The best display I have ever seen.

Pilot 3: no comments given.

Pilot 4: The shading of the real world, as displayed through the ND sector, altimeter and VS; is about two notches too dark. I would like to see it slightly brighter. I would like to see a partial compass rose on the ND. I'd like to see the wind direction/speed just below the flight director.

Pilot 5: no comments given.

Pilot 6: A/p excursions could be difficult to catch early - should be coupled to an automatic a/p disconnect if a/p is unable to follow course guidance. For the scenario where the a/p and sensor data were in conflict - requires interpretation of more data and/or symbology to determine what and how large the problem is. This I believe can be overcome with training.

Pilot 7: Item 20.

Pilot 8: For all OLD pilots like myself I support an mandatory 30 minute nap after lunch before any flying activity.

PROBE QUESTIONNAIRE

(check one)

___✔___	Conventional HUD (CH)
______	Enhanced HUD (EH)
______	Embedded Conventional (EC)
______	Pictorial Vision (PV)

The experimenter will complete the probe questionnaire based upon the **verbal** comments obtained from the evaluation pilot. This shall be done **immediately** after the blanking of the screen.

Question:

1. At the moment the screen went blank, what was your overall situation?

Pilot 4: TCAS advisory with a/c on parallel runway; GS flag on EADI.
Didn't notice removal of glideslope bar.

Pilot 6: Lost glideslope. Immediately disconnected AL approach.

3. At the moment the screen went blank, you were:

right of path	P6
left of path	______
on path	P4

4. At the moment the screen went blank, you were:

above the glideslope	______
below the glideslope	______
on the glideslope	P4; P6

6. CONVENTIONAL AND PICTORIAL

a. Your lateral error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P4 P6

b. Your vertical error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P4
P6

8. Mention any other anomalies you may have detected.

Pilot 4: none.

Pilot 6: Looked like initially AP not following FD. Then loss of GS.

9. If this had been an actual flight situation, what would you have done? (prioritize)

Pilot 4: Disconnect a/p since VMC. Given more time, evaluate traffic alert and adjust situation. Take care of traffic conflict first.

Pilot 6: Disconnect a/p and manually fly the visual landing.

10. Evaluate this display for ease of maintaining "spatial awareness" while monitoring the approach.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐
			P4	P6

11. Suggestions and/or comments concerning the probe scenario.

Pilot 4: When getting localizer or g/s flag failure would like to see flashing indication (even though in today's a/c this flashing doesn't exist.

Pilot 6: Very useful since subject has not been cued into looking and memorizing status just in case this scenario comes up. "Perfectly legal".

PROBE QUESTIONNAIRE

(check one)

______	Conventional HUD (CH)
___✔___	Enhanced HUD (EH)
______	Embedded Conventional (EC)
______	Pictorial Vision (PV)

The experimenter will complete the probe questionnaire based upon the **verbal** comments obtained from the evaluation pilot. This shall be done **immediately** after the blanking of the screen.

Question:

1. At the moment the screen went blank, what was your overall situation?

Pilot 7: Initially F/D command continued turn to left and a/p wasn't following. Saw g/s flags and so TOGA'd.

Pilot 8: Left hand descending, left bank (8°), 5° pitch up. Intercepting final approach with G/S, LOC captured. (Was looking at heads down display when screen blanked).

3. At the moment the screen went blank, you were:

right of path	P7 P8
left of path	______
on path	______

4. At the moment the screen went blank, you were:

above the glideslope	P7
below the glideslope	______
on the glideslope	P8

6. CONVENTIONAL AND PICTORIAL

a. Your lateral error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P8 P7

b. Your vertical error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P7
P8

8. Mention any other anomalies you may have detected.

Pilot 7: none.

Pilot 8: Lost G/S.

9. If this had been an actual flight situation, what would you have done? (prioritize)

Pilot 7: Would have TOGA'd and continued left hand turn to stay away from parallel track..

Pilot 8: Called ATC for "missed approach" (lost g/s in IMC), turn toward runway and climb to MA altitude on runway heading.

10. Evaluate this display for ease of maintaining "spatial awareness" while monitoring the approach.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐
			P7 P8	

11. Suggestions and/or comments concerning the probe scenario.

Pilot 7: Has learned points at which scenarios occur and was fixating on a/p and f/d. Loss glideslope and localizer error indicators because of fixations. Typically go to HUD after rolled out on final. No comments/suggestions for the probe.

Pilot 8: Just feels that this scenario shows why one crew member must monitor a/c instruments at all times. Good scenario for finding out what pilots will do when you lose main instruments and have to use stand-by instruments.

PROBE QUESTIONNAIRE

(check one)

______	Conventional HUD (CH)
______	Enhanced HUD (EH)
__✔__	Embedded Conventional (EC)
______	Pictorial Vision (PV)

The experimenter will complete the probe questionnaire based upon the **verbal** comments obtained from the evaluation pilot. This shall be done **immediately** after the blanking of the screen.

Question:

1. At the moment the screen went blank, what was your overall situation?

Pilot 1: TCAS advisory, lost G/S, before that having tough time with circles moving apart (that was the 1st concern).

Pilot 3: AP not following FD, TA, Loss of LOC.

3. At the moment the screen went blank, you were:

right of path	P3 ___
left of path	______
on path	P1 ____

4. At the moment the screen went blank, you were:

above the glideslope	______
below the glideslope	P3____
on the glideslope	P1____

6. CONVENTIONAL AND PICTORIAL

a. Your lateral error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P1 P3

b. Your vertical error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P1 P3

8. Mention any other anomalies you may have detected.

Pilot 1: Just circles chasing each other although needles were pretty much on.

Pilot 3: no comments given

9. If this had been an actual flight situation, what would you have done? (prioritize)

Pilot 1: TCAS was a major concern (that close in). Almost ready to "wave it off" (go around). At loss of g/s would have already done it.

Pilot 3: Taken over manually and broken off approach (GA) and gone left (to avoid traffic that generated TA). Ask for clearance for special approach (NON localizer).

10. Evaluate this display for ease of maintaining "spatial awareness" while monitoring the approach.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐
		P1	P3	

11. Suggestions and/or comments concerning the probe scenario.

Pilot 1: Good scenario. Some of those things happen in real life (traffic landing on wrong runway.

Pilot 3: Good scenario, if at least to break monotony.

PROBE QUESTIONNAIRE

(check one)

______	Conventional HUD (CH)
______	Enhanced HUD (EH)
______	Embedded Conventional (EC)
__✔__	Pictorial Vision (PV)

The experimenter will complete the probe questionnaire based upon the **verbal** comments obtained from the evaluation pilot. This shall be done **immediately** after the blanking of the screen.

Question:

1. At the moment the screen went blank, what was your overall situation?

<u>Pilot 2</u>: TA right in front - pressed Concern, lost GS but wan on GS when it went out.

<u>Pilot 5</u>: TCAS advisory and had g/s failure. Had no vertical guidance and that's what he's concerned about. Concern press for TCAS and TOGA for g/s failure.

3. At the moment the screen went blank, you were:

right of path	<u>P5</u>
left of path	______
on path	<u>P2</u>

4. At the moment the screen went blank, you were:

above the glideslope	______
below the glideslope	______
on the glideslope	<u>P2; P5</u>

6. CONVENTIONAL AND PICTORIAL

a. Your lateral error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P2 P5

b. Your vertical error was : 0 - 1/4 - 1/2 - 3/4 - 1 - 1 1/2 - 2 dot error units
P2 P5(1/8)

8. Mention any other anomalies you may have detected.

Pilot 2: None.
Pilot 5: None.

9. If this had been an actual flight situation, what would you have done? (prioritize)

Pilot 2: TOGA because of GS and executed G/A. G/S should have cleared TA traffic since he was below us. Advise tower.

Pilot 5: Disconnect a/p and make a climbing right turn.

10. Evaluate this display for ease of maintaining "spatial awareness" while monitoring the approach.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐
			P5	P2

11. Suggestions and/or comments concerning the probe scenario.

Pilot 2: Nervous when answering questions.

Pilot 5: To make it a little harder, throw in some talking. In actual flight situation, typically have person talking, something happening and you're flying. Impression is that other a/c is coming into our path.

Final Questionnaire

(note: The average rating (of the 8 evaluation pilots) for each display concept is shown above the rating scale.)

1. Based upon exposure to the three cockpit displays flown during this experiment in IMC conditions, please indicate your **OVERALL** relative ranking/grading of the displays by placing "EH", "EC", or "PV" at the appropriate location on the horizontal line shown below. In determining the overall evaluation, consider all monitoring tasks, i.e., the approach, verifying the location of the runway, detecting ground runway incursions, etc.

   where:

   "EH": indicates Enhanced HUD (IMC)

   "EC": indicates Embedded Conventional (HUD info in PD)

   "PV": indicates Pictorial Vision

```
     EXAMPLE                          EH
                                 PV   EC
|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
   1     2     3     4     5     6    7     8     9    10
least desirable                                  most desirable
display                                          display
                           EC(5.75)    EH(7.75)   PV(9.38)
|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|
   1     2     3     4     5     6    7     8     9    10
least desirable                                  most desirable
display                                          display
```

2. Discuss your rationale in determining the overall evaluation in item 1 above.

<u>Pilot 1</u>: CH superb piece of equipment that allows pilot to remain out of cockpit, looking for traffic, etc...EH also exceptional with a lot of info that is very helpful.

<u>Pilot 2</u>: EC was such a small display that some information was covered. e.g. a/c on taxiway was blocked by f/o a/p display. EH was an excellent display but did not display other aircraft in TCAS adequately. PV had virtually no flaws.

<u>Pilot 3</u>: Taking into consideration overall ease of use and information available.

Pilot 4: PV has a much wider field of view with better situational awareness. EC lacked FOV but made up for some of that by centrally locating more info in one small area. EH required additional crosschecking over large distances and additional time to comprehend symbolics due to use of monochrome.

Pilot 5: PV was easy to monitor and all info was readily available. Conditions were closest to actually looking out of the window. Guidance was easy to determine due to tunnel so interpretation of pathway deviations was almost instantaneous. Felt TCAS symbology could be worked on, to present a more realistic aircraft icon with better depth of field and less obtrusive on display. Enhanced HUD was fairly easy to use except for the continuing transition from top to bottom display. Can sometimes miss information on one display while looking at the other. If all info is repeated on both displays then could get rid of one display stopping the transition (of course then you would probably have a PV). EC display was a somewhat dated display that didn't provide much more than today's displays. Easy to assimilate all it's info but a little confusing to interpret ADI info such as TCAS, runway, traffic info due to size of display.

Pilot 6: I'm a picture book kind of guy! It's easier for me to see a picture, than have my weak brain try to create a picture derived from gauges and analog information. I strongly believe a HUD will enhance any system or display of flight guidance and could even be incorporated with the PV display. The embedded conventional HUD in my determination would only be useful in an emergency situation (i.e. loss of HUD) - the information could then be displayed in a redundant format on the PFD - but not as a primary mean's for displaying traffic and navigational approach information.

Pilot 7: The embedded conventional was not a system that would make the pilot workload less. It required too much mental interpretation. Moving up this scale EH was an improvement with Pictorial Vision at the top improving on the other two systems almost to perfection. When comparing all three systems PV was only system that would make a CAT IIIc a comfortable approach.

Pilot 8: The EH simply incorporates the sensors and the HUD making it the best display, however PV graphics are the best and could improve EH especially in the TCAS info. area. EC is equally good however runway and incursion graphics need to be expanded. PV data needs to be reduced and the map screen could be brighter.

Rank/Grade the three displays flown in IMC conditions with respect to the following factors.

where:

"EH": indicates Enhanced HUD (IMC)
"EC": indicates Embedded Conventional (HUD info in PD)
"PV": indicates Pictorial Vision

3. improving flying safety

EC(6.38) EH(7.75) PV(9.13)

|______|______|______|______|______|______|______|______|______|______|

1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

4. monitoring an "autoland" in restricted visibility conditions

EC(6.63) EH(8.13) PV(9.50)

|______|______|______|______|______|______|______|______|______|______|

1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

5. monitoring other traffic

EH(6.75)
EC(6.88) PV(8.88)

|______|______|______|______|______|______|______|______|______|______|

1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

6. allowing you to think ahead of the aircraft

EC(5.75) EH(8.13) PV(9.63)

|______|______|______|______|______|______|______|______|______|______|

1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

7. presenting sensor-based information

EC(6.63) EH(8.13) PV(9.50)

|______|______|______|______|______|______|______|______|______|______|

1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

8. recognizing aircraft runway incursions.

EC(4.63) EH(7.88) PV(9.50)

|______|______|______|______|______|______|______|______|______|______|

1 2 3 4 5 6 7 8 9 10

least desirable display — most desirable display

9. detecting a Flight Director and F/D Raw Data conflict.

EC(6.88) EH(7.63) PV(9.13)

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|

1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

10. understanding a Flight Director and F/D Raw Data conflict.

EC(7.00) EH(8.25) PV(9.25)

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|

1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

11. detecting the scenario where the autopilot stops following the F/D

EC(6.88) EH(8.25) PV(9.00)

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|

1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

12. understanding the scenario where the autopilot stops following the F/D

EC(7.13) EH(8.00) PV(9.13)

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|

1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

13. detecting an autopilot (assume a navigational system error) and sensor conflict.

EC(6.63) EH(7.75) PV(9.38)

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|

1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

14. understanding an autopilot (assume a navigational system error) and sensor conflict.

EC(6.00) EH(7.63) PV(9.38)

|_____|_____|_____|_____|_____|_____|_____|_____|_____|_____|

1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

15. detecting an autopilot oscillation.

EC(7.63) EH(8.63)
PV(9.25)

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

16. understanding an autopilot oscillation.

EC(7.75)
EH(8.63)
PV(9.25)

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

17. making the decision to go-around

EC(6.13) EH(7.75) PV(9.38)

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

18. reducing overall workload

EC(5.88) EH(8.25) PV(9.63)

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

19. maintaining situation awareness*

EC(6.25) EH(8.25) PV(9.75)

|______|______|______|______|______|______|______|______|______|______|
1 2 3 4 5 6 7 8 9 10

least desirable display | most desirable display

* Note: One could define situation awareness as "...the pilot has an integrated understanding of the factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions."

(note: For questions 20- 27, the scale ranges from 1 to 5 with strongly disagree =1 and strongly agree =5)

20. The Enhanced HUD (EH) system is a useful concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 4.38

21. The Embedded Conventional (EC) system is a useful concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 3.50

22. The Pictorial Vision (PV) system is a useful concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 5.00

23. I would feel comfortable flying with the sensor information presented in the Enhanced HUD (EH) concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 4.38

24. I would feel comfortable flying with the sensor information presented in the Embedded Conventional (EC) concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 3.25

25. I would feel comfortable flying with the sensor information presented in the Pictorial Vision (PV) concept.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 5.00

26. The sensor information is needed for landing in restricted visibility conditions.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 4.63

27. The sensor information could increase flight safety.

strongly disagree	disagree	neutral	agree	strongly agree
☐	☐	☐	☐	☐

average pilot rating is 4.75

28. Comments/suggestions concerning this experiment:

<u>Pilot 1</u>: Interesting to fly with the different cockpit displays! Both the conventional HUD and enhanced HUD would greatly aid the pilot regarding flight safety and situational awareness. Enjoyed working with everyone - hoped I helped!

<u>Pilot 2:</u> The program is well organized and presented. At the end of day one I was quite fatigued and made mistakes I might have caught earlier. Either a shorter 1st day or a

change of activity at the end of the day might help performance.

Pilot 3: Re: The monitoring on PV. Did not see traffic until within field of view. Although traffic would be displayed on nav display in lower left corner. It seemed as though I would not refer to that display very often. Traffic was easier to monitor on conventional nav display.

Pilot 4: None except for those comments already made on the individual questionnaires.

Pilot 5: During times when the eight ball *(the backup instrument represented by the ADI portion of the EFIS display format)* appears return the display to the original situation and allow pilot to return aircraft to path in an effort to determine how easily a display is to interpret gross deviations followed by a correction.

Pilot 6: *no comments written down.*

Pilot 7: Great set up. It might be better if each approach display was different, if this is an option. Overall a well run/important experiment. Take it from someone who would like to fell better/have a higher comfort level on a CAT III approach!

Pilot 8: The sensor information is a must for any future aircraft instrumentation for increased flight safety first and restricted visibility conditions approaches and landings.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
May 2000

3. REPORT TYPE AND DATES COVERED
Technical Publication

4. TITLE AND SUBTITLE
Comparison of Pilots' Situational Awareness While Monitoring Autoland Approaches Using Conventional and Advanced Flight Display Formats

5. FUNDING NUMBERS
WU 522-19-11-01

6. AUTHOR(S)
Lynda J. Kramer and Anthony M. Busquets

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17981

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TP-2000-210284

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 3 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
A simulation experiment was performed to assess situation awareness (SA) and workload of pilots while monitoring simulated autoland operations in Instrument Meteorological Conditions with three advanced display concepts: two enhanced electronic flight information system (EFIS)-type display concepts and one totally synthetic, integrated pictorial display concept. Each concept incorporated sensor-derived wireframe runway and iconic depictions of sensor-detected traffic in different locations on the display media. Various scenarios, involving conflicting traffic situation assessments, main display failures, and navigation/autopilot system errors, were used to assess the pilots' SA and workload during autoland approaches with the display concepts. From the results, for each scenario, the integrated pictorial display concept provided the pilots with statistically equivalent or substantially improved SA over the other display concepts. In addition to increased SA, subjective rankings indicated that the pictorial concept offered reductions in overall pilot workload (in both mean ranking and spread) over the two enhanced EFIS-type display concepts. Out of the display concepts flown, the pilots ranked the pictorial concept as the display that was easiest to use to maintain situational awareness, to monitor an autoland approach, to interpret information from the runway and obstacle detecting sensor systems, and to make the decision to go around.

14. SUBJECT TERMS
Situation Awareness, Pictorial Vision, Synthetic Vision, Advanced Display Concepts

15. NUMBER OF PAGES
125

16. PRICE CODE
A06

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL