The Efficacy of Head-Down and Head-Up Synthetic Vision Display Concepts for Retro- and Forward-Fit of Commercial Aircraft

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ABSTRACT

The retrofit question concerns whether useful and effective synthetic vision displays are usable in aircraft that have limited size display spaces. Two experiments were conducted to examine the efficacy of these displays and develop field-of-view and terrain texture recommendations for design. The first experiment examined issues of field-of-view and display size using an Asheville, NC synthetic vision database and fixed-based simulator. The second experiment was conducted on the NASA B-757 aircraft at DFW and investigated the efficacy of both head-down and head-up displays and generic and photo-realistic terrain texture. Both experiments confirmed the retrofit capability and that all sizes and texturing methods were found to be viable candidates for synthetic vision displays. These results, future directions, and implications for meeting national aeronautic safety and capacity goals are discussed.

INTRODUCTION

Background

The Synthetic Vision Systems (SVS) element of the National Aeronautics and Space Administration's (NASA) Aviation Safety Program (AvSP) is striving to eliminate poor visibility as a causal factor in aircraft accidents and to increase operational capabilities of general aviation (GA), business, and commercial aircraft. To accomplish these safety and situation awareness enhancements, the SVS concept will provide a clear view of the world ahead through the display of computer generated imagery derived from an onboard terrain, obstacle, and airport database and enhanced vision sensor (EVS) technologies.

The ability of a pilot to ascertain critical information through visual perception of the outside environment can be limited by various weather phenomena, such as rain, fog, and snow. Since the beginning of flight, the aviation industry has developed various devices to overcome these low-visibility limitations. These include attitude indicators, navigation aids, Instrument Landing Systems (ILS), moving map displays, and Terrain Awareness Warning Systems (TAWS). All of the aircraft information display concepts developed to date, however, still require the pilot to continuously perform information acquisition and decoding to update and maintain their mental model to "stay ahead" of the aircraft when outside visibility is reduced. The NASA SVS project is based on the premise that better pilot situation awareness during low visibility conditions can be achieved by reducing the steps required to build a mental model from disparate pieces of data through the presentation of how the outside world would look to the pilot if their visibility was not restricted.

Human-Centered SVS Displays

Although avionics have advanced significantly since Jimmy Doolittle flew the first "blind" flight in 1929, Theunissen (1993; 1997) noted that significant increases in aviation safety are unlikely to come by extrapolating from current display concepts. He further stated that, "new functionality and new technology cannot simply be layered onto previous design concepts, because the current system complexities are already too high. Better human-machine interfaces require a fundamentally new approach" (1997; p.7). Bennet and Flach (1994) argued that such an approach should not focus on development of "idiot-proof" systems because of the infinite potential problem space, but rather should provide to the pilot information that would enable successful solution sets to be generated. These displays should present continuous information about spatial constraints rather than command changes to reduce error states, and should show error margins that depict the bounds that the pilot may safety operate in contrast to the compensatory control strategy required by current cockpit instruments. They further concluded that dynamic, graphical representations hold the greatest promise to achieve such "human-centered" design because it allows human flexibility to best be exploited through the presentation of natural versus coded information to the pilot.

Natural information implies the method of information acquisition by the pilot similar to that experienced in Visual Meteorological Conditions (VMC) by looking out the window. Visual altitude judgment is an example of natural information. Coded information implies some type of information presentation to the pilot that requires interpretation to comprehend the actual value. An example of coded information is altimeter reading. Helmetag, Kaufhold, Lenhart, & Purpus (1997) argued that it is very important to give the pilot information required to maintain situation awareness in low-visibility conditions and that natural information presentation is intuitive and able to be perceived in a much more rapid manner than coded information. SVS displays provide exactly such a natural presentation of the outside world with proximity compatible, integrated information (Wickens & Andre, 1990) that is both intuitive and easy to process.

Safety Benefits of SVS

Synthetic vision technology may allow the issues associated with limited visibility to be solved with a visibility-based solution, making every flight the equivalent of a clear daylight operation, which will help improve situation awareness and support proper development of the pilots' mental model. Therefore, SVS can have a significant impact on improving aviation safety since limited visibility represents the single greatest contributing factor in many fatal worldwide airline accidents (Boeing, 1996).

Consider that one of the major types of commercial aviation accidents involving low visibility issues is Controlled Flight Into Terrain (CFIT) and that CFIT is one of the greatest causes of aviation fatalities (Moroze & Snow, 1999). A CFIT accident is defined as, "one in which an otherwise-serviceable aircraft, under control of the crew, is flown (unintentionally) into terrain, obstacles or water, with no prior awareness on the part of the crew of the impending collision" (Wiener, 1977). A Flight Safety Foundation (FSF) analysis evinced that 90% of CFIT accidents occurred in instrument meteorological conditions (IMC) and that 25% occurred with ground proximity warning system (GPWS)-equipped aircraft. The FSF also reported that non-precision approaches were five times more likely to result in a CFIT, and that lack of crew situation awareness of terrain and aircraft position was the leading contributing cause (Khatwa and Roelen, 1998). Although TAWS may help to mitigate some of these factors, the use of the technology generally follows the "warn-act" model and, therefore, requires the flightcrew to be reactive rather than proactive. Theoretically, TAWS provides a warning when the flightcrew has already lost situation awareness, and may not be optimal given the reaction time required to adequately recognize and assess the situation and initiate an escape maneuver (Moroze et al., 1999). Snow and Reising (1999) argued that what is needed is an intuitive system that improves pilot situation awareness with respect to spatial orientation in terms of terrain and flight path, and does not require the pilot to divert visual attention and cognitive resources away from possible external events and primary flight reference. A system that can help prevent rather than just warn the flightcrew of a potential collision with terrain is needed; such a system can be provided by synthetic vision.

Operational Benefits of SVS

The aviation safety benefits alone of synthetic vision are reason enough to pursue the technologies but, due to the costs associated with such a system, it must also present operational and economic benefits. NASA anticipates that SVS technology could serve to increase national airspace system capacity by providing the potential for increased VMC-type operations even under Category IIIb weather conditions (Williams et al., 2001). Benefits would include: (a) reduced runway occupancy time in low visibility; (b) reduced departure and arrival minimums; (c) better allow for converging and circling approaches, especially for dual and triple runway configurations; (d) reduce inter-arrival separations; and (e) provide for independent operations on closely-spaced parallel runways. A cost-benefit analysis of 10 airports (DFW, ORD, LAX, ATL, DTW, MSP, EWR, SEA, LGA, JFK) calculated the average cost savings to airlines for the years 2006 to 2015 to be 2.25 Billion (Williams et al., 2001).

Research Challenges of SVS

Although the safety and economic advantages and payoff to pursuing SVS are great, there are significant research challenges to be addressed before SVS can be considered viable as a technological alternative. To provide a better definition of the concept of operations

(CONOPS) of synthetic vision technology for commercial and business aircraft, a workshop resulting in a CONOPS document was held at the NASA Langley Research Center (Williams, et. al., 2001). The focus of this event was to obtain wide ranging input from the aviation community on the benefits and features which synthetic vision might incorporate. The outcome of the workshop and subsequent activities has been the identification of numerous challenges and research issues that need to be explored in developing SVS display concepts. Many of these issues can be classified as human perceptual, such as display size and Field-of-View (FOV) issues.

The issue of display size is driven largely by the need for displays compatible in size with current aircraft displays (the retrofit issue) and potential next generation larger display surfaces (forward fit issue). Because current aircraft have either electro-mechanical instruments (e.g., 737-200) or small "glass" displays (e.g., 757-200), there are concerns about the efficacy of these cockpits to support SVS because of the physically smaller instrument spaces. One option to address the retrofit issue would be to present SVS on a head-up display (HUD), and research questions turn to how best to display synthetic terrain on a HUD that has limited graphical capabilities. Another option is to simply remove the traditional instruments and replace them with synthetic vision displays, and research issues then turn to whether the "real estate" constraints will allow SVS presentations to be usable by the flightcrew. Because these displays have a small unity geometric field-of-view, the scale factor may need to be increased (i.e., minified) to allow more of the visual scene to be presented in order to make the SVS display effective (e.g., Roscoe, 1948). The "wide angle lens" effect of increasing FOV, however, interacts with display size and can lead to perceptual distortions as the MF is increased (i.e., virtual space effect; McGreevy & Ellis, 1986).

There are other perceptual issues concerning the content and type of information in the pictorial scene that also need to be addressed. SVS display scenes can be constructed from terrain elevation data and smoothed with generic terrain algorithms, or can be created by adding color and photo-realistic texture content information from aerial photographs. A research question that needs to be answered is which type of method provides the best information and situation awareness gain to the pilot. Is the additional data cost and computing requirements for photorealistic terrain worthwhile in terms of enhancements to pilot performance and situation awareness?

Research Purpose

Two experiments were performed to evaluate candidate FOV on each of the three display sizes on approach and landing tasks in a terrain-challenged (Asheville Airport; AVL) and a complex, nighttime operational environment (Dallas/Forth-Worth International Airport; DFW). The DFW flight test also examined the efficacy of SVS presentation on a HUD. The objectives of the experiments were to address:

1) The FOV recommendations for Head-Down Display (HDD) sizes (Experiments 1 & 2)
2) The effect of HDD size on pilot performance and situation awareness (SA) enhancements (Experiments 1 & 2)
3) The effect of SVS HUD concepts on pilot performance and SA enhancements (Experiment 2)
4) The effect of generic and photo-realistic terrain texturing methods on both HUD and HDD SVS display concepts (Experiment 2)
5) The evaluation and demonstration of SVS display concepts during complex, nighttime approaches at a large international airport (Experiment 2).

EXPERIMENT ONE

The objective of experiment one was to examine candidate fields-of-view and display sizes while pilot subjects made simulated approaches to Asheville Airport (AVL). The display sizes that were investigated were Size “A”, Size “D”, and Size “X” (see below). The fields-of-view (FOV) for this study were unity or one-to-one; 30°; 60°, and pilot-selectable. The hypotheses for Experiment One included the following: (1) All display sizes would provide adequate information for the successful conduct of the approach to AVL, as determined by performance and subjective response data; and (2) there is an optimal or preferred field-of-view for each display size as reflected in pilot selectable trials and in subjective response data.

METHOD

Participants

Eight transport-rated (ATP) airline captains served as test participants. Asheville was chosen from a list of domestic “terrain-challenged” airports and was the site of a 1998 NASA SVS flight research study. Figure 1 shows one synthetic vision display concept on approach to AVL that was used in Experiment One.

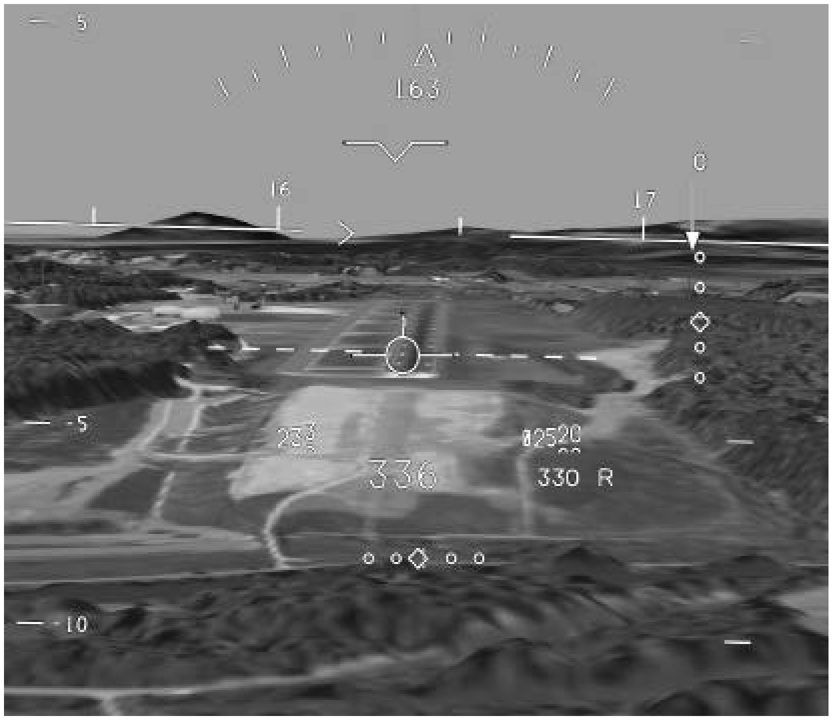

Figure 1. Synthetic Vision Display Concept on Approach to AVL

Simulation Facilities

The VISTAS-I (Visual Imaging Simulator for Transport Aircraft Systems) facility at the NASA Langley Research Center was used for evaluating synthetic vision display concepts for the AVL database (Figure 2). The VISTAS-I facility consists of a large head-down display surface, which uses a rear projection system (2 JVC models DLA-S10U) to present the HDD concepts, and an Electrohome Marquee 8000 forward system projector to present the "out-the-window" scene. Pilots were instructed to make the approaches with primary reference to the SVS display and simulated fog was used to restrict visibility and reduce pilot reliance on the OTW scene. All pilots commented that their focus was on the SVS display for the approaches until arriving at a decision height of 200 AGL at which time the trial was ended.

The simulation aircraft model used matched the performance capabilities of subsonic transports. Pilots made approaches with manual throttles and were instructed to maintain an approach speed target. The AVL scene and displays were generated using Silicon Graphics Onyx-2 Infinite Reality computer, Intergraph ZX-1 dual-Pentium processor computer, and Wildcat model 4110 high-speed graphics cards. The operating system platform was Windows NT.

Figure 2. Visual Imaging Simulator for Transport Aircraft Systems (VISTAS-I)

SVS Display Sizes and Format

Three display sizes were evaluated in the study and the dimensions from pilot eye reference point of these SVS display concepts are shown in Table 1. The smallest size, designated “A”, approximated the size of the Electronic Attitude Direction Indicator (EADI) in the current generation B757 / B767 aircraft, and the display concept represented a retrofit concept of extracting the current EADI and replacing it with a SVS display. The “A” size SVS display concept, therefore, did not incorporate airspeed, altitude, or vertical speed information and pilots obtained the data from traditional round dials (9.5 cm diameter) that were presented adjacent to the SVS display.

The next size represented a form factor size “D” display, which approximated the size of a primary flight display (PFD) in the B777 or B747-400 aircraft. The largest of the displays tested, was designated size “X” and represented display sizes envisioned as a potential display size in future transport aircraft. Both the “D” and “X” displays had integrated airspeed, altitude, and vertical rate information in a moving “tape” format found in a typical PFD. Each SVS display size, including Size A, had superimposed symbology showing the horizon, body axis indicator (waterline symbol), pitch information, roll scale, horizontal and vertical path deviation scales, radar altitude (below 500 feet above ground level), and a flight path / velocity vector.

A navigation display was presented with the SVS concepts that showed moving map format waypoints (track-up) along the programmed magenta path. For Experiment One, the SVS display showed the perspective terrain with photo-texturing of terrain features around the airport area. Photo-texturing consists of superimposing aerial photography on the terrain elevation information to recreate a realistic perspective scene. At AVL, the photo-texture covered an area 3 miles wide by 8 miles long centered about the airport. Outside the photo-textured area, generic shading of terrain features was presented.

Table 1. SVS Display Size Dimensions and Unity Field-of-View.

	Size "A"	Size "D"	Size "X"
Width	12.9 cm	16.0 cm	25.0 cm
Height	12.6 cm	16.0 cm	20.2 cm
Horizontal	11.5°	14.2°	22.0°
Vertical	11.2°	14.2°	17.8°

Display Field-of-View

Experiment One evaluated a subset of the possible FOVs that could be used in a SVS display. For each SVS display size, unity, 30°, and 60° FOVs were evaluated. FOV is based on horizontal FOV and vertical FOV is based on aspect ratio. For 75% of the experimental trials, the FOV was held fixed for each display size condition. For the remaining trials, the FOV was pilot selectable and the pilot could change the FOV as desired at any point during the approach. Each pilot participant, therefore, was presented with each FOV option for each display size including trials that were pilot selectable.

Experimental Design and Procedure

A 2 Runway (16 / 34) X 3 Display Size (A, D, X) X 4 FOV (unity, 30, 60, Pilot Selectable) repeated experimental design was used. Display size and FOV was counterbalanced across pilot participants for a total of 12 experimental data runs. Runway was randomized for an equal number of data runs to each runway across display size and FOV. All pilots were given baseline training with a traditional EADI to familiarize them with the simulator and participated in training runs with each display size concept before data collection began.

Six different scenarios were tested for approaches to AVL, which consisted of three starting points for the published ILS approaches to the North-bound runway (RWY 34) and three starting points for the South-bound runway (RWY 16). Each received an equal number of approaches to the two runways, and the six starting points were randomly presented to reduce pilot recognition and rote task completion. Each scenario began at 4400 MSL on a stabilized approach to AVL inside the initial approach fix. Data collection began 8.5 nm from runway threshold.

Using these scenarios, each test subject was presented with each factorial combination of display size and FOV option. An additional data run was performed at 90 degree FOV and display size was cycled to expose the pilot to the option, but no data was collected or analyzed. Performance data and subjective ratings and comments were recorded throughout the trials. After all experimental trials were completed, pilots were given a Situation Awareness Subjective Workload Dominance (SA-SWORD; Vidulich & Hughes, 1991) scale and participated in a semi-structured interview and debriefing. Pilots remained seated at the simulator while completing the SA-SWORD and while participating in the semi-structured interview in order to cycle through each display concept and FOV combination including the 90° FOV option.

RESULTS

Pilot Performance

No significant differences were found for runway ($p > .05$) and, therefore, data was collapsed across the independent variable. For the test trials with fixed display size and FOV, there were a total of nine combinations that could be compared at selected points on the approach. The approach segments consisted of mean path error derived over a 10,000 foot path segment. For example, the segment labeled "Seg- 45" represents data obtained from –50,000 to –40,000 feet prior to runway threshold crossing. Baseline data was not collected because the objective was to evaluate the effect of display size and FOV and develop a set of recommendations. Research, however, has demonstrated consistently the advantages of SVS for pilot performance and situation awareness. The interested reader is directed to several studies that directly compared the performance and situation awareness benefits of SVS (Bailey, Parrish, Arthur, & Norman, 2002; Glabb & Takalu, 2002; Prinzel et al., 2002; Stark et al., 2001; Uenking & Hughes, 2002).

Lateral Path Performance. A repeated measures analysis of variance (ANOVA) showed a significant effect for flight segment, $F(4,28) = 9.15$, $p < .01$, but no significant main effects or interactions were reported for display size or FOV levels ($p > .05$). The significant difference for flight segment shows the effect of being more accurately on the horizontal path in proximity to the runway threshold because of the increased ILS guidance precision.

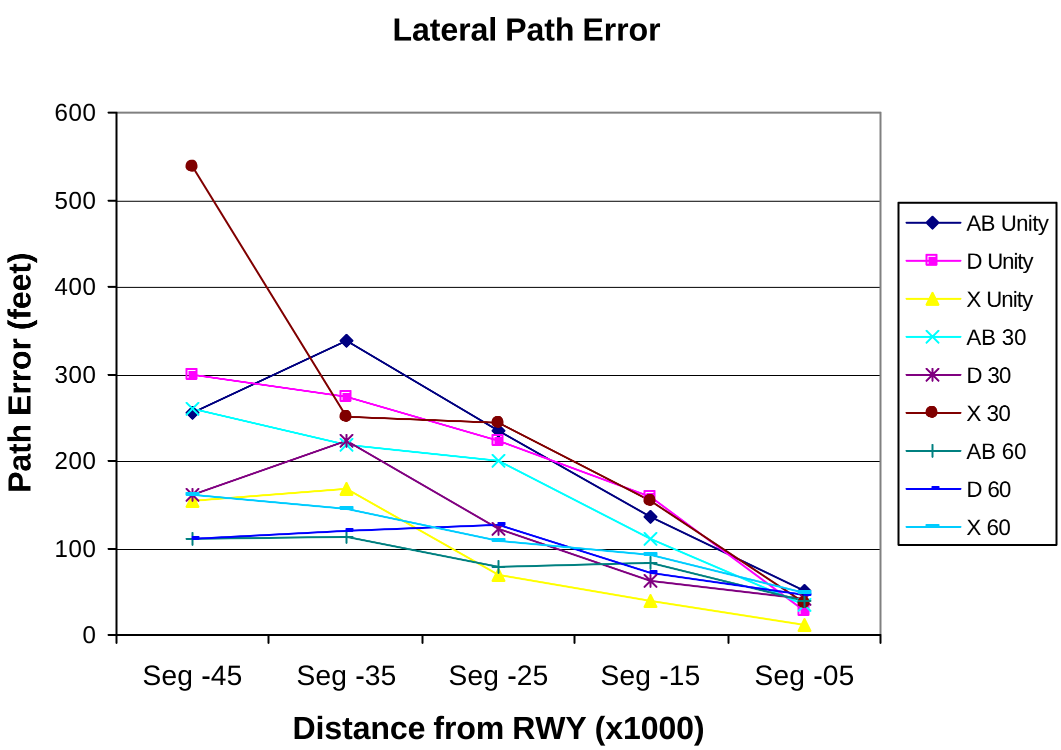

Figure 3. Lateral path error

Vertical Path Performance. The same method for defining flight segments was used for analysis of vertical path performance. A repeated measures ANOVA also revealed a significant effect for flight segment (Figure 4), $F(4,28) = 7.52$, $p < .01$), but no significant main effects or interactions ($p < .05$) for display size or FOV conditions. As for lateral path error, the significant difference by segment reflects decreased vertical error near the runway because of greater precision of ILS guidance nearer the runway threshold.

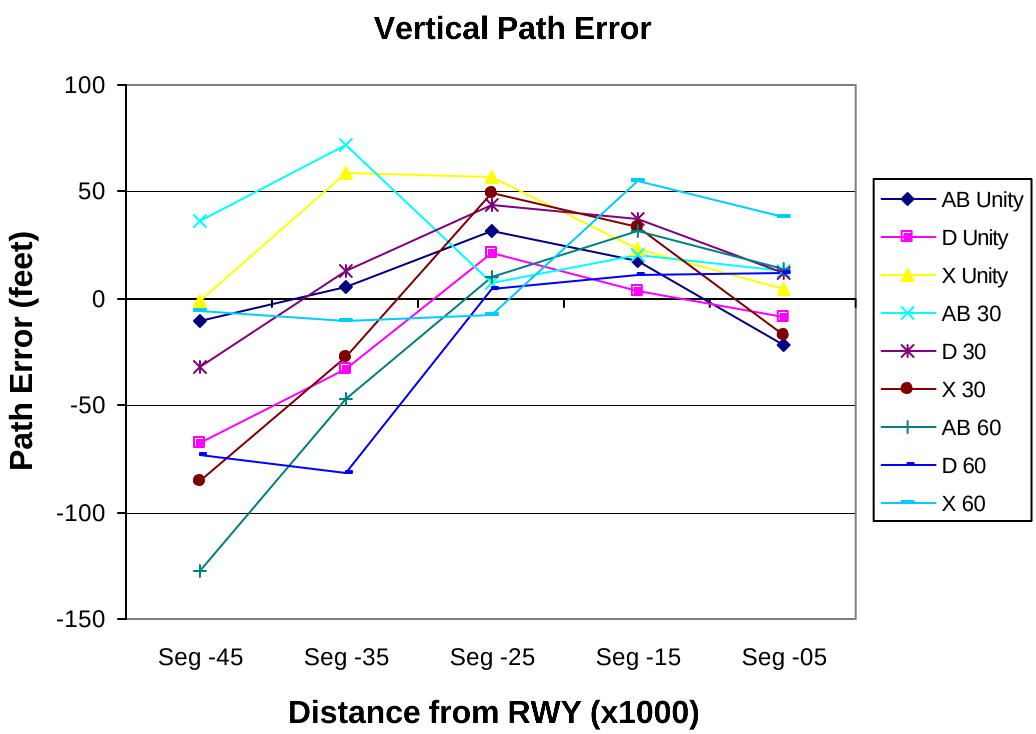

Figure 4. Vertical path error

Field-of-View Preferences

For the pilot selectable trials, participants consistently selected a fixed FOV option approximately 4 nm to touchdown. Pilots tended to select Unity (80%) and 30° FOV (15%) with only 5% of the trials being flown with a 60° FOV setting. Figure 5 shows the mean time in each FOV that mirrors these results, but also shows that the 30° FOV option was selected most often before the final approach fix wherein pilots selected Unity. Pilots rarely chose 60° or 90° FOV options except for Size X. The distance prior to runway threshold where the last change in FOV was made was analyzed and no significant differences by display size condition were found (p > .05). Changes in FOV were not made near the runway and, averaging across pilot selectable trials, the mean distance for the final FOV change was 3.7 nautical miles prior to runway threshold crossing. It is interesting to note the decrease in larger FOV selections for the smaller display sizes, which matches subjective comments that indicated that information in the size "A" display "just gets too small" with larger FOV selections.

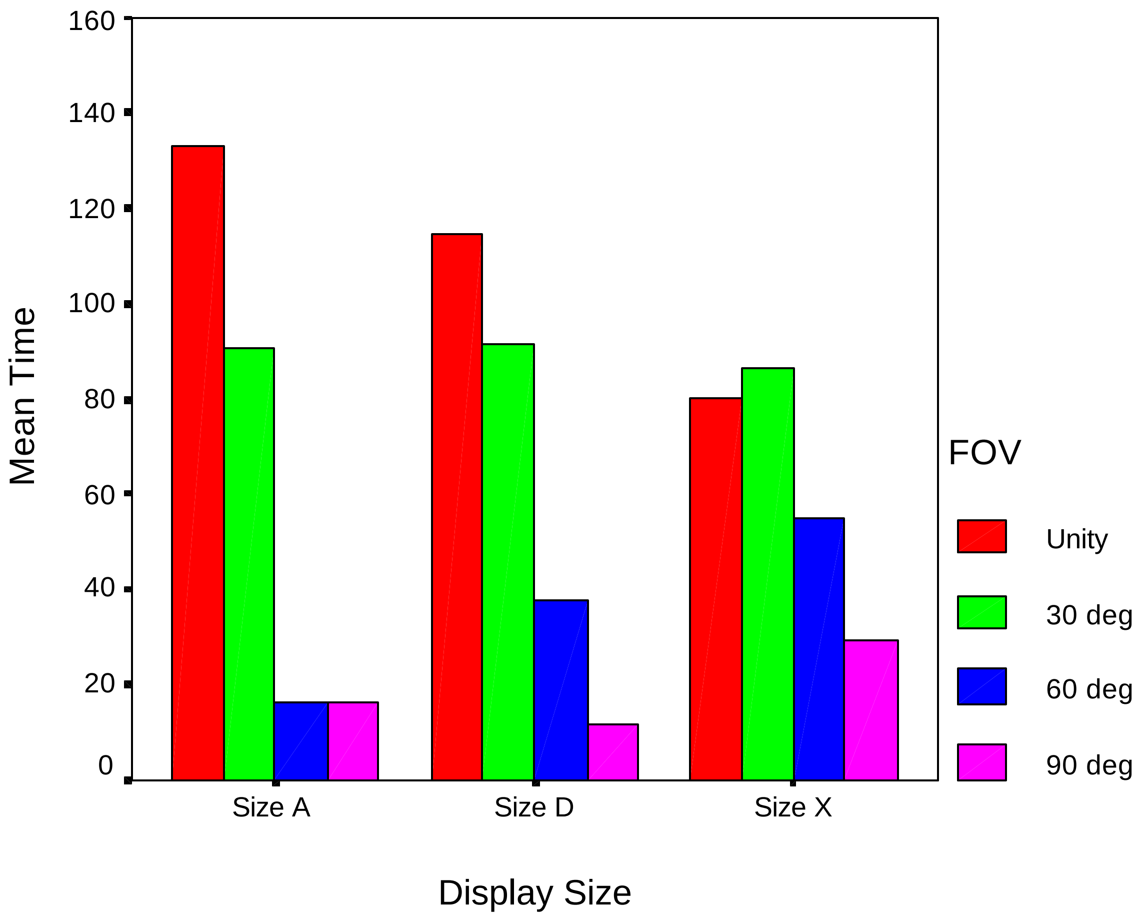

Figure 5. Mean seconds of FOV selection during pilot selectable trials.

The distribution of selected FOVs reflects pilot responses to a question asking which two FOV options would they chose if SVS was available in their cockpit. Pilots tended to chose Unity (86%) and 30° (57%) FOV. Some pilots did select the 60° (28%) and 90° (28%) options because of a requirement for larger FOVs with the smaller Size "A" display concept (totals to 200% due to choice of two FOVs). Although 86% of pilots (7/8) chose unity, it was often the second choice. Based on mean ratings for order of preference, pilots preferred to have 30°, then unity, then 60°, and finally 90°. Pilots were consistent in pilot preferences across display sizes ($p > .05$).

Situation Awareness

A SA-SWORD (Situation Awareness - Subjective Workload Dominance; Vidulich & Hughes, 1991) was administered after each block run of a display size to assess situation awareness preferences for field-of-view (FOV) for that size display (A, D, X). Pilots were asked to base ratings on their operational experience and the definition of situation awareness given 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" (Regal, Rogers, & Boucek, 1988). Separate analyses were conducted for each display size, and ANOVAs revealed significant effects for Size A, ($F(3,18) = 131.430$, $p < .0001$); Size D, ($F(3,18) = 483.885$, $p < .0001$); and Size X, ($F(3,18) = 37.932$, $p < .001$). A Student-Newman-Kuels (SNK) post-hoc analysis revealed 4 unique pairwise groupings: 30 > unity > 60 > 90 for Size A. For Size D and X, there were 3 unique pairwise groupings: unity > 30 > 60 = 90.

EXPERIMENT TWO

The objectives of Experiment Two were similar to Experiment One with a few exceptions. The most notable difference was that the experiment was a flight test using the

NASA B-757-200 research airplane. Three different HDD configurations (Size A, D, & X) were evaluated during this flight test, but evaluation pilots also evaluated a SVS HUD concept. For both the HDD and HUD concepts, an evaluation of generic and photo-realistic terrain-texturing methods was also performed. The hypotheses for Experiment Two were the following: (1) All display sizes would provide adequate information for the successful conduct of the complex, nighttime approaches to DFW; (2) there is an optimal or preferred field-of-view for each HDD display size; (3) the HUD would be shown to be a viable retrofit candidate; and (4) no performance differences would be found between generic and photo-realistic texture, but participants have higher preference ratings for the photo-realistic presentation.

METHOD

Participants

Six Air Transport Rated (ATP) commercial airline pilots were the participants for Experiment Two. All participants were current commercial B757 pilots who had experience with HUDs, mostly through military background. These participants were provided with familiarization training at the NASA Langley Research Center (LaRC) and, during the training, participated in Experiment One.

HDD Research Display

HDD SVS concepts were presented on the SVS research display (SVS-RD), which was 14.5 in. wide by 10.9 in. tall producing a viewing area of 158.1 in-sq. The display was operated in XGA mode with vertical and horizontal test resolution of 71 pixels per inch (ppi). The SVS-RD has a brightness of 900 nits and was removable in-flight to address safety-of-flight concerns.

HUD Research Display

The HUD employed for Experiment Two was a Flight Dynamics Model 2300R HGS. The field of view of the HUD was 30 degrees horizontal by 24 degrees vertical with a 4-degree look-down bias. The resulting effective FOV was 16 degrees below and 8 degrees above the reference waterline. Symbology and terrain information was provided to the HUD via a raster to stroke converter unit. Maximum brightness of the HUD image was greater than 1000 ft-Lamberts and brightness and contrast of both the HUD symbology and synthetic terrain was adjustable by the evaluation pilot. The evaluation pilot could view the HUD image within an eye-box approximately 5” wide, 2.8” tall and 6” deep.

Display Symbology

Common symbology included a 5 degree increment pitch scale with reference waterline, roll scale with small tickmarks every 5 degrees and large tickmarks every 10 degrees, bank indicator with sideslip wedge and digital magnetic heading, wind speed and relative direction, heading scale with labels every ten degrees and tickmarks every 5 degrees, flight path marker with acceleration along the flight path indicator, reference airspeed error, and sideslip flag. Localizer and glideslope course deviation indicators were also included. In addition, a magenta runway outline box and extended runway centerline were included for the initial runway. The ND included the defined path and provided primary lateral navigation guidance, prior to final approach. For the Size-D and Size-X SVS PFDs, airspeed, altitude, and vertical speed were presented in a nominal tape format with airspeed bugs and limit speeds present. Traditional round-dials were employed for airspeed, altitude and vertical speed for the Size-A display. Airspeed and altitude were displayed digitally for the SVS-HUD concepts. Airspeed, altitude and vertical speed were colored white on the HDDs and airspeed limits were shown in standard red and white “barber pole” format.

A minimal tunnel-in-the-sky was incorporated into the symbology set for evaluation purposes. Intended to provide a 3-dimensional representation of the intended flight path, the tunnel-in-the-sky was presented to the evaluation pilots by magenta “crows feet” triads located at all four corners of the defined path. The dimensions of the minimal tunnel in the sky were based on the navigation performance of standard Instrument Landing Systems (ILS) and were 1 dot wide, limited to a maximum width of 600 ft, and 2 dots high, limited to a maximum height of 350 feet and a minimum height of 50 ft. Pilots were instructed to observe the tunnel-in-the-sky but to not use it as a guidance system nor perform closed-loop high-gain maneuvering with respect to it. The primary purpose of the tunnel-in-the-sky was to define where the 3-dimensional path was. Research has demonstrated the advantages of tunnel displays for maintaining lateral and vertical path awareness (e.g., Haskell & Wickens, 1993; Snow, Reising, Liggett, & Barry, 1999; Williams, 2002) and that the inclusion of synthetic terrain may significantly improve situation awareness potential of tunnel displays (Snow & French, 2001; Snow et al., 1999; Williams, 2002).

Terrain Database

The DFW terrain database was generated using 1-arcsec (98 ft) post-spacing digital elevation model (DEM) data and covered an area of approximately 100nm by 100nm centered about DFW airport with an elevation accuracy of approximately 3.2 ft. One terrain texturing option, generically textured terrain, used different color shades to represent terrain on the HDD. The HUD concept used the green RGB channel and varied color shades, rather than different colors, to reflect changes in elevation. The second terrain texturing option was photo-realistic, and used ortho-rectified aerial photographs to texture the terrain to generate a highly realistic looking presentation (hence, “photo-realistic”) with 3 meter / pixel resolution. High-resolution, photo texturing was applied to an area 6 nm by 15 nm center aligned with runways 17C/35C. The photo-realistic HUD concept used the RGB file format and masked out the red and blue channels coming from the photo-realistic database and converted the image back to ECW format.

Flight Task Scenarios

Four pilot's tasks were employed for the DFW flight test. Two of the tasks, referred to as the straight in approaches, required the pilot to perform a nominal downwind, baseleg, and straight-in final approach to runways 17C/35C. The other two tasks, referred to as the runway change or "side step maneuver", required the pilot to fly the same downwind path and initial baseleg as for the straight-in maneuvers. However, the baseleg was shortened to establish an initial final approach to either runway 17L or 35R, depending on prevailing traffic flow at DFW. Once the aircraft was 5nm from the initial runway, the pilots were instructed by the DFW tower to execute the side step maneuver to runway 17C/35C.

Figure 6 depicts the south-flow straight-in and side-step maneuver tasks for approaches to runway 17L / 17C. All four tasks required the evaluation pilot to assume control of the aircraft abeam the mid-field position of runway 17C/35C at 5,000ft on downwind leg and maintain nominal approach airspeed. Just downwind of the mid-field position, the pilot executed a descent to an altitude of 3,500 ft following tunnel symbology. The pilot was instructed to maintain 3,500 ft on baseleg and to execute the turn to final following the path guidance from the electronic horizontal situation indicator (EHSI) and tunnel symbology. Flap settings were adjusted based on nominal B-757 operations. Pilots were instructed to use the autothrottles to maintain airspeed.

For the runway change tasks, the pilot was instructed to change to runway 17C/35C at 5nm from the initial runway threshold. Pilots were required to maneuver the aircraft with reference to the SVS display concept being evaluated, which also captured and presented localizer and glideslope information for the target runway.

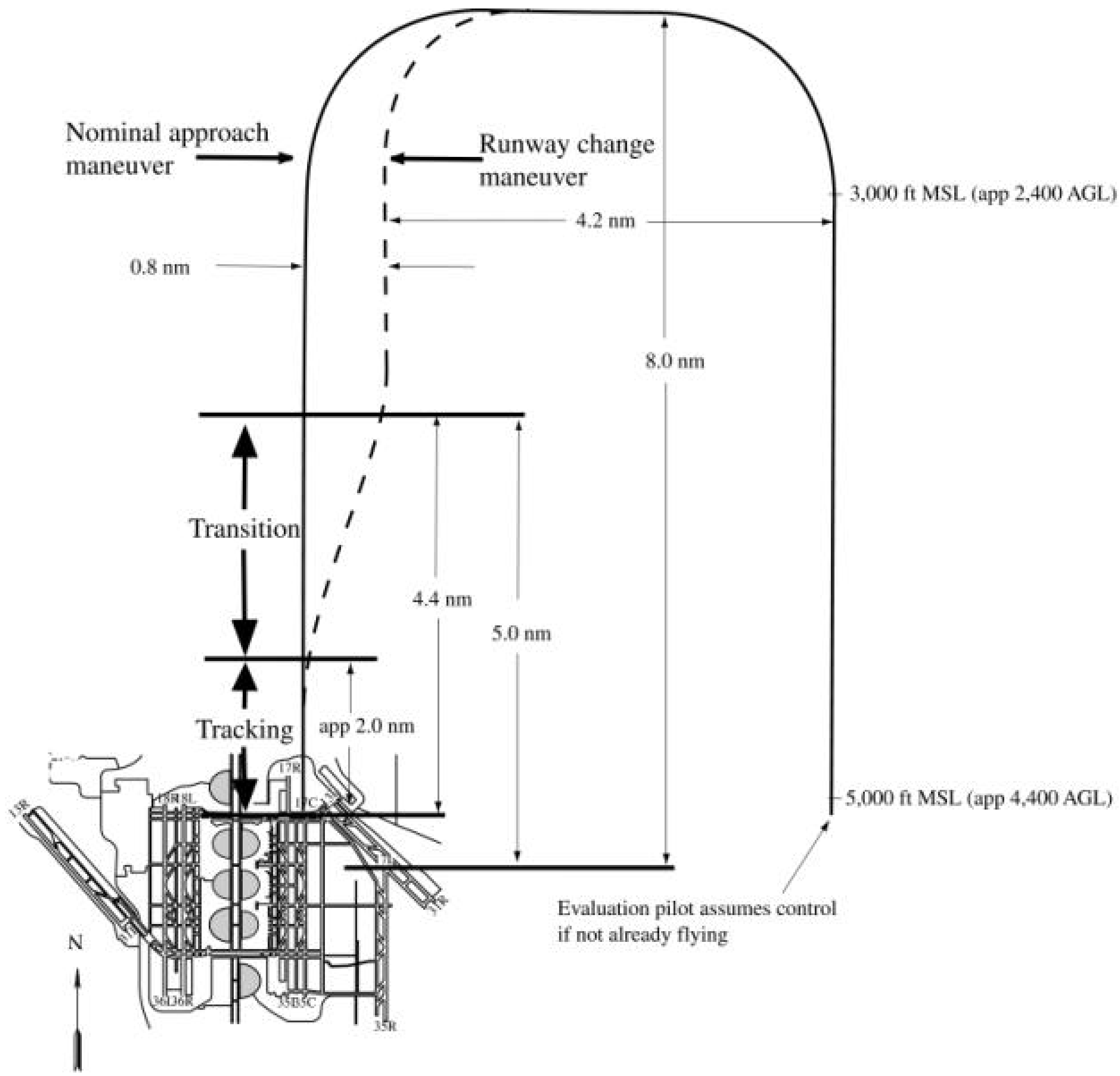

Figure 6. Evaluation Tasks for South-Flow DFW Operations

Data Collection and Recording

Qualitative Measures. Qualitative pilot ratings and comments were collected during the flight and in post-flight debriefings. Pilots were also encouraged to provide a running commentary during the flight and these were recorded on the audio channel for later analysis.

Responses to in-flight questions were collected once control of the aircraft was handed over to the safety pilot.

Quantitative Measures. The quantitative dependent variables were root-mean-square (RMS) values for pilot wheel, column, and rudder pedal control inputs for workload; lateral and vertical path performance during the side-step maneuver tracking phase; maximum heading change; minimum, maximum, and mean FOV settings; and minification factor (MF). MF represents the relative FOV difference between selected FOV and unity FOV for a given display size (e.g., 30° Size A = 30°/11.5° = 2.6 MF). Pilot performance data were recorded at a rate of 10Hz and was collected on final approach 5 nm from the runway and terminated on go-around.

Data was divided into transition and tracking segments once established on final approximately 5 nm from runway threshold. The transition segment began at 5nm from the initial runway threshold and ended when the pilot had re-established the aircraft onto the target final approach path. Root-Mean-Square (RMS) of bank angle, column deviation, and wheel deviation and maximum heading change were the primary dependent variables of interest for the transition phase. The tracking phase began when the pilot had re-established the aircraft onto the target final approach path and ended at 200 ft AGL when the pilot initiated a go-around (Figure 6). Lateral and vertical path RMS error was collected and analyzed to measure pilot performance during this phase. The criteria to establish the end of the transition segment and the initiation of the tracking segment were +/-1 dot of localizer and glideslope, +/- 5 degrees in track error and +/-3 degree in flight path angle error.

Experimental Design and Procedure

A 4 display type (HUD, A, X, D) X 2 texture type (photo, generic) X 2 runway (17C/35C) repeated measures, randomized experimental design was used. Runway was not randomized because runway was determined by the prevailing traffic pattern although an equal number of runs were conducted to both ends of the runway. Experiment Two was part of a larger flight at DFW examining a number of aviation safety technologies that will be part of the total synthetic vision system, such as runway incursion prevention technologies. No baseline data runs were flown because of the operational, cost, and time constraints associated with combining nighttime flight tests at a busy airport and flight test objectives. The flight test took place over a two-week period during the late evening and early morning hours when operations at DFW were fewer.

All pilots were fully briefed regarding the research objectives of the flight test, evaluation maneuvers, and data collection methods prior to each flight. Two test runs were completed with each pilot to familiarize them with the aircraft and SVS display concepts. All pilots also participated in extensive training at the NASA Langley Research Center simulation facilities.

Control to the evaluation pilot once the aircraft was established climbing in a low-workload condition. The safety pilot interacted with ATC and performed pilot-not-flying functions (e.g., ATC; flap settings). Once established at 5000 ft MSL on the downwind leg, the experimental trial began and was terminated at 200 ft AGL above the runway when the evaluation pilot initiated the go-around. Once go-around checklists were completed and the aircraft was established climbing in a low-workload condition, control was transferred to the safety pilot and in-flight questionnaires were administered. After the research flight was completed, pilots participated in a semi-structured interview and debriefing.

RESULTS

Transition Phase Performance

No significant differences were found for transition or tracking phase performance for the dependent variables of RMS maximum heading error, bank angle, and column and wheel deviation ($p > .05$). An ANOVA reported comparable pilot performance for these measures regardless of display size, texture, and FOV. No differences were also found for these dependent variables between the transition phase and tracking phase ($p > .05$).

Tracking Phase Performance

Lateral Performance. An ANOVA analysis on the lateral tracking error during the tracking segment revealed a significant main effect for display size, $F(3,38) = 3.10$, $p < .05$. A Student-Newman-Keuls (SNK) post-hoc test revealed that mean lateral path error (Figure 7) was significantly larger for Size X (112 ft.) compared to HUD (49 ft), Size A (92 ft.), or Size D (59 ft.), which were not statistically different from each other. No significant differences were found for terrain texture, ($F(1, 38) = 0.790$, $p > .05$), or display*interaction, ($F(3,38) = 1.440$, $p > .05$). Average RMS lateral error was 76 feet for generic and 87 feet for photo-realistic terrain texture.

Vertical Performance. An ANOVA reported no significant difference for RMS vertical error across display concepts, ($F(3, 38) = 0.241$, $p > .05$), terrain texture, ($F(1, 38) = 0.378$, $p > .05$), display*interaction, ($F(3,38) = 0.127$, $p > .05$). The average RMS error was 26 feet and ranged from 33 feet (Size A, photo) to 22 ft (HUD, photo). For terrain texture, average RMS vertical error was 25 feet for generic and 28 feet for photo-realistic terrain texture. Mean vertical error across display concepts are shown in Figure 7.

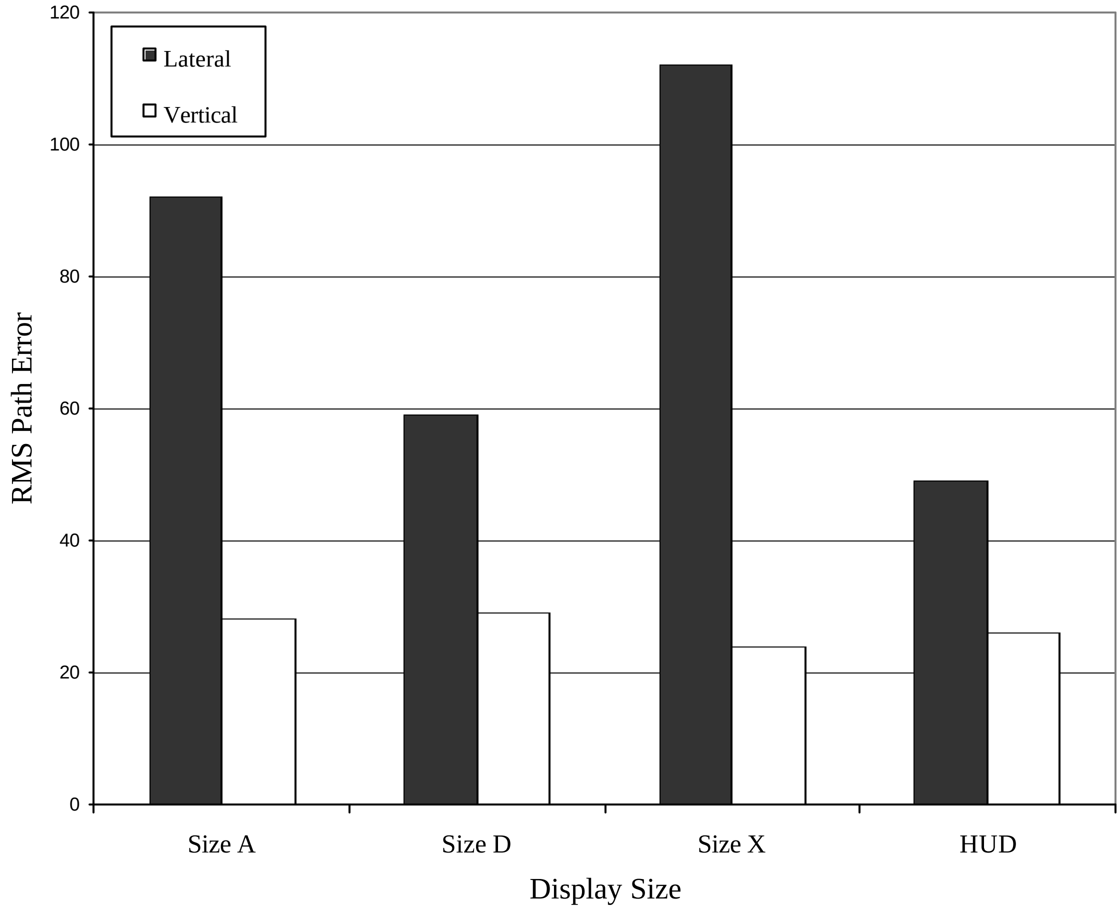

Figure 7. Lateral and Vertical Path Error for Tracking Phase

Field of View Preferences

An ANOVA found a significant main effect for MF as a function of display size for both the transition, ($F(2, 34) = 8.614$, $p < .01$), and tracking phases, ($F(2,34) = 8.146$, $p < .01$). SNK post-hoc tests showed that pilots tended to chose a higher MF for Size A (3.63) than both Size D (2.44) and X (1.78) displays during the transition phase. For the tracking phase, pilots chose significantly higher MF for both Size A (2.39) and Size D (1.88) than for Size X (1.26). Overall, pilots selected the same FOV independent of HDD display size or terrain texture with a larger FOV during the transition phase and a smaller FOV for the tracking phase of the maneuver. Therefore, as range to touchdown decreased, the MF for the larger display sizes moved toward unity (i.e., no minification). Pilots, however, tended to select a higher minification scale factor as display size decreased because the smaller display size (i.e., Size A) was reported to be inadequate at unity FOV.

Pilot comments regarding FOV suggest that pilot selectable FOV would be the preferred option but that the set of FOV options should be limited to a few FOV choices to improve the ability to move quickly between the FOV modes. All pilots commented that a single FOV would not be the best solution and would impose undue restrictions on display usage. Pilots recommended that multiple FOV options based on phase-of-flight should be considered and all but one recommended an exclusively manual control technique for FOV selection. The single pilot suggested instead that an automatic function be implemented that changed FOV through phase-of-flight with a manual override capability.

Overall, a higher FOV (i.e., 50°) was recommended during early stages of an approach and smaller FOVs (e.g., 30°) for the final approach segment because of a perceived need for a smaller MF and better view of the airport environment. Pilots were asked to select two FOVs that they would select and the preferred choice was 30° and 50° FOVs, which aligns with the results from Experiment One (i.e., 60°) and may reflect pilot familiarity since the typical PFD provides approximately 50° (+/- 25°) of pitch attitude.

Workload

Despite the performance data that suggests that pilots performed comparable across the HDD display concepts, pilot ratings indicated the “ease of performing the approach” was significantly harder with Size A, ($F(2, 15) = 9.39$, $p < .01$). The 0 to 10 point scale went from “very hard” (1), to “neutral” (5), to “very easy” (10). On average, pilots gave a “neutral” (6.0) rating to Size A, a “somewhat easy” (7.5) rating to Size D, and “very easy” (9.5) rating to Size

D. No significant differences were found for workload comparisons between generic and photo-realistic texture, ($F(1, 20) = 3.22$, $p > .05$), and comparisons between HDD and HUD, ($F(1,20) = 0.36$, $p > .05$).

Situation Awareness

An ANOVA reported no significant differences for in-flight questions regarding situation awareness for HDD concepts, ($F(2,15) = 1.24$, $p > .05$) and "ease of predicting flight path", ($F(2,15) = 1.94$, $p > .05$). Overall, as HDD size increased, maintaining situation awareness and predicting flight path became easier, but was not significant. As expected, all pilots expressed the "larger is better" preference and rated Size X "somewhat easy" to maintain situation awareness and predicting flight path (Figure 8). No significant differences were reported between HDD and HUD, ($F(1,20) = 2.32$, $p > .05$).

A review of pilot comments indicated that only one pilot reported that the Size A display concept could not achieve an effective presentation of the synthetic terrain to significantly enhance SA compared to an EADI. All pilots, however, noted that large MFs (e.g., Size A at 60° FOV) produced an illusion that objects in the SVS scene were much farther away and that perceived altitudes were lower than actual. Larger MFs (i.e., > 4.8) also created significant runway viewing problems because objects subtended at angles on the display smaller than in the real world.

Another question asked of pilots was their preferences for photo-realistic or generic texture (Figure 8). Despite pilot performance results that showed no differences between the two texture methods, pilot ratings indicated that it was easier to maintain situation awareness with photo-realistic than generic texturing although it was not found to be significant, ($F(1, 20) = 2.54$, $p > .05$). These pilots were very familiar with the Dallas-Fort Worth area and noted the depiction of shopping malls, roads, and population areas were very helpful in maintaining situation awareness. Other comments included that the photo-realistic texture helped determine rate of closure with objects on the ground and supplied cueing for runway centerline alignment. Generic texturing, however, was thought to be better for non-terminal operations because the level of detail found in photo-realism would not be necessary and that cultural features stood out better against the generic terrain.

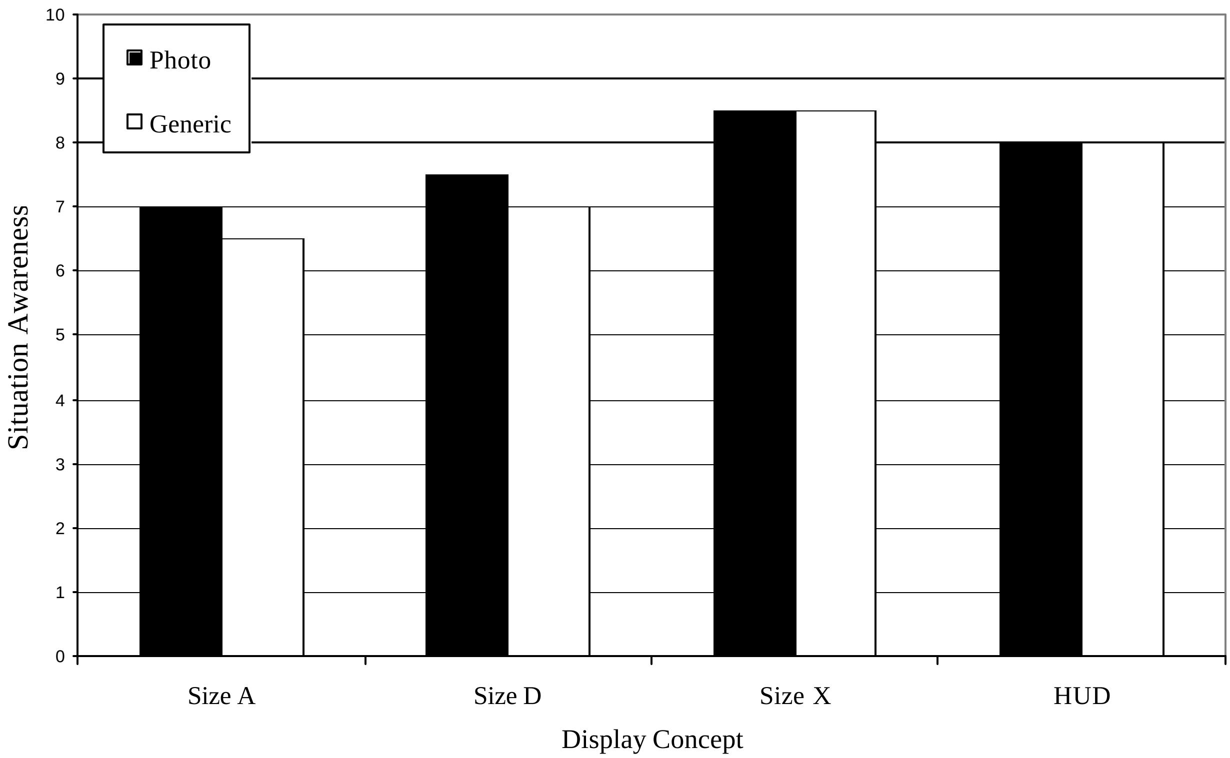

Figure 8. Pilot Ratings of Situation Awareness for Display Size and Texture

DISCUSSION

Synthetic vision has the potential to provide significant safety and economic benefits particularly if the system is effective as both a retrofit and forward fit solution to visibility restricted problems. Previous research has shown the efficacy of synthetic vision on large-size displays and, therefore, synthetic vision is expected to be capable of effective presentation as glass displays become larger with each generation of aircraft. Because the majority of the current commercial aircraft fleet has electromechanical instruments or limited glass real estate, however, any significant benefits would require answering the retrofit question of whether effective presentation of synthetic vision can also be made in current aircraft cockpits.

Display Size. The retrofit question concerns our hypothesis that the HUD and smaller SVS display sizes would provide adequate information to enable the pilot to make safe and precise approaches. The results of the experiments confirmed the hypothesis and suggest that SVS is viable as a retrofit candidate. Experiment One showed no differences in path performance between display sizes or FOV, and Experiment Two showed differences only for the HUD concept for lateral path performance.

One explanation for the superiority of the HUD is that the most frequently selected FOV was 30° for all the HDD concepts, which represents a MF of 2.67 for Size A, 1.82 for Size D, 1.31 for Size X, but only 1 for HUD (unity FOV is 30°). The pilots would use the flight path marker to center on the runway in the synthetic scene to shoot the approach. However, as the MF was increased, greater path error was required to displace the flight path marker to be noticeable to the pilot. Despite this, the difference between the worse and best lateral performance was approximately 61 feet from the runway threshold during final approach. Considering that there were also no differences found in vertical path performance, the result can be interpreted as being not practically significant.

Field-of-View. Another hypothesis of the experiments was that there was an optimal or preferred FOV setting for synthetic vision displays, and this was confirmed by the results of the experiments. The SA-SWORD and pilot preference data from Experiment One showed that pilots preferred 30 degrees and unity, and pilots in both experiments used these FOV options between 90% (Size A) and 70% (Size X) of the approach. Overall, the option of 90 degrees was found unusable for both Size A and Size D because of the high MF (8.0 and 5.48, respectively) while used only 12% of the time with Size X display. Pilot comments noted that 90 degrees was difficult to use on approach because of the precision required but may be optimal for the enroute phase-of-flight where the increased visual scene would help with situation awareness.

Terrain Texture. The final hypothesis concerned the use of photo-realistic or generic terrain texture; that pilots would prefer the photo-realistic terrain presentation but would reveal no differences in pilot performance. The results of Experiment Two confirm this hypothesis. No significant main effects or interactions were found for pilot performance as a function of terrain texture. The mean difference between generic and photo-realistic was 15.5 feet lateral and 2.6 feet vertical during the tracking phase. All pilots, however, commented and gave higher subjective ratings to the photo-realistic concept, and this represents a common dissociation in display evaluation where participants prefer a concept to another but show no differences in performance.

PRACTICAL APPLICATION

Taken together, the conclusions that can be drawn from these experiments are that synthetic vision can be implemented on retrofit sizes and, therefore, can successfully be introduced into the current aircraft fleet. To be effective, synthetic vision presented on small display sizes would have to be minified and our results indicate that the MF should not exceed 4.5 for optimal performance although more research is needed to confirm such a conclusion.

Because no performance differences were found between photo-realistic and generic terrain texture methods, the generic terrain presentation may represent an effective and lower cost option for synthetic vision displays although photo-realistic does have properties that can increase the margin for safety and operations. Several pilots did comment that photo-realistic texture would be helpful for situation awareness during climb, enroute, and descent phases of flight. A recent flight test in the terrain-challenged area of Eagle-Vail, CO, however, found no performance or situation awareness penalties for the generic texture concept although pilots reported an overall preference for the photo-realistic presentation (Bailey, Parrish, Arthur, & Norman, 2002; Prinzel et al., 2002). The NASA Aviation Safety Program is currently evaluating a synthetic vision concept that combines generic and photo-realistic terrain texture to take advantage of the benefits both methods offer for situation awareness.

FUTURE DIRECTIONS

> "Solving a problem simply means representing it so as to make the solution transparent"
> Simon (1981).

The problem of reduced visibility challenges aviation goals to reduce the accident rate and improve operational capacity (FAA, 2001; NASA, 2001). The approach of synthetic vision is to solve the problem through the presentation of how the outside world would look to the pilot if vision were not restricted; it will make the solution literally "transparent" to the flight crew. Terrain Awareness Warning Systems are steps in the right direction and TAWS has significantly improved safety, but the solution treats the symptoms and not the cause (Moroze & Snow, 1999). Synthetic vision instead provides for proactive prevention of visibility-induced accidents while also increasing the capability to make approaches in weather conditions and airports not currently legal for low-visibility operations. Although our research did not specifically address these aviation safety and operational benefits, subsequent studies (e.g., Prinzel et. al., 2002) have substantiated the performance and situation awareness enhancements of synthetic vision even while making complex, circling approaches under conditions that beyond current cockpit technology capabilities. Furthermore, the concept described here represents only the database and display concepts and not the total synthetic vision system, which will include synthetic vision navigation displays; runway incursion prevention technology; database integrity monitoring equipment; enhanced vision sensors; taxi navigation displays; and advanced communication, navigation, and surveillance technologies (McCann et al., 1998; Williams et. al., 2001; Timmerman, 2001; Uijt de Haag et al., 2002; Young & Jones, 2001). These technologies represent a comprehensive solution that will be evaluated in near-term NASA simulation and flight research. Together, synthetic vision may considerably help meet national aeronautic goals to "reduce the fatal accident rate by a factor of 5" and to "double the capacity of the aviation system" both with 10 years (NASA, 2001).

REFERENCES

AOPA Air Safety Foundation (2001). 2001 Nall report: General aviation accident trends and factors for 2000. Frederick, MD: Aircraft Owners and Pilots Association

Bailey, R.E., Parrish, R.V, Arthur, J.J., & Norman, R.M. (2002). Flight test evaluation of tactical synthetic vision display concepts in a terrain-challenged operating environment. In J.G. Verly (Ed.), Enhanced and Synthetic Vision 2002 (pp. 178-189). Bellingham, Washington: International Society for Optical Engineering (SPIE).

Boeing (1996). Statistical summary of commercial jet aircraft accidents, Worldwide Operations, 1959-1995. Seattle, WA: Airplane Safety Engineering, Boeing Commercial Airplane Group.

Enders, J.H., Dodd, R., Tarrel, R., Khatwa, R., Roelen, A.L.C., & Karwal, A.K. (1996). Airport safety: A study of accidents and available approach-and-landing aids. Flight Safety Digest, 1996(3), 1-36.

Federal Aviation Administration (2001). FAA Strategic Plan. Washington, D.C.: FAA.

Glabb, L.J., & Takalu, M.A. (2002). Preliminary effect of synthetic vision systems displays to reduce low-visibility loss of control and controlled flight into terrain accidents. SAE Technical Paper 2002-01-1550. Warrendale, PA: Society of Automotive Engineers.

Haskell, I.D., & Wickens, C.D. (1993). Two- and three-dimensional displays for aviation: A theoretical and empirical comparison. International Journal of Aviation Psychology, 3, 87-109.

Helmetag, A., Kaufhold, R, Lenhart, P.M., & Purpus, M. (1997). Analysis, design, and evaluation of a 3D flight guidance display. Institute of Flight Mechanics and Control.

Khatwa, R., & Roelen, A. (1998). An analysis of controlled-flight-into-terrain (CFIT) accidents of commercial operators, 1988 through 1994. Flight Safety Digest, November 1998 – February 1999, 166-212.

McCann, R.S., Foyle, D. C., Hooey, B.L., Andre, A.D., Parke, B., & Kanki, B. (1998). An evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) system in high-fidelity simulation. SAE Technical Paper 985541. Warrendale, PA: Society of Automotive Engineers.

McGreevy, M.W., & Ellis, S.R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. Human Factors, 28(4), 439-456.

Moroze, M.L., & Snow, M.P. (1999). Causes and remedies of controlled flight into terrain (CFIT) in military and civil aviation. Proceedings of the 10th International Symposium on Aviation Psychology. Columbus, OH: Ohio State University.

National Aeronautics and Space Administration (2001). Aerospace Technology Enterprise. Washington, D.C.: NASA.

Prinzel, L.J., Kramer, L.J., Comstock, J.R., Bailey, R.E., Hughes, M.F., & Parrish, R.V. (2002). NASA synthetic vision EGE flight test. Proceedings of the Annual Human Factors and Ergonomics Meeting, 46, 135-139.

Regal, D.M., Rogers, W.H., & Boucek, G.P. (1988). Situational awareness in the commercial flight deck: Definition, measurement, and enhancement. SAE Technical Paper 881508. Warrendale, PA: Society of Automotive Engineers.

Roscoe, S. N. (1948). The effects of eliminating binocular and peripheral monocular visual cues upon airplane pilot performance in landing. Journal of Applied Psychology, 32, 649-662.

Simon, H. A. (1981). The Sciences of the Artificial. Cambridge, Mass: Massachusetts Institute of Technology (MIT) press.

Snow, M.P., & French, G.A. (2001). Human factors in head-up synthetic vision display. SAE Technical Paper 2001-01-2652. Warrendale, PA: Society of Automotive Engineers.

Snow, M. P., and Reising, J. M. (1999). Effect of pathway-in-the-sky and synthetic terrain imagery on situation awareness in a simulated low-level ingress scenario. Proceedings of the 4th Annual Symposium on Situation Awareness in the Tactical Air Environment (pp. 198-207). Patuxent River, MD: NAWCAD.

Stark, J., Comstock, J.R., Prinzel, L.J., Burdette, D, & Scerbo, M.W. (2001). A preliminary examination of situation awareness and pilot performance in a synthetic vision environment. Proceedings of the Human Factors & Ergonomics Society, 45, 40-43.

Theunissen, E. (1993). A primary flight display for four-dimensional guidance and navigation – Influence of tunnel size and level of additional information on pilot performance and control behavior. Proccedings of the AIAA Flight Simulation Technologies Conference (pp. 140-146). Scottsdale, AZ: AIAA.

Theunissen, E. (1997). Integrated design of a man-machine interface for 4-D navigation. Netherlands: Delft University Press.

Timmerman, J. (2001). Runway Incursion Prevention System – ADS-B and DGPS Data Link Analysis, Dallas – Ft. Worth International Airport. NASA CR-2001-211242. Hampton, VA: NASA Langley Research Center.

Uijt de Haag, M., Young, S., Sayre, J., Campbell, J., & Vadlamani, A. (2002). DEM integrity monitor equipment (DIME) flight test results. In J.G. Verly (Ed.), Enhanced and Synthetic Vision 2002 (pp. 72-83). Bellingham, Washington: International Society for Optical Engineering (SPIE).

Vidulich, M.A., & Hughes, E.R. (1991). Testing a subjective metric of situation awareness. Proceedings of the Human Factors & Ergonomics Society, 35, 1307-1311.

Wickens, C.D., & Andre, A.D. (1990). Proximity compatibility principle and information display: effects of color, space, and objectness on information integration. Human Factors, 32, 61-77.

Wiener, E. L. (1977). Controlled flight into terrain accidents: System-induced errors. Human Factors, 19, 171-181.

Williams, D., Waller, M., Koelling, J., Burdette, D., Doyle, T., Capron, W., Barry, J., & Gifford, R. (2001). Concept of operations for commercial and business aircraft synthetic vision systems. NASA Langley Research Center: NASA Technical Memorandum TM-2001-211058.
Uenking &Hughes

Young, S., & Jones, D.R. (2001). Runway incursion prevention: A technology solution. Proceedings of the Flight Safety Foundation Air Safety Seminar, 54, 1-18.