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Summary

Although modern flight decks now feature sophisticated computer-generated electronic displays, the display formats themselves are largely electronic renditions of earlier electromechanical instruments. New computer graphics capabilities make possible large-screen, integrated pictorial formats to improve situation awareness, pilot/vehicle interaction, and aircraft safety with the potential for significant operational benefits. The purpose of this research was to compare the spatial awareness of commercial airline pilots on simulated landing approaches using conventional flight displays with their awareness using advanced pictorial "pathway in the sky" displays. An extensive simulation study was conducted in which 16 commercial airline pilots repeatedly performed simulated complex microwave landing system (MLS) approaches to closely spaced parallel runways with an extremely short final segment. Four separate display configurations were utilized in the simulated flights: a conventional primary flight and navigation display with raw guidance data and the Traffic Collision and Avoidance System (TCAS) II; the same conventional instruments with an active flight director; a 40° field-of-view (FOV), integrated, pictorial pathway format with TCAS II symbology; and a large-screen 70° FOV version of the pictorial display. Scenarios involving conflicting traffic situation assessments and recoveries from flight path offset conditions were used to assess spatial awareness (own ship position relative to the desired flight route, the runway, and other traffic) with the various display formats. The study showed that the integrated pictorial displays consistently provided substantially increased spatial awareness over the conventional electronic flight information systems (EFIS) display formats. The wider FOV pictorial display gave equivalent objective results as the narrower pictorial format and subjectively was preferred by 14 of the 16 pilots. The other two pilots had no preference between the two pictorial formats.

Introduction

Advances in future airplane cockpits are being made possible by the rapid progress in display media, graphics and pictorial displays, computer technologies, and human factor methodologies. These technologies may enable the design of cockpits with improved crew situation awareness and workload, safety, and operational efficiency during critical mission phases. (See ref. 1.) Government and industry research programs have been established to develop and apply these technologies. One such program involves the use of "synthetic vision" to enable subsonic transport operations when visibility is restricted and to provide the cornerstone technology for more advanced airplanes, such as a high-speed civil transport that may have limited forward visibility because of complex aerodynamic and economic requirements.

Various studies have been undertaken to assess the requirements (ref. 2) and to determine the performance (ref. 3) of synthetic vision systems. One study (ref. 4) has indicated numerous potential benefits for a future high-speed civil transport in which synthetic vision is used instead of lowering the nose during landing, taxiing, and takeoff maneuvers. These potential benefits include improved aerodynamic efficiency, reduced weight, and as much as a 15-percent reduction in takeoff gross weight through reduced fuel reserves. Synthetic vision capabilities are defined herein as the resourceful merging of imaging sensors (such as fog-cutting sensors), pictorial graphics displays incorporating geographic and feature databases, and advanced navigational aids (such as the differential Global Positioning System). An ever-increasing interrelationship between onboard capabilities and airspace management systems is also generally accepted; therefore, higher levels of crew situation awareness are required to improve performance and safety. (See ref. 5.) Initial investigations are being conducted on cockpit flight displays to optimize the spatial awareness component of situation awareness. (See refs. 6–8.) This paper focuses on large-screen, integrated pictorial displays as an approach to synthetic vision technology and on optimizing crew spatial awareness.

To understand situation awareness (SA) in civil transport operations, a definition is necessary. Regal, Rogers, and Boucek (ref. 8) state that SA implies "that 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." As SA increases, "the pilot is increasingly able to 'think ahead of the aircraft,' and . . . do this for a wider variety of situations." This anticipation entails "a knowledge of present states, future goals, and the procedures used to get from one to the other." Regal, Rogers, and Boucek go on to expound that, for the commercial pilot, another dimension of SA involves the individual components. One of the more important of these components is spatial awareness, which in this paper involves knowledge of the own ship position relative to the desired flight route, the runway, and the other traffic.

The objective of the investigation reported herein was to evaluate and compare the spatial awareness component of pilots using displays representative

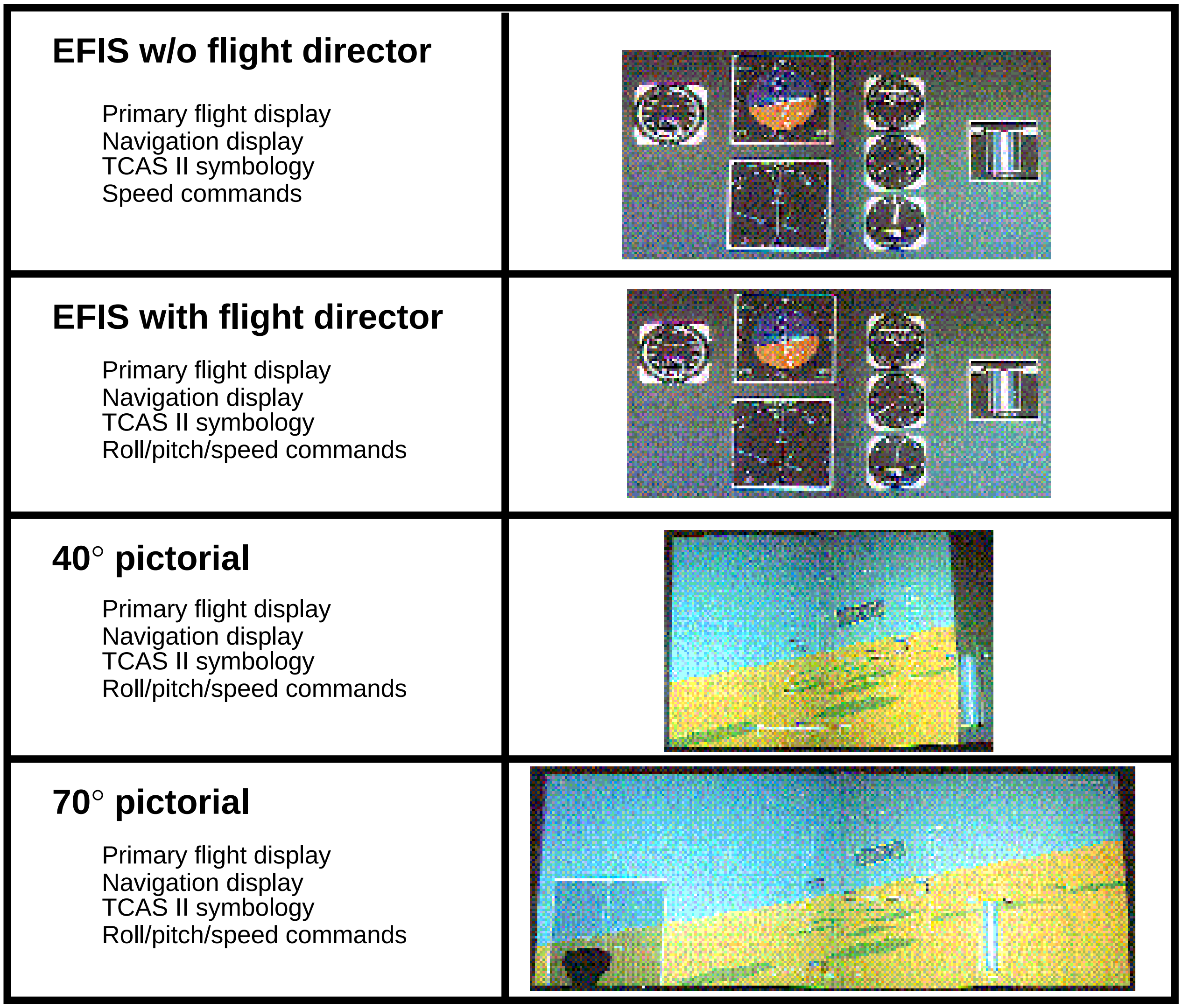


Figure 1. Spatial awareness study display formats.

of conventional electronic flight information systems (EFIS) with two wide-field-of-view pictorial display concepts. (See fig. 1.) Two formats based on a Boeing 757 instrumentation layout were used as the representative conventional EFIS formats. Four alternate display concepts were compared. The EFIS formats, used as baselines, were identical except that one incorporated a flight director (with pitch and roll commands displayed on two perpendicular needles in the attitude display) and the other forced the pilot to employ raw deviation error (instrument landing system localizer and glideslope indicators) without the benefit of flight director guidance. Both formats were included for calibration purposes, as spatial awareness was hypothesized to be quite different for the two conditions. For example, if the pilot concentrated only on centering the flight director needles, awareness of surrounding events might suffer; if the pilot employed raw position errors, spacial awareness might increase.

The two pictorial concepts were identical "pathway in the sky" formats, varying only in horizontal field-of-view (FOV) presentations of 40° and 70°. Pictorial perspective displays with pathway formats have been investigated extensively by flight display researchers (refs. 6, 7, and 9–15) because of the potential benefit of enhanced SA. However, in those studies, the researchers have not attempted to measure the benefits directly. The investigation reported in this paper was intended to test the hypothesis of gains in spatial awareness from the pictorial aspects of the display formats. The investigation was cast in terms of a single pilot who employs head-down displays. Further explanation of the display formats follows in the section "Display Conditions."

Abbreviations

AGL	above ground level
CRT	cathode ray tube
DERP	design-eye reference point
EFIS	electronic flight information system
FMS	flight management system
FOV	field of view
HUD	head-up display
ILS	instrument landing system
MLS	microwave landing system
ND	navigation display
OTW	out the window
PFD	primary flight display
rms	root mean square
SAL	standard approach to landing
TCAS	Traffic Collision and Avoidance System
VISTAS	visual imaging simulator for transport aircraft systems
VSI	vertical speed indicator

Simulator Description

The Cockpit Technology Branch at Langley Research Center has developed a flexible, large-screen flight display research system, the VISTAS (visual imaging simulator for transport aircraft systems), which was utilized in this experiment. The simulator contains the following elements: the simulator visual system (visual system hardware and graphics generation hardware and software), the aircraft mathematical model, and the simulator cockpit.

Simulator Visual System

The flexible 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 aspect ratio by matching the edges and overlapping the images from each projector. Each projected image is 15 in. high by 20 in. wide (standard 3:4 aspect ratio), so a maximum 15- by 40-in. image can be achieved. This maximum configuration was used to present the four display concepts for this investigation. The images are generated by the dual graphics display generators that operated in synchronization and used the same visual database to produce a single, large-screen, integrated picture (combined by the projection system onto the rear-projection screen that serves as the main instrument panel for the simulated aircraft). Each generator provides image resolutions up to 1280 × 1024 pixels in a 60-Hz progressive scan format (per projector). As the design-eye reference point (DERP) for transport cockpit applications is typically about 28 in., the full 40-in-wide display provides a maximum 70° FOV.

Aircraft Mathematical Model

A simplified six-degree-of-freedom mathematical model of a two-engine, medium-weight transport airplane was used in this study. The linear transfer functions and gains were obtained empirically to represent a fixed-wing generic transport airplane. The control system represented a system with a basic-rate command without attitude hold. Turbulence was introduced into the mathematical model through the addition of a disturbance component (a summation of eight independent sine waves) to the roll rate variable. The level of turbulence was considered moderate by the participating pilots.

Simulator Cockpit

The visual and interactive control elements of this flight display research tool have been integrated into a pilot workstation. (See fig. 2.) The pilot workstation was configured as the pilot side of a generic transport, fixed-wing airplane in which the seat could be positioned to place the pilot's eyes at DERP. The workstation also accommodated the dual-head projection system and the rear-projection screen that simulated the instrument panel. A two-degree-of-freedom sidearm hand controller with spring centering provided pitch and roll inputs to the airplane mathematical model. A throttle level provided the throttle inputs; typical self-centering rudder pedals provided yaw inputs. The display screen (instrument panel) was titled to provide a 17° line of sight (from horizontal) over the top of the screen, which is typical of over-the-glareshield views in most airplanes. The screen display surface was set perpendicular to the pilot's light of sight. This workstation was then used to explore the advantages and limitations of large-screen pictorial, reconfigurable display concepts and associated interactive techniques.

Display Conditions

This experiment was designed to assess the spatial awareness component based on integrated pictorial displays compared with conventional EFIS formats. The two EFIS displays, utilized as baseline measures, differed only in that one lacked the flight director command bars. A basic T instrument arrangement

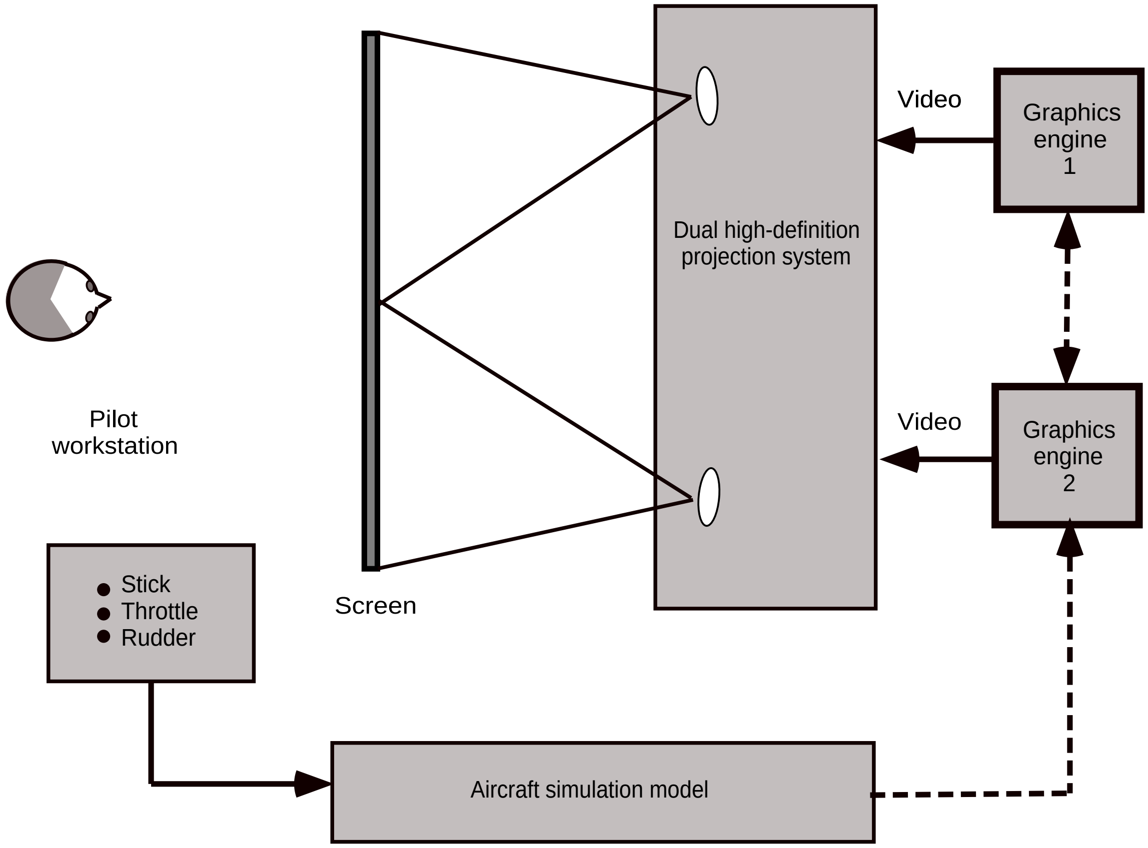


Figure 2. VISTAS architecture.

was used with a rendition of a Boeing 757 primary flight display (PFD) over a navigation display (ND). (See fig. 3.) The pilot adjusted the ND radius scale through a switch on the hand controller that incremented continually through a discrete loop of the available scales (4 to 50 n.mi. in radius). 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 vertically in that order. An innovative and unconventional power indicator was used in all four display concepts that integrated engine and ambient condition information and displayed actual power (including engine spool up) in percent of thrust. (See ref. 16.) The power indicator also displayed power commanded by the throttle setting and power desired by the flight management system (FMS) for the programmed approach.

For the integrated pictorial display formats, a computer-generated out-the-window (OTW) scene with overlaid head-up display (HUD) symbology was presented. (See fig. 4.) One pictorial concept was rendered for a 70° FOV and the other for a 40° FOV. (See fig. 1.) The OTW portion of the display consisted of a pathway-based approach, depicted by green goalposts the widths and heights of which corresponded to fractions of lateral and vertical instrument landing system (ILS) beam errors (±1/2 and ±1 dot, respectively, with maximum limits of ±300 ft in width and ±175 ft in height applied at the longer ranges). Also, a tiled roadway consisting of 20 tiles was presented within the goalposts to aid in vertical path control and to present a speed cue (the tiles were 150 ft wide, 30 ft deep, and were spaced 140 ft apart). When the airplane center of gravity passed the closest tile, a new tile replaced it at the end of the path such that 20 tiles were always present. The HUD symbology provided roll and pitch scales (in degrees), vertical airspeed and altitude tapes, and a horizontal heading tape. All of the tapes incorporated flight management system (FMS) command "bugs." The heading tape also showed ground track and the airspeed tape also showed ground speed. A vertical speed indicator was integrated onto the altitude tape as a growing or shrinking barber pole with a digital vertical speed tag. (The tag position on the altitude scale would denote the altitude attained in 1 min based on current vertical speed.) The central HUD symbology consisted of a diamond

Figure 3. Over-and-under arrangement of conventional primary flight and navigation displays with supporting instrumentation.

Figure 4. Seventy-degree FOV, large-screen, integrated, pictorial display concept.

that depicted pitch attitude and winged-V symbols for instantaneous and predicted flight path vectors. The display was attitude centered for an attitude rate command control system, although the pilots attempted to control the flight path vector. A secondary smoked-glass (see-through) ND was on the left side of the pictorial displays and basically duplicated the EFIS ND. (Map scale control was provided in the same manner as that of the EFIS display conditions.) Thus, horizontal situation display information was provided that also depicted traffic within the OTW-display FOV (delineated by the acute lines about the own ship centerline) as well as traffic outside the FOV.

To evaluate spatial awareness, scenarios (discussed in the section "Situation Awareness Assessment Tools and Techniques") were constructed that required the use of the Traffic Collision and Avoidance System (TCAS) II. Therefore, both display types (all four conditions) incorporated TCAS symbology, but the implementation differed with respect

(a) TCAS II advisory (yellow circle symbology).

(b) TCAS II resolution (red square symbology).

Figure 5. TCAS II advisory and resolution displays.

to the TCAS command portion. (See fig. 5.) The conventional displays incorporated TCAS symbology on the ND that depicted airplane positions, relative altitude tags, and vertical direction (if climbing or descending). The symbology is defined for purposes of this experiment in table I. In actual field service, the TCAS advisory algorithms have changed and their implementation has become more sophisticated since the inception of this experiment. For the conventional displays, the TCAS command to either climb or descend was implemented on the vertical speed indicator (VSI) as a color-coded command bar. (See fig. 5.) The pilot responded by keeping the VSI needle in the green portion of the indicator (and out of the red).[1] When this response was achieved, the pilot was following the TCAS command at an appropriate vertical rate. Warnings and commands were strictly visual. Auditory displays (which are normally a part of TCAS) were considered but were not employed because they would negate the ability to measure spatial awareness differences between display formats.

For the pictorial displays, TCAS symbology was implemented in the same manner on the secondary see-through ND. However, one important augmentation was made to the pictorial scene: the computer-generated image of traffic in the OTW scene was also enclosed in a TCAS symbol with the appropriate color- and shape-coded warnings. No resolution command (i.e., no vertical speed command) was presented with the pictorial formats. Full-state-variable depiction of the OTW traffic was utilized to avoid undesirable discrete updates, which could cause undue notice or awareness of traffic. (TCAS transponders do not presently encode sufficient state information for full-state-variable depiction.) For all four display conditions, TCAS was turned off below 500 ft above ground level (AGL), although unfilled blue squares were used to represent other traffic on the ND displays (an unfilled black square was used on the OTW portion of the pictorial displays), and their positions were continually updated.

[1]The actual display is in color; those colors are not shown herein.

Table I. TCAS II Symbology

Symbol[a]	Definition
◇ Unfilled blue diamond	Nonthreatening
◆ Solid blue diamond	Proximity traffic: Within 1200 ft altitude 6 n.mi. Nonthreatening
● Solid yellow circle	Traffic advisory: Within 1200 ft altitude $\leq$45 sec
■ Solid red box	Resolution advisory: Estimated miss distance $\leq$750 ft $\leq$30 sec

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

The pictorial formats discussed above incorporate none of the *sensor* elements associated with synthetic vision systems for reduced visibility operations with subsonic airplanes or for the lack of forward visibility with a future high-speed civil transport (in which synthetic vision is used instead of lowering the nose). However, the other pictorial elements of synthetic vision are included (pathway representation, geographic/feature databases, and dependence on advanced navigational aids). Therefore, this paper focuses on large-screen, integrated, pictorial displays as an approach to synthetic vision technology and the problem of optimizing crew spatial awareness.

Situation Awareness Assessment Tools and Techniques

The assessment of situation awareness is probably much more difficult than any attempted definition. Several techniques have been suggested in the literature, each with advantages and drawbacks. The most common method is to measure traditional pilot/vehicle performance; however, no direct relationship has been established between performance and awareness. Therefore, performance measures should be supplemented by additional techniques. (See refs. 17–21.) The following additional techniques, compiled from Tenney et al. (ref. 18), were considered.

Think-Aloud Protocols

Subjects are encouraged to verbalize what they are thinking and describe what they are doing and why. This technique is somewhat intrusive and is utilized only if the subject verbalizes anyway. The experimenter takes notes and compares the subject's statements with the subject's actions.

Anomalous Cues and Detection Time

Scenarios are set up that introduce slowly developing problems that may require some subject interaction. The experimenter then measures the time elapsed before the subject detects the problem as well as the time before any corrective action is taken.

Freezing and Probing

This method entails a direct approach in which the experimenter either interrupts or "freezes" the task, then takes some form of measurement. Usually, the experimenter asks relevant questions (in effect, probing the subject) concerning that task. (See refs. 19 and 20.) Often questions are asked about future events (based on what has transpired until the moment of task freezing), which may provide greater insight about the subject's awareness of the situation at that moment. In other words, the better the SA, the more accurately the subject will predict the immediate future. In addition, after resuming the task, the experimenter may take other measurements indicative of SA (such as time to restore to some predetermined condition). These methods require caution because not only has the original task been corrupted, but the probe results must rely on the subject's short-term memory.

Static Image Flash and Quiz

Subjects are evaluated for recognition of static information, scenarios, or conditions when presented over a short period. The more accurately the subject perceives or recognizes the situation thus presented, the better the SA must be with that particular information display system.

Garden Path and Detection Time

The subject is led to an erroneous conclusion by slowly developing parallel events. Then the experimenter measures the time elapsed before the subject detects the mistake in interpretation. (The subject is presented information in such a way that a failure is correctly realized; however, it is attributed to the wrong source.) Scenarios for this technique are more difficult to formulate.

Subjective Methods

The subject completes questionnaires either verbally or by handwritten means and expresses personal opinions or feelings about the topic.

Spatial Awareness Techniques

For this experiment, several techniques from the literature were chosen based upon the ability to generate suitable transport approach and landing operations. Some of these techniques were successfully applied; others were either incorrectly implemented or were unsuccessful in providing meaningful results, usually because replicates were lacking or because statistical control of experimental conditions was insufficient. Reference 21 addresses the successful and unsuccessful applications of these techniques in the subject study from the standpoint of effective SA assessment methodologies. As the focus of this paper is on the comparison of integrated pictorial displays and conventional EFIS displays, only the successful techniques (those that yielded meaningful results) are discussed herein.

The traditional lateral and vertical root mean square errors were recorded directly during the basic or standard task, which was to follow a standard approach to landing (SAL). Three SA scenarios, which induced new tasks, were implemented within the SAL. Two conflicting traffic scenarios were generated, one which consisted of crossing traffic situations that caused TCAS alerts (the Traffic Conflict Scenario), and the other which involved runway blunders by traffic on landing approach to a parallel runway (the Runway Blunder Scenario). The third scenario, the Path Offset Scenario, exposed each pilot to incidents of total display system failure followed by simulated display recovery. The pilot's task was, upon display system recovery, to determine the own ship location relative to the desired flight path, then to return to the flight path in a timely manner. Finally, numerous subjective questionnaires were administered in which the subject evaluated the displays by answering relevant questions and by ranking the displays based upon the perception of the awareness afforded. Unsolicited subject comments were also recorded throughout the trials. Further explanations of the individual scenarios, SA evaluation techniques, and measures are in the next section.

Experimental Tasks, Schedule, and Questionnaires

Sixteen pilots were the subjects of the experiment. All have extensive cockpit experience and most are with national commercial airlines. (Three are test pilots with commercial airplane manufacturers.) Four separate experimental tasks were embedded within the spatial awareness assessment efforts. These tasks were induced by scenarios generated to exercise the selected SA assessment methods previously discussed. These scenarios included the Standard Approach to Landing, the Traffic Conflict Scenario, the Runway Blunder Scenario, and the Offset Scenario, all of which were implemented within the SAL.

Standard Approach to Landing

The Standard Approach to Landing task was about 27 n.mi. long and involved a simulated complex, microwave landing system (MLS) approach (fig. 6) to closely spaced, parallel runways. The short final approach segment was only 1.7 n.mi. long. The SAL, the neighboring traffic routes (fig. 7), and the runway configuration (fig. 8) were constructed to provide a very complex environment of sufficient duration (about 10 min per flight) for exercising the selected SA measurement tools. The environment was not intended to replicate the real world but merely to represent a somewhat realistic, demanding future environment. Active traffic was included on all routes; that is, several airplanes preceded and followed the own ship on the basic SAL, a constant stream of traffic was on the SAL leading to the parallel runway, and occasional traffic was on the crossing route.

Figure 6. Simulated MLS standard approach to right runway.

The pilot's task was to fly the SAL manually (including throttle inputs) using the head-down display. Although recognized that conventional EFIS displays are not used to fly below decision height altitudes in real situations (e.g., 200 ft) without an OTW transition, for this investigation the flight ended at the runway threshold without an OTW transition. However, all awareness scenarios in the investigation were completed well before a 200-ft altitude was reached. The

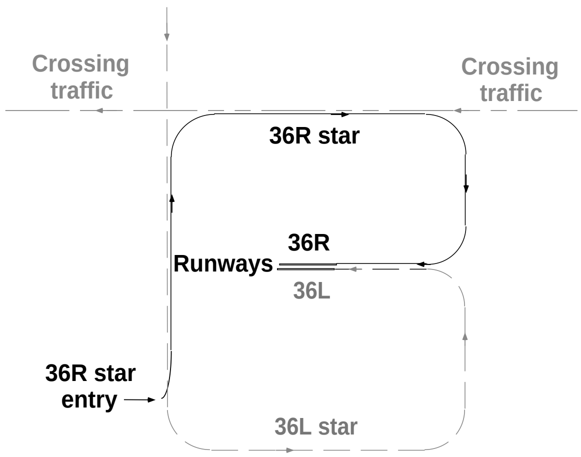


Figure 7. Traffic routes of SAL, parallel approach, and crossing traffic.

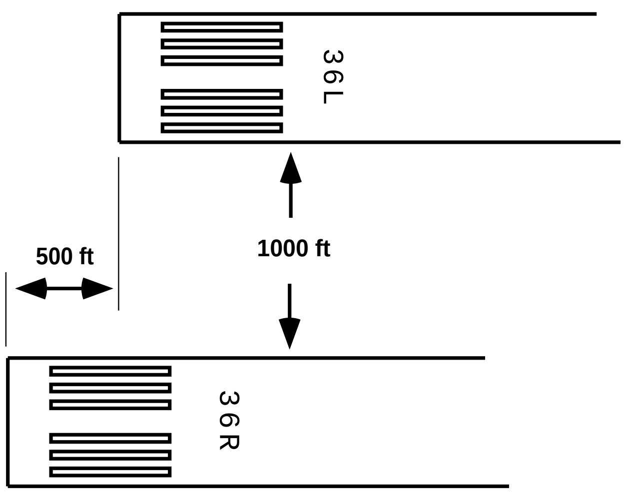


Figure 8. Offset, parallel runways.

SAL was divided into segments for analysis (fig. 9), and the performance metrics for the standard task were the traditional lateral and vertical path tracking performances. These metrics are not really spatial awareness measurements, but they are of related interest as they do provide the assurance that any enhanced spatial awareness, as measured by the other measurement tools, would not be gained at the expense of degraded tracking performance.

Traffic Conflict Scenario

The basic approach pattern (to the right parallel runway) always included other aircraft on an approach to the left runway. (See figs. 7 and 8.) For the Traffic Conflict Scenario, which each pilot

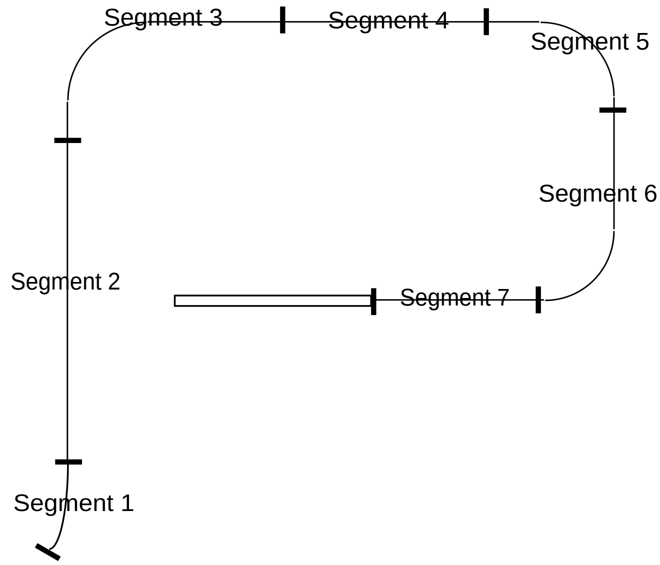


Figure 9. Segmentation of SAL route for statistical analysis.

encountered in the data collection session only once for each display condition, any one of two aircraft on an opposing heading from the own ship on segment 2 of the basic SAL (fig. 9) would inexplicably (to the subject pilot, but not to the experimenter) initiate an altitude maneuver intended to lead to a TCAS advisory situation for the own ship. The performance metrics for this scenario were the detection time (from the beginning of the approaching traffic altitude maneuver to the pilot's announced detection of the resulting threatening situation) and maneuver time (from the beginning of the approaching traffic altitude maneuver to the initiation of an avoidance maneuver, if initiated, by the own ship pilot). These metrics reflect the supposition that better spatial awareness would allow earlier detection time, although earlier maneuver time expectations may not be as implicit. Better awareness of the location and movement of the other traffic may delay or even eliminate the need for an avoidance maneuver.

The data run ended after the Traffic Conflict Scenario without continuing to the threshold. Naturally, the effect of prior exposure to this type of scenario can be significant; therefore, the pilots became well trained for the scenario under all four display conditions. However, the occurrence of this scenario during the data collection session was infrequent and unpredictable.

Runway Blunder Scenario

The basic approach pattern for the Runway Blunder Scenario always included another airplane landing on the left runway 30 sec ahead of the own ship (landing on the right parallel runway). For this scenario, which each pilot encountered in the data collection session only once for each display condition, the lead aircraft would inexplicably leave the designated landing pattern and cross in front of the own ship flight path during final approach. (This deviation would occur while the own ship's planned altitude was 400 ft AGL. The TCAS advisory and resolution logic was turned off below 500 ft, although the appropriate displays still presented the traffic with unfilled blue squares.) The performance metrics for this scenario were the detection time (from the beginning of the crossing maneuver by the neighboring traffic to the pilot's announced detection of the resulting threatening situation) and the maneuver time (from the beginning of the crossing maneuver to the initiation of an avoidance maneuver, if initiated, by the own ship pilot). As with the Traffic Conflict Scenario, better spatial awareness was assumed to allow earlier detection time, although earlier maneuver time expectations may not be as implicit. Better awareness of the location and movement of the other traffic may delay or even eliminate the need for an avoidance maneuver.

The effect of prior exposure to this type of scenario can also be significant; therefore, the pilots became well trained for the scenario under all four display conditions. As with the Traffic Conflict Scenario, the occurrence of the Runway Blunder Scenario during the data collection session was infrequent and unpredictable. Collection of the root mean square (rms) tracking data ended before initiation of the Runway Blunder Scenario.

Offset Scenario

The Offset Scenario exposed each of the 16 pilots to 4 incidents of simulated recovery from display system failure for each display condition. In this scenario, the standard task was interrupted when the display screen was blanked for a significant period, after which the original display condition would reappear (simulating recovery from a main display system failure). Upon reappearance, the position of the own ship relative to the desired flight path had changed (the aircraft had been offset to one of two predetermined positions relative to the planned flight path), which thus introduced a new task. The pilot's new task in this scenario was to determine the location of the own ship relative to the desired flight path, then to return to the flight path in a timely manner; the pilot was to respond as though the simulated vehicle were a passenger airliner. Two scenario conditions were used: placing own ship 1000 ft above and 750 ft to the left of the flight path in segment 4 of figure 9 (directly in line with approaching traffic and in a TCAS resolution situation); the other involved placing the own ship above and to the right of the flight path (again in segment 4, with no threatening traffic). Two replicates of each scenario condition (and thus four offset runs per display condition) were used to increase the statistical power. Because the airplane heading was not changed for either offset position, the pathway was always in view with the pictorial displays upon display system recovery.

The performance measure for this scenario was recovery time. A return to flight path was defined as achievement of an error of less than half a dot in lateral and vertical tracking and a heading error of less than 5°. Better spatial awareness was assumed to allow earlier position determination and result in a shorter recovery time. For this scenario, the standard task was interrupted in segment 3 of figure 9, and the offset placed the airplane in segment 4. The standard rms tracking performance measures were not gathered for segments 3 and 4 during an approach that included the Offset Scenario. However, tracking data collection was resumed after path recovery for the remaining segments of the flight (segments 5–7).

Schedule

Table II presents a typical 2-day schedule for a pilot participating in the experiment. After being briefed on the purpose of the experiment, the details of each display condition, and the various scenario conditions, the pilot was allowed about 20 min to become familiarized with the handling characteristics of the airplane model in unstructured flight maneuvers. Half the pilots used the conventional EFIS without the flight director display condition for this purpose; the other half used the 70° pictorial display condition. The pilots were thoroughly trained with the standard approach task, then were thoroughly exposed to the scenario condition for each display condition. The second day was the data collection session. The display conditions were randomly blocked

Table II. Spatial Awareness Schedule

Day 1 (≈10 hr)
- Briefing session
- Training session:
  - Characteristics familiarization
  - Display conditions 1–4

Day 2 (≈10 hr with rest periods)
- Data collection:
  - Display conditions 1–4
  - Questionnaires

Table III. Data Collection Session

Display condition	Approach conditions[a]	Questionnaires		
		Intrusion	Display evaluation	Display comparison
3	R*, O_4, O_1, R, O_3, T, R, O_2	x	x	
1	R, O_1, T, R, O_3, O_4, R*, O_2	x	x	
2	R, O_3, T, R, O_2, R*, O_4, O_1	x	x	
4	R, O_2, R*, O_4, O_1, R, O_3, T	x	x	x

[a]Conditions:
R signifies a standard approach.
R* signifies a standard approach with runway blunder.
T signifies a traffic avoidance maneuver.
O_n signifies an offset occurrence.

across pilots, and the experimental tasks were randomized within each display condition. Table III presents an outline of a typical session, the details of which varied from pilot to pilot.

Questionnaires

As shown in table III, each pilot was asked to complete two questionnaires at the end of the data-gathering runs for each display condition. The first questionnaire probed specific items concerning the traffic scenarios encountered with that display condition, and the second dealt with the evaluation of that display concept in general. After completing all runs and the individual display concept questionnaires for each display condition, the pilots completed a final questionnaire that involved detailed comparisons of the four display concepts.

Experimental Results and Discussion

The four scenarios were designed as full-factorial, within-subjects experiments, with pilots, display condition, any scenario conditions, and any replicates as the factors. Extensive pilot variability is expected; therefore, pilot variability was isolated from the rest of the analyses by its inclusion as a main factor in the experiments. The data collected in the experiments were analyzed using univariate analyses of variance for each metric. Newman-Keuls tests (discussed in ref. 22) of individual means were performed at various stages in the analyses. (All such tests were made at a 1-percent significance level.) The objective results are presented and discussed for each scenario, and some subjective results are discussed thereafter.

Traffic Conflict Scenario

The Traffic Conflict Scenario exposed each pilot to one of two similar traffic avoidance situations for each display condition. No replication was used; therefore, the only factors in the experimental design were the pilots and the display conditions.

Table IV summarizes the analysis results for detection time and maneuver time. Figures 10 and 11 graphically present the results of the Traffic Conflict Scenario. All 16 pilots detected each threatening situation, regardless of the display condition. (See fig. 10.) However, the differences between the detection times for the EFIS display conditions and the pictorial display conditions (fig. 11, about 10 sec) were statistically significant. Differences within the display types (EFIS and pictorial) were not significant.

Table IV. Analysis of Variance Results for Traffic Conflict Scenario

[From figures 10 and 11]

Factor	Degrees of freedom	Significance[a]
Detection time		
Pilots	15	*
Display	3	**
Error	45	-
Total	63	-
Maneuver time		
Pilots	14	-
Display	3	-
Error	20	-
Total	[b]37	-

[a]Significance:
-Not significant at levels considered.
*Significant at 5-percent level.
**Significant at 1-percent level.
[b]Missing 26 cases.

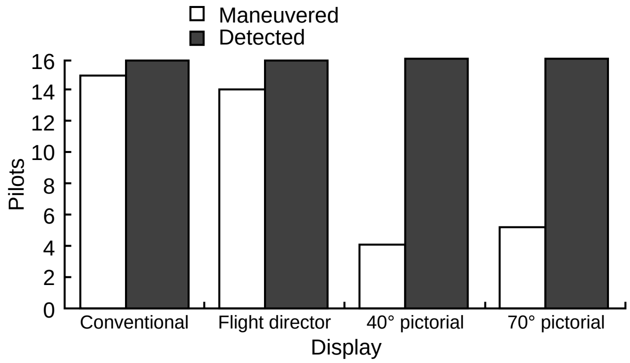


Figure 10. Traffic Conflict Scenario number of detections and subsequent maneuvers.

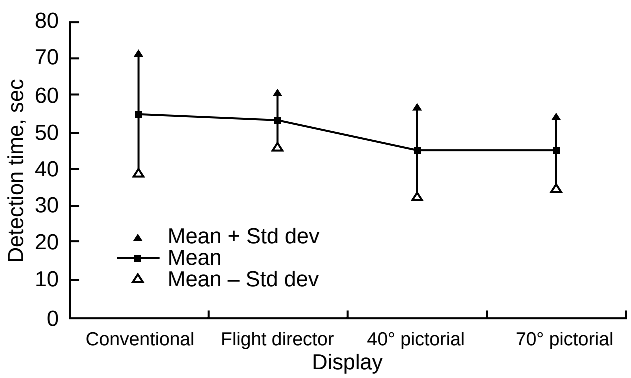


Figure 11. Traffic Conflict Scenario mean detection times per display concept and condition.

The altitude maneuver executed by the approaching traffic usually resulted in a TCAS advisory or a TCAS resolution, with the outcome dependent upon the current tracking performance of the own ship. Thirty-eight own ship avoidance maneuvers were executed (fig. 10); in 26 cases the pilot decided not to execute a maneuver. The maneuvers may have resulted from a TCAS resolution or from an independent decision of the own ship pilot. The no-maneuver decisions may have been made because the situation was judged not serious. The 23 no-maneuver cases with the pictorial displays can be attributed to such judgments, as no TCAS resolution was presented to the pilots and the requirement for a maneuver was wholly their decision. Detailed analysis of the three no-maneuver cases with the conventional displays revealed that TCAS resolutions were presented. However, in each case the pilot's response to the TCAS command came so late that the maneuver detection logic used for scoring was not tripped before the run ended. In any case, the analysis of variance for the maneuver time measure found no statistically significant differences for any factors of the scenario experiment (and no figures are presented).

The inference from these results is that the pictorial displays provided the pilot with better traffic information than did the EFIS displays. Detection of the threatening traffic situations occurred earlier and at greater distances (the 10-sec-earlier detection time translates into 1 n.mi. of increased separation) with the pictorial displays; and with the increased awareness of the situation, the pilots initiated fewer avoidance maneuvers.

Runway Blunder Scenario

The Runway Blunder Scenario exposed each pilot to one incident for each display condition in which another airplane landing on the left parallel runway 30 sec ahead of the own ship inexplicably (to the subject pilot, but not to the experimenter) crosses the own ship flight path on final approach to the right runway. Figure 12 illustrates the Runway Blunder Scenario and the obvious visual advantages of the pictorial display formats. No replication was used; therefore, only pilot factors and display conditions were analyzed.

Table V summarizes the results of the analyses for detection time and maneuver time. With the EFIS displays, about *half* the blunders were detected. (The map scale was always on maximum on final approach.) With the pictorial displays, the

Table V. Analysis of Variance Results for Runway Blunder Scenario

Factor	Degrees of freedom	Significance[a]
Detection time		
Pilots	15	-
Display	3	**
Error	30	-
Total	[b]48	-
Maneuver time		
Pilots	12	*
Display	3	**
Error	15	-
Total	[c]30	-

[a]Significance:
-Not significant at levels considered.
*Significant at 5-percent level.
**Significant at 1-percent level.
[b]Missing 15 cases.
[c]Missing 33 cases.

(a) Conventional EFIS with flight director display format with incurring traffic (unfilled blue diamond in color version) near beginning of incursion maneuver.

(b) Conventional EFIS with flight director display format with incurring traffic (unfilled blue diamond in color version) near end of incursion maneuver.

(c) Portion of pictorial display format with incurring traffic (airplane silhouette enclosed by black square) near beginning of incursion maneuver.

(d) Portion of pictorial display format with incurring traffic (airplane silhouette enclosed by black square) near end of incursion maneuver.

Figure 12. Runway Blunder Scenario depicting parallel traffic incursions.

16 pilots detected *all* threatening situations. (See fig. 13.) The differences between the mean detection times for the EFIS display conditions and the pictorial display conditions (fig. 14, about 8 sec) were statistically significant. The difference within the EFIS display types (3.3 sec sooner for the flight director condition versus without the flight director) also was significant, whereas the difference between the pictorial conditions (0.7 sec sooner for the 40° condition) was not.

Of the 64 runway blunder incidents, 15 went undetected under the EFIS display conditions. (See fig. 13.) Within the 49 detected incidents, the pilots chose to initiate a go-round maneuver in 31 cases. Analysis of the maneuver time measure for those 31 cases revealed significant differences between most paired means comparisons. (See fig. 15.) The maneuver time difference between the EFIS displays was statistically significant, with the flight director mean 4.6 sec earlier than the EFIS without the flight

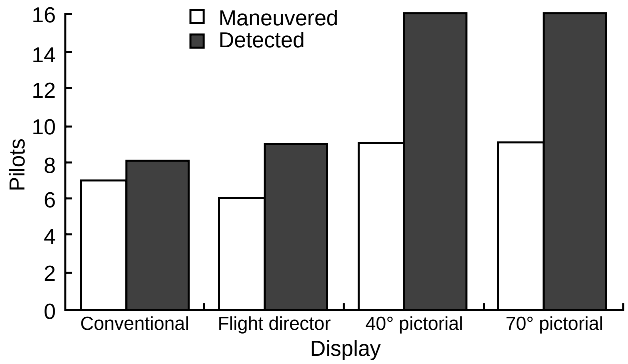


Figure 13. Runway Blunder Scenario number of detections and subsequent maneuvers.

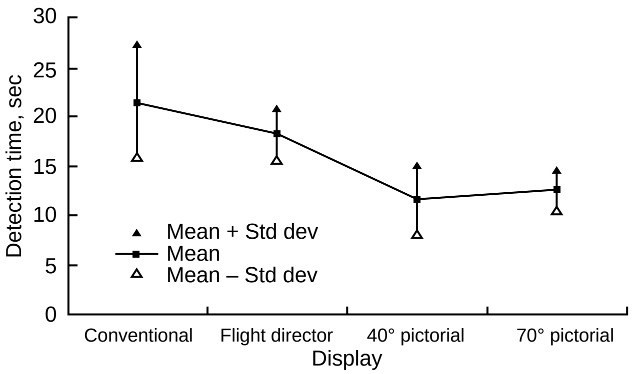


Figure 14. Runway Blunder Scenario mean detection times per display concept and condition.

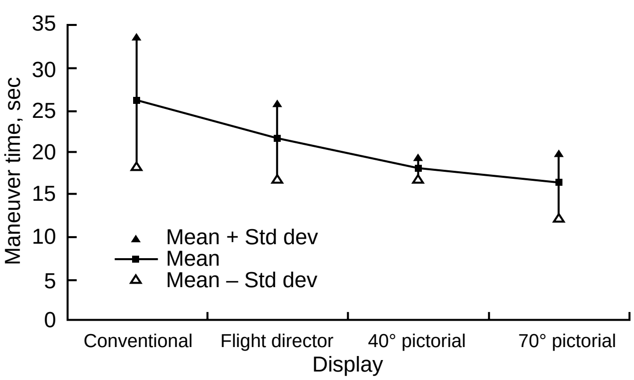


Figure 15. Runway Blunder Scenario mean times to maneuver since detection.

director mean. The pictorial display mean of 40° was a significant 3.4 sec earlier than the flight director mean. The difference between the 40° and the 70° pictorial display means (2.0 sec earlier with the 70° pictorial display) was not statistically significant.

The inference from these results is that the pictorial displays provided the pilot with better traffic awareness near the runway than did the EFIS displays. Fifteen of the 32 runway blunder incidences went undetected with the EFIS displays; detection in the remaining 17 incidents came later than with the pictorial displays. Also, with the increased awareness of the runway situation, the pilots initiated fewer go-round maneuvers when they used the pictorial displays. Within the EFIS display conditions, the detection time and the maneuver time means were lower for the EFIS flight director condition. Without the flight director, the pilot is probably intent on interpreting the raw error information and controlling to minimize glide slope and localizer deviations during final approach. Less time would thus be available to monitor the neighboring traffic than when just following the flight director commands.

Offset Scenario

The Offset Scenario exposed each pilot to four incidents of simulated recovery from display system failure for each display condition. The pilot's task in this scenario was, upon display system recovery, to determine the location of the own ship relative to the desired flight path, then to return to the flight path in a timely manner. Two scenario conditions were used, one placing the own ship in a TCAS resolution situation and the other in an unthreatened position. Two replicates of each scenario condition were used; and therefore, the factors analyzed were pilots, displays, scenario condition, and replicates.

Table VI summarizes the results of the analyses for recovery time. (A return to path was defined as achievement of an error of less than half a dot in lateral and vertical tracking and a heading error of less than 5°.) Statistically significant differences were found between the displays and the interaction between the displays and the scenario conditions. Figure 16 presents the results for the display factor and figure 17 graphically presents the results for the second-order interaction between the displays and the scenario conditions. In figure 16, more time is required to recover when using the conventional EFIS displays without the flight director. With the flight director, the recovery time was 14.6 sec quicker than without the flight director, and the performances with the pictorial displays were at least 10.2 sec faster than the flight director results; these differences were statistically significant. The difference between the pictorial conditions (2.5 sec faster for the 40° condition) was not significant.

Figure 17 shows that with the two conventional EFIS display conditions, the pilots took longer to

Table VI. Analysis of Variance Results for Offset Scenario

Factor	Degrees of freedom	Significance[a] of recovery time
Pilots	15	**
Displays	3	**
Conditions	1	-
Replicates	1	-
Pilots × Displays	45	-
Pilots × Conditions	15	-
Displays × Conditions	3	*
Pilots × Displays × Condition	45	-
Error	127	-
Total	255	

[a]Significance:
-Not significant at levels considered.
*Significant at 5-percent level.
**Significant at 1-percent level.

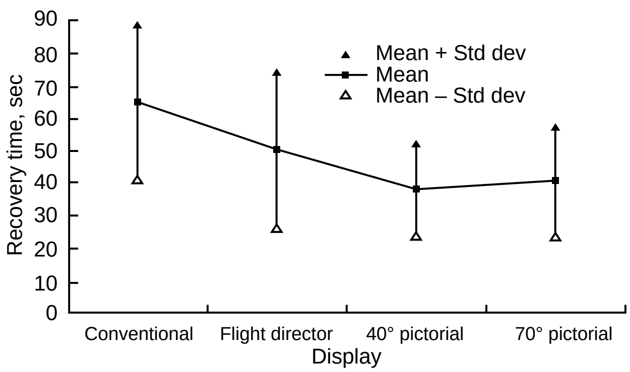


Figure 16. Offset Scenario mean times to recover to intended flight path per display concept and condition.

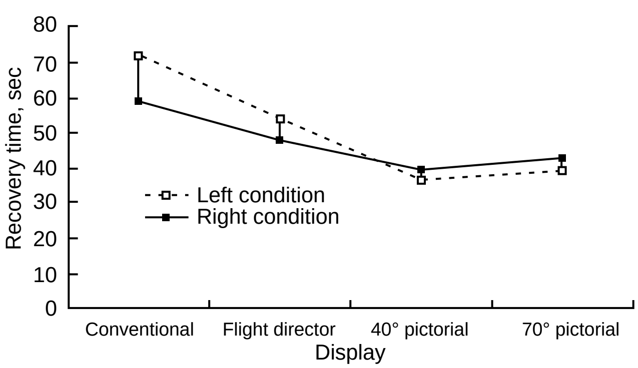


Figure 17. Offset Scenario second-order interaction between displays and scenario conditions; mean times to recover to intended flight path per display concept and condition.

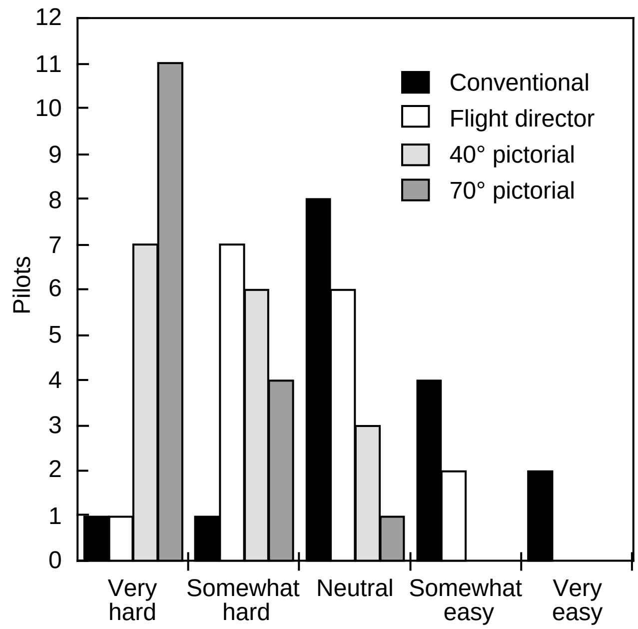
recover from the left offset condition (the TCAS traffic resolution case) than from the right offset condition. For the conventional EFIS without the flight director, the difference was a significant 13 sec, whereas the significant difference for the flight director case was about 6 sec. The differences for the two pictorial cases were not statistically significant.

The inference from these results is that the pilots were able to determine the own ship location relative to the desired flight path and return to the flight path more quickly with the pictorial displays. The flight director recovery was faster than the conventional display without the flight director, probably because interpreting the raw error information was more time-consuming than just following the flight director commands. The difference in recovery time between the pictorial displays and the flight director display was attributed to better spatial awareness, but it might also involve more aggressive manual intercepts of the flight path with the pictorial displays versus the intercept logic within the flight director. Perhaps a better spatial awareness metric for this scenario would have been maneuver time (the time elapsed before maneuvering began, as was used in the Runway Blunder scenario).

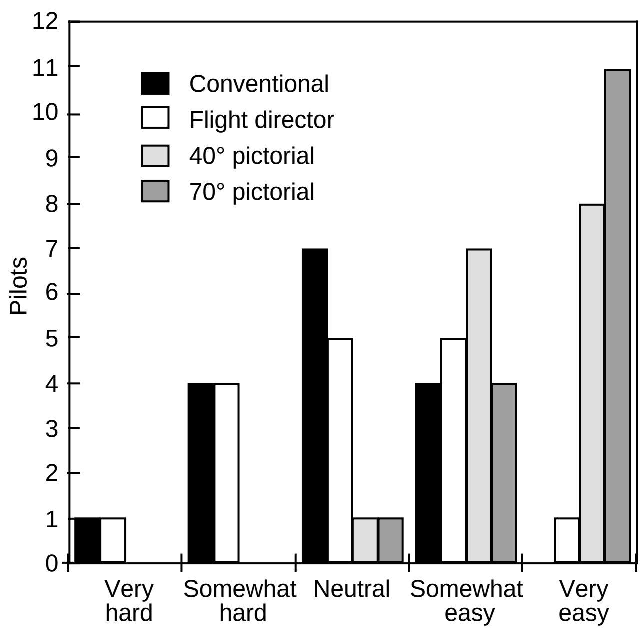
The statistically meaningful results from the scenario conditions within the Offset Scenario (the second-order interaction term) occurred with the conventional EFIS displays. When the display system recovered from the simulated display failure to reveal a TCAS resolution situation (the left offset condition), the pilots probably responded to the TCAS vertical resolution before attempting to determine the own ship location relative to the desired flight path and returning to the flight path. Therefore, recovery took longer for the left offset condition than for the right. With the pictorial displays, the sense of urgency to move is much higher for the left offset condition, and the direction of desired movement is readily determined from the visual presentation. (The maneuvering response to a TCAS resolution under the pictorial display conditions was left to the pilot's discretion, as opposed to the EFIS TCAS resolution of vertical movement.) Therefore, recovery was initiated more quickly for the left offset condition than for the right (offset condition with no threatening traffic), although the 3- to 3.5-sec differences were not statistically significant.

Subjective Results

Table III enumerates the nine questionnaires administered to each pilot. The summary of those subjective results (which is sufficient for this paper) revealed a dramatic improvement in all aspects of



(a) Ease of becoming disoriented.



(b) Ease of maintaining spatial awareness.

Figure 18. Rating results from pilots for two subjective categories.

spatial awareness when both pictorial formats were used and, in particular, when the large-screen 70° version was involved. Figure 18 presents rating results for two subjective categories as typical examples. The pilots were asked to rate, the ease of becoming disoriented and, in an opposite connotation (as a sanity check, the same question), the ease of maintaining spatial awareness when using each display configuration (without comparison to the other display configurations). In both instances, the two pictorial formats dramatically improved spatial awareness and, in particular, when the large-screen 70° version was involved.

Another subjective assessment of each display configuration (without comparison to the other display configurations) used the Modified Cooper-Harper scale (modified to extend its utility beyond handling quality evaluations; ref. 23) that is shown in figure 19. Figure 20 presents the average, maximum, and minimum ratings (not plus or minus the standard deviations) for all experiment scenarios. The two pictorial formats distinctly improved the modified rating (in both mean rating and spread), although differences between the two fields of view were hard to assess within the confinements of lower end of the scale.

Figure 21 presents the results of comparative rank ordering by the pilots for several categories on a scale of 1 (the most desirable display) to 10 (the least desirable display). The average, maximum, and minimum rankings presented (not plus or minus the standard deviations). The categories are used to compare the display concepts over all the scenarios. The pilots ranked display effectiveness for success in monitoring traffic, for reduction of their workload, and for their reactions regarding the entire experiment. Again, based on the subjective comments, the pictorial formats substantially improved all aspects of spatial awareness (in both average ranking and spread). In particular, the large-screen 70° version was preferred by 14 of the 16 pilots; two pilots had no preference.

In addition to the formal questionnaire results, other subjective comments were obtained. Particularly notable are the following:

"Like flying on a beautiful VFR [visual flight rules] day."

"Provides immediate assessment of the situation. . . ."

"Ability to fly complex approaches is greatly improved."

"Easier to detect traffic incursions and runway blunders."

"Display of pictorial world is natural and easy to interpret."

Objective Tracking Performance Results

In addition to the SA measurement techniques, standard rms tracking data were collected and

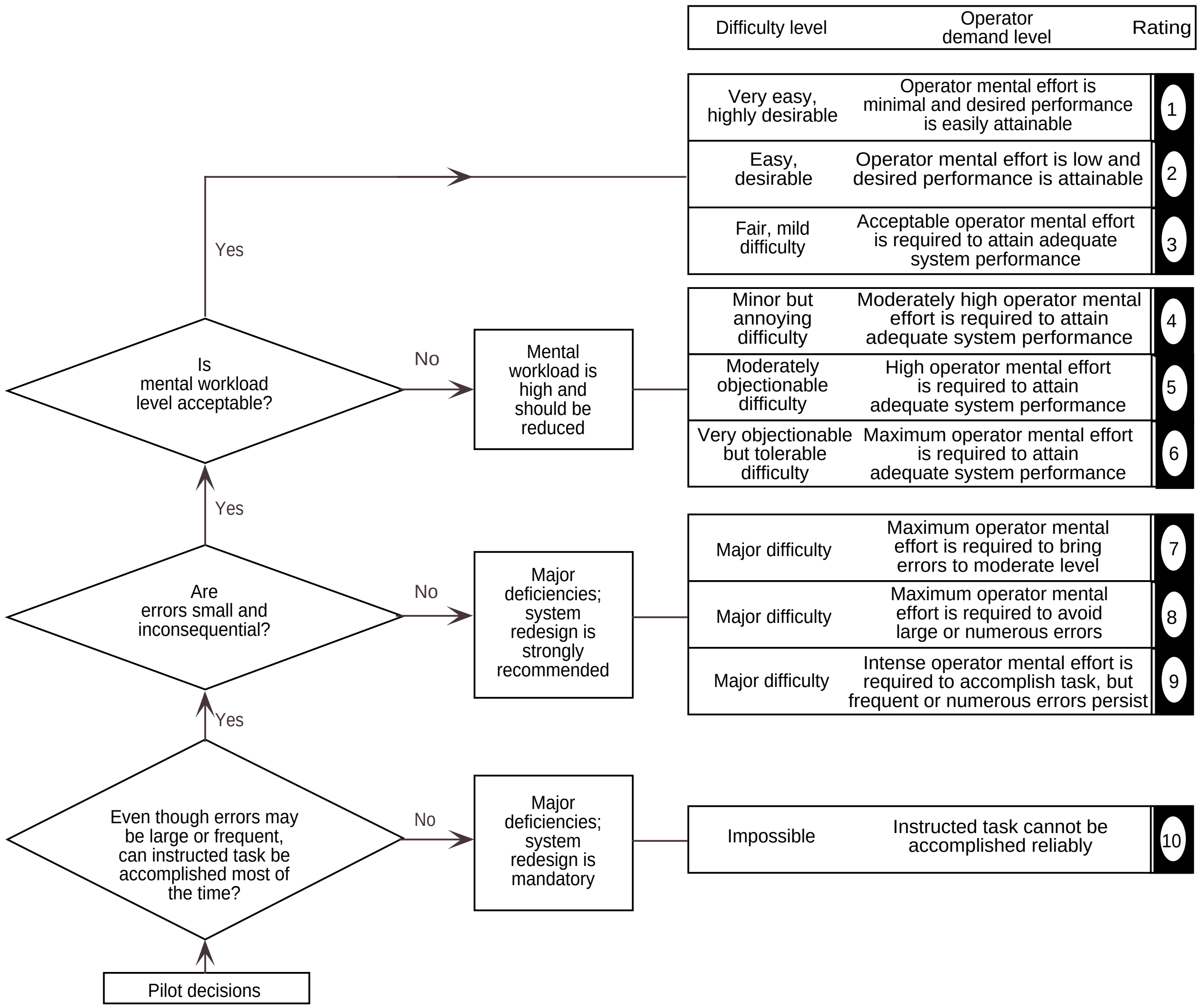


Figure 19. Modified Cooper-Harper scale for mental workload assessment.

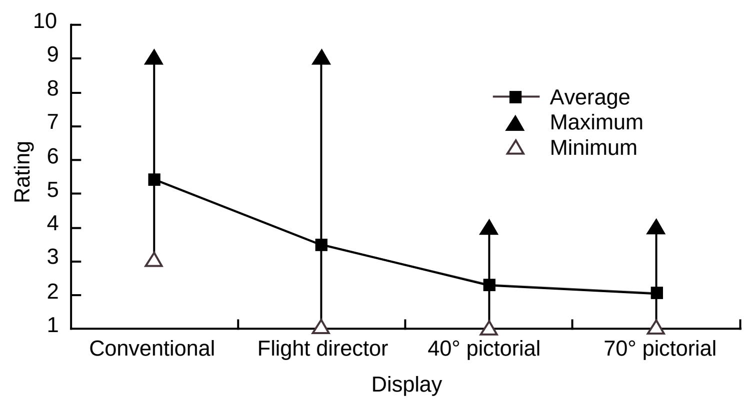


Figure 20. Modified Cooper-Harper mean rating results over all experiment scenarios.

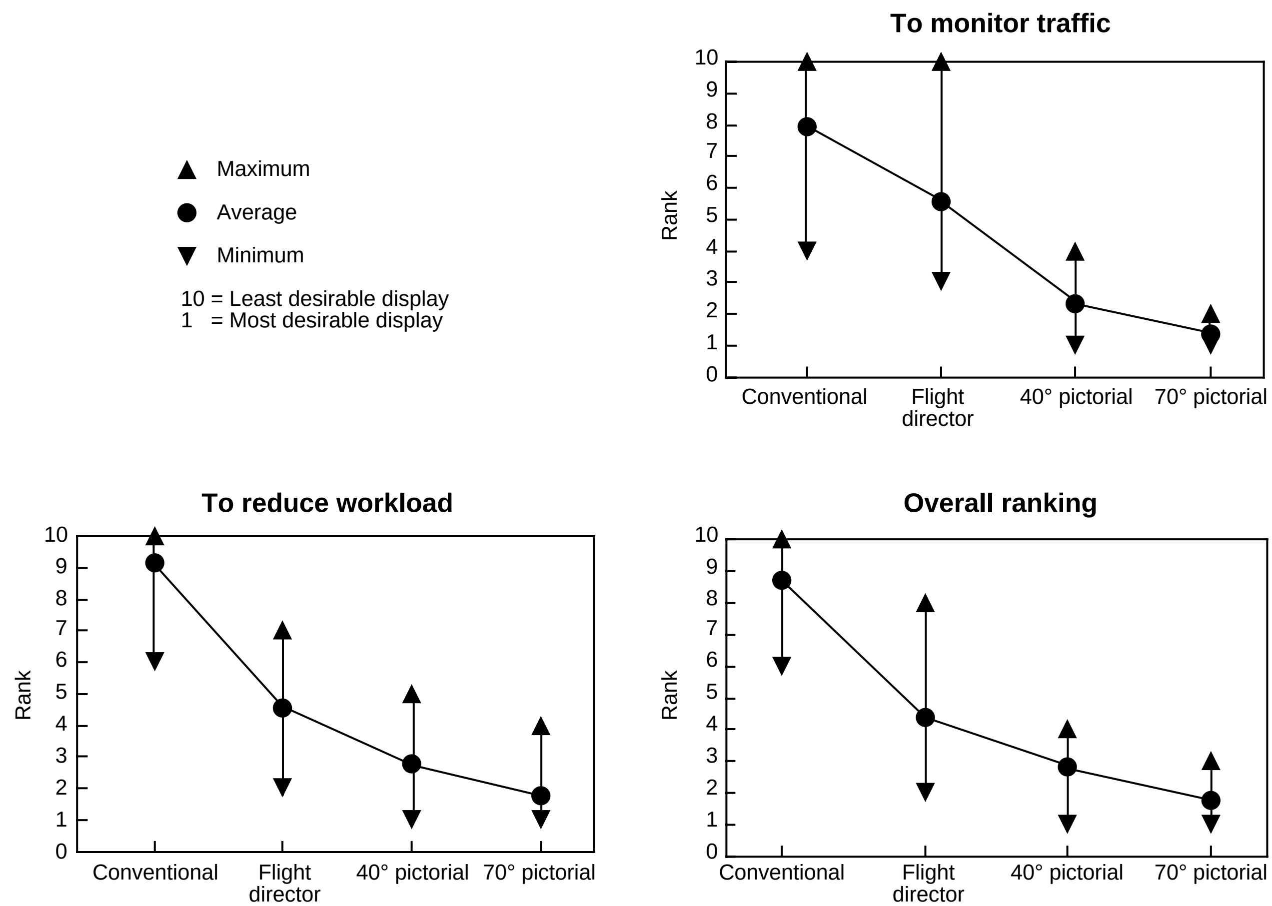


Figure 21. Comparative rank ordering by pilots for three categories.

analyzed. The standard or basic SAL was divided into segments for this purpose (fig. 9), with the following designations:

Segment	Description
1	Turning entry
2	Straight descent
3	Descending turn
4	Transition to straight and level, deceleration
5	Level turn
6	3° descent, deceleration, and turn final
7	Short final approach

The analysis for segment 1 (entry to the SAL from the off-path initial conditions) was not meaningful in terms of spatial awareness or display format results and is not presented. Table VII presents a summary of the analyses of variance results for the rms of the vertical and lateral tracking errors for the other segments. Statistically significant differences were found between pilots, displays, and the interaction of those two factors. Pilot response varied greatly (as expected); therefore, pilot variability was isolated from the rest of the analyses by its inclusion as a main factor in the analyses. The pilot-by-display interaction typically indicated that the pilots reacted differently to the display effect; that is, one pilot might exhibit a very large difference during two display conditions, whereas another pilot would exhibit a smaller difference. The differences were typically in the same direction, with only the magnitudes varying among pilots.

Figure 22 presents a comparison of the display condition rms lateral error means from the 16 pilots for each segment. Not surprisingly, the lateral tracking performance error was significantly larger for every segment of the SAL in which the conventional EFIS was used without the flight director display. Differences between the conventional EFIS with the

Table VII. Significance of Variance Results for Tracking Performance Measures

(a) Summary of analyses for segments 2, 5, and 6

Factor	Degrees of freedom	Significance[a] of rms performance for— Vertical	Lateral
Pilots	15	**	**
Displays	3	**	**
Replicates	6	-	-
Pilots × Displays	45	**	**
Error	378		
Total	447		

(b) Summary of analyses for segments 3 and 4

Factor	Degrees of freedom	Significance[a] of rms performance for— Vertical	Lateral
Segment 3			
Pilots	15	**	**
Displays	3	**	**
Replicates	2	*	-
Pilots × Displays	45	**	**
Error	126		
Total	191		
Segment 4			
Pilots	15	**	**
Displays	3	**	**
Replicates	2	-	-
Pilots × Displays	45	**	**
Error	126		
Total	191		

(c) Summary of analysis for segment 7

Factor	Degrees of freedom	Significance[a] of rms performance for— Vertical	Lateral
Pilots	15	**	**
Displays	3	**	**
Replicates	5	-	-
Pilots × Displays	45	**	**
Error	315		
Total	383		

[a]Significance:
-Not significant at levels considered.
*Significant at 5-percent level.
**Significant at 1-percent level.

flight director and the two pictorial display conditions were also significant (flight director error was larger), whereas differences between the 40° and 70° display conditions were not. Differences in performance between segments for a particular display condition can be attributed to the type of segment. (Segments 3, 5, and 6 included turns and segments 2, 4, and 7 were straightaways.)

Figure 23 presents a comparison of the display condition rms vertical error means from the 16 pilots for each segment. Not surprisingly, the vertical tracking performance error was significantly larger for every segment for the conventional EFIS without the flight director display. Differences among the conventional EFIS with the flight director and the two pictorial display conditions were also significant, but only for segments 2, 3, and 6 (flight director error was larger). Differences between the 40° and the 70° display conditions were not significant for any segment. Differences in performance between segments for a particular display condition can be attributed to the type of segment (segments 2, 3, 6, and 7 included descents, whereas segments 4 and 5 were level).

The lateral and vertical tracking performances with the pictorial display conditions were at least as good as or better than the performances with the EFIS flight director display, and the flight director performances were much better than the EFIS without the flight director. Although no conclusions may be drawn from these facts about increased or decreased spatial awareness, they do provide the assurance that the increased spatial awareness from the pictorial displays, as measured by the other measurement tools, did not degrade tracking performance.

Inferences From Results

Conclusive inferences can be drawn from the objective and subjective results. Meaningful comparisons are possible between the two EFIS display formats, between the two pictorial display formats, and between the conventional EFIS displays and the pictorial displays.

EFIS Comparisons

In all cases in which objective or subjective comparisons were possible, EFIS displays with the flight director achieved either equivalent or better performance. The earlier supposition had been that concentration only on centering the flight director needles might reduce the pilot's awareness of surrounding events, whereas using raw position errors might increase spatial awareness. However, that

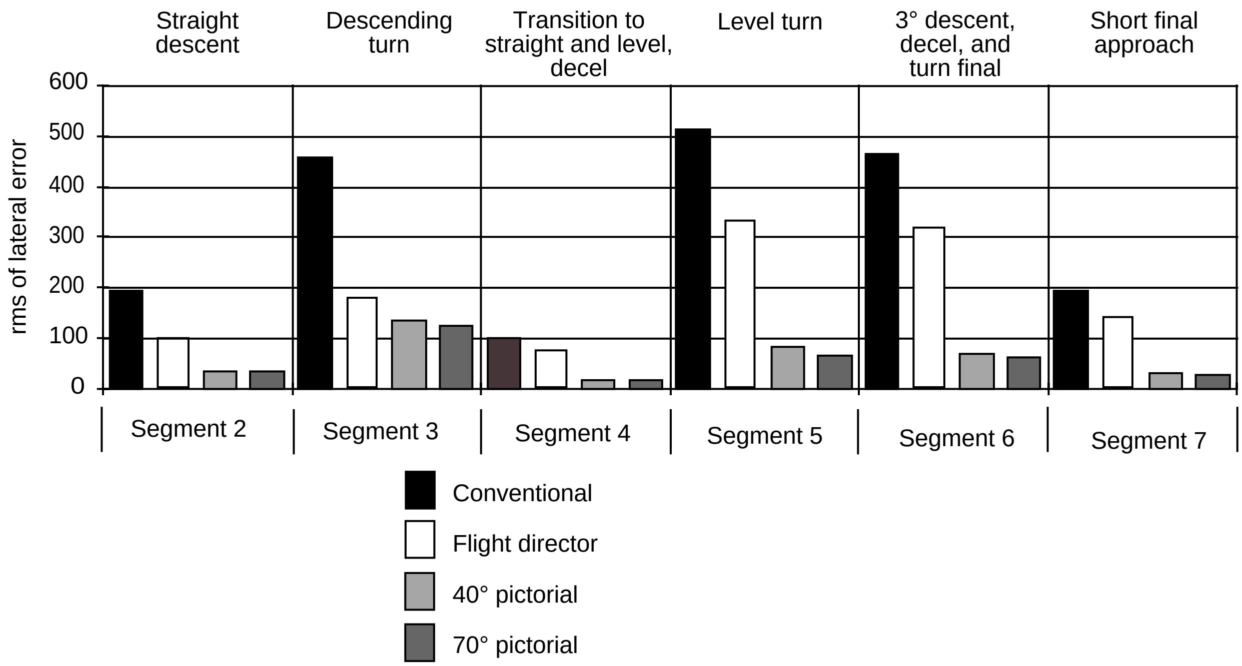


Figure 22. Mean lateral errors (for all pilots) per display concept and condition for each path segment.

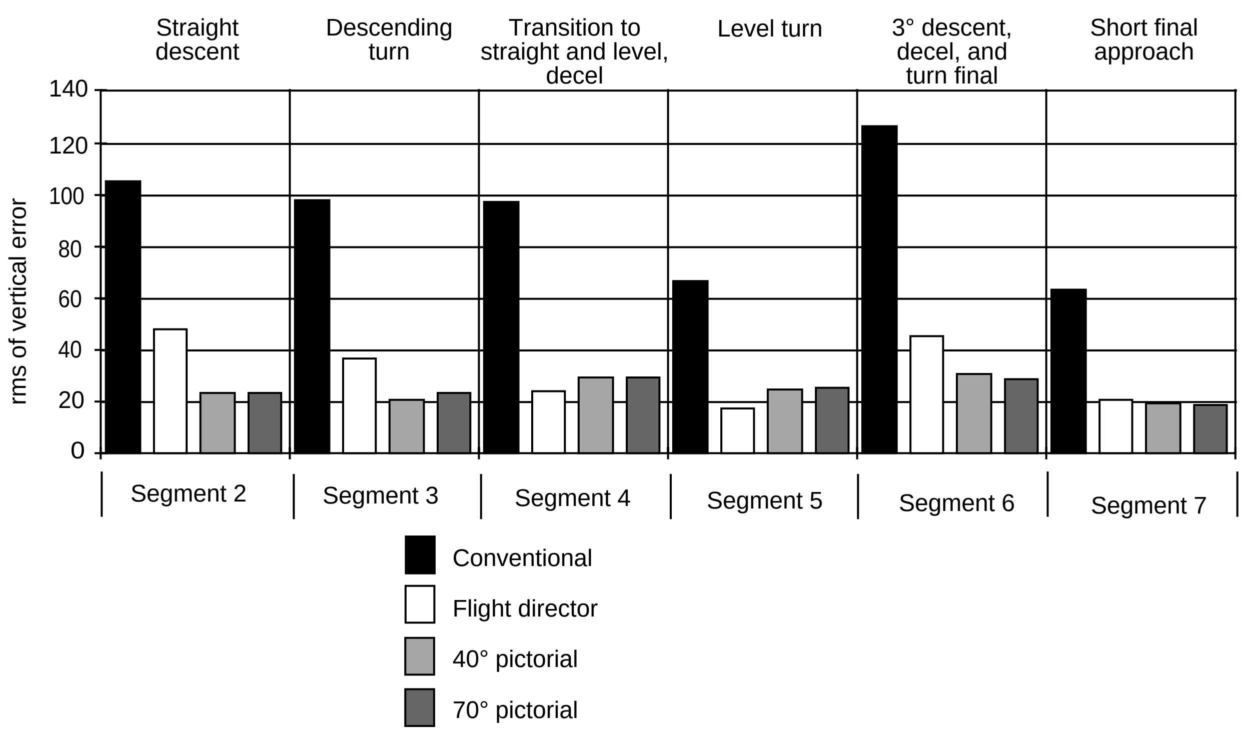


Figure 23. Mean vertical errors (for all pilots) per display concept and condition for each path segment.

supposition was proved invalid here. Perhaps the key word in that supposition was the word *only*. Better spatial awareness appears to be gained because the flight director imposes a lower path-tracking workload on the pilot, thereby allowing time to scan other sources of information besides the flight director needles. Use of raw data error in the EFIS without the flight director requires that almost constant attention be devoted to the path-tracking task.

Pictorial Comparisons

The objective data revealed equivalent performance for the 70° pictorial display compared with the 40° FOV. The subjective data, however, revealed a strong preference for the wider FOV, particularly for awareness during turning entry and traffic situations.

EFIS and Pictorial Comparisons

Both the objective and subjective data demonstrated that the integrated pictorial displays increased spatial awareness over the conventional EFIS display formats.

Concluding Remarks

An extensive simulation study was performed to determine and compare the spatial awareness of commercial airline pilots on simulated landing approaches using conventional flight displays with their awareness using advanced pictorial "pathway in the sky" displays. Various situation awareness measurement techniques were incorporated within the scenarios. Conflicting traffic situation assessments and flight path recaptures after recovery from simulated display system failure were created to assess spatial awareness using different display formats. Both objective and subjective techniques were employed. The spatial awareness scenarios yielded results that were consistent across and within the objective and subjective measures.

The objective data analyses revealed that better spatial awareness performance was achieved when the flight director was included in the electronic flight information systems (EFIS) display. However, the integrated pictorial displays consistently provided substantially increased spatial awareness compared with either of the conventional EFIS display formats. Objective data results for the wider field-of-view (FOV) pictorial display were equivalent to those obtained with the narrower pictorial format.

The subjective results, which were also summarized herein, indicated a strong preference for the flight director within the EFIS displays. However, the subjective study revealed that all aspects of spatial awareness were dramatically improved by the two pictorial formats and, in particular, by the large-screen version with a 70° FOV.

Therefore, integrated pictorial displays show significant promise for improving situation awareness. These types of formats also can be the basis for an effective synthetic vision system, one which can solve restricted visibility problems associated with advanced subsonic and future high-speed civil transports.

NASA Langley Research Center
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July 1, 1994

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Figure 1. Spatial awareness study display formats.

Figure 2. VISTAS architecture.

Figure 3. Over-and-under arrangement of conventional primary flight and navigation displays with supporting instrumentation.

Figure 4. Seventy-degree FOV, large-screen, integrated, pictorial display concept.

Figure 5. TCAS II advisory and resolution displays.

Figure 6. Simulated MLS standard approach to right runway.

Figure 7. Traffic routes of SAL, parallel approach, and crossing traffic.

Figure 8. Offset, parallel runways.

Figure 9. Segmentation of SAL route for statistical analysis.

Figure 10. Traffic scenario number of detections and subsequent maneuvers.

Figure 11. Traffic scenario mean detection times per display concept and condition.

Figure 12. Runway Blunder scenario depicting parallel traffic incursions.

(a) Conventional EFIS with flight director display format and incurring traffic (unfilled blue diamond in color version) near beginning of incursion maneuver.

(b) Conventional EFIS with flight director display format with incurring traffic (unfilled blue diamond in color version) near end of incursion maneuver.

(c) Portion of pictorial display format with incurring traffic (airplane silhouette enclosed by black square) near beginning of incursion maneuver.

(d) Portion of pictorial display format with incurring traffic (airplane silhouette enclosed by black square) near end of incursion maneuver.

Figure 13. Runway Blunder scenario number of detections and subsequent maneuvers.

Figure 14. Runway Blunder scenario mean detection times per display concept and condition.

Figure 15. Runway Blunder scenario mean times to maneuver since detection.

Figure 16. Offset Scenario mean times to recover to intended flight path per display concept and condition.

Figure 17. Offset Scenario second-order interaction between displays and scenario conditions; mean times to recover to intended flight path per display concept and condition.

Figure 18. Rating results from pilots for two subjective categories.

Figure 19. Modified Cooper-Harper scale for mental workload assessment.

Figure 20. Modified Cooper-Harper mean rating results over all experiment scenarios.

Figure 21. Comparative rank ordering by pilots for three categories.

Figure 22. Mean lateral errors (for all pilots) per display concept and condition for each path segment.

Figure 23. Mean vertical errors (for all pilots) per display concept and condition for each path segment.

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13. ABSTRACT *(Maximum 200 words)*
An extensive simulation study was performed to determine and compare the spatial awareness of commercial airline pilots on simulated landing approaches using conventional flight displays with their awareness using advanced pictorial "pathway in the sky" displays. Sixteen commercial airline pilots repeatedly made simulated complex microwave landing system approaches to closely spaced parallel runways with an extremely short final segment. Scenarios involving conflicting traffic situation assessments and recoveries from flight path offset conditions were used to assess spatial awareness (own ship position relative to the desired flight route, the runway, and other traffic) with the various display formats. The situation assessment tools are presented, as well as the experimental designs and the results. The results demonstrate that the integrated pictorial displays substantially increase spatial awareness over conventional electronic flight information systems display formats.

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Spatial awareness; Large screen, Integrated pictorial displays; Electronic flight information systems; EFIS displays; Simulated landing approaches; VISTAS

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