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Abbreviations

3-D	Three dimensional
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above ground level, ft.
AHRS	Attitude and Heading Reference System
ANOVA	Analysis of variance
BSBG	Blue Sky Brown Ground, baseline primary flight display
BSBGV	BSBG used in simulated visual meteorological conditions
CBT	Connected Boxes Tunnel with guidance square
CCFN	Constant Color Fishnet terrain portrayal
CDI	Course Deviation Indicator
CFIT	Controlled flight into terrain
CFT	Crows Feet Tunnel
CFTGP	Crows Feet Tunnel with Ghost Plane
DEM	Digital Elevation Model
EBG	Elevation Based Generic terrain portrayal
EP	Evaluation Pilot
FAA	Federal Aviation Administration
FPM	Flight Path Marker
FOV	Field of View
ft	Length Scale in Feet
FTE	Flight Technical Error
GA	General Aviation
GAWS	General Aviation Work Station at NASA Langley Research Center
GP	Ghost Plane
GPS	Global Positioning System
GSC	Guidance Symbology Concept
HDD	Head-Down Display
H-IFR	High Time Evaluation Pilots with IFR Rating
IAS	Indicated Air Speed, nautical miles per hour

IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
kt	Nautical miles per hour
LaRC	Langley Research Center
LCD	Liquid Crystal Display
LPD	Lateral Path Deviation, ft
LOC	Loss of Control
LVLOC	Low Visibility Loss of Control
Max	Maximum value
MF	Minification Factor
Min	Minimum value
MSL	Mean Sea Level, ft
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NGNT	Primary Flight Display with No Guidance Cue and No Tunnel
NM	Nautical miles
OTW	Out of the Window
p	Statistical level of significance
PC	Personal Computer
PCATD	PC-based Aviation Training Device
PFD	Primary Flight Display
PPL	Private Pilot License
PR	Photo Realistic terrain portrayal
PRFD	Pitch/Roll Flight Director
PTS	FAA Practical Test Standard
RMS	Root Mean Square
s1laerms	Mean RMS of Lateral Path Deviation for Segment 1
s1verms	Mean RMS of Vertical Path Deviation for Segment 1
s2laerms	Mean RMS of Lateral Path Deviation for Segment 2
s2verms	Mean RMS of Vertical Path Deviation for Segment 2
s3laerms	Mean RMS of Lateral Path Deviation for Segment 3
s3verms	Mean RMS of Vertical Path Deviation for Segment 3

SA	Situation Awareness
SART	Computed SA Rating
SD	Spatial Disorientation
SD-HDD	Symbolgy Development for Head-Down Displays
SPSS	Trade Mark for the SPSS, Inc.
Std	Standard deviation
SVS	Synthetic Vision Systems
SXGA	Super XVGA (1280x1024 resolution)
TENDS	Time to End of Scenario (rare event) in seconds
TLX	Task Load Index
TPC	Terrain Portrayal Concept
TP-HDD	Terrain Portrayals for Head-Down Displays
TRECS	Time to Recognition of problem (rare event) in Seconds
UBT	Unconnected Boxes Tunnel
VFR	Visual Flight Rules
VGA	Video Graphics Array
VMC	Visual Meteorological Conditions
VPD	Vertical Path Deviation, ft
VSI	Vertical Speed Indicator
V-Speeds	Aircraft Reference Airspeeds
WP	Waypoint
XVGA	Extended Video Graphics Array (1024x786 resolution)

Abstract

In support of the NASA Aviation Safety and Security Program's Synthetic Vision Systems Project, a series of piloted simulations were conducted to explore and quantify the relationship between candidate Terrain Portrayal Concepts and Guidance/tunnel Symbology Concepts, specific to General Aviation.

This work was the second part of a three-part study related to the Symbology Development for Head-Down Displays test series. The objective of the these experiments were to determine if there were any interactions between terrain portrayal and guidance symbology concepts over a spectrum of these, as well as to confirm that increases in pilot performance due to guidance symbology concepts were preserved with the addition of Synthetic Vision Systems terrain. The focus of this experiment was on an advanced application of this technology to fully exploit its' potential for safe operations during a low altitude en route maneuver in Instrument Metrological Conditions in the central mountains of Alaska (Merrill Pass). These types of operations are not practical with current technology. A total of 18 general aviation pilots, with three levels of pilot experience, evaluated a test matrix of four terrain portrayal concepts and six guidance symbology concepts.

Both quantitative and qualitative measures were recorded and analyzed. Quantitative measures included various pilot/aircraft performance data, flight technical errors and flight control inputs. The qualitative measures included pilot comments and pilot responses to the structured questionnaires such as perceived workload, subjective situation awareness, pilot preferences, and the rare event recognition.

There were statistically significant effects found from guidance symbology concepts and terrain portrayal concepts but no significant interactions between them. The lack of significant interactions between guidance symbology concepts and terrain portrayal concepts might help Synthetic Vision Systems display designers to select terrain portrayal and guidance symbology concepts independent of each other. Lower flight technical errors and increased situation awareness were achieved using Synthetic Vision Systems displays, as compared to the baseline Pitch/Roll Flight Director and Blue Sky Brown Ground combination. The results indicate that all pilots performed very well, mostly within the 75 ft of vertical and lateral limits indicated by one dot of the path based course deviation indicators. With the same Synthetic Vision Systems training provided to all three pilot groups, low time pilots (with no Instrument Flight Rules rating) performed as well as pilots with instrument flight rules rating during this low altitude en-route scenario in simulated instrument meteorological conditions with Synthetic Vision Systems displays. Overall, those guidance symbology concepts that have both path based guidance cue and tunnel display performed better than the other guidance concepts.

Introduction

Limited visibility has been the single most critical factor affecting both the safety and capacity of worldwide aviation operations [1]. A goal of the Synthetic Vision Systems (SVS) Project of the NASA Aviation Safety Program is to eliminate poor visibility as a causal factor in aircraft accidents as well as enhance operational capabilities through application of SVS technology. SVS displays can enhance pilot's Situation Awareness (SA) [1-8] and have the potential to reduce the occurrence of Controlled Flight into Terrain (CFIT) accidents. In addition, SVS displays may reduce or eliminate pilots' Spatial Disorientation (SD), a primary cause of Low Visibility Loss of Control (LVLOC) accidents.

With the integration of Global Positioning Systems (GPS), advanced solid state Attitude and Heading Reference Systems (AHRS), and the imagery derived from terrain, obstacle, and airport databases, into Primary Flight Displays (PFD), SVS displays provide pilots with clear, day time view of the outside world, regardless of weather conditions and time of day [2]. In addition, through the integration of advanced symbology (i.e. highway in the sky, Flight Path Marker, etc.), pilot situation awareness and control performance is drastically improved with no effective increase in pilot workload. Recently, there have been many studies dealing with various components of SVS and the merit of SVS for General Aviation (GA) as a whole [5-6]. However, the proper marriage of SVS terrain and guidance symbology technologies into the PFD has a profound implication to the overall integrated performance of these displays, and it is of utmost interest to the NASA, FAA, and the aircraft/avionics manufacturers as discussed in a recently published FAA advisory circular [12].

As an initial investigation, the GA element of the SVS Project conducted a simulation study that focused on determining the associated benefits of SVS displays towards reducing LVLOC and CFIT accidents for GA pilots [5-6]. The study simulated an inadvertent Instrument Meteorological Condition (IMC) encounter during basic air maneuvers Results of those simulations demonstrated the effectiveness of SVS as compared to conventional GA round dial instrumentation in reducing pilot errors and thus improving pilot's ability to control the aircraft while in IMC.

The next series of experiments were the Terrain Portrayal for Head-Down Displays (TP-HDD) simulation, conducted in the General Aviation Work Station (GAWS) at the NASA Langley Research Center (LaRC), and flight experiments, in the Langley Cessna 206 research aircraft [10-12]. The TP-HDD experiment series was conducted to examine the effect of combinations of Digital Elevation Model (DEM) resolution, terrain texture, and Field of View (FOV) on pilot's SA, workload, and FTE. Variations of display type were: 1) conventional round dials with a pair of Course Deviation Indicators (CDI); 2) baseline PFD (no terrain) with a single simple tunnel; and 3) SVS terrain depicted on the PFD with the same tunnel. SVS Terrain Portrayal Concepts (TPC) were created through combinations of various digital elevation models and terrain texturing concepts with large variations existing with each. The researchers were able to demonstrate the efficacy of SVS displays for a comprehensive spectrum of pilots in both mountainous and flat-maritime environments. Pilots preferred higher-resolution digital elevation models. Based on pilot preference evaluations, 3 arc-sec digital elevation model (DEM) resolution was considered satisfactory, and the 30 arc-sec digital elevation model, while least preferred of the digital elevation models investigated, was still considered a substantial enhancement over standard gauges. In addition, the field of view of the display device can also influence the effect of SVS terrain displays. Among the three field-of- view values (30º, 60º, and 90º) studied, 60º field-of-view was the most useful and values lower than 60º were only possible in calm conditions (during the flight tests in the Cessna 206).

Many studies have compared various Guidance Symbology Concepts (GSC) during development of this technology. Most of these studies were based on a simple blue-sky over brown ground terrain representation, common to conventional primary flight displays [13-16] and, successfully have led to various recommendations and guidelines for the design of advanced cockpit displays [20-21]. Consequently, one area of interest to SVS researchers was the integration of guidance symbology with the background terrain portrayal to minimize the clutter of the SVS displays. While providing much more information to the pilot than a conventional blue-sky over brown-ground primary flight display, the effect of SVS terrain on display clutter was not defined prior to this study reported herein, leading to concerns regarding viable SVS guidance and symbology concepts [17-18].

The general progression of SVS studies have moved from initial higher-altitude operational concepts into low altitude terminal and low en route operations in close proximity to terrain [19-21].

Motivated by the safety concerns of GA operations in mountainous terrain, in particular in central mountains of Alaska [22], a series of experiments was conducted in the General Aviation Work Station that were referred to as the 'Symbology Development for Head Down Displays (SD-HDD)' test series. The objective of the these experiments were to determine if there were any interactions between SVS terrain portrayal or guidance symbology concepts over a spectrum of these, as well as to confirm that increases in pilot performance due to guidance and symbology concepts were preserved with the addition of SVS terrain.

The first experiment in this series, applied to terminal area operations, evaluated a curved approach and a missed approach scenario at Juneau, Alaska. Discussion of the results of this experiment can be found in [23]. The second and the third experiments of the SD-HDD concentrated on low altitude en route maneuvers in the central mountains of Alaska (Merrill Pass). The second experiment is the focus of this paper. The preliminary results of this experiment were summarized in [24]. It is intended that this paper provide the reader with a detailed report of the experiment goals and methodology, experiment set-up and scenario, the conduct and administration of the experiment, results of objective and subjective measures, and pilots' response to structured questionnaires and their comments throughout the experiment.

Method

The focus of this experiment was on an advanced application of SVS technology to fully exploit its potential for safe operations during a low altitude en route maneuver in instrument metrological conditions in the central mountains of Alaska (Merrill Pass), not practical with current technology. This section provides a description of the experiment apparatus and methodology. When discussing the experiment apparatus, a detailed discussion of the display concepts will be presented and the independent variables will be defined. The description of the methodology will include discussions related to the experiment scenarios, selection of the Evaluation Pilots (EP), training of pilots, the test protocol, and selection of dependent variables.

Experimental Apparatus

General Aviation Work Station

The experiment was conducted in the General Aviation Work-Station, a fixed based flight simulator equipped with two separate 6-inch LCD Head down Displays (HDD) as illustrated in Figure 1. The General Aviation Work-Station had been successfully used for previous SVS-GA experiments and it has established itself as a low cost but effective simulator that allows rapid replacement of display concepts and experiment scenarios. The two 6-inch displays were Commercial-Off-The-Shelf (COTS) VGA (640x480) monitors. The left 6-inch display served as the SVS-PFD and the right one as a Navigation Display (ND) with multi-level range selection capability, developed at NASA LaRC. Pilot selectable fields of view (horizontal angle of the image that is presented on the display) of 30 and 60 degrees were available throughout the scenarios for the PFD and the current FOV boundaries were depicted on the ND. An SXGA (1280x1024) overhead projector provided the Out-The-Window (OTW) view depiction providing approximately 25 degrees vertical and 33 degrees lateral field of view, Figure 2. The OTW imagery used in this experiment was based on the same database as the photo realistic terrain portrayal, which will be discussed below under the terrain portrayal concepts. The quality and validity of OTW projected displays during ground based simulations have been discussed by many researchers and their limitations and remedies, which were studied for low speed and hover flight [25], have been taken in consideration here.

The GAWS was based on a modified Precision Flight Controls PC-based Aviation Training Device (PFC-PCATD), model PI-142 instrument trainer, consisting of dual yoke and rudder pedals with a radio stack positioned between the two pilot seats. The evaluation pilots flew the scenarios from the left seat. The right seat was occupied by the instructor during the training sessions only. The flight simulator software was configured with a Cessna C-172 dynamic flight model from Initiative Computing Electronic Instrument Training Environment (ELITE*™) Simulation Solutions Company.

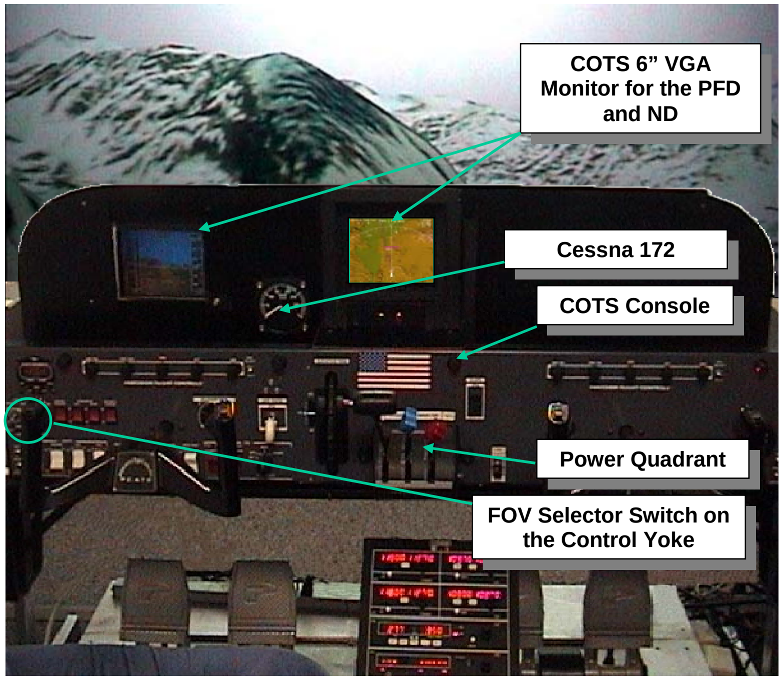


Figure 1: General Aviation WorkStation (GAWS) Set-up

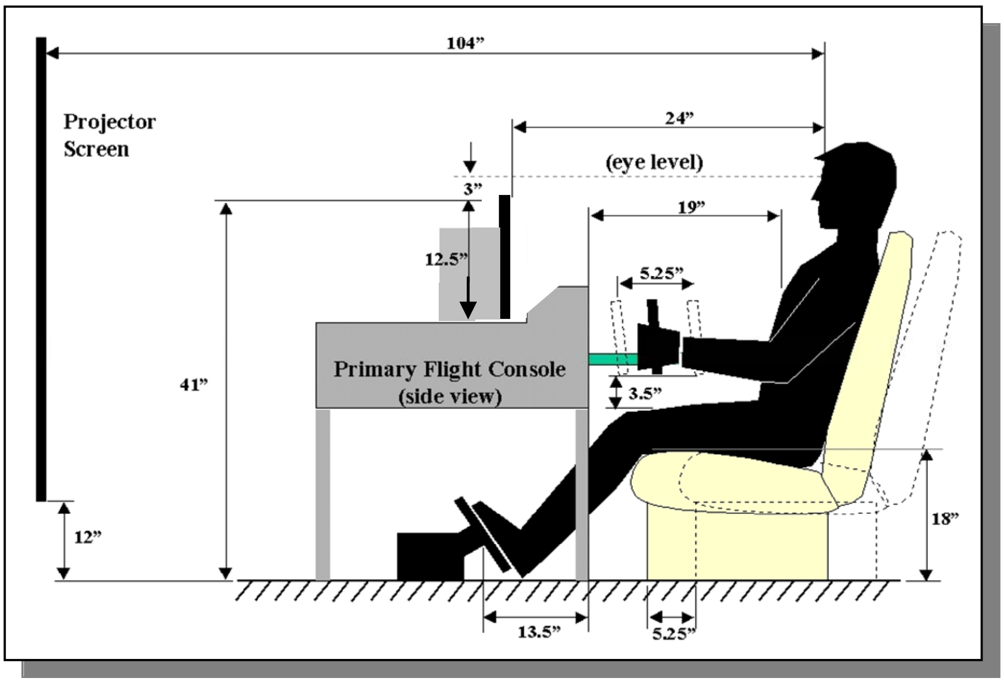


Figure 2: General Aviation WorkStation (GAWS) Side View Schematics

Basic Symbology for Navigation Display:

The ND served as a strategic display depicting the top view of the outside world, Figure 3. Ownship position was indicated by a white arrowhead in a track up mode. The preplanned route (flight path) and the desired waypoints were displayed in magenta color. The boundary of the FOV, selected for PFD, was depicted in green to help associate items in the navigation display with the SVS primary flight display. The terrain displayed on ND was simply the 2-D overhead view of the same terrain database as used on SVS primary flight display (see terrain portrayal concepts below). In addition to the typical ND speed and distance information, the wind direction and speed were also displayed. Magnetic heading, track and course were labeled on the compass rose. The range and the scale of the viewing area were displayed on the magnetic track line.

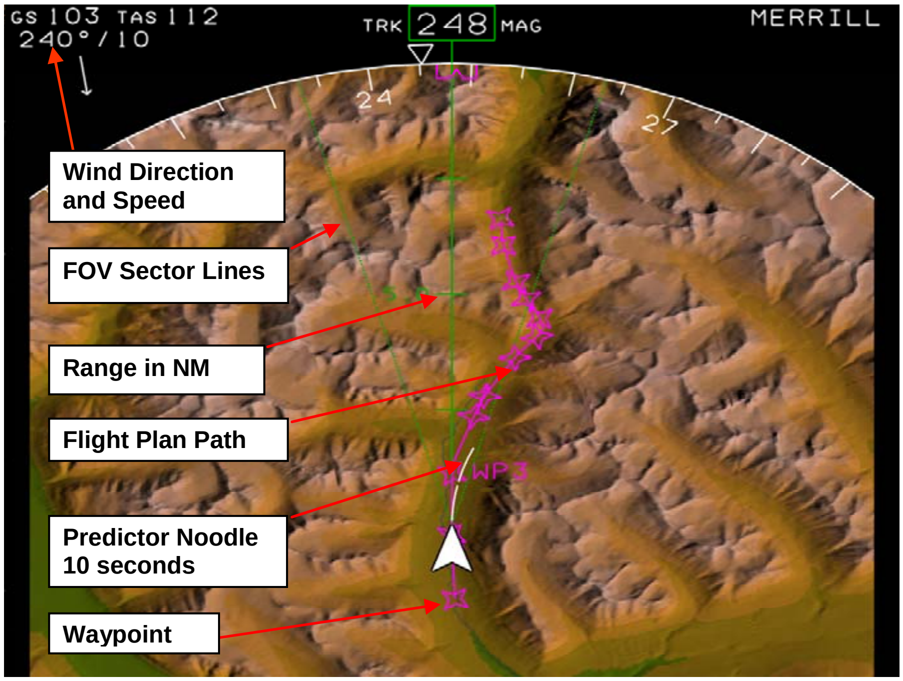


Figure 3: Navigation Display (ND)

Basic Symbology of the Primary Flight Display:

Basic symbology for all displays included integrated airspeed and altitude tapes, roll scale, etc., typical of modern GA primary flight displays (Figure 4). The pitch ladder label was displayed on the left side of the viewing area with increments of 5 and 10 degrees, up and down. The bank angle was shown on the roll scale on top of the display with increments of 5 and 10 degrees, right and left. A roll pointer with an integrated sideslip indicator shows the instantaneous bank angle and below the sideslip indicator the digital magnetic heading was displayed. The airspeed and altitude tapes were on either side of the viewing area with a Vertical Speed Indicator (VSI) integrated into the altitude tape. The airspeed tape was color-coded based on Cessna 172 Reference Airspeeds (V-speeds) and the airspeed bug was pre-set to the assigned airspeed. Part of the airspeed tape included an airspeed trend indicator that predicted the airspeed change 10 seconds in future. The longitudinal attitude (the pitch attitude) was shown by a waterline marker when used with the pitch reference scale while the Flight Path Marker (FPM) provided information about the current flight path. The FPM cluster included the sideslip indicator, displayed again on the top of the vertical tail of the FPM symbol, and airspeed error (the difference between current indicated airspeed and the assigned airspeed). This airspeed error was shown as an increasing or decreasing column on left wing of FPM symbol. An acceleration arrow that moved up and down from the left wing of FPM symbol was implemented. This arrow indicated acceleration along the flight path and could be adjusted by the power setting to maintain the desired airspeed for the given vertical path. Linear vertical and lateral path deviations where displayed using the CDI scale with "dog bone" shaped indicators. The selected FOV was digitally displayed in the lower left corner of the PFD display area.

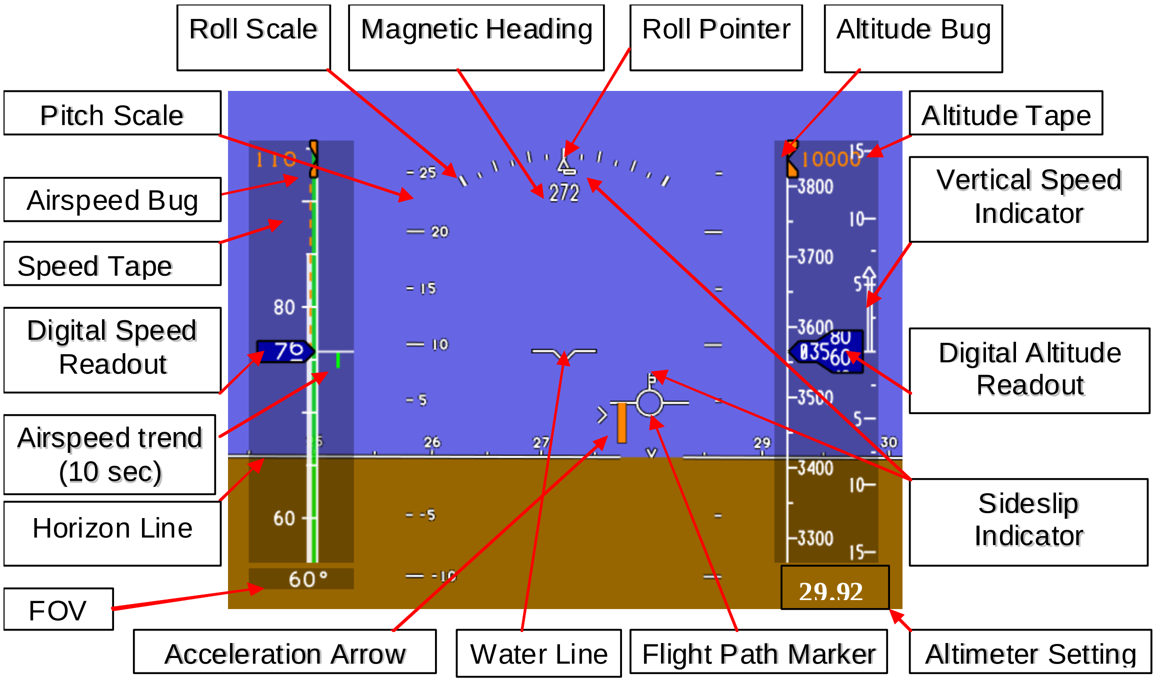


Figure 4: Basic Symbology of the Primary Flight Display (PFD)

Terrain Portrayal Concepts

The distance between elevation data points (post-spacing) for a given database is referred to as the digital elevation model resolution. The highest terrain resolution available (2 arc-sec) was selected for the Merrill Pass simulations. The smallest triangular polygon capable of being rendered has sides equal to the digital elevation model resolution.

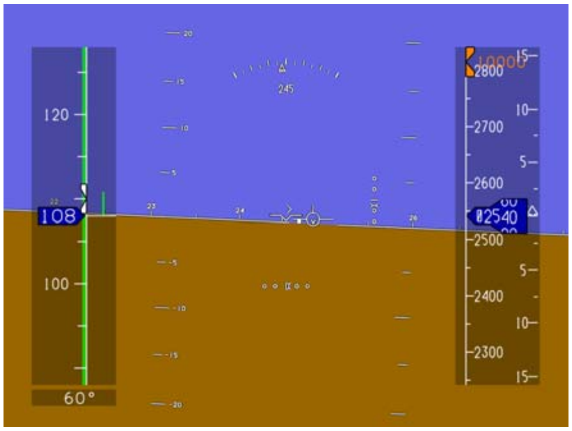
The SVS terrain database generation process used a precompiled method that allocated polygons in areas with large terrain variations. Terrain texturing refers to the method used to color the polygons that comprise the SVS terrain database. The three primary SVS texturing concepts tested were Constant-Color Fishnet (CCFN), Elevation-Based Generic (EBG), and Photo-Realistic (PR). Cultural features, such as roads and rivers, were included as objects in the SVS terrain database. A sample comparison of the four terrain display concepts utilized in this experiment is shown in Figures 5 a-d. These figures show the same view and orientation of Merrill Pass in Alaska, with the following variations;

1- A standard generic Blue Sky Brown Ground (BSBG) primary flight display served as the baseline terrain portrayal concept (Figure 5a).

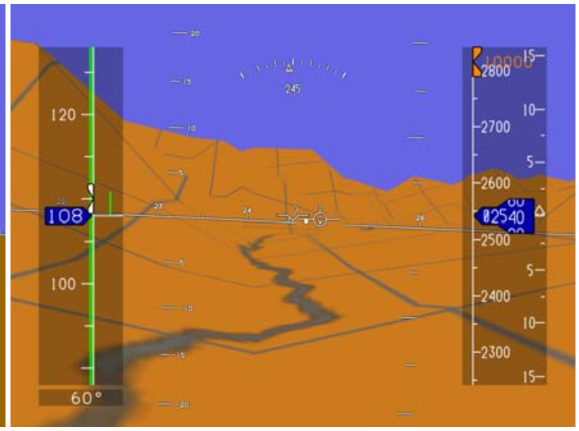
2- The constant-color texturing concept was developed to represent a current industry concept. The fishnet had 500 ft squares (Figure 5b).

3- The elevation based texturing concept consisted of twelve equal-height coloring bands that correspond to different absolute terrain elevation levels, similar to the colors employed for Visual Flight Rules (VFR) sectional charts. Lower terrain levels were colored with darker colors; higher terrain levels were assigned lighter colors. A shade of green was set to the sea level elevation. The lightest color was set to the highest terrain within a rectangle of 157x180 Nautical Miles (NM) surrounding Merrill Pass, approximately 9,000 ft MSL (Figure 5c).

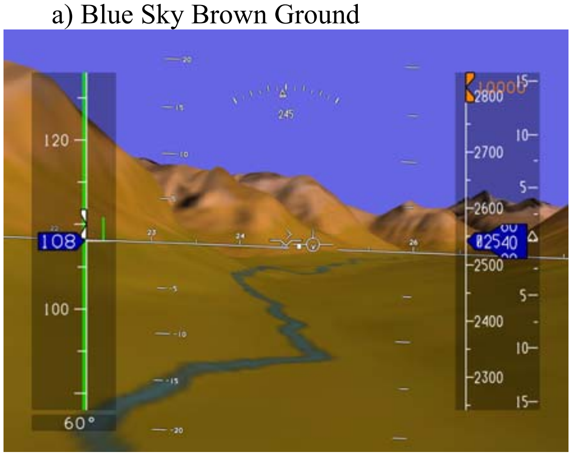
4- The Photo Realistic texturing concept was derived from full color ortho-rectified 4 m satellite imagery data. The resulting scene was a highly realistic view due to the photographic imagery employed. The PR texturing required special graphics hardware due to the amount of texture memory required to render the realistic scene at an acceptable frame rate (i.e. > 30 Hz) (Figure 5d). As mentioned earlier, PR concept was also used as the out-the-window display which was projected at the GAWS wall with a field of view of 33 degrees.



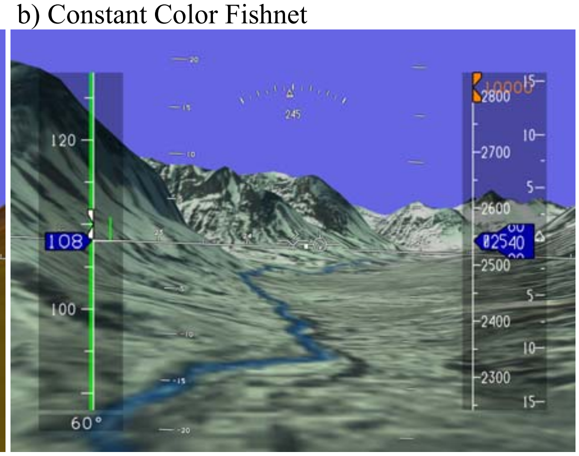
a) Blue Sky Brown Ground



b) Constant Color Fishnet



c) Elevation Based Generic



d) Photo Realistic

Figure 5: Terrain Portrayal Concepts

Guidance/Tunnel Symbology Concepts

As employed for this experiment, Highway-in-the-Sky (HITS) concepts consisted of two main elements. The first element was a Three Dimensional (3-D) pathway of various dimensions and physical presentations and the second feature was referred to as the guidance cue. One of the most common depictions of a pathway is a tunnel. Common variations of tunnels are the shape, size, color, whether the corners are connected, and whether the boxes are connected along the flight path, etc.

Each pathway-based guidance symbology concept employed for this effort represents guidance symbology designs developed and used in commercial products as well as other pathway-based guidance symbology concepts guidance and symbology concepts extensively evaluated in previous research efforts and proposed for future SVS display applications. The approach for this study was to employ each GSC as developed and not refine each concept to preserve specific independent parameters (such as tunnel size, color, etc.). The selection of guidance and symbology concepts was intended to provide a spectrum of visual complexity from simple

Pitch/Roll Flight Director (PRFD) command bars up to connected box tunnels with sliding box guidance cues and lateral predictors.

In addition to the tunnels depicting the flight path, path based course deviation indicators were also implemented. The limits of the CDI values were set to +/-150 ft, with 2 dots indication (75 ft per dot) for a full deflection in both horizontal and vertical directions from the flight path. The limits of the CDI values were selected to match the displacement limits (in feet) at the missed approach point (MAP) during challenging SVS approaches investigated in reference 22. In a typical precision instrument approach, below 500 ft Above Ground Level (AGL), the aircraft is expected to be established on a stabilized final approach segment with very small variations in lateral and vertical deviations from a prescribed flight path. As discussed earlier, the experiment scenario was to be a challenging scenario simulating a low en-route flight at 500 ft AGL. The CDI scale remained constant for every GSC studied in this experiment, even though tunnel sizes varied. This ensured that as long as CDI limits were not exceeded the own ship position remained within the boundaries of all four guidance and symbology concepts with a tunnel, as described below. Guidance cues selected were based on currently available technology and were 1) a split cue Pitch/Roll Flight Director; 2) a single cue Ghost Plane; and 3) a single cue guidance box with laterally quickened Flight Path Marker. There were four general categories of Guidance/Tunnel Symbology Concepts, comprising combinations of different guidance cues and Tunnels, as shown below:

A - Guidance Cue, No Tunnel

1- Pitch/Roll Flight Director

2- Ghost Plane (GP)

B- No Guidance Cue, With Tunnel:

3- Unconnected Boxes Tunnel (UBT)

4- Crows Feet Tunnel (CFT)

C- Guidance Cue, With Tunnel:

5- Crows Feet Tunnel with Ghost Plane (CFTGP)

6- Connected Boxes Tunnel (CBT) with Guidance Square and laterally quickened Flight Path Marker

D-No Guidance/No Tunnel:

7- Comparison of the three SVS terrain portrayal display concepts Constant Color Fishnet, Elevation Based Generic, and Photo Realistic (in simulated IMC) with the baseline PFD, Blue Sky Brown Ground, in simulated Visual Meteorological Condition (VMC).

Each one of the above Guidance/Tunnel Symbology Concepts are described in detail below and illustrated in Figures 6 through 11.

Guidance/Tunnel Symbology Concept: Pitch/Roll Flight Director

For the Pitch/Roll Flight Director the displacement of the horizontal and vertical error bars (magenta in color) from the water marker indicated the commands for pitch and roll, respectively, to correct for path errors [26]. Examples of the block diagrams and control logics for guidance and symbology concepts are shown in Appendix A. For the present study the time constants for both roll and pitch directors were set to 0.25 seconds.

To achieve precise path control (to center the CDI symbols), evaluation pilots were instructed to position the water-marker on the horizontal and vertical bars of PRFD, thus bringing the bars to a cross-hair shape.

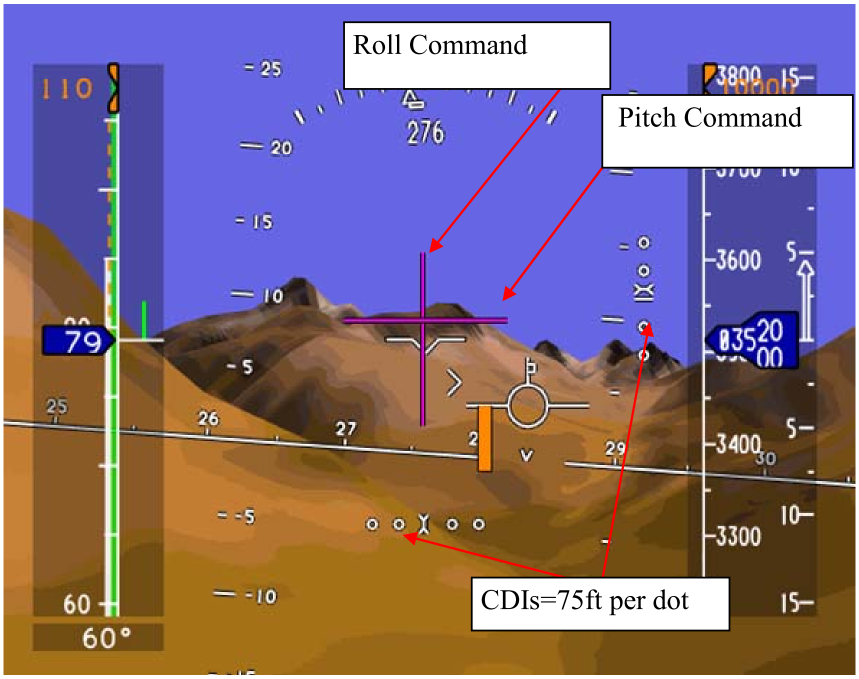


Figure 6: Pitch/Roll Flight Director

Guidance/Tunnel Symbology Concept: Ghost Plane

In this concept, a symbolic aircraft was depicted on the PFD moving 5 seconds ahead of own ship on the projected tangent of the current flight path [27]. The Ghost Plane shows the path correction necessary to get back on the desired flight path. To achieve precise path control (to center the CDI), evaluation pilots were instructed to position the Flight Path Marker on the Ghost Plane.

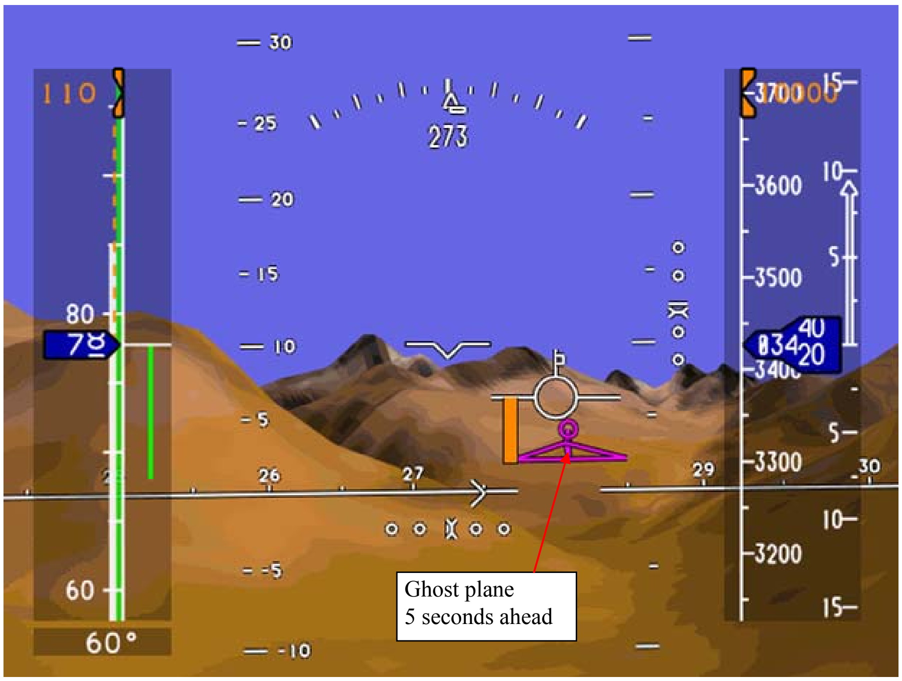


Figure 7: Ghost Plane

In extreme cases where the pilot was far off course, the GP remained pegged at the corner of viewing area, changed color to amber, and a line was drawn from Flight Path Marker to the GP indicating the direction of the required correction.

Guidance/Tunnel Symbology Concept: Unconnected Boxes Tunnel

This tunnel concept was implemented during the TP-HDD experiment which was adopted from an industry concept that was used in the FAA's Capstone-2 Project [28]. The corners of the green boxes were connected but the boxes were not connected to each other. Each tunnel box was 400 ft wide and 320 ft tall. The boxes extend to one nautical mile and the number of the boxes was directly related to the field of view selected. For a field of view of 60° there were 7 boxes in a mile. These uniformly placed rectangles depicted the desired path. For a curved path the boxes were tilted to 10° when the radius of the turn required a bank angle of more than 5°. There was no path based guidance cue for this concept. For precise flight path control, the evaluation pilots were instructed to position the Flight Path Marker within as many oncoming boxes as possible to ultimately center the CDIs. This concept also included 3-D visualization of waypoints as tethered balloons on the PFD.

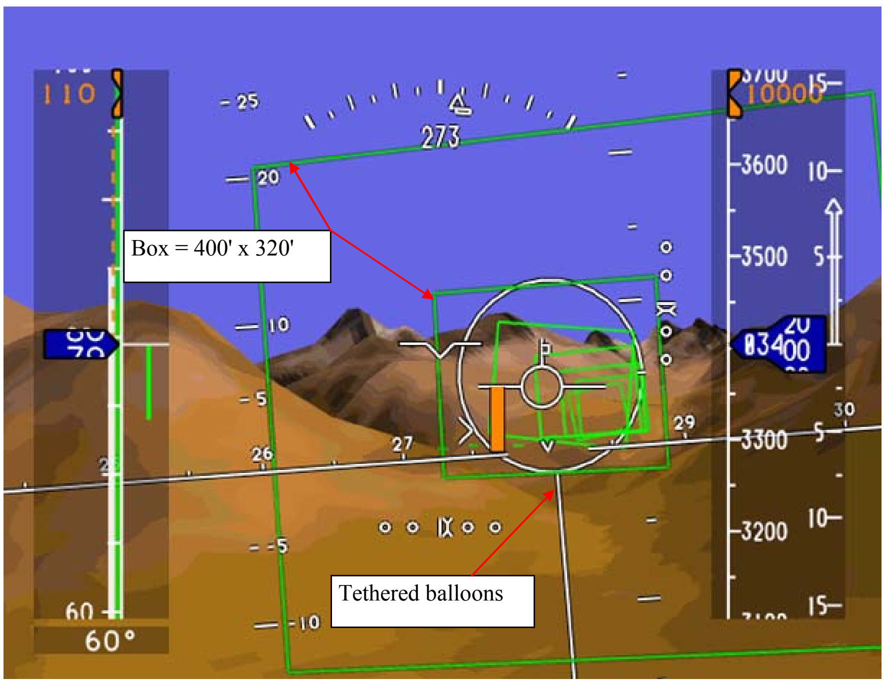


Figure 8: Unconnected Boxes Tunnel

Guidance/Tunnel Symbology Concept: Crows Feet Tunnel

The Crows Feet Tunnel concept was developed at NASA LaRC in conjunction with the Ghost Plane concept. The corners of the magenta boxes were not connected and were shaped in three dimensions, resembling crows' feet. The CFT dimensions were a constant 600 ft wide and 350 ft tall. The evaluation pilots were instructed to place the Flight Path Marker in the middle of the oncoming boxes to center the CDIs.

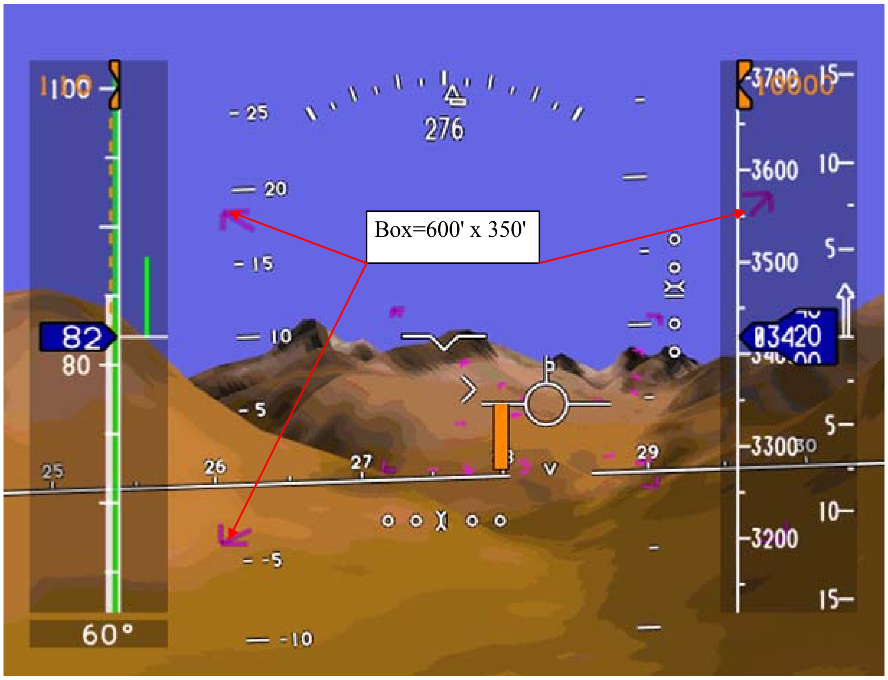


Figure 9: Crows Feet Tunnel

Guidance/Tunnel Symbology Concept: Connected Boxes Tunnel & Guidance Square

This concept was based on an industry research concept in which the white boxes defining the pathway were connected to each other and continued to the final waypoint. The tunnel disappeared after three nautical miles distance, also known as the total fade distance. In addition to the 300 ft by 300 ft tunnel, there was a magenta guidance square moving 5 seconds ahead of own ship providing the guidance cue [29]. As an integral part of this concept, the Flight Path Marker has a quickening of 5 seconds in the lateral direction thus it was referred to as a path predictor. For precise flight path control, evaluation pilots were instructed to use the tunnel and position the predictor in the center of the guidance square.

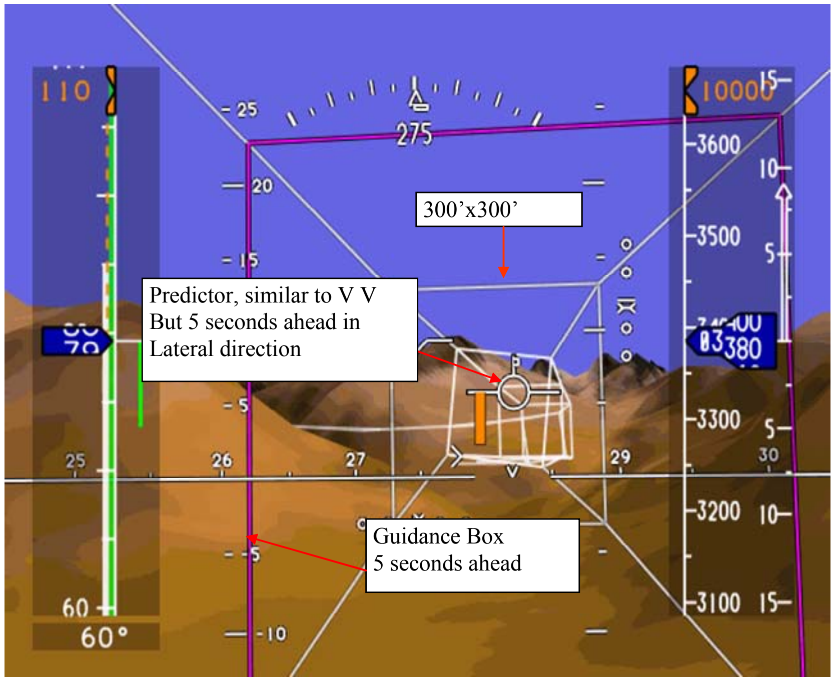


Figure 10: Connected Boxes Tunnel

Guidance/Tunnel Symbology Concept: Crows Feet Tunnel with Ghost Plane

This guidance and symbology concept was a combination of the CFT and GP concepts and (as described above) developed at NASA LaRC. The evaluation pilots were instructed to follow the tunnel and position the Flight Path Marker on the GP for precise flight path control. This GSC provides both a path based guidance cue and de-emphasized tunnel to manage visual clutter.

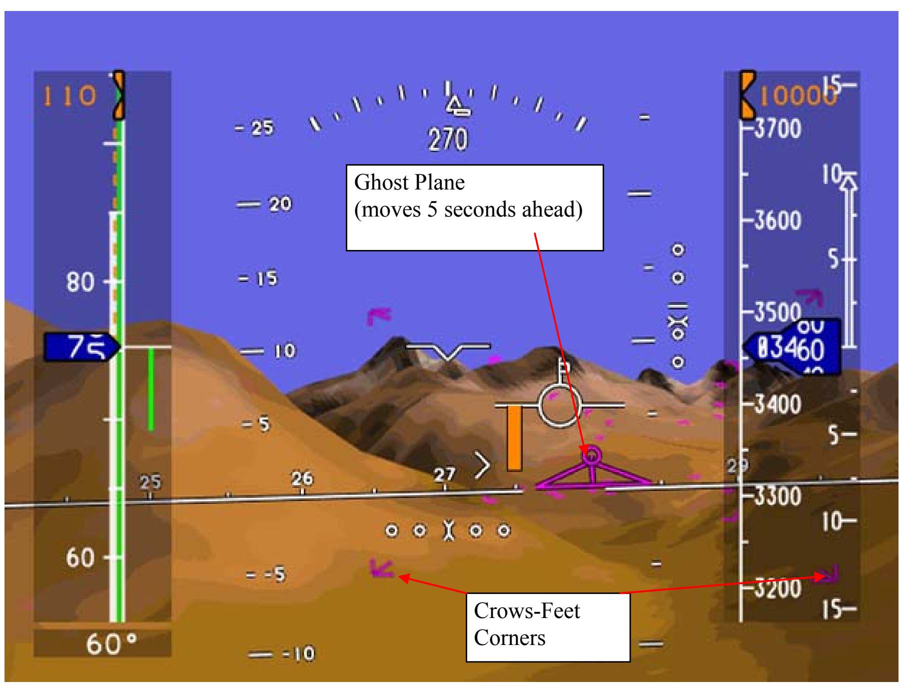


Figure 11: Crows Feet Tunnel with Ghost Plane

Guidance/Tunnel Symbology Concept: No-Guidance/No-Tunnel

This concept incorporated variations of terrain portrayal concepts on the Primary Flight Display, without any tunnel or guidance cues (see Figure 5). The combination of the Blue Sky Brown Ground display with no guidance and no tunnel during IMC was removed from the test matrix, as this case would not be practical. Instead, the baseline for no guidance no tunnel PFD (Blue Sky Brown Grown) was flown in simulated VMC. Thus, the three terrain portrayal concept runs with no guidance or tunnel in IMC were compared to BSBG runs in VMC. In fact, this combination (BSBG with no guidance and no tunnel used in simulated VMC) served as the baseline for when comparing use of any of SVS display combinations in IMC to VMC operations.

Experiment Scenario

In Alaska, many populated areas are surrounded by high mountainous terrain and are accessible only by air or sea. This has generated a high-reliance on GA aircraft as the main mode of transportation. Frequent low altitude icing levels exist in this region, and when combined with no low-level IFR infrastructure, it makes traditional Instrument Flight Rules (IFR) operations impossible for most of the GA aircraft in service. Pilots often find themselves navigating through treacherous mountain passes, in an attempt to remain in VMC but sometimes in very poor visibility, to complete their flights. There have been many accidents in these areas, especially around Merrill Pass. Thus, Merrill Pass and central mountains of Alaska were selected as a challenging low altitude en route scenario for this experiment in an effort to determine the extent that these types of operations could be improved by SVS technology. At Merrill pass, the terrain rises towards the pass, requiring the pilot to recognize the upslope from terrain depiction to climb through the pass. After passing through the crest of the mountain, the terrain slopes down towards the glaciers. In Alaska, pilots flying Alaskan mountain passes traditionally use “rules of the road” staying on the right side of the mountain path. These operations are both at higher altitude than simulated in this experiment and they are normally conducted in visual metrological conditions. After extensive consultations with numerous Alaskan pilots and air taxi operators, the experiment scenario was designed to be a) as challenging as possible, b) simulating an inadvertent transition from VMC to IMC, and c) it was assumed that in future aircraft equipped with SVS would be also capable of advanced traffic separation such Automatic Dependent Surveillance-Broadcast (ADS-B) . Therefore, the flight path was designed to follow the center of the pass. Maintaining path position was essential in maintaining adequate terrain clearance.

Primary Test Scenario

The scenario started with the aircraft flying at 500 ft AGL and Indicated Airspeed (IAS) of 100 kt in VMC. A transition to IMC was simulated at one minute into the scenario. The EPs task was to maintain 500 AGL while monitoring the path based course deviation indicators. The planned flight path for experiment scenario was designed to follow the terrain at an altitude of 500 ft AGL at all times. This path could provide an optimal altitude for search and rescue operations or a suitable altitude to avoid potential icing conditions. As illustrated in figure 12 the scenario terminates after passing through Merrill Pass. For better realism and added workload (typical of mountain flying), light turbulence and wind (variable both in speed and direction) were also simulated.

Figure 12: Experiment Scenario, Merrill Pass, AK

Rare Event Scenario

The rare event scenario was performed with the NGNT condition. Unknown to the evaluation pilot, one minute into the flight, the engine power was linearly reduced to a level (minimum) corresponding to 25% of max output without any changes to the simulated engine noise. The intent was to simulate degradation of aircraft performance due to structural icing. In all rare event runs, the performance degradation process started one minute into the flight and the power level reached its minimum within one minute. The purpose of this rare event scenario was to see if the presence of the terrain on PFD affected the evaluation pilot's situation awareness of the imminent emergency conditions. During the pilot briefing and pilot training (see Appendix B) evaluation pilots were reminded to a) "fly the simulation just like real flying avoiding any hazardous terrain of flight situations when they occur" and b) "communicate their intentions and take corrective action if necessary".

As it will be discussed later in the "Dependent Variable" section, various new variables particular to the rare event scenario were recorded. These included the time at which the evaluation pilot noticed the impending problem, 2) the time at which EP initiated any corrective action 3) the outcome of his/her corrective action. Based on the actions taken by the evaluation pilots, the outcome data was categorized into the following possibilities: 1) was EP successful in avoiding a controlled flight into terrain?, 2) did EP reverse the course and make a 180 degree-turn back to lower terrain?, 3) was there a loss of control?, and 4) was there a CFIT as a result of 180 degree-turn? Special software was developed to provide the experiment observer an instantaneous readout of all aircraft performance data and distance from the terrain. Accordingly, a LOC was defined as simultaneous large excursions in pitch (more than 30 degrees), bank (more than 60 degrees) or speed (increasing). A CFIT was declared when EP reached zero height, AGL, without any attempt to avoid the terrain or land on the terrain in a landing attitude. Of course, verbal acknowledgements of LOC or CFIT by the evaluation pilots were also utilized as other criteria.

Evaluation Pilots

Three groups of evaluation pilots, a total number of 18, were recruited from around the country representing a comprehensive sampling of the GA pilot spectrum. The grouping criteria were based on the earlier studies and results of GA studies on the subject of relation between accident rates and pilot flight experience [30 and 31]. These studies indicated that VFR-only pilots with total flight time (FT) less than 400 hours had the highest rate of accidents.

Accordingly, the first group of evaluation pilots (VFR group) consisted of 6 low-time pilots, each with less than 400 hours of FT and no formal instrument training beyond that required for the FAA private pilot's license (mean FT=175 hours; mean age=44 years). The second group (IFR) consisted of pilots with less than 1000 hours of FT and with an Instrument Rating (mean FT= 450 hours; mean age=38 years). The third group of evaluation pilots (H-IFR) consisted of professional pilots from NASA, Boeing, FAA, and Alaska commercial operators with several thousands of hours FT each (mean FT= 8574 hours; mean age=56 years), see table 1 for details.

Pilot Category	Age	Mean Age by Pilot category	Flight Hours	Mean Hours by Pilot category
HIFR	57	56	3000	8574
HIFR	53		1560	
HIFR	62		14000	
HIFR	50		7482	
HIFR	56		17000	
HIFR	55		8400	
IFR	43	38	600	450
IFR	38		850	
IFR	38		200	
IFR	54		500	
IFR	24		200	
IFR	29		350	
VFR	25	44	86	175
VFR	40		100	
VFR	52		250	
VFR	57		183	
VFR	43		64	
VFR	48		366	
Total Means		46		3066

Table 1: Evaluation Pilots' Qualification and Aeronautical Experience

Training of Evaluation Pilots

Before the start of the experiment, each pilot received an experiment briefing followed by a pilot briefing similar to a Ground School, as well as one-hour of simulator training in the GAWS with an FAA certificated flight instructor for instruments. The purpose the briefing and the training was to familiarize each EP with the objectives of the experiment and educate the subjects on the salient features of the symbology and simulator functionality. An FAA-style training syllabus was utilized for training and for testing of EP's skills according to the FAA Practical Test Standard (PTS) for Private Pilot License. Additionally, evaluation pilots were instructed to 1) Use all display information to minimize pilot flight technical errors; 2) Avoid hazardous terrain or flight situations; and 3) Communicate their intentions and take corrective action when encountering hazardous situations. A sample lesson of the training syllabus is included in Appendix B.

Test Protocol

Each EP participated in two 8-hour days of testing, conducting 56 runs of 5-minute duration and one rare event scenario. To avoid pilot fatigue all runs (including repeat runs) were randomized and short breaks of 10 minutes (every hour) and longer breaks of 20 minutes duration (every two hours) were scheduled. In addition, a lunch break of at least one hour duration per day was allocated for every EP. At the end of each run, the subject pilot was required to complete a set of subjective run questionnaires administered on a Tablet Personal Computer. The between-run questionnaires solicited the evaluation pilot's subjective estimates of situation awareness and perceived workload for each one of the 56 (4 TPC x 7 GSC x 2 Replicates = 56) displays immediately after exposure to each display. The general schedule was: Day 1; Pilot briefing, overall training, data collection for all guidance/tunnel concepts, Day 2; Data collection continued in the morning. In the afternoon, data collection continued for NGNT runs and finished with the rare event scenario. During the exit interview several sets of questionnaires related to EP preferences, workload, and SA were administered. All formal testing was audio and video recorded for future correlation to the actual data.

Dependent Variables

The dependent variables were both objective and subjective measures.

Subjective Measures:

The subjective data measures included a set of three batteries of between-run questionnaires, a battery of block questionnaires for each block of the experiment, and a battery of exit questionnaires administered at the conclusion of the experiment.

Between Run Questionnaires:

The first set of between-run questionnaires dealt with perceived situation awareness (see Figure 13.). To have an uninterrupted and complete FTE data set, it was decided to use a post-run Situation Awareness Rating Scale Technique (SART), [32]. Accordingly, a 3-D SART was computed from Figure 13 and is reported as the calculated Situation Awareness according to the following formula:

SA Calculated = Understanding – (Demand-Supply)

The set of questions related to perceived workload are shown in Figure 14. For this report, a standard 6-degree NASA- workload index (TLX Score) was computed as:

Score = (Mental +Physical + Temporal + Performance + Effort + Frustration) / 6.

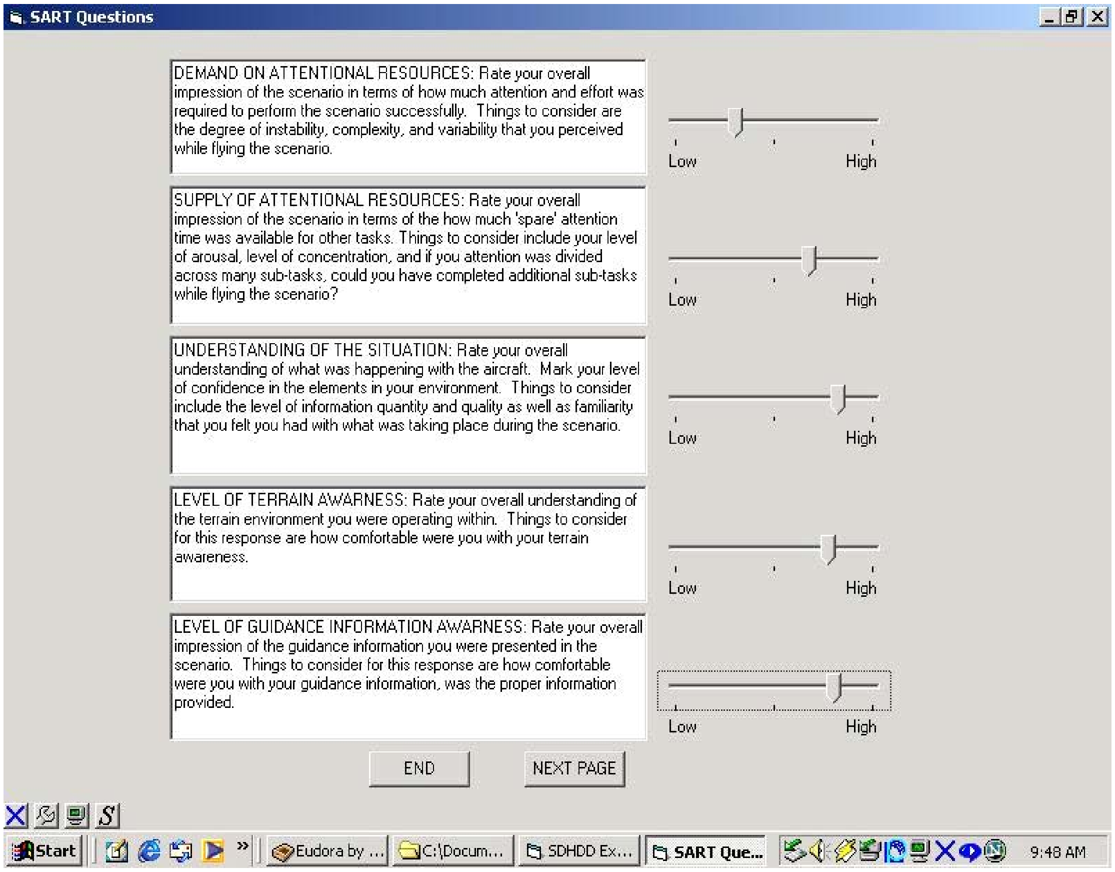


Figure 13: Scoring of Situation Awareness Rating (SART)

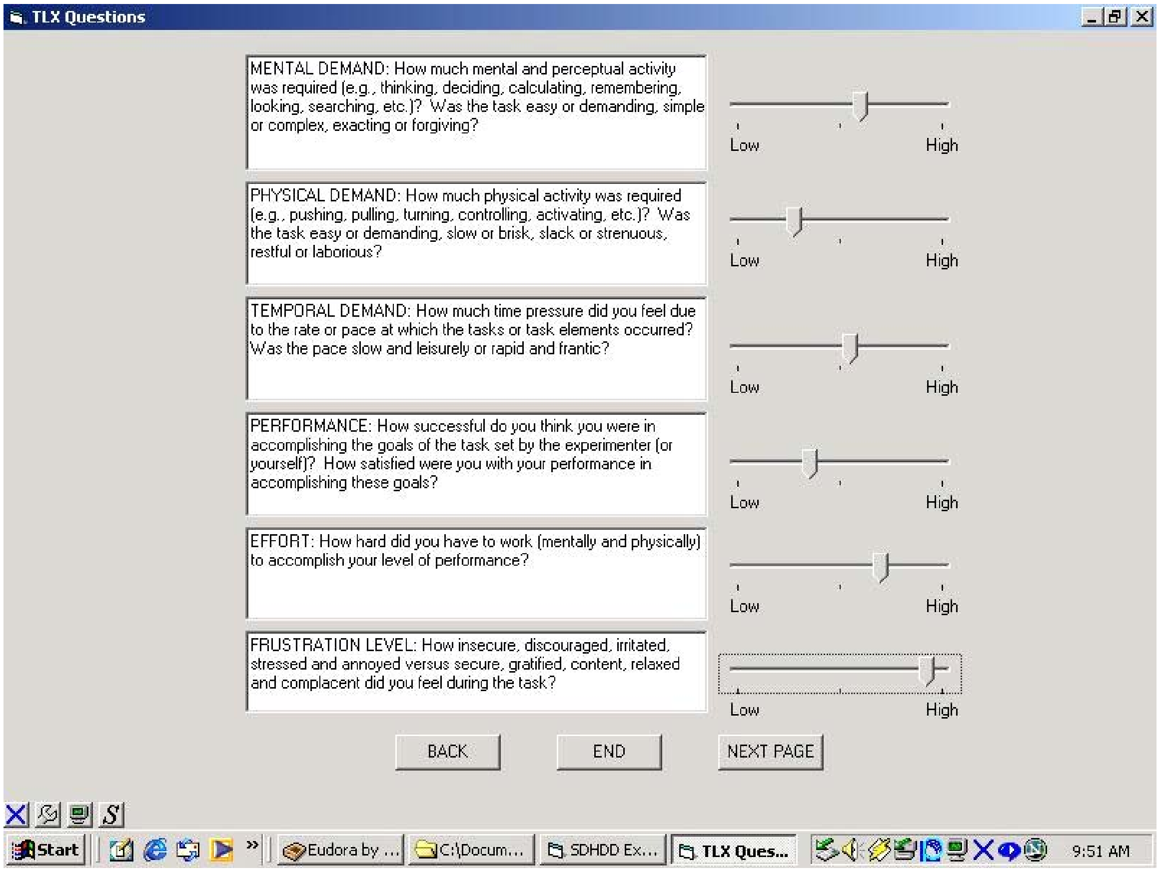


Figure 14: NASA Task Load Questionnaire

Block Questionnaires:

In addition to the above between-run-questionnaires, at the conclusion of all runs there were two more blocks of questionnaires administered. These questionnaires dealt with overall evaluation pilot situation awareness and workload when using the displays with guidance and tunnel (block one) and when using NGNT (Block two). At the conclusion of the two block questionnaires another set of questions were posed which dealt with EP preferences for any of the display combination used in this experiment. The copies of block questionnaires and preferences questionnaires that were administered at the end of EP visit are shown in Appendix D.

Objective Measures:

Even though numerous types of objective measures such as pilot control inputs, pilot/aircraft performance data, etc., were recorded, this report focuses on the vertical and lateral path errors, which are also referred to as Flight Technical Error (FTE). The FTE values were computed by using two different treatments. In the first treatment, the entire scenario was treated as a single segment. Note that each run scenario consisted of three distinct segments: the first segment was a straight and level flight; the second segment consisted of a shallow bank with a steep climb, and the third segment consisted of a moderately banked turn completed with a rollout. In the second treatment, the objective measures (i.e. FTE) were computed for all three segments separately. The purpose of the segmented treatment was to see if any significant interactions between TPC and GSC could be obtained during each one of those distinct maneuvers (segments) with different overall levels of workload induced by variations in the amount of required maneuvering.

Objective Measures for the Entire Run:

To obtain the EP flight technical errors for an entire run, time history data of all runs were analyzed and pertinent statistical parameters such as minimum, maximum, Root Mean Square (RMS), Standard Deviation (Std), etc. were computed for all objective measures including vertical and lateral flight path errors. However, this report focuses on RMS of vertical and lateral flight path errors. Computations were performed for a constant distance of 6.5 NM (1.80-8.3) which corresponds to a Waypoint (WP) near the start of IMC phase of flight (WP1) to a waypoint near the end of scenario, after clearing the Pass (WP8). Refer to Appendix C for more information about the waypoint locations. Both objective data and subjective measures (gathered from each run) were statistically analyzed over the participating EP population using statistics SPSS software package SPSS™ by SPSS, Inc. Multivariate Analysis of Variance (ANOVA) and Post Hoc analyses of all measures were performed.

Objective Measures for the Segmented Treatment:

In the second treatment, the objective measures (i.e. FTE) were computed for all three segments separately. Details of the segmentation methodology are also discussed in Appendix C. Computations were performed for three segments with following attributes. The first segment had a length of 3.08 NM which corresponds to a route from a waypoint near the start of IMC phase of flight (WP1=8.3) to a waypoint at the start of the first climbing turn (WP3=5.22). The second segment had a length of 2.64 NM from the waypoint at the start of the first climbing turn (WP3) to the waypoint before the start of the level turn into the mountain gap (WP6=2.578). The third segment had a length of 0.778 NM, which started at the waypoint for the level turn before the mountain gap (WP6) and into a distance 1.8 near the end of scenario, after clearing the Pass (WP7=1.882). The starting point for segment 1 and the end point for the segment 3 were the same points as those selected for the start and end of the complete scenario (un-segmented treatment), respectively.

Additional Objective Measures for the Rare Event:

For the rare event scenario, in addition to the above objective and subjective measures (after each run), the following data were also recorded: 1) The time at which the evaluation pilot noticed the impending problem, 2) the time at which EP initiated any corrective action 3) the outcome of his/her corrective action. Based on the actions taken by the evaluation pilots, the outcome data was categorized into the following possibilities: 1) was EP successful in avoiding a controlled flight into terrain?, 2) did EP reverse the course and make a 180 degree-turn back to lower terrain?, 3) was there a loss of control?, and 4) was there a CFIT as a result of 180 degree-turn? Special software was developed to provide the experiment observer an instantaneous readout of all aircraft performance data and distance from the terrain. Accordingly, a LOC was defined as simultaneous large excursions in pitch (more than 30 degrees), bank (more than 60 degrees) or speed (increasing). A CFIT was declared when evaluation pilot reached zero height, AGL, without any attempt to avoid the terrain or land on the terrain in a landing attitude. Of course, verbal acknowledgements of LOC or CFIT by the evaluation pilots were also utilized as other criteria. As it will be discussed in the results section of this paper, there were no LOC incidents observed during the rare event scenario.

Results

The results of the study are presented in this section and are grouped in the following manner. First the objective and subjective measures that were gathered during and after each run will be statistically summarized and discussed in detail. Next the results of the structured block questionnaires will be presented, followed by results of the evaluation pilot preferences questionnaires and the summary of EP comments. The focus of the results of the objective measures will be on the results of flight technical errors for the each run either as a complete segment or as a segmented treatment when the run is partitioned into three arbitrary segments. Prior to the presentation of the results of objective and subjective measures for the complete scenario, the methodology for handling the flight technical errors is discussed first.

Runs Excluded from Flight Technical Errors

There were no “bad” data in this experiment due to technical problems. All runs were included in the statistical analyses of the subjective measures. Only during the computation of the flight technical errors, these unusual runs were treated as the statistical outliers, as some of these runs either were not completed or evaluation pilots did not follow the prescribed flight path during the NGNT runs. These FTE values were removed and replaced by the values of the replicate runs. None of the values of the subjective measures were treated as outliers.

Among the 864 runs (6 guidance symbology concepts * 4 terrain portrayal concepts * 2 replicates * 18 evaluation pilots) conducted for the cases with guidance and tunnel, there were 4 actual CFIT incidents and 8 runs where the evaluation pilots encountered temporary loss of situation awareness without LOC or CFIT. Table E.1 in Appendix E shows the details of these unusual runs, including comments recorded by the experiment conductor. The table indicates that, among terrain portrayal concepts tested here, there were no unusual runs for the EBG. However, there were 6 unusual runs for BSBG, 4 for CCFN, and 3 for PR. Among the guidance symbology concepts, one can see that evaluation pilots had problems with PRFD (5 unusual runs), 5 for CFT, 3 for GP, and none for UBT, CBT or CFTGP. As it will be shown in the next sections UBT, CBT and CFTGP were also the most favored guidance symbology concepts by the evaluation pilots. Consistently, EBG was the most favored terrain portrayal concept by evaluation pilots.

As mentioned earlier, the subjective measures were designed to be non-intrusive to pilot performance and, by design, the questionnaires were administered after the completion of each run and could only be applied to the entire scenario. Therefore, the remaining question was if there were any interactions between terrain portrayal concepts and guidance symbology concepts for any of the three segments of the scenario base on the resulting flight technical errors as the entire scenario was compromised of various levels of required maneuvering. For the segmented treatment of FTE, all pertinent measures in each segment were reexamined and the outliers were removed from the corresponding segments. Appendix E shows the frequency plots of the segmented measures before and after the removal of the outliers. As discussed in the appendix, the second tier outliers were based on a single run. In this particular run, the evaluation pilot mentioned that he lost his lateral situation awareness as he was “distracted by focusing too much on the navigation display.” Details of these discussions and other evaluation pilot comments can be found in the section under Highlights of EP Comments and Appendix F.

For no guidance no tunnel runs (4 terrain portrayal concepts * 2 replicates * 18 evaluation pilots), Table E.2 in Appendix E shows the list of the unusual runs among these 144 NGNT runs. There were 4 CFIT runs with CCFN and 2 with EBG. Among the unusual NGNT runs, there were not any cases with PR (in IMC) or BSBG in VMC. It means that evaluation pilots using Photo Realistic terrain display concept in simulated IMC were able to avoid any CFIT just like those who used the baseline primary flight display in simulated VMC.

Results of Objective and Subjective Measures for Complete Scenario

The results discussed here will include both objective and subjective measures. The focus on the RMS of the FTE will be on lateral and vertical path errors and focus of subjective measures will be the results of SART and TLX averaged over the particular evaluation pilot population. First plots of the variations of both subjective and objective independent variables (as a function of independent variables terrain portrayal concepts, guidance symbology concepts, and pilot ratings) will be presented and discussed. In the second level of analyses, their interactions between the variables will be presented and discussed. Except view special cases, only the results of the statistically significant results will be discussed in the following.

Effect of Terrain Portrayal Concept

The particular type of terrain displayed on the PFD affected both pilot objective and subjective measures. Analyses of variances were performed on these measures and all post hoc groupings discussed in this report were based on the Student, Newman, Keuls method. The mean RMS of the Lateral Path Deviation (LPD) showed a statistically significant effect due to levels of terrain portrayal concept, ($F(3,720) = 5.009$, $P<.05$), creating two post hoc subgroups. In the first group, the two concepts with the smallest LPDs were Elevation Based Generic and Photo Realistic concepts. The Constant Color Fishnet and Blue Sky Brown Ground concepts belonged in the other subgroup. Figure 15 illustrates the bar charts of the mean RMS of LPD. It can be seen that the LPD values were approximately 8 ft less for PR and EBG than CCFN and BSBG. This indicates that using higher fidelity terrain such as PR or EBG not only improves pilot situation awareness (see SART results below) but also can invoke lower values for lateral flight path deviation than when using CCFN or baseline BSBG.

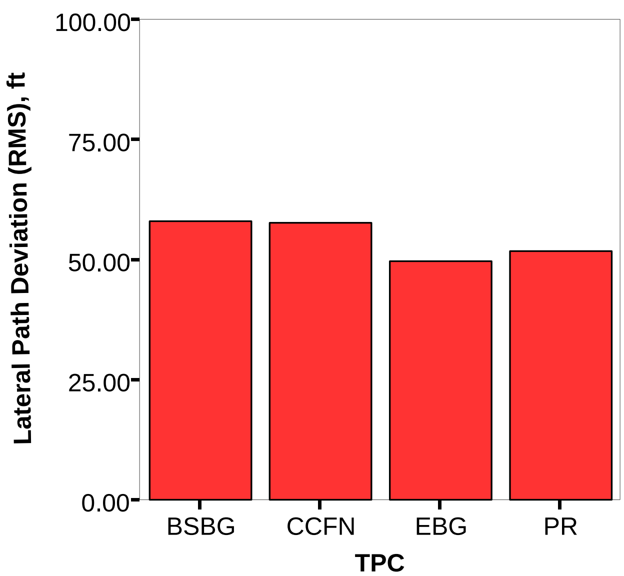


Figure 15: Mean RMS of Lateral Path Deviation

The RMS of Vertical Path Deviation (VPD) showed a statistically significant effect of TPC, ($F(3,720) = 4.24$, $P<.05$), creating two subgroups (Figure 16). Here, vertical path deviation values were statistically lower for EBG than the other 3 terrain portrayal concepts (PR, CCFN, and BSBG) with a mean of 25.5 for EBG versus 28.5, 30.1, and 30.2 for PR, CCFN, and BSBG, respectively. Again, while the difference in VPD between

EBG and the other terrain portrayal concepts may not be operationally significant, it does indicate a pilot response to the terrain stimulus with reductions in VPD associated with an increased amount of SA and decreased workload (see subjective results below). The EBG concept provides terrain in a somewhat coded yet highly intuitive manner providing the pilot with useful information, (e.g., where is the high terrain?), and eliminating secondary information, (e.g., whether the terrain is rock or soil).

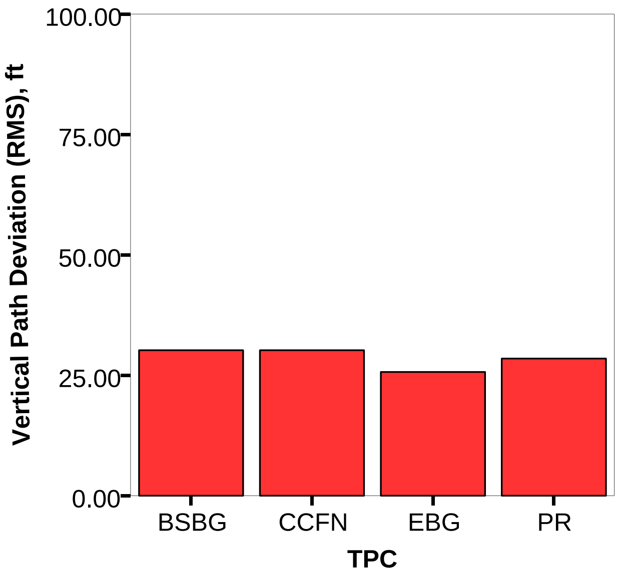


Figure 16: Mean RMS of Vertical Path Deviation

Effect of terrain portrayal concepts on situation awareness is shown by the SART data in figure 17. The statistically significant results, ($F(3,720) = 31.5$, $p<.05$), reveal that there were 3 subgroups formed. BSBG had the lowest SA; CCFN was in the middle; and EBG and PR providing the highest levels of SA. The value of perceived situation awareness for EBG and PR was almost twice the value for the other two terrain portrayal concepts.

The results of subjective workload, as indicated by TLX data, are provided in figure 18. The effect of terrain portrayal concept on TLX data was statistically significant, ($F(3,720) = 19.5$, $p<.05$), with two subgroups emerging from the post-hoc analyses. EBG and PR provided the lowest perceived workload with CCFN and BSBG being in the other group. This is an important result as it indicates that situation awareness was increased while workload was actually decreased through the integration of SVS terrain. Interestingly, as it will be shown later in section for NGNT data, both SA and TLX values are almost equal or better than to those obtained for baseline BSBG in simulated VMC.

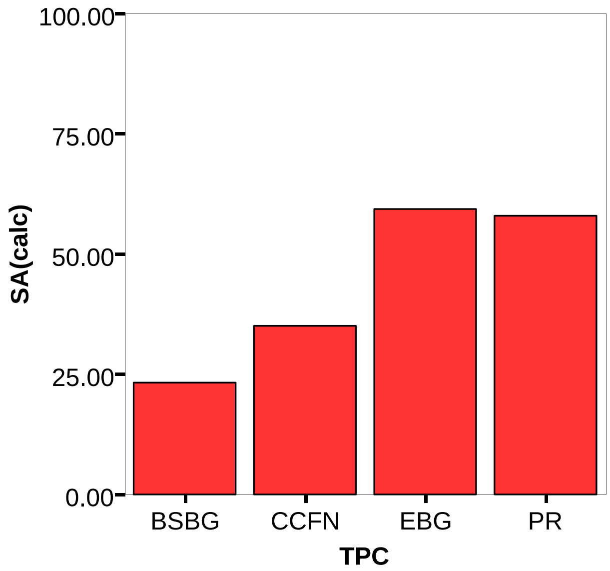


Figure 17: Perceived Situation Awareness, SART

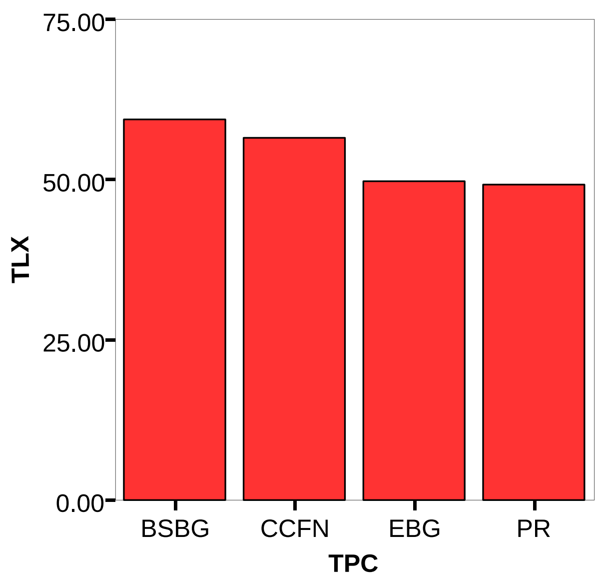


Figure 18: Perceived Workload, TLX

Effect of Guidance Symbology Concept

The overall effect of guidance symbology concepts on objective and subjective measures are discussed here. These concepts included Pitch/Roll Flight Director, Unconnected Boxes Tunnel, Crows Feet Tunnel with Ghost Plane, Ghost Plane with no tunnel, Crows Feet Tunnel without any path based guidance, and Connected

Boxes Tunnel. The results of the lateral path deviation for GSC are presented in figure 19. ANOVA results for these data ($F(5,720) = 108.12$, $p<.05$) indicate that the CBT, CFTGP, and GP concepts were in the first subset, UBT in the second, and CFT and PRFD providing the worst performance. It should be noted that the best performing guidance and symbology concepts (CBT, CFTGP, and GP) provide lateral path deviations that were approximately one-half of the worst group (PRFD and CFT). The magnitude of this result was operationally significant and may greatly facilitate accepting new types of operations requiring low flight technical errors.

Mean RMS values of vertical path deviations for guidance symbology concepts are provided in figure 20. The effect of GSC on VPD was statistically significant, ($F(5,720) = 105.48$, $p<.05$), with post-hoc analysis generating five subgroups. The CFTGP and GP generated the lowest vertical path deviation, with CBT being the next lowest followed by UBT, PRFD and finally CFT, in that order. Similar to results obtained for lateral path deviation, VPD results for the best group (CFTGP and GP) were less than one-half of the worst subset (CFT).

The promise of a tunnel/Flight Path Marker combination presentation is that the pilot, in a glance, can observe own ship position, orientation, and trajectory trend relative to the current and future path. This is in contrast to a flight director where awareness has to be built-up and inferred through observation of the CDI, flight director symbology, attitude indicator, and probably heading and turn-rate over a period of time. This additional information bundle increases pilot SA (see Figure 21) leading to lower workload (Figure 22) and better FTE (see above figures 19 and 20).

The exception among the tunnel concepts seemed to be Crows Feet Tunnel display concept. It is speculated that the CFT was perceived by the pilots as a tunnel with fragmented corner elements (crows' feet) and was lacking a focused information bundle, leading to the poorly perceived situation awareness. It should be noted that the addition of Ghost Plane guidance cue to the CFT concept (crows feet tunnel with Ghost Plane concept) may have moved the focus of the pilots from the corners to the central guidance cue. Unlike the Pitch/Roll Flight Director concept, the information was readily available but not perceived as easily or quickly as other tunnel concepts. Note that the CFTGP (not CFT) concept was based on a variation of NASA concept discussed in [33].

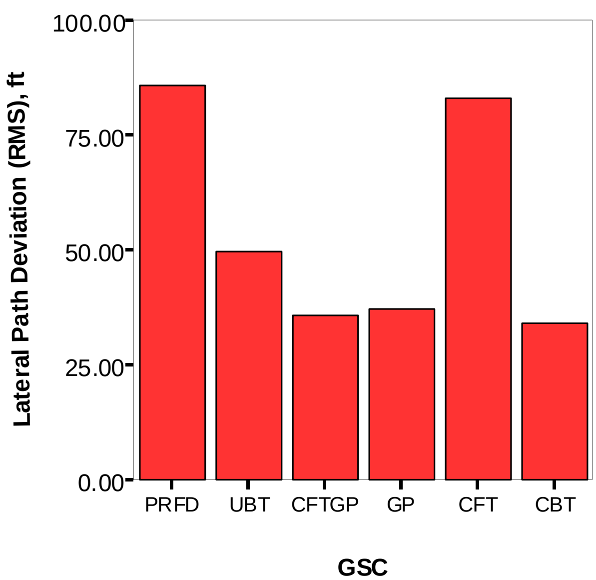


Figure 19: Mean RMS of Lateral Path Deviation

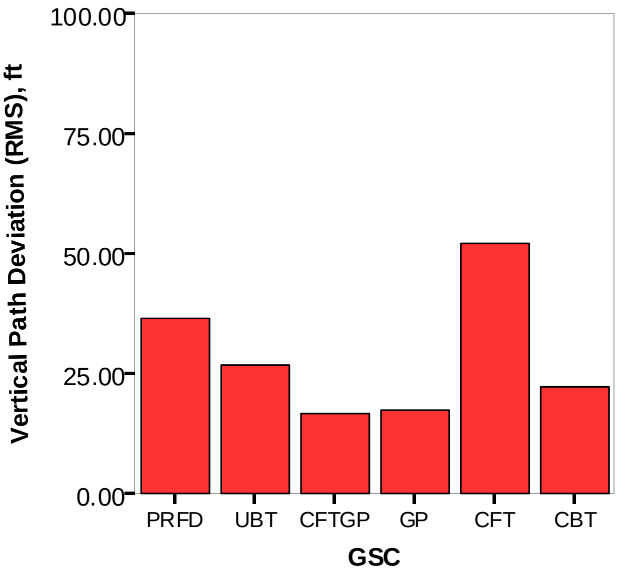


Figure 20: Mean RMS of Vertical Path Deviation

Results of perceived situation awareness for each guidance symbology concept are presented in figure 21. ANOVA results, ($F(5,720) = 68.84$, $p<.05$), indicate that the CFT and PRFD belonged to the first subset with the lowest perceived situation awareness which is consistent with the above FTE results. However, GP belongs to the 2nd subset, CFTGP to the 3rd, UBT to the 4th, and CBT to the last subset, with the values of the last subset almost six times as large as the first one, ~15 versus ~87, respectively. It can be seen from figure 21 that in general guidance symbology concepts with tunnel provided increased SA. As discussed above, the primary exception to that trend was the Crows Feet Tunnel. Path preview, as provided by the more visually complex tunnels, was a main reason cited for the SA results. EP comments indicated that the corners of CFT were sometimes perceived as multiple cues as some of evaluation pilots had difficulty forming the 3-D image of the pathway. The Crows Feet Tunnel required pilot's increased attention, lowering GSC situation awareness. Even though the vertical and horizontal path deviations for CFTGP concept were equal or less than those for CBT, perceived SA for CBT shows a higher value. This is consistent with EP comments and results of preferences questionnaires (to be discussed in the next sections). The reason for this might be that: a) unlike the CFT and CFTGP, the CBT's white tunnel was displayed as a continuous tunnel (not fragmented path information) extending to the destination and b) the size of the CBT's tunnel was exactly the same as the limits of the CDI values and not spread farther out of center of the viewing area.

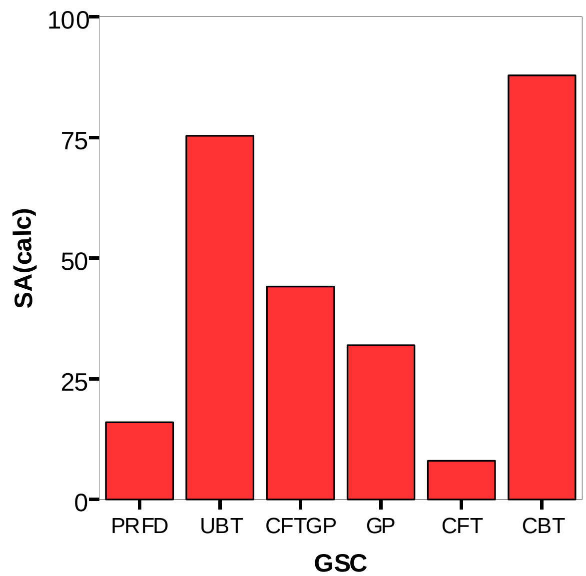


Figure 21: Mean of Situation Awareness, SART

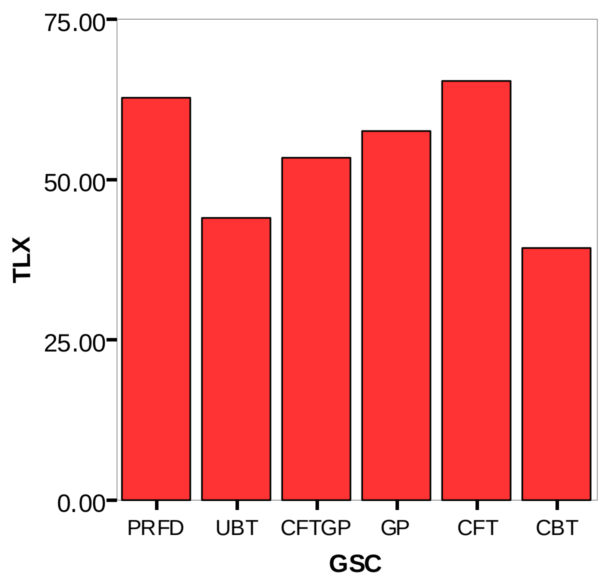


Figure 22: Mean Workload Measure, TLX

The effect of guidance symbology concept on TLX results was statistically significant, ($F(5,720) = 37.22$, $p<.05$). Five subgroups were formed from post-hoc analysis. The TLX data indicate that CBT and UBT produced the lowest perceived workload, CFTGP and GP produced the next higher workload, and the CFT and PRFD created the highest workload (Figure 22) as a subgroup. This is somewhat consistent with the results of calculated situation awareness as both PRFD and CFT provided the lowest SA, and UBT and CBT provided the highest SA. As noted above, pilot comments indicated that the corners of CFT were sometimes perceived as multiple cues with Evaluation pilots having difficulty forming the 3-D image of the pathway. Again, the fragmentation of the information, by the crows feet corners about the current and future path, required pilot's increased attention (low GSC situation awareness) and also increased their scanning effort (high GSC workload). The contribution of the Ghost Plane in CFTGP, as a path based guidance cue, elevated the standing of CFTGP to the second subset with GP, for both SA and TLX. Here again, similar to the SA results, CBT showed better results (lower TLX) than CFTGP, due to the issues discussed above.

Effect of Evaluation Pilot Qualifications

An ANOVA performed on objective and subjective measures for evaluation pilot qualification levels (Rating) showed statistically significant results for LPD, ($F(2,720) = 4.64$, $p<.05$); VPD, ($F(2,720) = 3.07$, $p<.05$); and SA, ($F(2,720) = 6.63$, $p<.05$) but not for TLX, ($F,2,720)=2.78$, $p=0.063$).

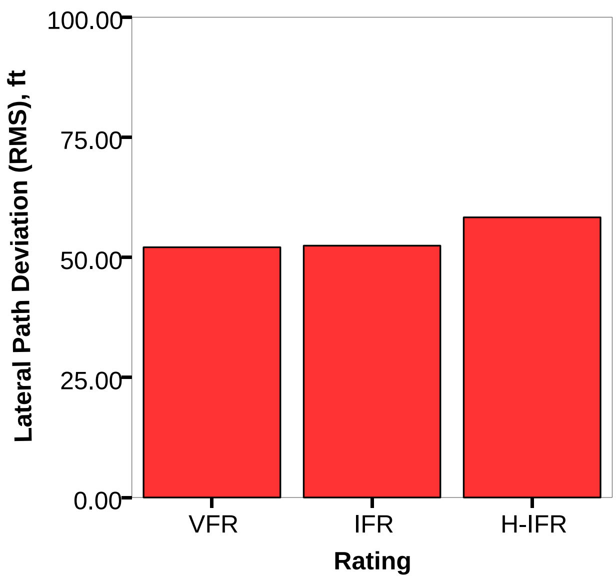


Figure 23: Mean RMS of Lateral Path Deviation

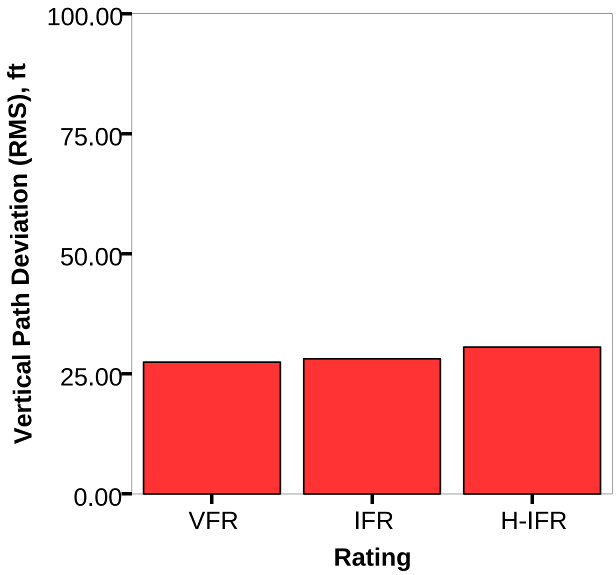


Figure 24: Mean RMS of Vertical Path Deviation

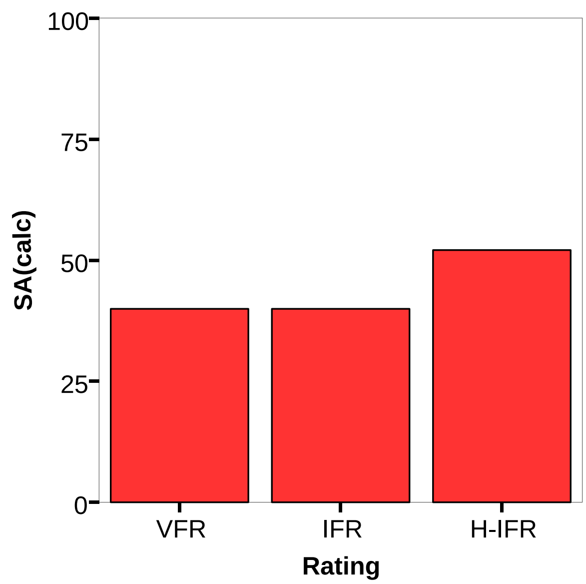


Figure 25: Mean of Situation Awareness, SART

The above results appear to be unusual as the H-IFR pilots with higher perceived situation awareness than other pilots were not able to have the same level of flight technical errors. However, as it will be shown in the analyses of the variables interactions and the results of the block questionnaires, it is not surprising that H-IFR pilots gained increased situation awareness from the advanced displays but were not able to assimilate and implement the new concepts as well as the other pilots. As it will be shown below, for example, these pilots were able to have lower flight technical errors when using a familiar guidance concept such as a flight director (PRFD) but not when using the new Crows Feet Tunnel.

Independent Variables Interactions

Careful study of all interactions showed that there were no statistically significant interactions between TPC and guidance and symbology concepts for the independent variables considered above.

There were no statistically significant interactions between evaluation pilot levels (Rating) and TPC, either. However, statistically significant interactions were found between Rating and GSC for objective measures LPD ($F(10,720) = 2.034$, $p<.05$); VPD ($F(10,720) = 3.37$, $p<.05$); and also SA ($F(10,720) = 1.8$, $p<.05$) but not for TLX.

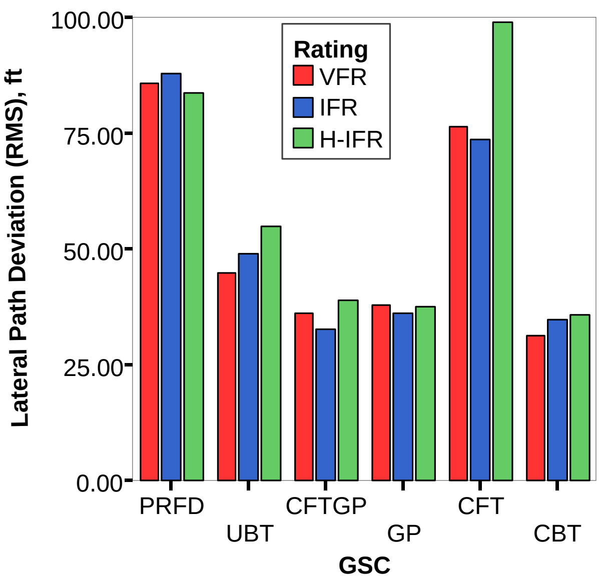


Figure 26: Mean of Lateral Path Deviation

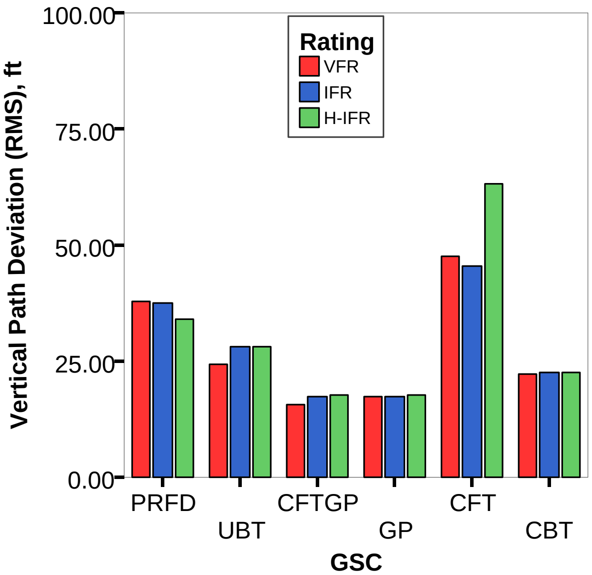


Figure 27: Mean of Vertical Path Deviation

As shown above (Figures 26 - 27), H-IFR pilots performed somewhat better using flight director (traditional guidance) and only slightly worse than the other two pilot groups for other guidance symbology concepts except for CFT. This could be attributed to the effects of the fragmented path information provided by CFT, which was the most challenging GSC even for the other two pilot groups. In addition, information provided by the visual integration of SVS terrain and advanced guidance symbology seemed to be easier to assimilate by the lower-time pilots. This is consistent with the results of the perceived SA (see Figure 25). The H-IFR pilots rated their SA higher than other pilots for all concepts except for CFT. It seems that H-IFR pilots appreciated (perceived positively) any type of modern guidance compared to baseline display (BSBG with flight director) (see also block questionnaires), however they were not able to utilize this increased SA to reduce (improve) their flight technical errors at the same rate. Overall, consistent with other two EP groups, H-IFR pilots also perceived higher SA with CBT and UBT.

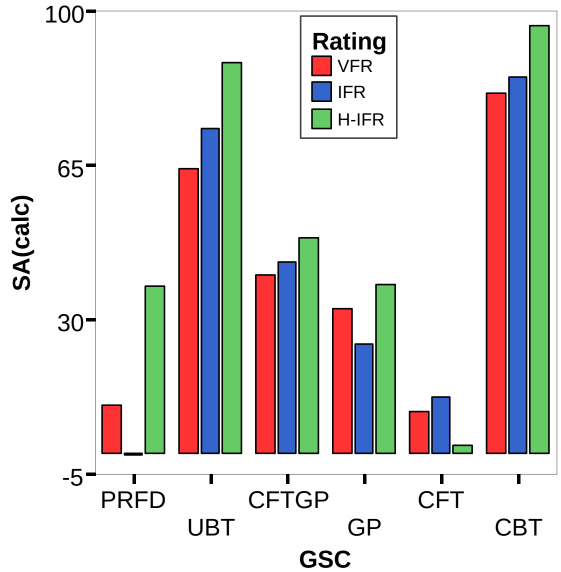


Figure 28: Mean of Situation Awareness

Results of Objective Measures for Segmented Treatment

As mentioned above, there were no significant interactions between the terrain portrayal concepts and the guidance symbology concepts for the enter scenario. The question remained if one would observe any interactions between TPC and GSC for a specific segment of the scenario as the entire scenario was compromised of various levels of required maneuvering. Thus, the entire run was subdivided into three distinct segments and the time history of objective measures was analyzed for each segment. As mentioned earlier, the subjective measures were designed to be non-intrusive to pilot performance and, by design, the questionnaires were administered after the completion of each run and can only be applied to the entire scenario. Therefore, the remaining question is if there were any interactions between terrain portrayal concepts and guidance symbology concepts for any of the three segments of the scenario base on the resulting flight technical errors. The complete results of FTE for the segmented treatment is shown in Appendix G and only the results of the FTE for segment 3 will be discussed here. Segment 3 contained the most challenging maneuver of the scenario while the aircraft was maneuvered within Merrill Pass at very close proximity of the surrounding terrain. The results of FTE for segment 3 are discussed below (see Figures 29-32). Note that the scale of the FTE is expanded to 220 ft to account for the larger RMS of deviations in segment 3.

Effect of Terrain Portrayal Concepts on Flight Technical Errors for Segment 3

The effect of TPC on the results of mean RMS of lateral path and vertical path deviations were similar to the results obtained for the analyses of the complete scenario (recall Figures 15-16) but they were not statistically significant as the flight technical error were dominated by the guidance symbology effect in this more complex segment of the flight (see also next section). The intensity of maneuvering tasks during this segment introduced a larger degree of variability into the data that overwhelmed the relatively small effects from terrain portrayal concept.

Effect of Guidance Symbology Concepts on Flight Technical Errors for Segment 3

The effects of the GSC on the segment 3 values of mean RMS of the lateral path deviation (s3laerms) and vertical path deviation (s3verms) are plotted in figures 29 and 30, respectively. The results of lateral path deviation for GSC effects was statistically significant, $F(5, 717)= 90.0$ ($p<.05$). Very similar to the results of the complete scenario (Figure 15), Pitch/Roll Flight Director and Crows Feet Tunnel exhibited the highest mean RMS of lateral path deviation for this segment. PRFD and CFT placed in the first and second post hoc group, respectively, while CBT, GP, and CFTGP were in a third group showing the lowest levels of lateral path deviation. Again, the guidance symbology concepts with path based guidance cues outperformed the other three guidance and symbology concepts tested here.

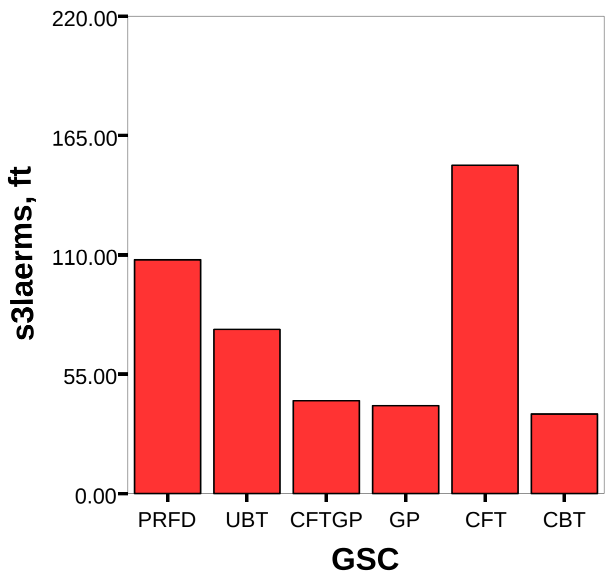


Figure 29: Mean of Lateral Path Deviations for Segment 3, s3laerms

The mean RMS of the vertical path deviations for segment 3 (s3verms) for guidance symbology concepts are plotted in figure 26. Here again, the results were statistically significant, ($F(5,717)=63.9$, $p<.05$), and the overall trend for this segment was the same as the results of the analyses for the complete scenario (Figure 16). While the post hoc groupings were somewhat different, overall the CFT shows the highest mean RMS of vertical path deviation followed by UBT, PRFD and CBT as a second group. Here again, the two concepts with the Ghost Plane as path based guidance cue (CFTGP and GP) resulted in the lowest vertical path deviation. This indicates that during complex maneuvers near the terrain (segment 3) the displays with path based guidance cue (GP and CFTGP) helped evaluation pilots maintain their vertical track better than the other Guidance and symbology concepts. Note that this seems to be in contrast to the SA and TLX results as the CBT provided better subjective ratings, however the SA and TLX measures were gathered for the entire scenario and not for the segment 3.

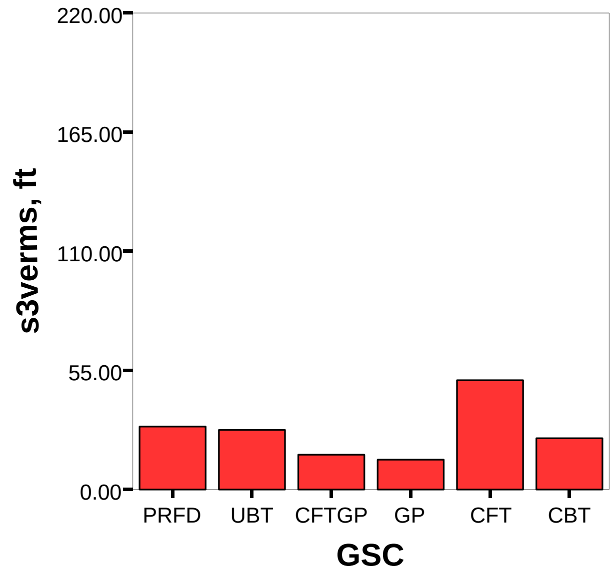


Figure 30: Mean of Vertical Path Deviations for Segment 3, s3verms

Effect of Evaluation Pilot Qualifications on Flight Technical Errors for Segment 3

The mean RMS of the LPDs and VPDs for segment 3 were analyzed compared against the three evaluation pilot subgroups and there were not any statistically significant results across EP Ratings.

Interaction Effects for Segment 3

The only statistically significant interaction results for segment 3 were obtained for the interaction effects of the guidance symbology concepts and Rating. Not only were significant FTE interactions obtained for Rating and GSC but also the level of the lateral and vertical path errors were much higher for the various Ratings. Here again, similar to the results of the complete scenario (Figures 19 and 20), pilots performed best when using guidance and symbology concepts with guidance cue systems (CFTGP, GP and CBT) and weaker, resulting in highest FTE when using CFT and PRFD. Within each GSC, the high time pilots performed better (less lateral and vertical path deviations) than other evaluation pilots when using flight director, as they were more familiar with this type of guidance than less experienced evaluation pilots. However, the same group, H-IFR, did not perform as well as the other evaluation pilots when using CFT, consistent with their perceived SA rating that was shown in Figure 21.

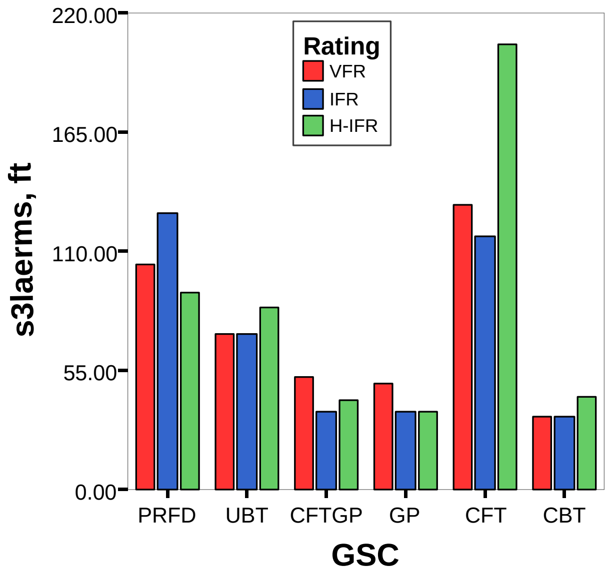


Figure 31: Mean of Lateral Path Deviations for Segment 3

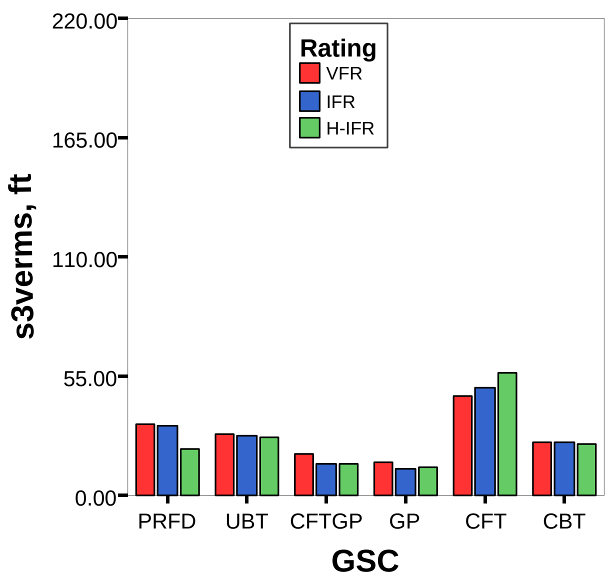


Figure 32: Mean of Vertical Path Deviations for Segment 3

Results of No-Guidance/No-Tunnel Runs

As it was shown in both the results of the complete scenario and the segmented analysis of flight technical errors, the effect of guidance on pilot performance measures was very strong. The purpose of the No Guidance/No Tunnel (NGNT) runs was to remove the influence of the GSC and study the main terrain effects on the basic primary flight display. The experiment scenario was the same as previous with-GSC runs. The Blue Sky Brown Ground display with the out the window visual display simulating visual meteorological conditions was used as a baseline VFR test condition. Here again the evaluation pilot's task was to fly at 500 ft AGL but without any path guidance, using terrain information provided by the PFD, ND and OTW display.

Effect of Independent Variables Subjective Measures

As it is shown in Figure 33, the calculated situation awareness for terrain portrayal concepts was statistically significant, (F= (3,119) =13.0, p<0.05). In fact, the post hoc analysis showed that use of BSBG in VMC and PR display in IMC provided the highest SA group while EBG belonged to the second highest SA group. The lowest SA group computed was for CCFN, with a negative value. Recall that calculated SA was computed from SART = Understanding – (Demand-Supply). Thus, negative value for three dimensional SART means that the magnitude of 'Demand on Attentional Resources' had been higher than the sum of both 'Understanding of the Situation' and 'Supply of Attentional Resources.'

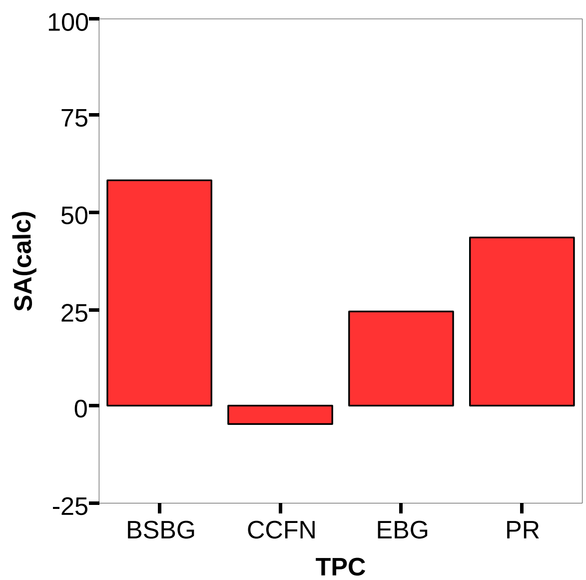


Figure 33: Mean of SA for Basic SVS (NGNT)

There were no statistically significant SA results for different evaluation pilot qualifications levels (Rating).

The perceived workload, shown in Figure 34, was statistically significant, (F=(3,119)=7.8, p<0.05) and confirmed the same results as those obtained when displays with guidance were used. Here, of course, BSBG in VMC (48.29) showed the lowest workload sharing the same post hoc group as PR (54.1) in IMC. Photo Realistic terrain portrayal concept also shared the second group with EBG (62.67) while CCFN placed in the third group (66.2) and shared this group with EBG.

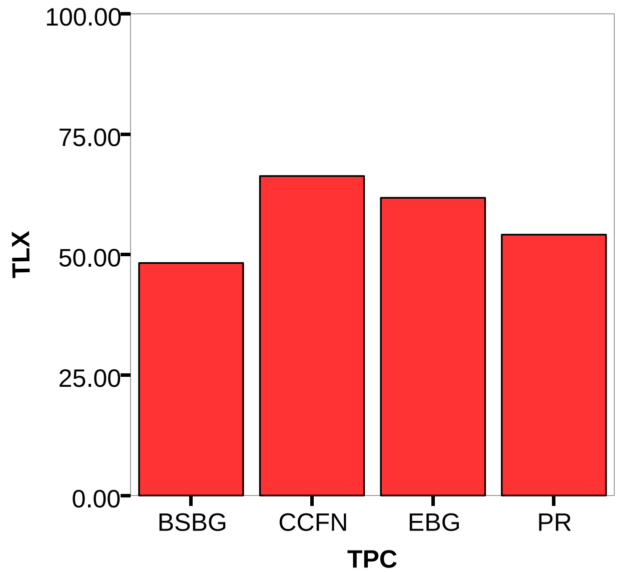


Figure 34: Mean of NASA TLX Score for Basic SVS (NGNT)

There were no statistically significant TLX results for different evaluation pilot qualification levels (Rating).

Independent Variables Interactions

There were no statistically significant interactions between the TPC and EP Rating for subjective measures.

Results of Rare Event Scenario

As discussed earlier, the rare event scenario was a subset of the no guidance no tunnel display combinations. Each evaluation pilot was exposed to the rare event scenario only once, at the conclusion of the two-day experiment. The order of the terrain portrayal concept for each pilot was randomly selected and care was taken to expose the pilot at least once to the particular display (used in his/her rare event scenario) prior to the rare event use. As discussed earlier, the purpose of this rare event scenario was to see if the presence of the terrain on PFD affected the evaluation pilot's situation awareness of the imminent emergency conditions. Only two of several rare event objective measures are discussed here. The two new measures are the Recognition Time in Seconds (TRECS) and the Time to the End of the flight in Seconds (TENDS).

Figure 35 shows the distribution of TRECS of each rare event run for each evaluation pilot tested. This time was measured from the onset of the run to the moment that the evaluation pilot recognized the impending emergency. Plotted is also the outcome of the scenario. Those runs that ended with a controlled flight into terrain from continuation of flight path were designated as Straight-CFIT (S-CFIT); those CFIT runs that occurred after an attempt was made to return to a lower terrain were labeled as U- turn CFIT (U-CFIT); and cases where the evaluation pilots performed a successful (intentional) Off-field landing were labeled as Straight landing (S-land). As mentioned earlier, evaluation pilots were instructed to communicate their intentions when avoiding any hazardous terrain. In Figure 35, the green circle with the label 'Y' for COMM refers to those pilots who communicated their situation or their intensions to the test conductor. The blue circle with the label 'N' means these pilots did not communicate.

All rare event runs were terminated prematurely. Out of the 15 evaluation pilots tested, 12 pilots encountered a CFIT straight ahead and two pilots experienced a CFIT during an attempt to return to lower grounds while executing a 180 degree turn. One pilot recognized the problem and attempted to land safely straight ahead utilizing the one mile out the window visibility. Only six evaluation pilots had recognized the impending emergency early enough and had time to communicate their intentions before/while taking an action. Note that the onset of 'icing' simulation occurred after one minute into the experiment run. The full 'icing' was encountered after additional 60 seconds, i.e. 2 minutes into the flight (see 120 seconds lines in Figure 35).

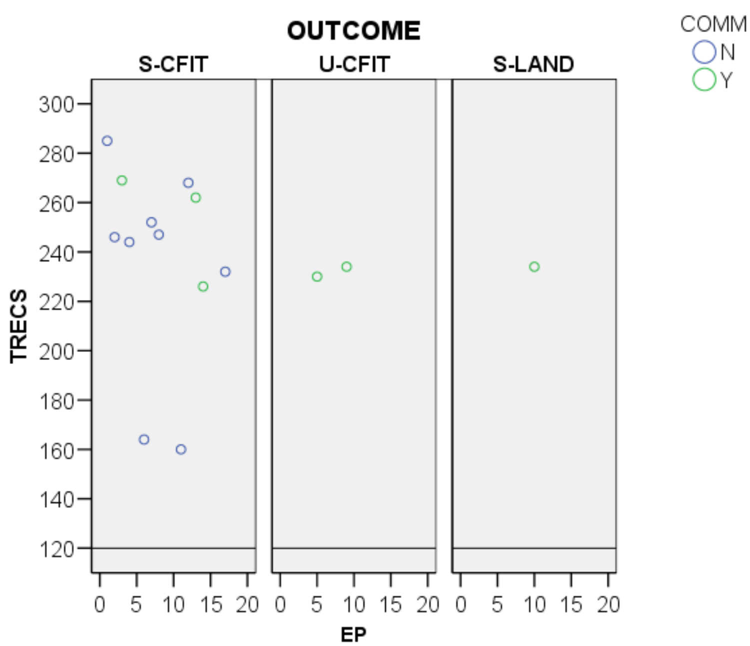


Figure 35: Results of Recognition Time for each EP by OUTCOME and Verbal Communication

Results of Rare Event Measures by Terrain Portrayal Concept

It should be noted that the following results were not statistically significant ($F(3,8)=3.2$, $p<0.09$). However, the data suggests interesting trends for various terrain portrayal concepts. Figure 36 shows the mean values of the recognition time and scenario end time, for different terrain portrayal concepts. Recall that the baseline Blue Sky Brown Ground display concept was used with simulated VMC and the results are accordingly labeled as BSBGV while the other displays were utilized in a simulated IMC. Therefore, one could consider the results of the BSBGV as the time that the pilots were utilizing the out of window visual cues as compared to the results of CCFN, EBG and PR which were in simulated IMC where the pilots had to heavily rely on the head down displays. Accordingly, it could be concluded that using CCFN without any guidance or tunnel in simulated IMC during an emergency, did not help pilots to perform as well as they could have performed if they had used baseline display in VMC or if they had used EBG of PR in simulated IMC. In fact the pilots who used EBG in IMC were able to recognize the problem (TREC) about the same time as those who used the baseline display. Furthermore, these pilots were also able to prolong their flights (TENDS) as long as those who used BSBGV. The results of the TREC and TENDS for Photo Realistic terrain portrayal concept shows that pilots who where using PR in IMC had a slightly longer recognition time but more time between recognition of the problem and the end of their flights than those pilots who used the baseline BSBG in VMC. As mentioned earlier, the above results were not strong enough in statistical power and significance. However, the trend observed from the above results could indicate that using higher quality terrain portrayal concepts, such as EBG and PR in IMC, might have provided evaluation pilots the same or better terrain situation awareness and also early warning as the out the window visual cues by the BSBG in VMC.

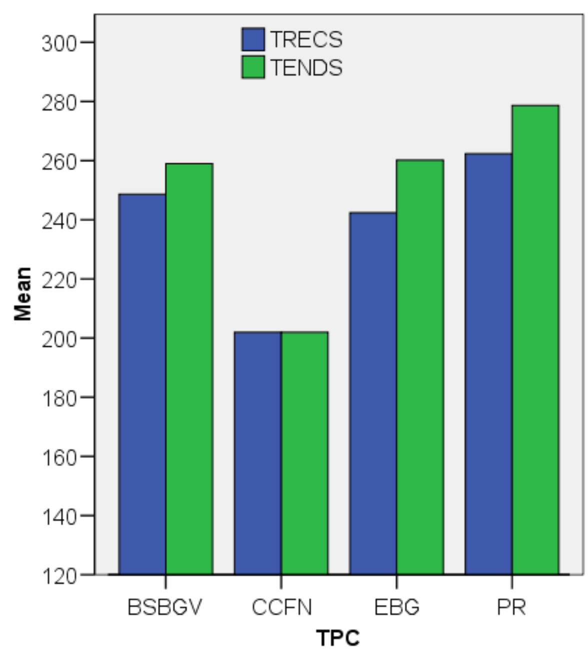


Figure 36: Mean Recognition Time for each TPC

Block Interviews

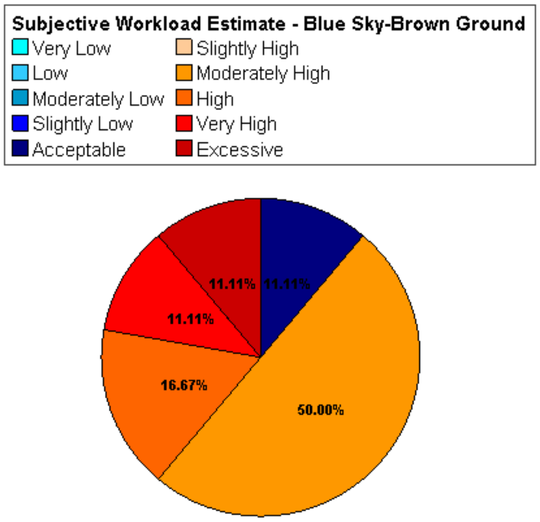
Recall that in the first block of runs, combinations of terrain portrayal concepts and guidance symbology concepts were presented to each one of the evaluation pilots. During the second block of the runs, the basic SVS displays (no guidance, no tunnel) were tested. After the completion of both blocks two batteries of questionnaires were administered, each specific to each block. Appendix C shows a copy of both Block Questionnaires. Accordingly, the first battery of the questionnaires was specific to guidance, terrain, and terrain/guidance interactions. The second battery of questionnaires focused on the terrain portrayal concepts and the value of the basic SVS display. Both packages covered a series of workload, situation awareness, and preferences related questions.

Results of Block One Questionnaires

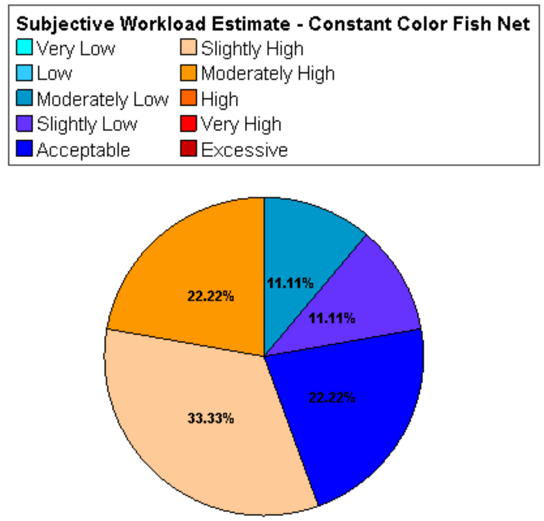
Here the evaluation pilots were shown all display combinations tested and were asked to answer the questionnaires for each display combination. In the first block of questionnaires, pilots were asked to answer the questions related to TPC independent of any GSC. In the second block, they were asked about the guidance symbology concepts regardless of TPC used.

Answers Related to Terrain Portrayal Concepts

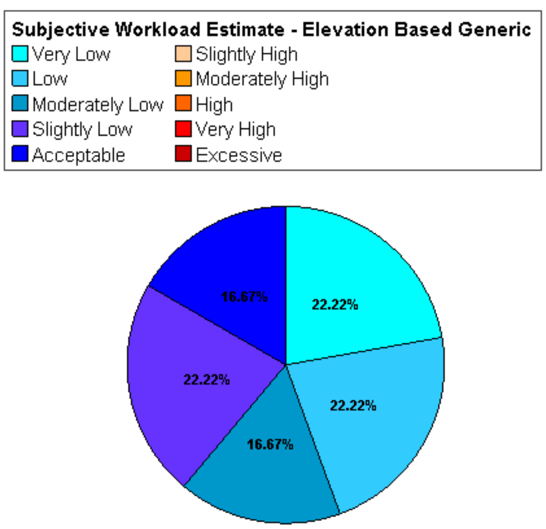
Figure 37 shows the level of workload perceived by evaluation pilots for different terrain portrayal concepts independent of GSC. Note the ratings for workload were color coded from very low to excessive and the color scale in the pie charts starts from light blue to darker blue for low to acceptable and continues towards darker red for the excessive rating. Overall, one can observe that the colors of perceived workload for BSBG and CCFN are much darker and more towards red than those of EBG and PR are. This means (consistent with TLX results) that the perceived workload for PR and EBG was lower than for CCFN and BSBG.



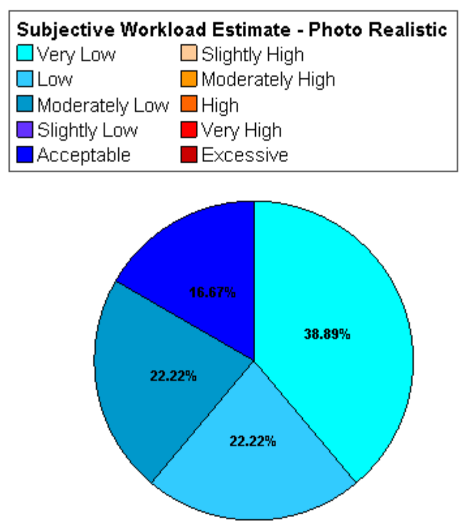
37a) Workload Question, BSBG



37b) Workload Question, CCFN

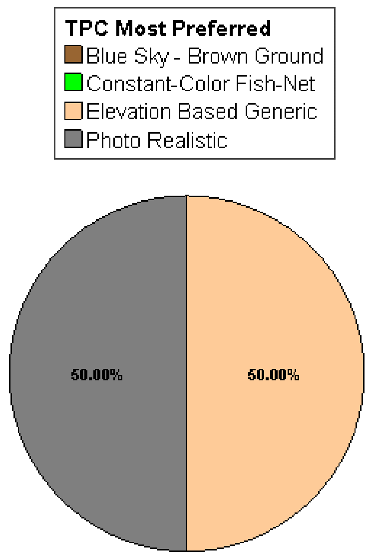


37c) Workload Question, EBG

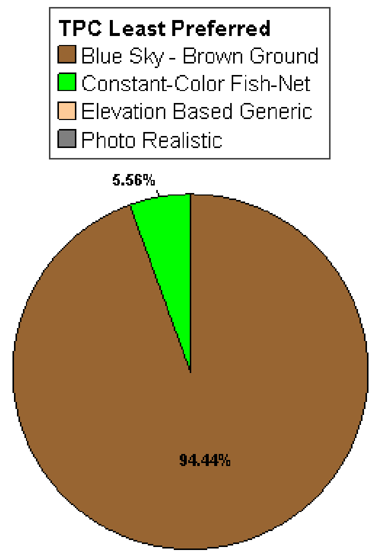


37d) Workload Question, PR

Figure 37: Levels of Overall Workload Perceived by Each TPC



38a) Most Preferred TPC



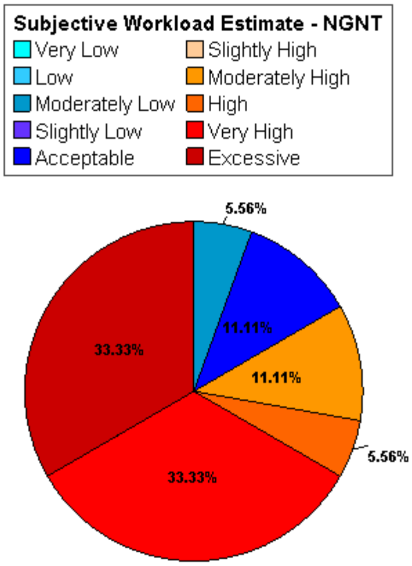
38b) Least Preferred TPC

Figure 38: Overall Preferences for TPC

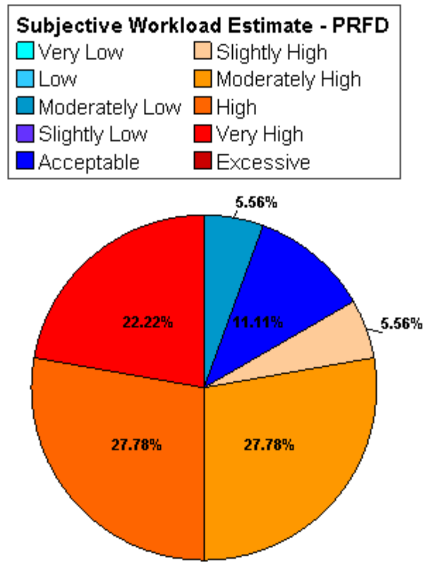
Next, Figure 38 shows the overall EP preferences for each TPC regardless of GSC. This summary chart for terrain portrayal concepts indicates the dislike for BSBG and CCFN, and clearly shows the pilots' preferences for EBG and PR terrain portrayal concepts. One interesting result was the exact split of preference between EBG and PR as the most preferred TPC. In fact, this exact split between EBG and PR was maintained within pilot groups only for the VFR pilots, while most of IFR pilots preferred PR over EBG and H-IFR preferred EBG over PR.

Answers Related Guidance Symbology Concepts

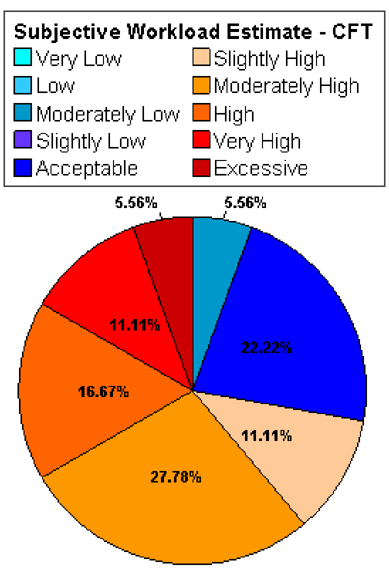
Figure 39 shows the level of workload perceived by evaluation pilots for different guidance symbology concepts independent on the TPC. Again, the ratings for workload start from very low to excessive. Overall, one can observe that the perceived workload for NGNT concept and PRFD were much higher (red/darker) than those of other concepts. The lowest workload ratings were observed for CBT. In fact, looking at Figure 40, it can be seen that a clear relationship exists between the workload ratings and preferences. Here again the CBT shows the highest EP preference rating. As it was seen from the results of the between-run measures (both subjective and objective), the guidance and symbology concepts with path based guidance cue and a tunnel showed the highest SA and lowest FTE and workload measures. Within this preferred subgroup of guidance and symbology concepts, CBT showed even better block scores than CFTGP. Recall that in addition to the differences in the design of the two guidance and symbology concepts (CBT versus CFTGP) the size of the tunnel for CBT matched exactly the vertical and lateral boundaries of the CDIs while the size the CFTGP tunnel was almost twice the CDIs. While the tunnel was not intended to indicate desired or required performance boundaries, EP's tendency was to associate the CDI limits (max deflections) with the lateral and vertical dimensions of the tunnel. This partially accounts for some of the SA results as well. One other reason cited by evaluation pilots (see also the summary of EP comments in the next section) was the difficulty by H-IFR pilots with the Crows Feet Tunnel.



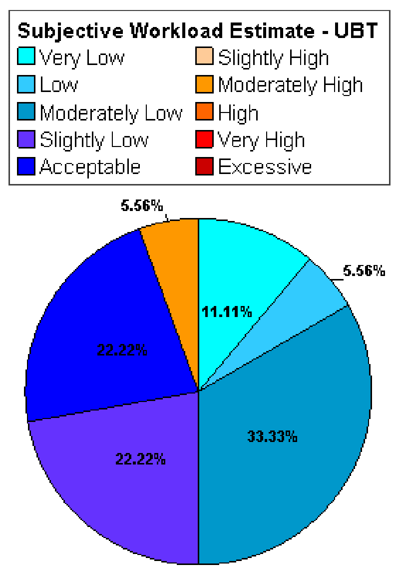
39a) Workload Question, NGNT



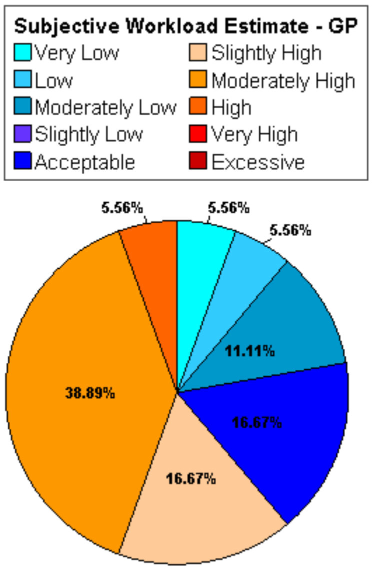
39b) Workload Question, PRFD



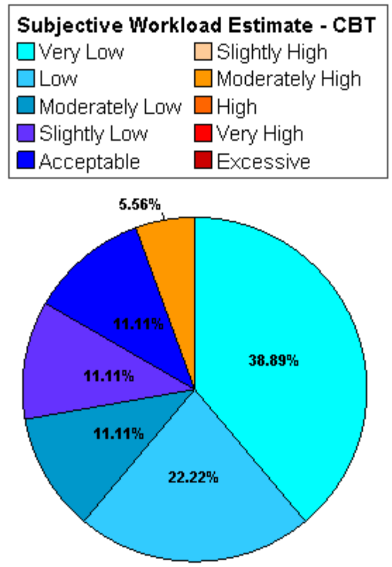
39c) Workload Question, CFT



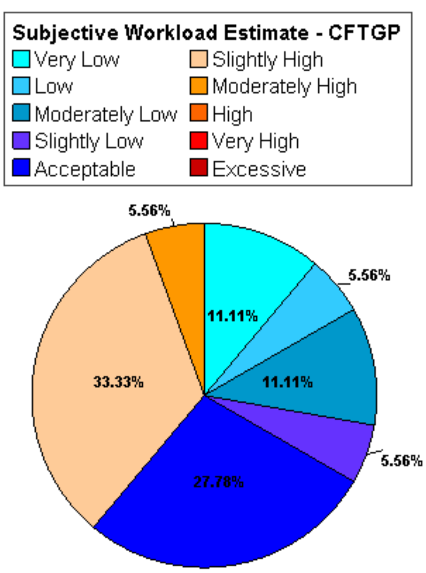
39d) Workload Question, UBT



39e) Workload Question, GP

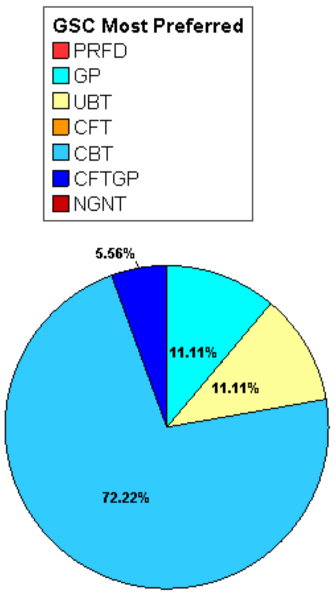


39f) Workload Question, CBT

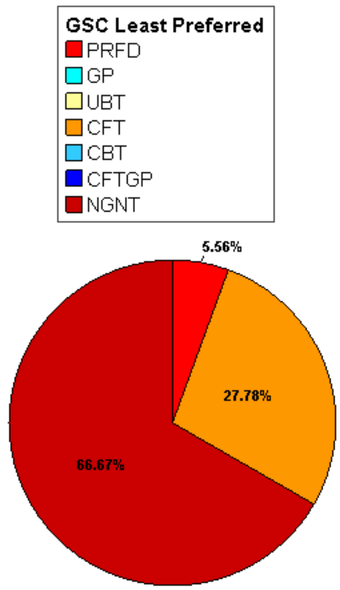


39g) Workload Question, CFTGP

Figure 39: Levels of Overall Workload Perceived by Each GSC



40a) Most Preferred GSC

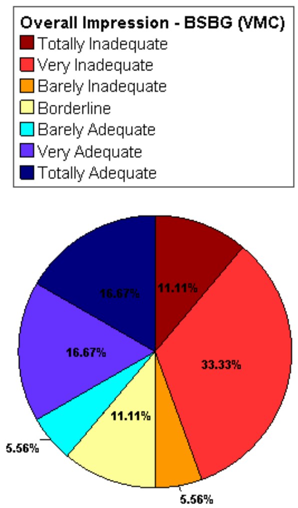


40b) Least Preferred GSC

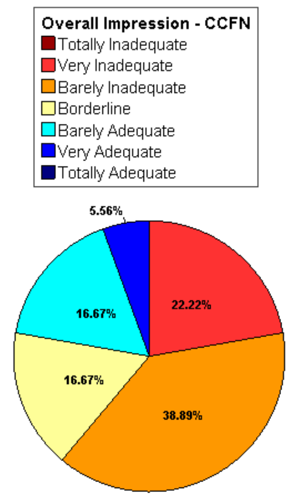
Figure 40: Overall Preferences for GSC

Results of Block Two Questionnaires

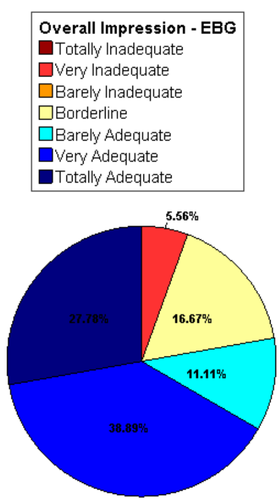
Evaluation pilots were shown all four basic SVS displays without any guidance and any tunnel and were asked to answer the questionnaires for each terrain portrayal concept. In the first set of questionnaires pilots were asked to rate their overall impression of the TPC (Figure 40). Here, BSBG in VMC and CCFN in IMC were clearly dominated by inadequate rating and EBG and PR in IMC were perceived as more towards adequate. This might seem rather surprising that the BSBG in VMC was rated lower than PR and EBG in IMC. Pilots' strong preference for EBG and PR might have overshadowed the relevance of OTW in their rating of their overall impression of terrain portrayal concepts. Also recall that the OTW presented to the pilots was based on the PR terrain projected on the GAWS front wall. The only difference between the PR displayed on the primary flight display and the one in OTW was the Minification Factor.



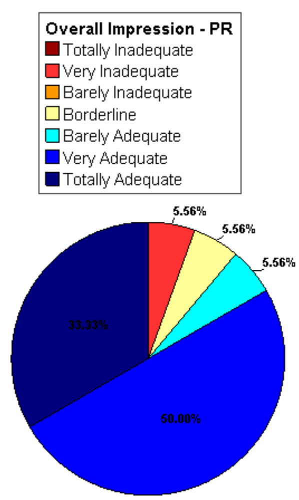
41a) BSBG in VMC



41b) CCFN in IMC



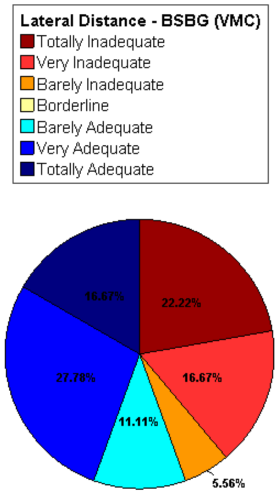
41c) EBG in IMC



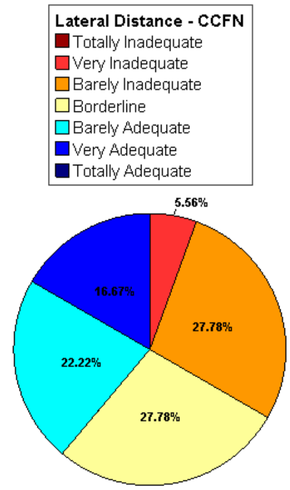
41c) PR in IMC

Figure 41: Overall Impression of TPC, NGNT

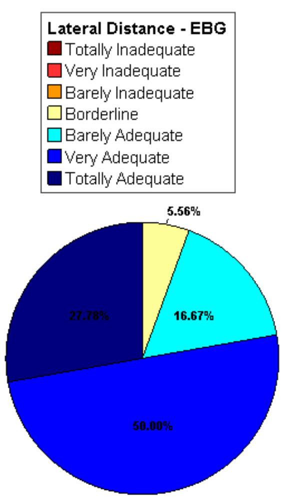
In the second set, evaluation pilots were asked to rate the information provided by different terrain portrayal concepts for lateral distance from terrain (Figure 42). Here again, BSBG in VMC and CCFN in IMC were rated as less adequate than EBG and PR in IMC. This is consistent with the FTE results shown in Figure 29 for lateral path deviation.



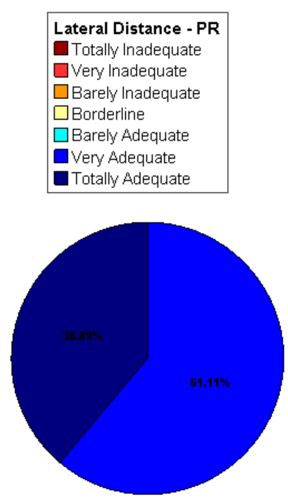
42a) Lateral Distance, BSBG in VMC



42b) Lateral Distance, CCFN in IMC



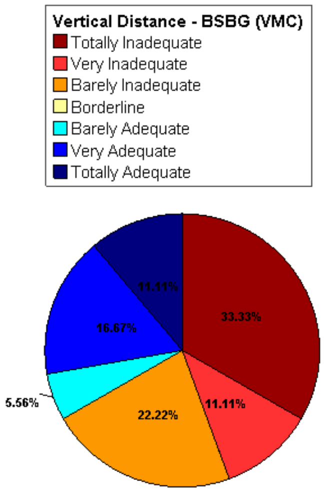
42c) Lateral Distance, EBG in IMC



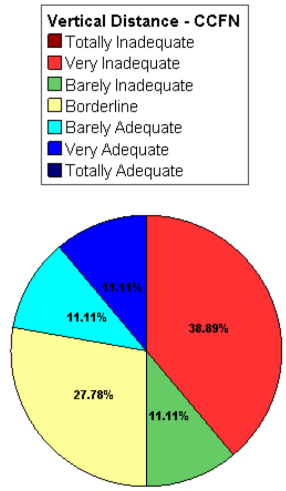
42d) Lateral Distance, PR in IMC

Figure 42: Lateral Distance from Terrain, NGNT

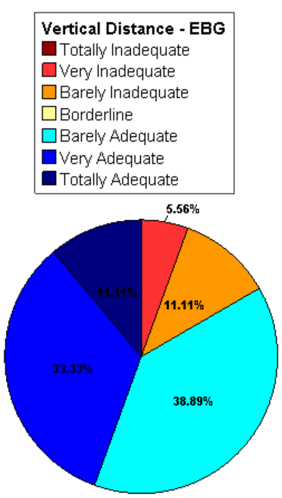
Similarly, response to questions related to the third set, information regarding the vertical distance from terrain (Figure 43), was also consistent with the results of SA (Figure 33).



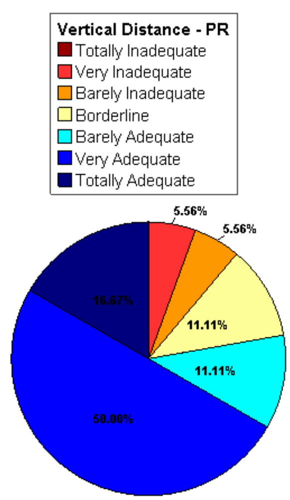
43a) Vertical Distance, BSBG in VMC



43b) Vertical Distance, CCFN in IMC



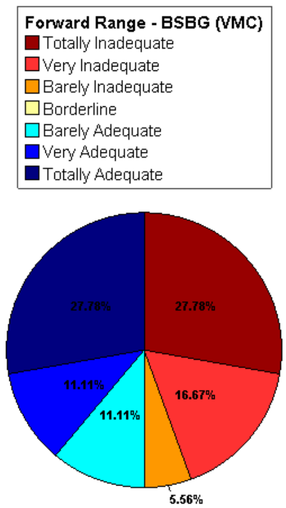
43c) Vertical Distance, EBG in IMC



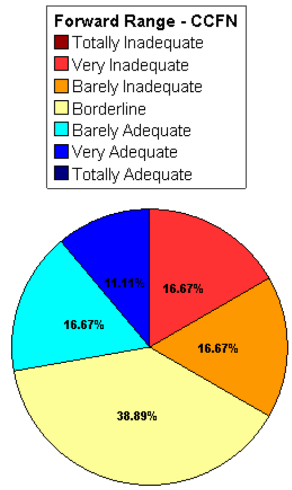
43d) Vertical Distance, PR in IMC

Figure 43: Vertical Distance from Terrain, NGNT

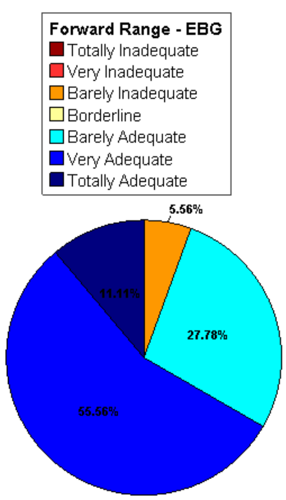
The fourth set of questions was related to the information provided by terrain portrayal concepts regarding the forward range from the terrain (Figure 44). It seems that the evaluation pilots could gain more information related to forward range with CCFN than with BSBG in VMC but the highest scores were again given to EBG and PR.



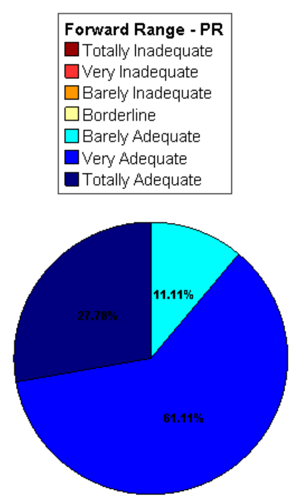
44a) Forward Range, BSBG in VMC



44b) Forward Range, CCFN in IMC



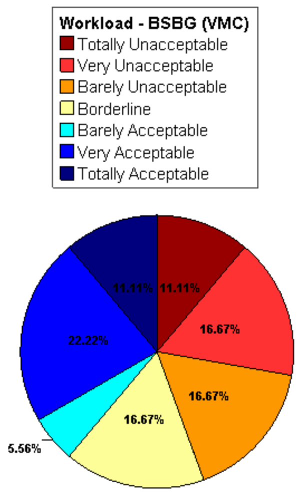
44c) Forward Range, EBG in IMC



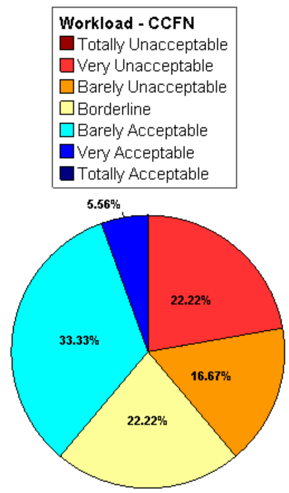
44d) Forward Range, PR in IMC

Figure 44: Forward Range from Terrain, NGNT

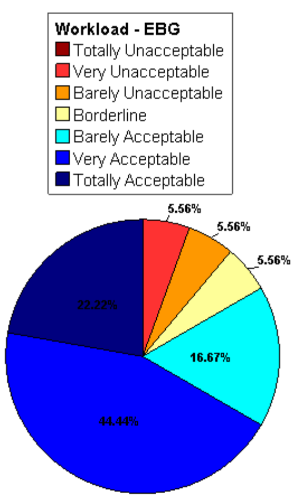
The next sets of questionnaires dealt with workload and SA as shown in Figures 45 and 46, respectively. The perceived SA and workload scores were consistent with the results of SART shown in Figure 33 and TLX in Figure 34, respectively. Again, PR and EBG scored better than CCFN for both SA and workload.



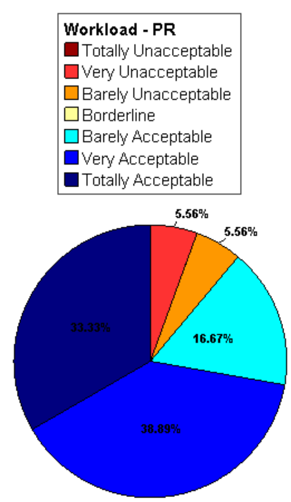
45a) Workload Question, BSBG in IMC



45b) Workload Question, CCFN in IMC

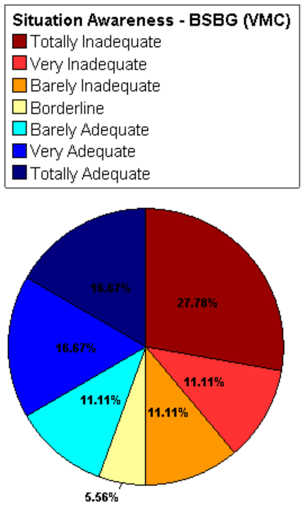


45c) Workload Question, EBG in IMC

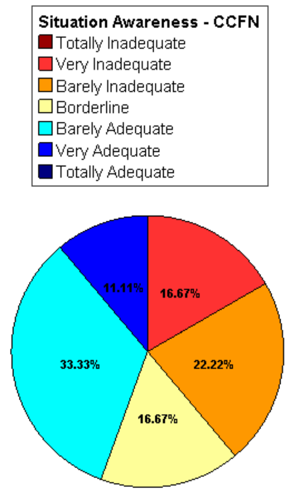


45d) Workload Question, PR in IMC

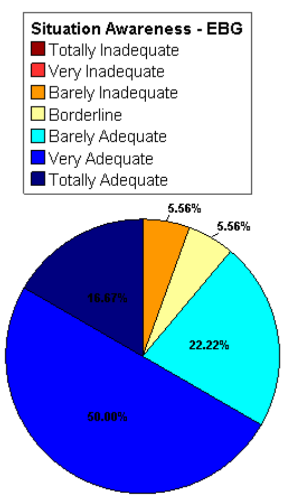
Figure 45: Perceived Workload, NGNT



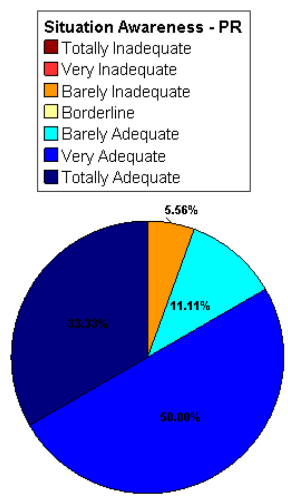
46a) SA Question, BSBG in VMC



46b) SA Question, CCFN in IMC



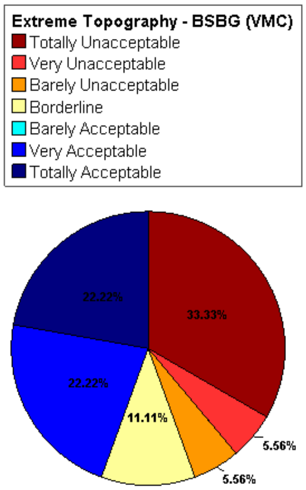
46c) SA Question, EBG in IMC



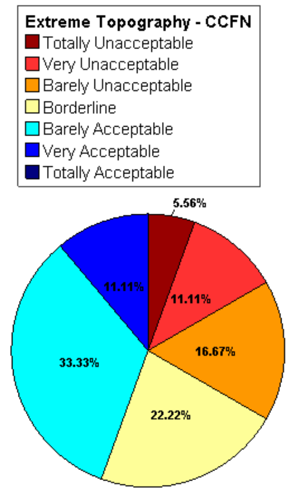
46d) SA Question, PR in IMC

Figure 46: Perceived Situation Awareness, NGNT

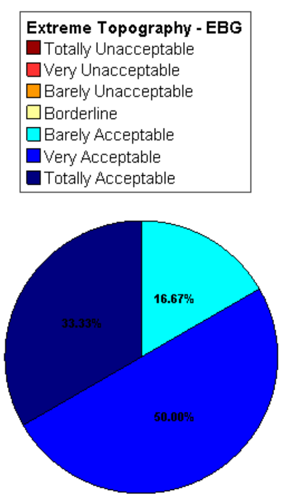
The next set of questions was specific to the how well the TPC provided the information about the extreme topography (Figure 47). Here again both EBG and PR were rated higher than CCFN and even BSBG in VMC.



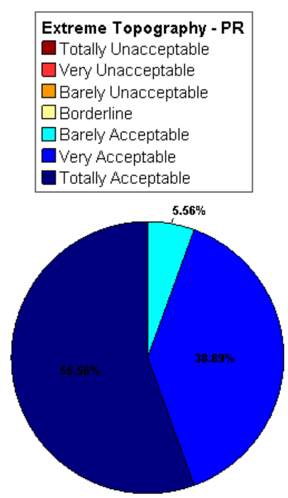
47a) Topography Question, BSBG in VMC



47b) Topography Question, CCFN in IMC



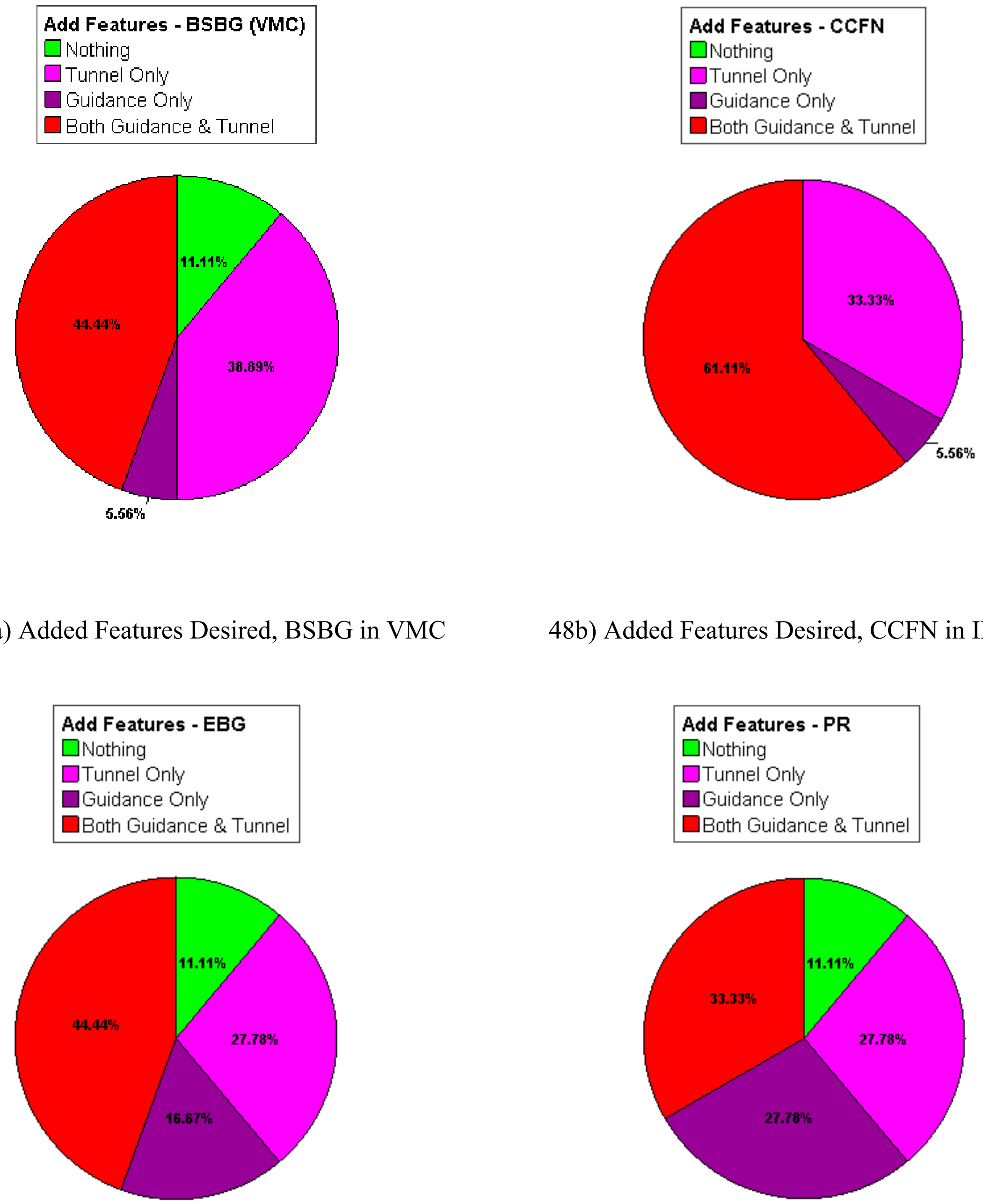
47c) Topography Question, EBG in IMC



47d) Topography Question, PR in IMC

Figure 47: Recognition of Extreme Topography, NGNT

Finally, evaluation pilots were asked if they would like to see any added features to the four terrain portrayal concepts, Figure 48. The suggested options for the added features were: a) no additions needed, b) it needs tunnel guidance, c) it needs guidance cue, and d) it needs both tunnel and guidance cue. A careful observation of the pie charts shows that pilots liked to see both tunnel and a guidance cue for all terrain portrayal concepts. Surprisingly, CCFN seemed to be unacceptable without any guidance and tunnel (no green area).



48a) Added Features Desired, BSBG in VMC

48b) Added Features Desired, CCFN in IMC

48c) Added Features Desired, EBG in IMC

48d) Added Features Desired, PR in IMC

Figure 48: If Any Added Features Needed, NGNT

Exit Interviews - Results of Evaluation Pilot-Preferences Questionnaires

At the conclusion of the experiment and structured questionnaires, evaluation pilots were shown the pictures of the 28 possible combinations of terrain portrayal concepts and guidance and symbology concepts and were asked to rank their most favorite display first as number one, second most favorite as number 2, and etc. A summary of the average results and standard deviation of this subjective measure is plotted in Figure 49 and the numerical results are shown in table 2, below.

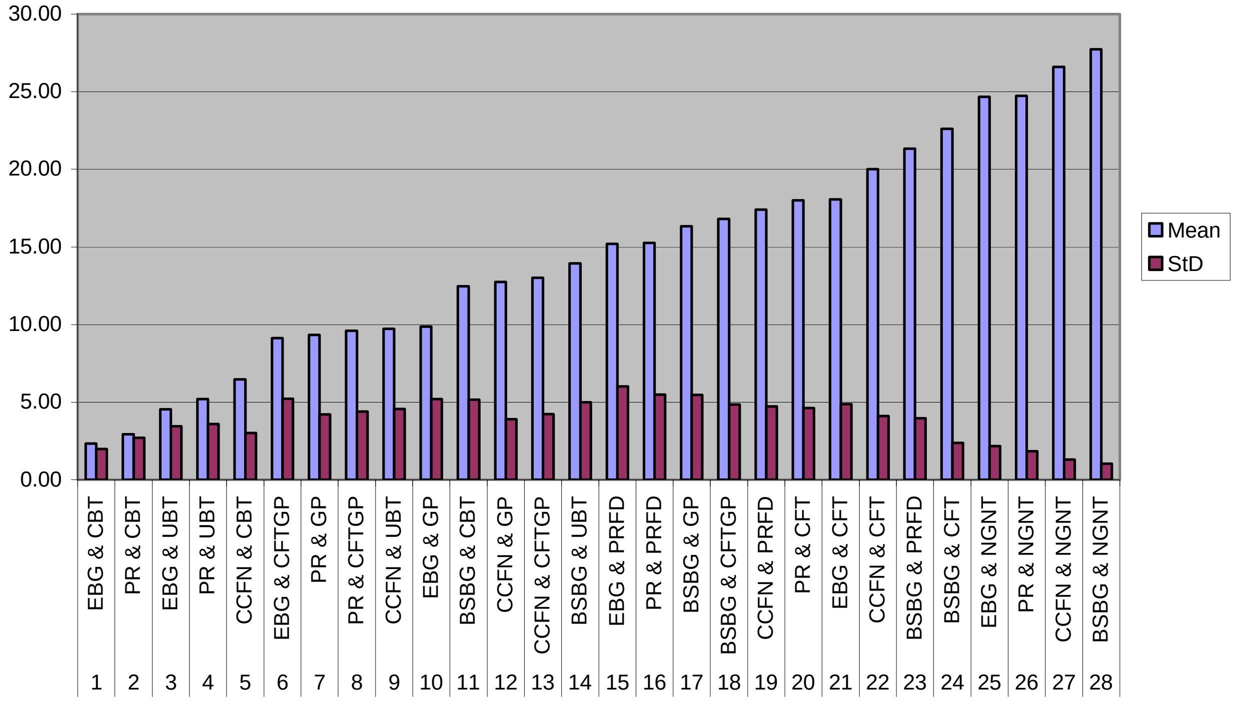


Figure 49: Overall EP Ranking, Order of Preferred Display Combination from 1-28

Rank	Display Concept	Mean	StD
1	EBG & CBT	2.33	1.99
2	PR & CBT	2.93	2.71
3	EBG & UBT	4.53	3.44
4	PR & UBT	5.20	3.59
5	CCFN & CBT	6.47	3.02
6	EBG & CFTGP	9.13	5.22
7	PR & GP	9.33	4.20
8	PR & CFTGP	9.60	4.39
9	CCFN & UBT	9.73	4.56
10	EBG & GP	9.87	5.19
11	BSBG & CBT	12.47	5.15
12	CCFN & GP	12.73	3.90
13	CCFN & CFTGP	13.00	4.24
14	BSBG & UBT	13.93	4.99
15	EBG & PRFD	15.20	6.00
16	PR & PRFD	15.27	5.48
17	BSBG & GP	16.33	5.47
18	BSBG & CFTGP	16.80	4.84
19	CCFN & PRFD	17.40	4.73
20	PR & CFT	18.00	4.63
21	EBG & CFT	18.07	4.88
22	CCFN & CFT	20.00	4.11
23	BSBG & PRFD	21.33	3.96
24	BSBG & CFT	22.60	2.38
25	EBG & NGNT	24.67	2.16
26	PR & NGNT	24.73	1.83
27	CCFN & NGNT	26.60	1.30
28	BSBG & NGNT	27.73	1.03

Legend	GSC
(magenta)	Guidance Only
(blue)	Tunnel Only
(green)	Guidance &Tunnel
(red)	NGNT

Table 2: EP Overall Ranking, Order of Preferred Display Combinations from 1-28

Best ranking scores were registered for displays with both guidance cue and tunnel in combinations of PR and EBG. Next, displays with tunnel were favored over displays with guidance only in conjunction with PR and EBG. Note that all displays without guidance cue and tunnel ranked the lowest.

Summary Results Based on a Glass Cockpit Classification

In the following an attempt is made to establish a measurable comparison between the Blue Sky Brown Ground, as the existing glass cockpit technology (baseline BSBG), and SVS concepts, tested here, as the future technology. Thus, the results of the above subjective and objective measures were reorganized based on five possible TPC/GSC combinations and are discussed in this section. The first category selected was the combination of Pitch/Roll Flight Director and BSBG as a representative of current glass cockpit displays, i.e. a typical PFD with flight director (PRFD-BSBG). The second category was based on the PRFD with the three SVS terrain portrayal concepts used in this experiment (PRFD-SVS). This category represents a class of new SVS displays with a traditional guidance concept (in development by some avionics manufacturers). The third category was comprised of all guidance and symbology concepts except PRFD in combination with BSBG (HITS-BSBG). This category represents a class of glass cockpits that display some kind of pathway or HITS on a typical PFD without terrain display. The fourth category was based on all guidance and symbology concepts (utilized in this experiment) except PRFD in combination with all terrain portrayal concepts except BSBG (HITS-SVS). This represents the state of the art for SVS glass cockpits. The fifth/last category was based on the results of BSBG with VMC like OTW view. This category should represent recently popular GA glass cockpits that use PFD with no guidance cue during VFR operations. Recall that the OTW display (in this experiment) was based on the Photo Realistic terrain database with a Minification Factor (MF) of unity, while the MF for PR display was about 5.

Results of FTE, SART, and TLX for these new categories were statistically significant and are shown in Figures 50-53. Following statistical data were obtained: ($F(4,870) = 187.7$, $P<.05$) for LPD; ($F(4,870) = 231$, $P<.05$) for VPD; ($F(4,870) = 23.9$, $P<.05$) for SART; and ($F(4,870) = 17.7$, $P<.05$), for TLX.

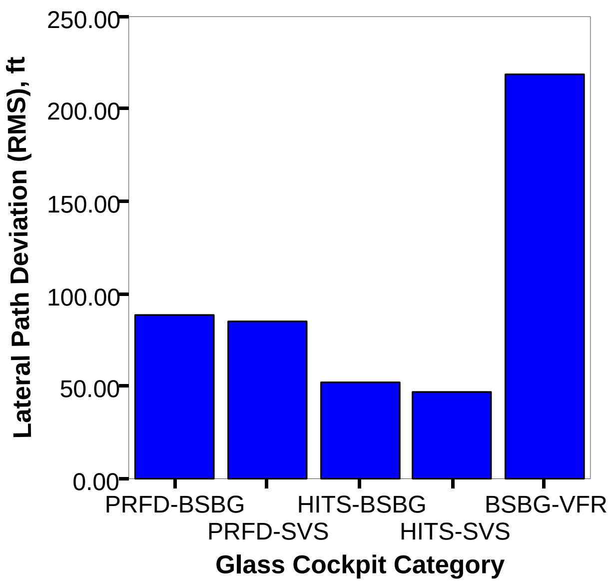


Figure 50: Lateral Path Deviation for Different Display Categories

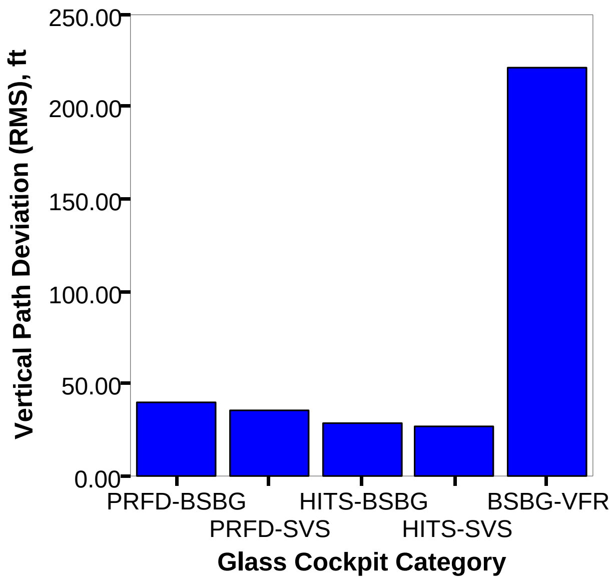


Figure 51: Vertical Path Deviation for Different Display Categories

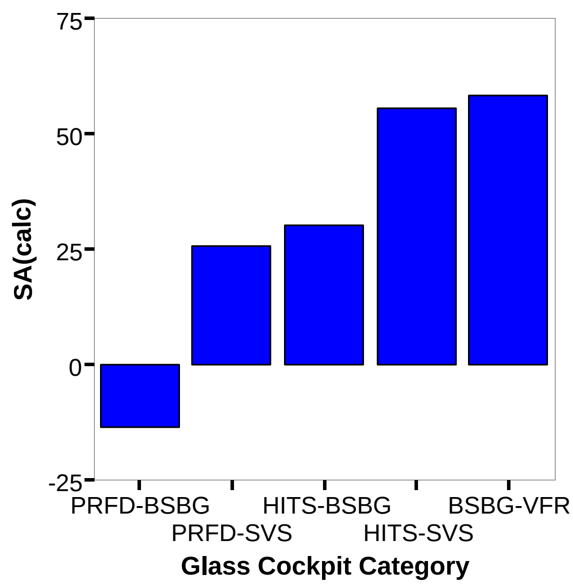


Figure 52: Computed SA for Different Display Categories

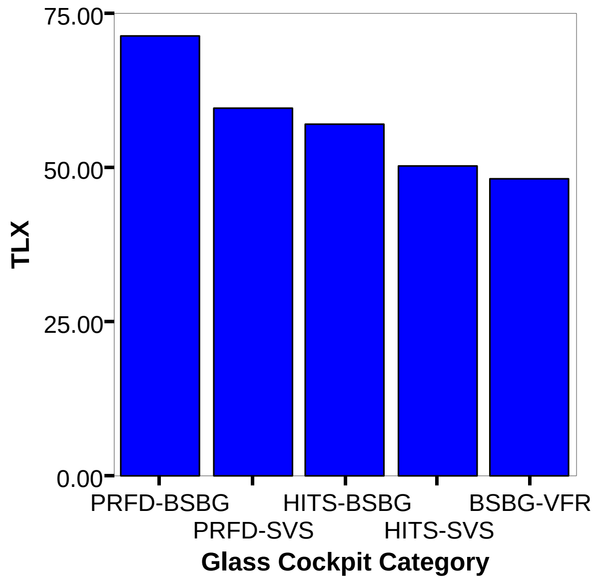


Figure 53: Perceived Workload for Different Display Categories

A close analysis of these figures shows that except for BSBG-VFR, the PRFD-BSBG resulted in highest flight technical errors and workload with lowest situation awareness. The addition of terrain to flight director (PRFD-SVS) results in some improvement of objective and subjective measures, i.e. FTE and TLX are lower and SA is higher for PRFD-SVS as compared to PRFD-BSBG. The next larger improvement in FTE, TLX, and SA occurs when the HITS is added to the primary flight display. Next level of improvement in all three measures is obtained when SVS terrain is added to the HITS-BSBG (now HITS-SVS). The HITS-SVS category resulted in lowest FTE, highest SA, and lowest workload among the five categories flown in IMC. These findings reinforce earlier results that SVS displays improve pilot performance while reducing the workload and increasing SA as compared to other glass cockpit combinations. Post hoc analysis of SA and TLX showed that the SA and TLX for HITS-SVS were in the same group as the results of BSBG-VFR. One could conclude that SVS displays used in IMC provide the pilots with the same level of perceived situation awareness and workload as a baseline primary flight display used in VMC while drastically improving pilot performance, as evidenced by lower flight technical errors.

Summary of Evaluation Pilots' Comments

During the entire experiment process (during the runs, between the runs and during the exit interviews), all evaluation pilot conversations and comments were recorded digitally, have been transcribed, and "cleaned up" by the use of correct abbreviations and removal of any participant names. These transcripts may possibly be published as a separate document; however, they are readily available to the reader upon request to the authors.

In addition to the digitally recorded comments, the experiment observers/conductors logged their own notes of the pilots' comments as they understood them at that moment in time. Samples of EP comments, as extracted from conductors' notes during the runs, are shown in tables F1-14 in Appendix F.

In the following a summary of evaluation pilots' comments based on experiment conductors' notes are presented. The summary is subdivided into terrain portrayal concepts, guidance symbology concepts, and TPC/GSC interactions related comments:

Comments related to TPC:

BSBG was inadequate for SA, difficult in combination with PRFD

CCFN was better than BSBG but inadequate in many cases, especially CCFN with PRFD or CFT.

EBG was easy to understand and favored by many, just as good as PR type TPC.

PR was felt to be the most natural presentation of outside world, some pilots liked EBG better.

Comments related to GSC:

PRFD was least favored GSC, especially by VFR pilots.

CFT corners were difficult to see, but it provided good SA to some pilots.

GP caused high workload to follow it, but very helpful in reducing FTE.

UBT provided, overall, good SA, but hard to center, and was lacking a path based cue.

CFTGP led to very good FTE results and favored by many evaluation pilots.

CBT was the most favorite guidance as the tunnel continued to the destination, the size of the tunnel matched the course deviation indicators and the guidance box was easy to follow.

Comments about Combination of TPC and GSC:

Only a few pilots were concerned about combinations such as CFT on CCFN and very few saw any interactions between the TPC and GSC. This also supports the results of subjective and objective measures.

Conclusions

A fixed based simulation of four Synthetic Vision System terrain portrayal concepts and seven guidance symbology concepts on a primary flight display was conducted and employed three groups of evaluation pilots. The scenario was a challenging mountain pass maneuver reflecting an advanced application of SVS technology in instrument meteorological conditions. A total of 28 combinations of the above independent variables were flown (randomly) twice by each of the 18 evaluation pilots.

The four terrain portrayal concepts evaluated included the baseline PFD with blue sky/ brown ground depiction, Constant Color Fishnet, Elevation Based Generic, and Photo Realistic terrain portrayal. The seven guidance symbology concepts tested included Crows Feet Tunnel, Unconnected Boxes Tunnel, connected boxes tunnel, Ghost Plane, Pitch/Roll Flight Director, Crows Feet Tunnel with Ghost Plane and no guidance no tunnel condition. The effect of guidance symbology concept and terrain portrayal concept was statistically significant for both lateral and vertical path deviations, calculated situation awareness rating, and computed NASA Task Load Index. The Elevation Based Generic terrain produced the statistically lowest vertical path deviation, indicating an increased awareness of flight path and terrain resulting from this terrain portrayal concept. While this result was statistically significant with an approximate 10% reduction in error, it was potentially not operationally meaningful (3 ft). Photo Realistic and Elevation Based Generic terrain portrayal concepts produced the lowest lateral path deviations with an approximate 14% reduction in error. However, while the reduction in lateral path error may also not be operationally significant, it does indicate a positive response to the terrain stimulus. These results may be attributed to the effective integration of terrain information, as intuitively provided by the Elevation Based Generic and Photo Realistic concepts with the various guidance concepts. Furthermore, the Elevation Based Generic concept may provide important terrain information to the pilot in an easier to assimilate format than other terrain portrayal concepts, leading to improved vertical path deviation results. These results are different from previous experiments with SVS terrain, which had indicated only an improvement in pilot situation awareness, and are likely due to the extreme presence of terrain with the evaluation task (i.e. maintain 500 ft AGL in a mountain pass).

The lowest flight path deviation was achieved by the use of Crows Feet Tunnel with Ghost Plane, Connected Boxes Tunnel, and Ghost Plane (pathway based) guidance symbology concepts. These guidance symbology concepts reduced flight technical error by approximately 50% compared to the Pitch/Roll Flight Director, demonstrating the enhanced pilot control provided. The Unconnected Box Tunnel, improved lateral path deviation over the Pitch/Roll Flight Director, but was not significantly different from the Pitch/roll Flight Director for vertical path deviation. The Crows Feet Tunnel performed statistically worse than the Pitch/Roll Flight Director for vertical path deviation. This could be based on the very fragmented corner elements (crows' feet) and the lacking of a focused information bundle. The promise of a tunnel and Flight Path Marker combination presentation is that the pilot, in a glance, can observe own ship position, orientation, and trajectory trend relative to the current and future path. In contrast to a flight director where the awareness has to be built-up and inferred through observation of the course deviation indicators, flight director symbology, attitude indicator, and probably heading and turn-rate over a period of time. Unlike PRFD, the information was readily available by crows feet concept but not perceived easily or quickly as other tunnel concepts.

Qualitative measures of pilot situation awareness and workload followed the quantitative results. The Crows Feet Tunnel with Ghost Plane, Unconnected Boxes Tunnel, and Connected Boxes Tunnel all provided significantly superior situation awareness to the other guidance symbology concepts tested. This reflects effect of the path preview provided by these tunnel concepts. The connected box and Unconnected Box Tunnel concepts produced lower workload results with an approximate 30% reduction compared to the Pitch/Roll Flight Director and Crows Feet Tunnel concepts. The Crows Feet Tunnel with Ghost Plane and Ghost Plane guidance symbology concepts also significantly reduced workload from the Pitch/Roll Flight Director and Crows Feet Tunnel concepts, but to a lesser extent. It should be noted that the Crows Feet Tunnel with Ghost Plane and Ghost Plane guidance symbology concepts also improved vertical and lateral path deviation. As a result, the increased workload due to the Crows Feet Tunnel with Ghost Plane and Ghost Plane guidance symbology concepts did indicate some associated benefit in terms of improved pilot performance. A major impact of the terrain portrayal concepts was on pilot situation awareness. For the Elevation Based Generic and

Photo Realistic terrain portrayal concepts, higher situation awareness and reduced workload was observed for all pilots as compared to blue-sky/brown ground baseline as well as the Constant Color Fishnet terrain portrayal concepts. The level of SA provided by constant-color fishnet was statistically higher than BSBG but less than EBG and PR terrain portrayal concepts.

There were no statistically significant interactions found between terrain portrayal or guidance symbology concepts for any of the objective and subjective variables considered. This suggests that the SVS terrain may have similar benefits for all guidance symbology concepts tested.

In general, all pilot groups performed similarly well when using Crows Feet Tunnel with Ghost Plane, Unconnected Boxes Tunnel, and Connected Boxes Tunnel and Ghost Plane (with vertical path deviation less than 30 ft and lateral path deviation less than 50 ft). With the same SVS training provided to all three groups, low time VFR pilots performed as well as IFR pilots in the low altitude en-route scenario (in IMC) evaluated for this study.

All SVS displays achieved increased pilot situation awareness, lower flight technical errors and workload as compared to the baseline Pitch/Roll Flight Director. Also, the same level of situation awareness and workload, with drastic reduction in flight technical error, was achieved for all SVS displays in IMC as compared to the blue-sky/brown ground (baseline) display in VMC. These results and results of the pilot preferences clearly demonstrate the potential and the effectiveness of SVS displays to enable advanced IFR operations by IFR rated pilots.

Acknowledgements:

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APPENDIX A: Flight Director Control Logics

The block diagrams of the Pitch/Roll Flight Director's control logics, as implemented in this experiment, are provided in Figures A.1 and A.2. Tables A.1 and A.2 are the summary lists of the required input and output parameters of the algorithms. Note that variables marked "configurable" were adjustable through the configuration file and the GUI interface in the SVS software.

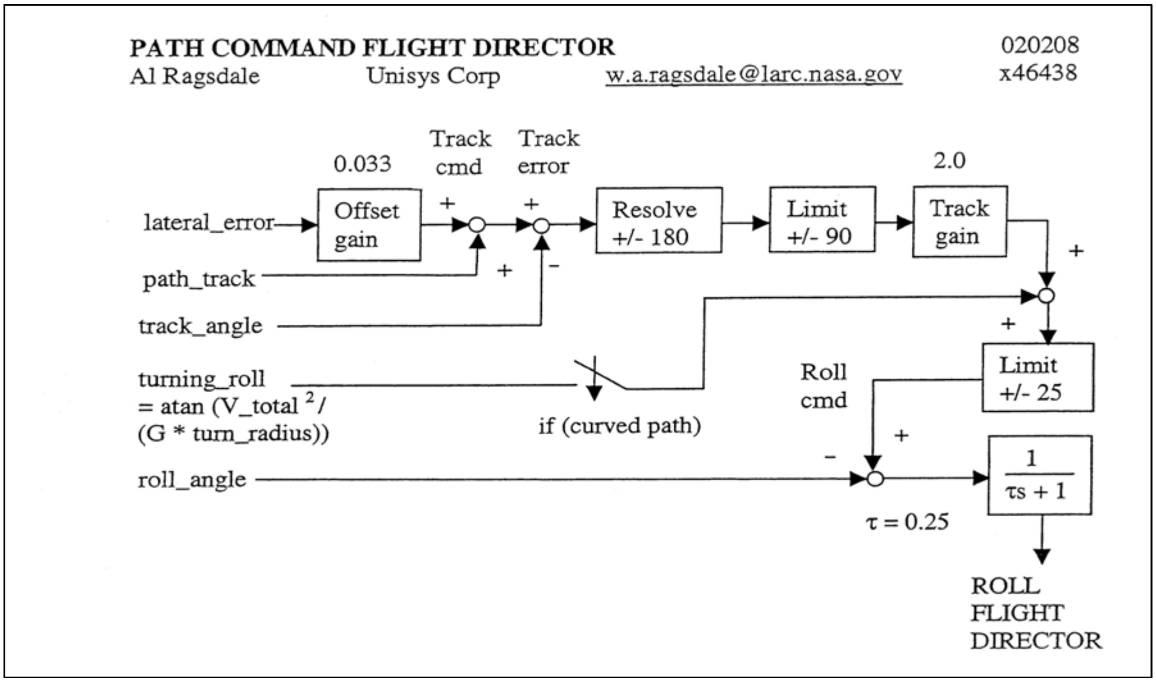

Figure A.1: Roll Flight Director Block Diagram

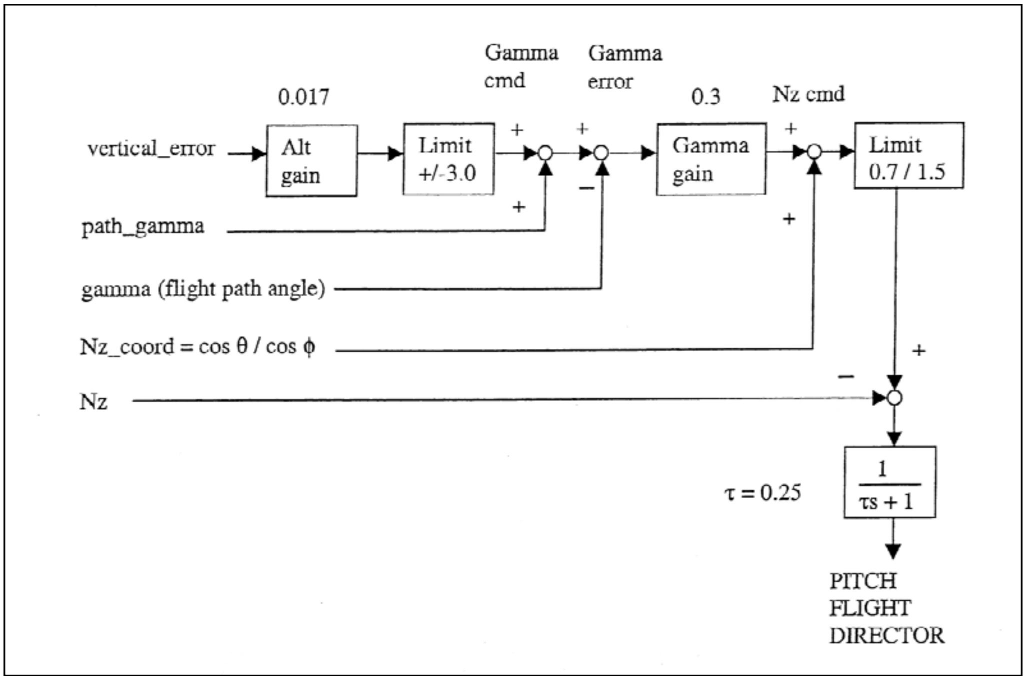

Figure A.2: Pitch Flight Director Block Diagram

Table A.1: Roll Flight Director Parameters

Symbol	Type	Description	Elite Variable(s) Required	Configur-able*	Unit/ Value
Lateral_error	Input	Ownship lateral distance closest to the flightpath	fLatitude, fLongitude	No	ft
Path_track	Input	Heading of flightpath	NA	No	deg
Track_angle	Input	Actual ownship track angle	fTrueTrack	No	deg
Turning_roll	Input	Desired roll angle (for curved path only)	NA	No	deg
V_total	Var	True airspeed	fTAS	No	ft/sec
G	Const	Gravitational acceleration	NA	No	32.2 ft/sec^2
Turn_radius	Var	Turning radius from the flightpath	NA	No	ft
Roll_angle	Input	Ownship actual roll angle	fRoll	No	deg
Offset gain	Const	Lateral_error gain	NA	Yes	0.033 deg/ft
Track gain	Const	Track error gain	NA	Yes	2.0
τ	Const	Roll flight director filter time constant	NA	Yes	0.25 sec

* Configurable variables are highlighted in yellow.

Table A.2: Pitch Flight Director Parameters

Symbol	Type	Description	Elite Variable(s) Required	Configurable*	Unit/ Value
vertical_error	Input	Current Ownship vertical flight path error	fAltMSL	No	ft
path_gamma	Input	Commanded flight path pitch angle	fPitch	No	deg
Gamma	Input	Actual flight path pitch angle	NA	No	deg
ϕ	Input	Ownship roll angle	fRoll	No	rad
θ	Input	Ownship pitch angle	fPitch	No	rad
Nz_coord	Input	Vertical acceleration of a co-ordinated turn = cos [illegible]cos [illegible]	NA	No	g
Nz	Input	Actual vertical acceleration	Gload	No	g
Alt gain	Const	vertical_error gain	NA	Yes	0.017 deg/ft
gamma gain	Const	Vertical flight path angle gain	NA	Yes	0.6 g/deg
τ	Const	Pitch flight director filter time constant	NA	Yes	sec

* Configurable variables are highlighted in yellow.

APPENDIX B: Evaluation Pilot Training Syllabus

Each evaluation pilot was given about 2.1 hours of training. Before starting the training in the simulator a ground school type Power Point presentation was conducted explaining each step of the training. Figure B.1 shows the outline of this presentation. Figure B.2 shows the training objectives and Figure B.3 shows a sample of the actual syllabus for a typical scenario.

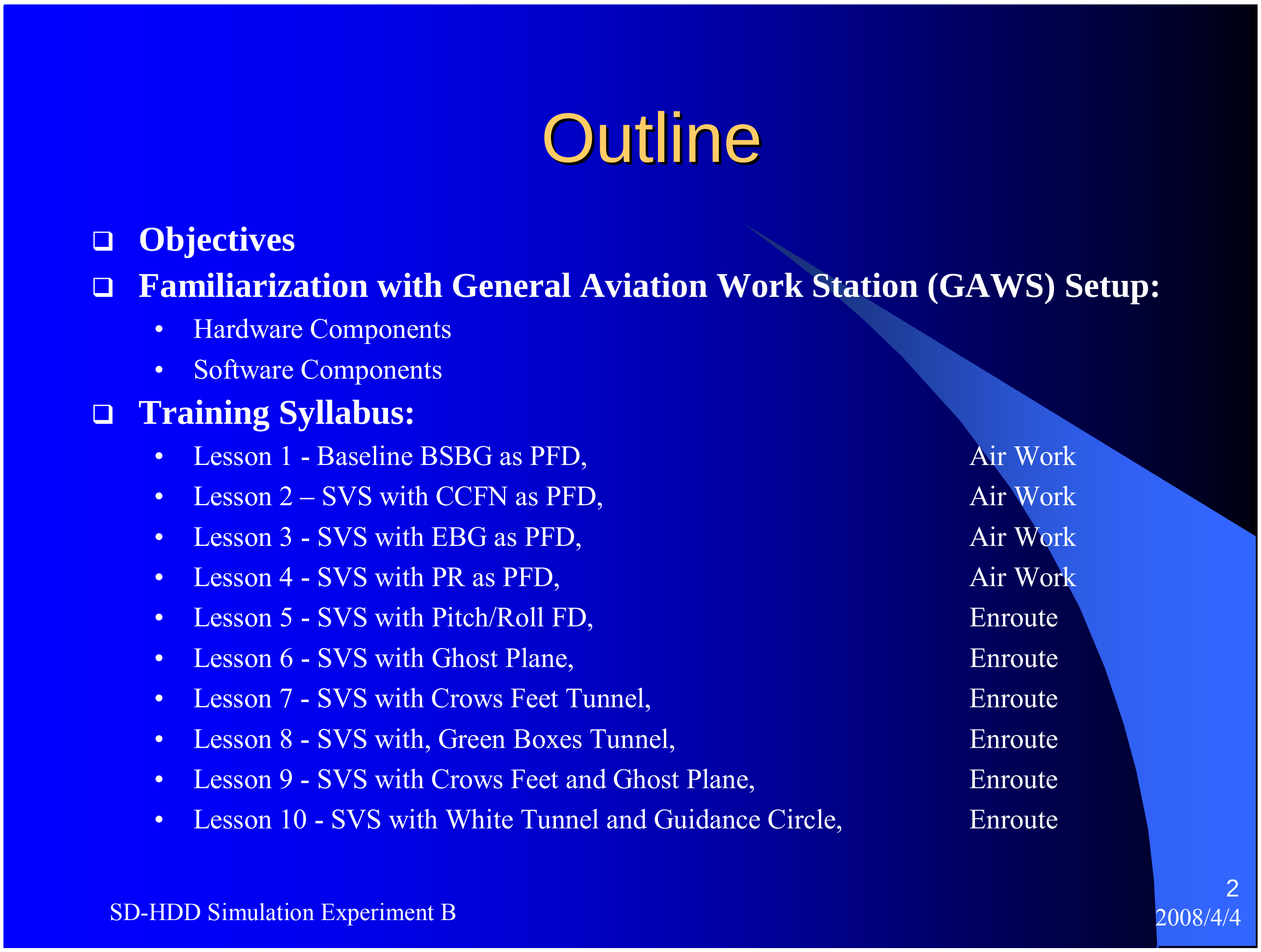

Figure B.1: Outline of EP Training Syllabus

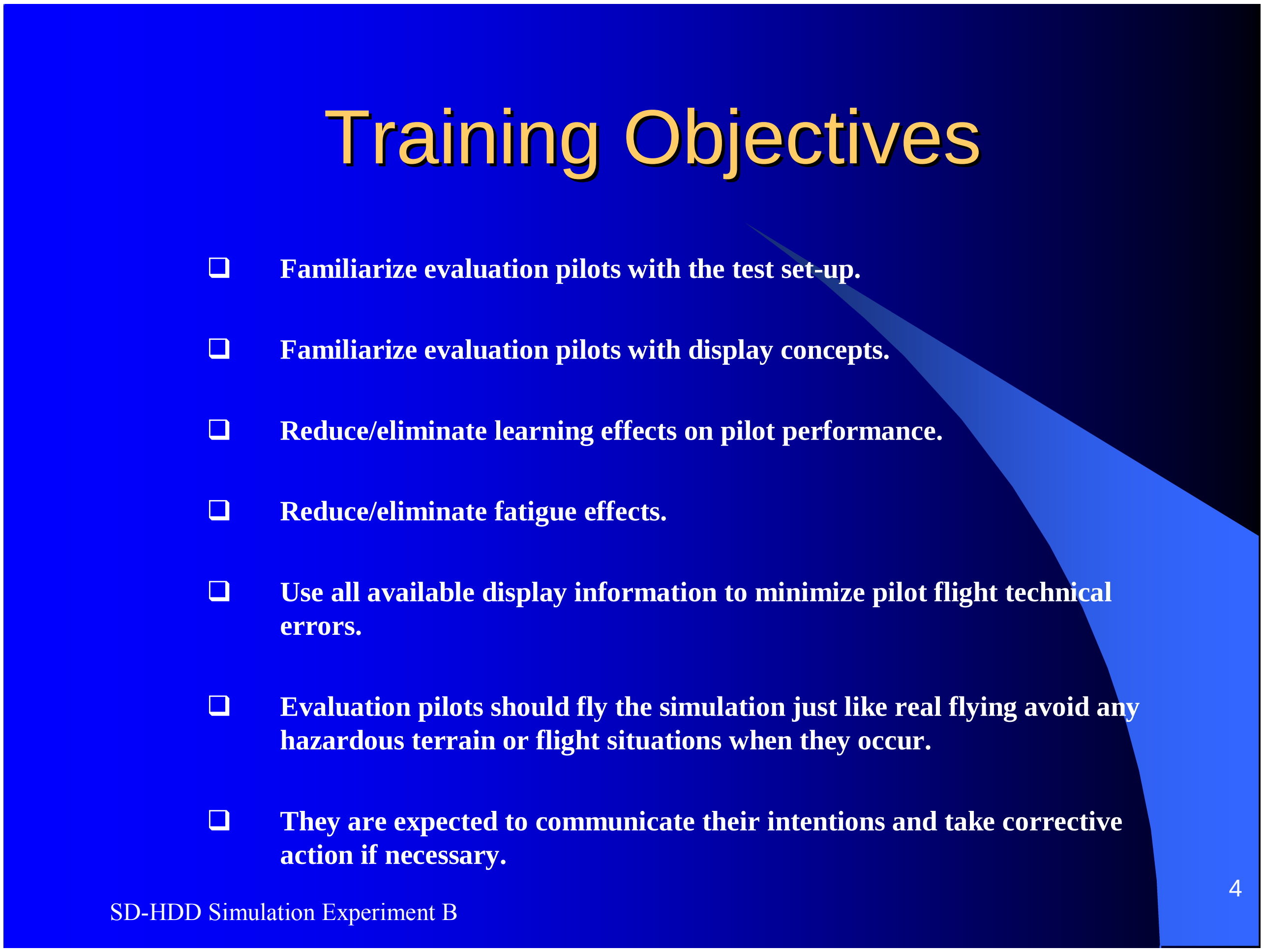

Figure B.2: Training Objectives Presented to the Evaluation Pilots

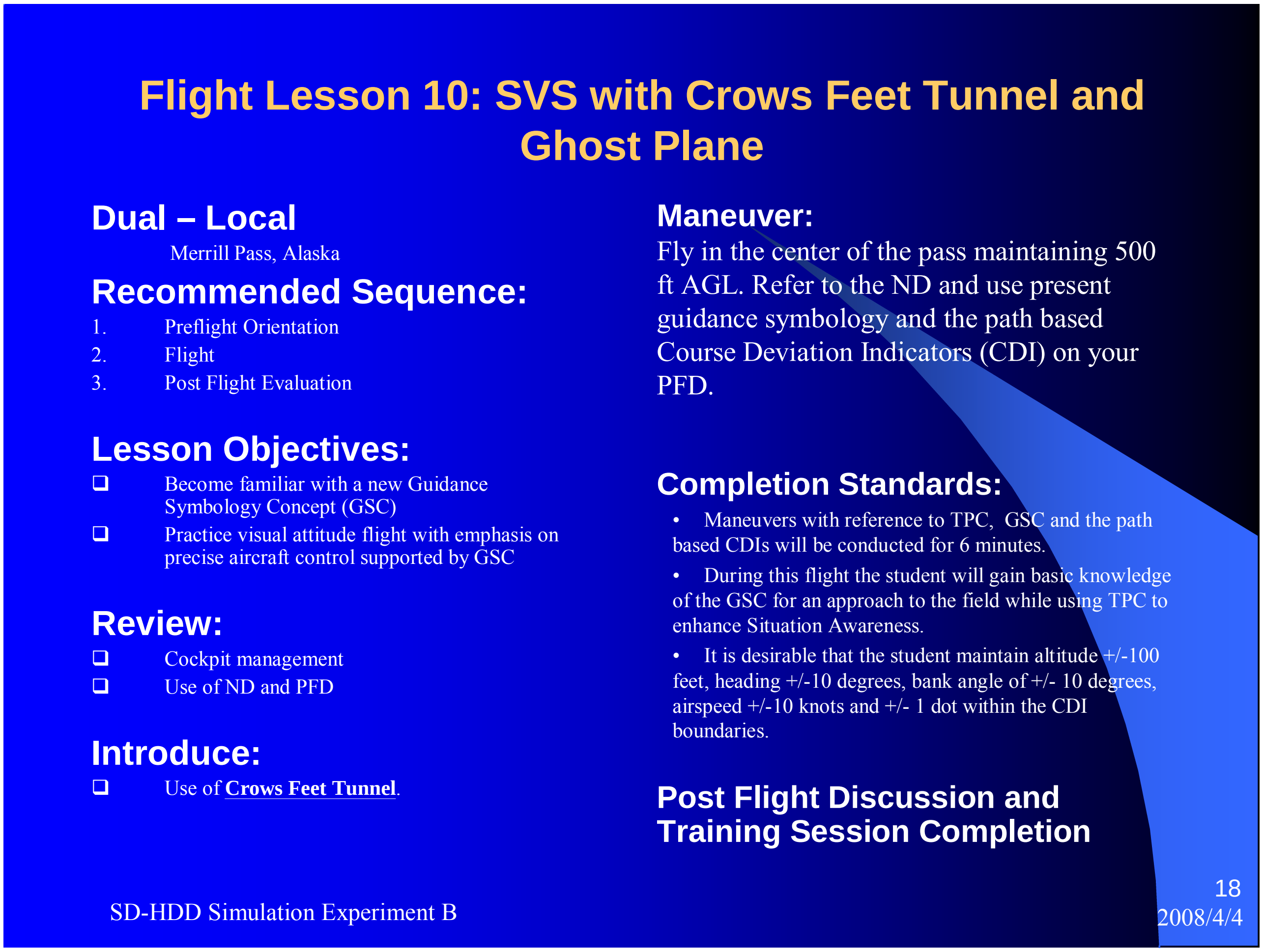

Figure B.3: A sample Syllabus for a Typical Training Scenario

APPENDIX C: Segmentation Methodology

The planed flight path had 12 waypoints as shown in Figure C.1. The flight path was broken into three segments with a distance-to-go measured from a fixed scenario end. The "end point" and the segment distance-to-go measurements are shown in Figure C.2 below.

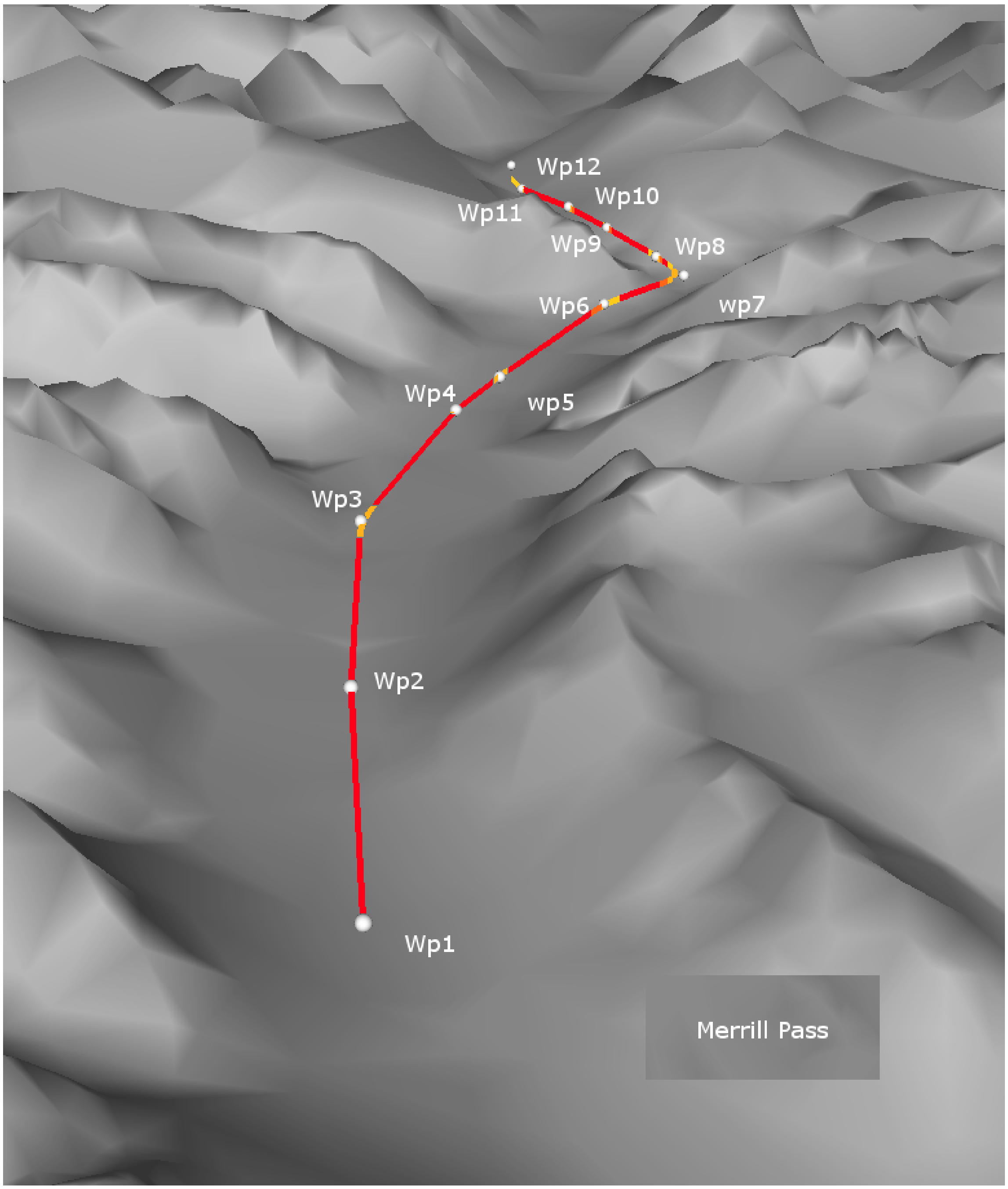

Figure C.1: Flight Path Way Points

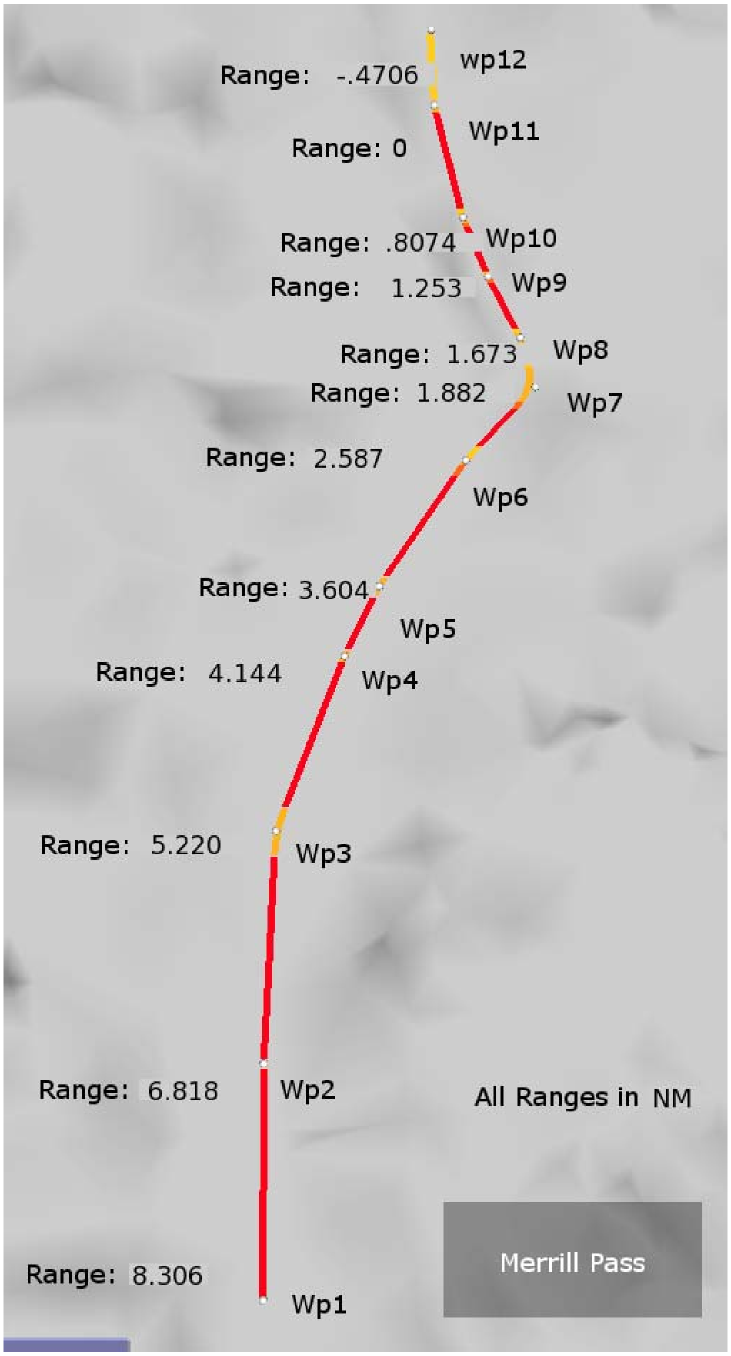

Figure C.2: Distance-to-go measure

In the segmented treatment of the runs for FTE, segment 1 included WP 1, WP 2, and WP 3. Segment 2 contained WP 3, WP 4, WP 5, and WP 6 and finally segment 3 includes WP 6, WP 7, and WP 8.

APPENDIX D: Block and Preferences Questionnaires

Questions related to Block Two runs were posed first. These questions related to the runs with no guidance/no tunnel displays, see Figures D.1-8:

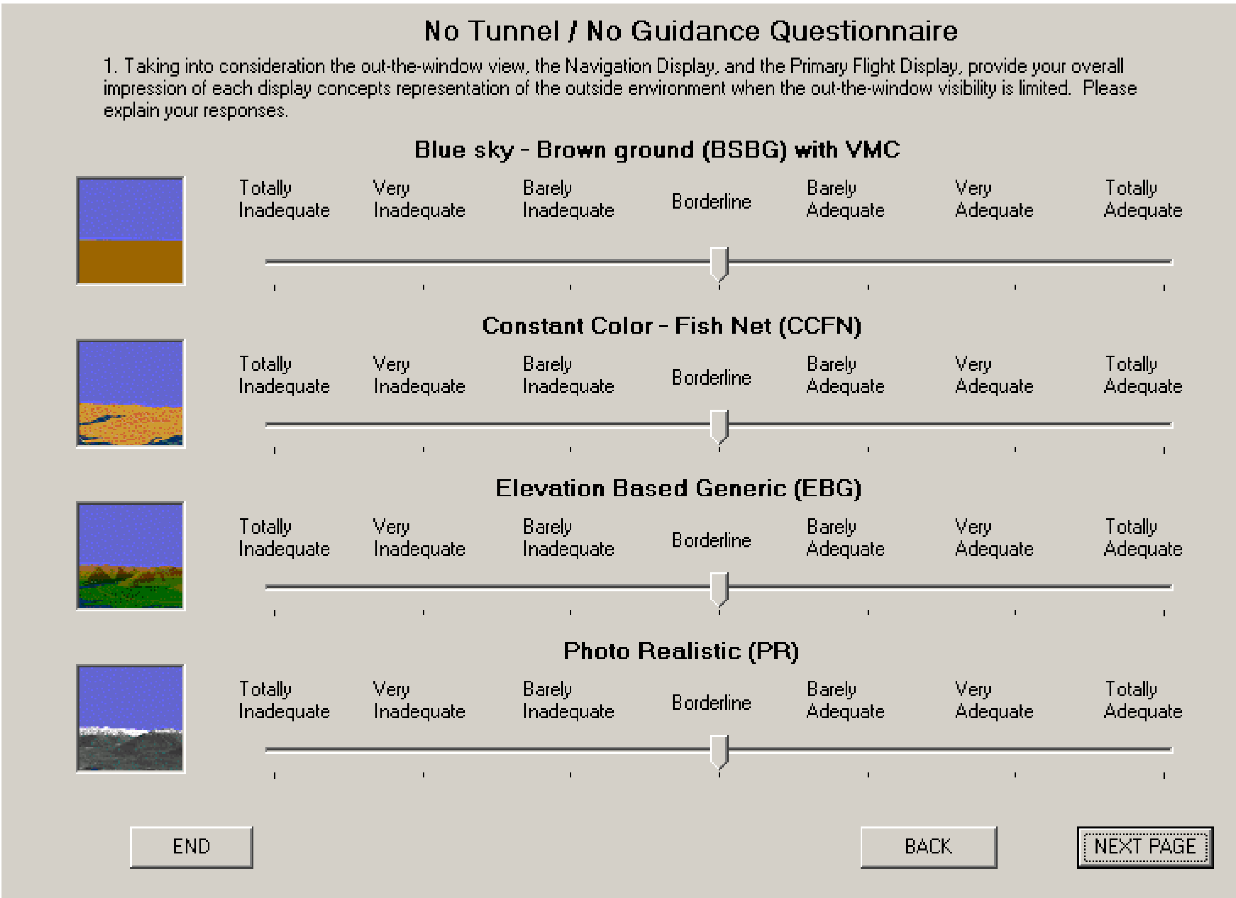

Figure D.1: Block Two, NGNT, Overall Impression for TPC

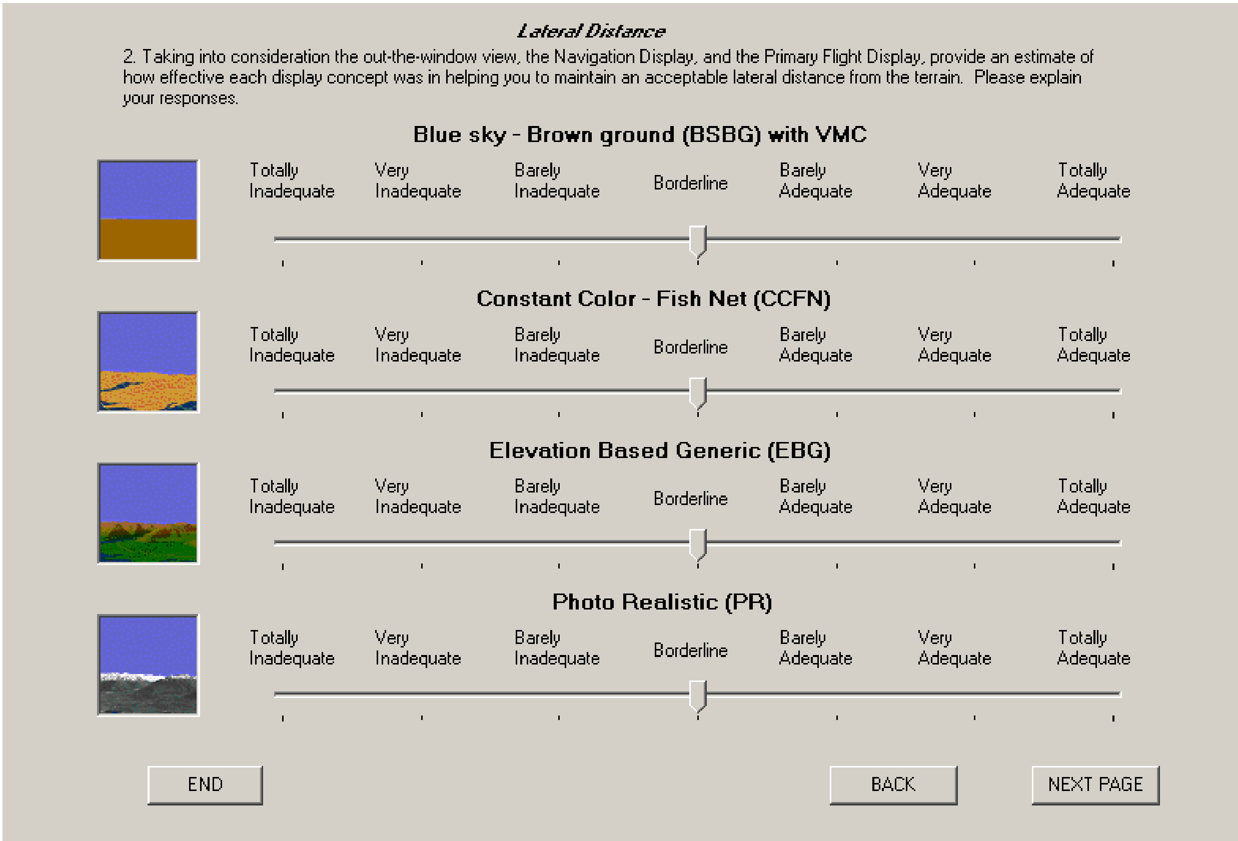

Figure D.2: Block Two, NGNT, Effectiveness for Maintaining Lateral Distance

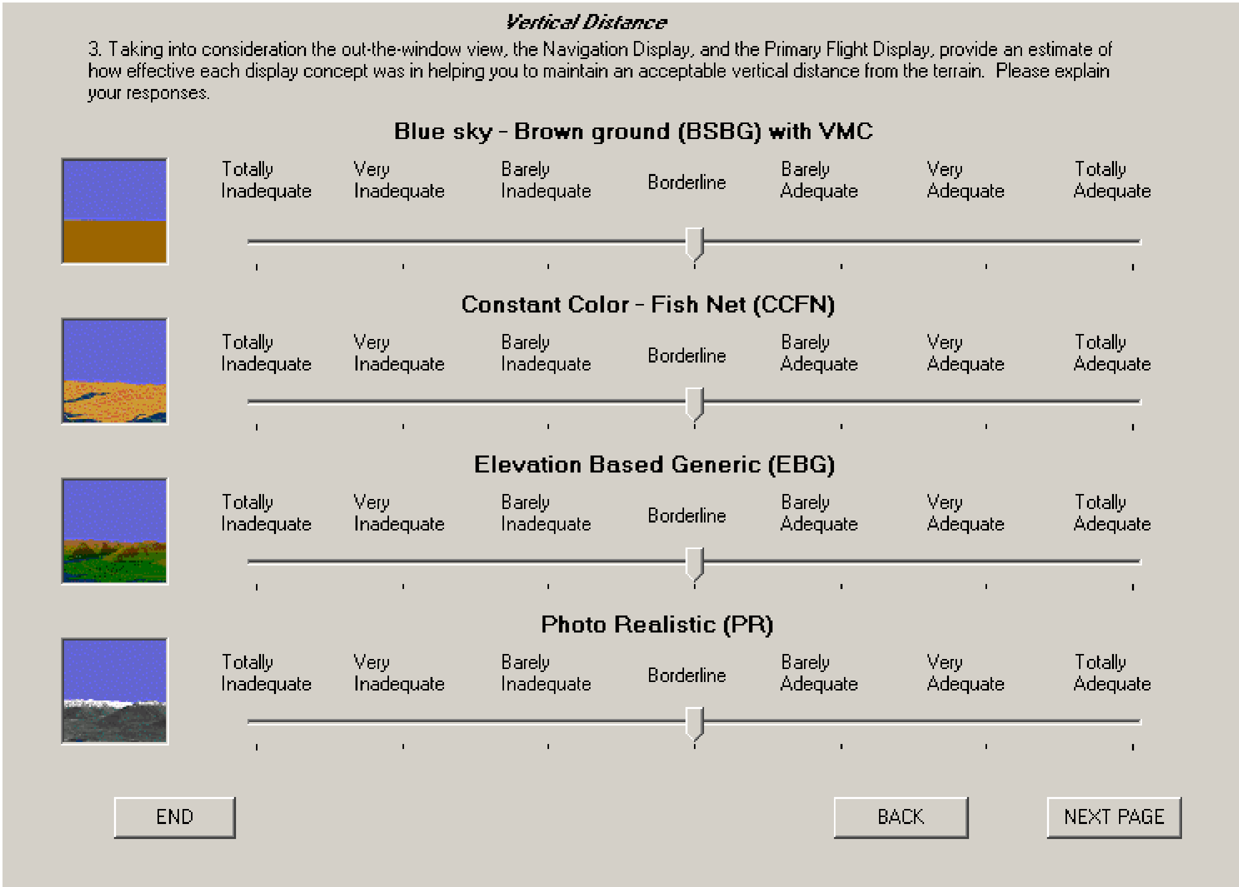

Figure D.3: Block Two, NGNT, Effectiveness for Maintaining Vertical Distance

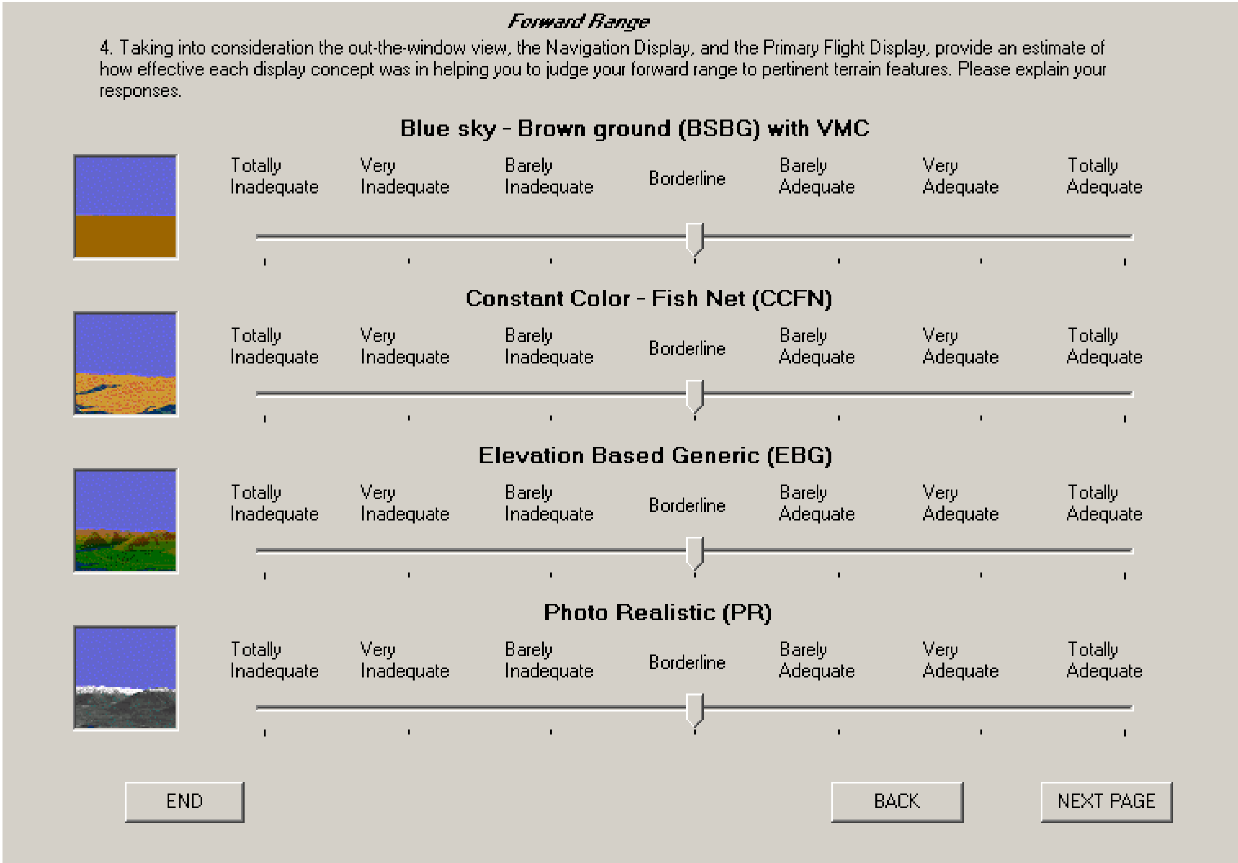

Figure D.4: Block Two, NGNT, Judging the Forward Range

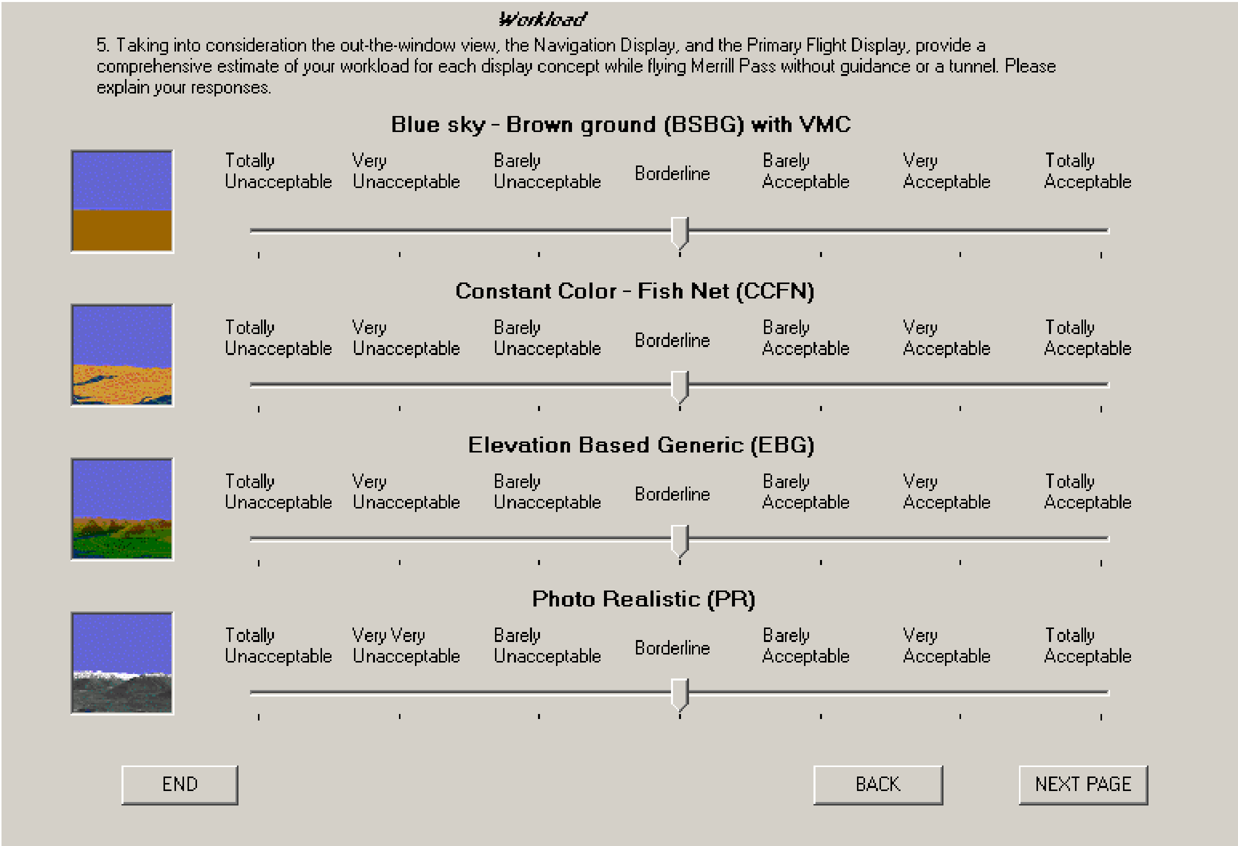

Figure D.5: Block Two, NGNT, Perceived Workload

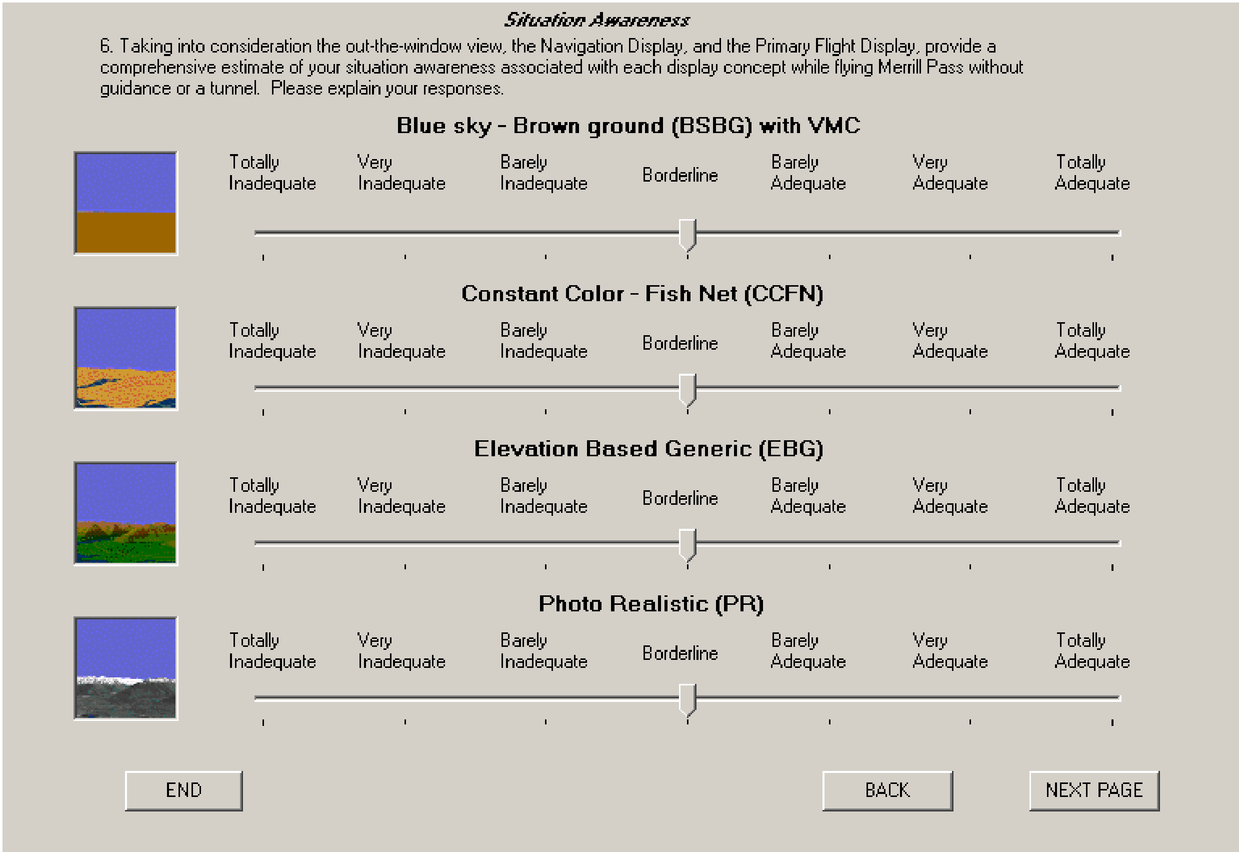

Figure D.6: Block Two, NGNT, Perceived Situation Awareness

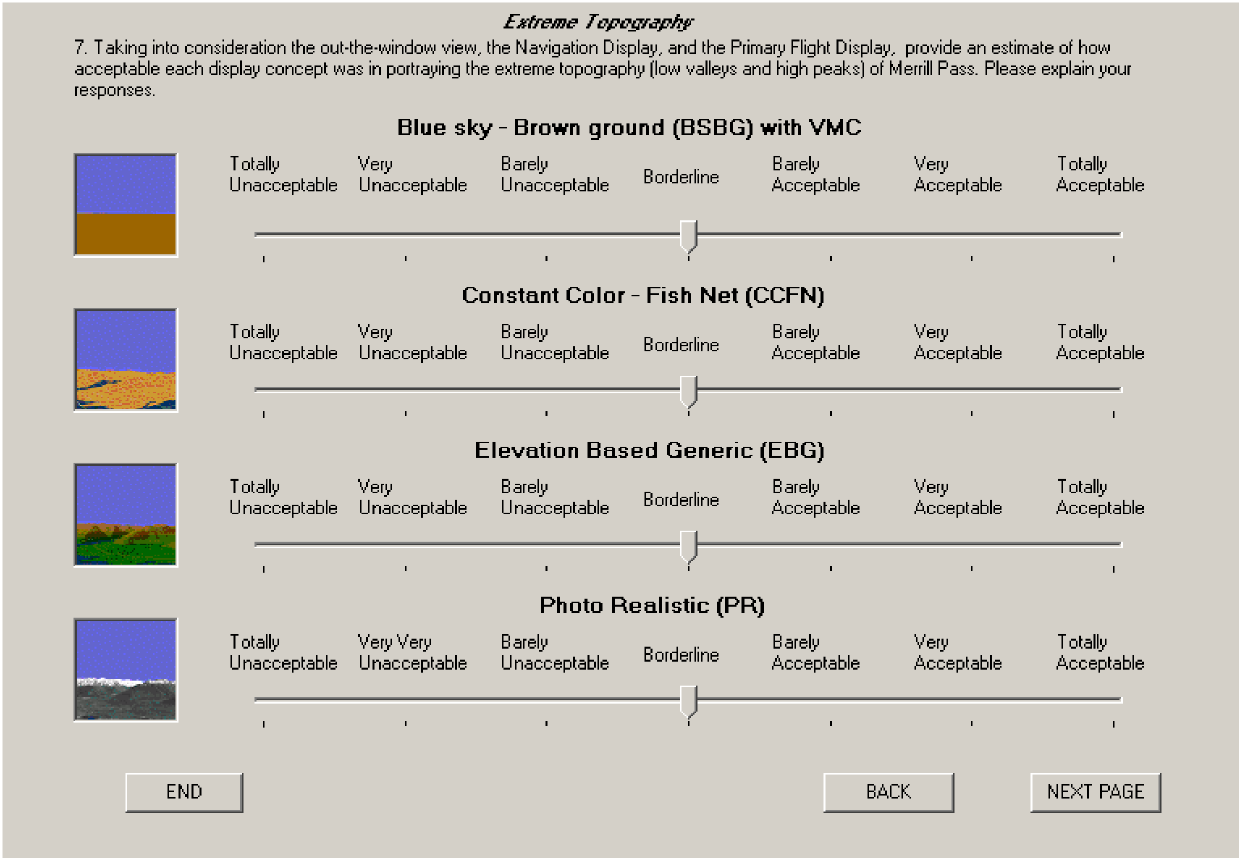

Figure D.7: Block Two, NGNT, Portrayal of Extreme Topology

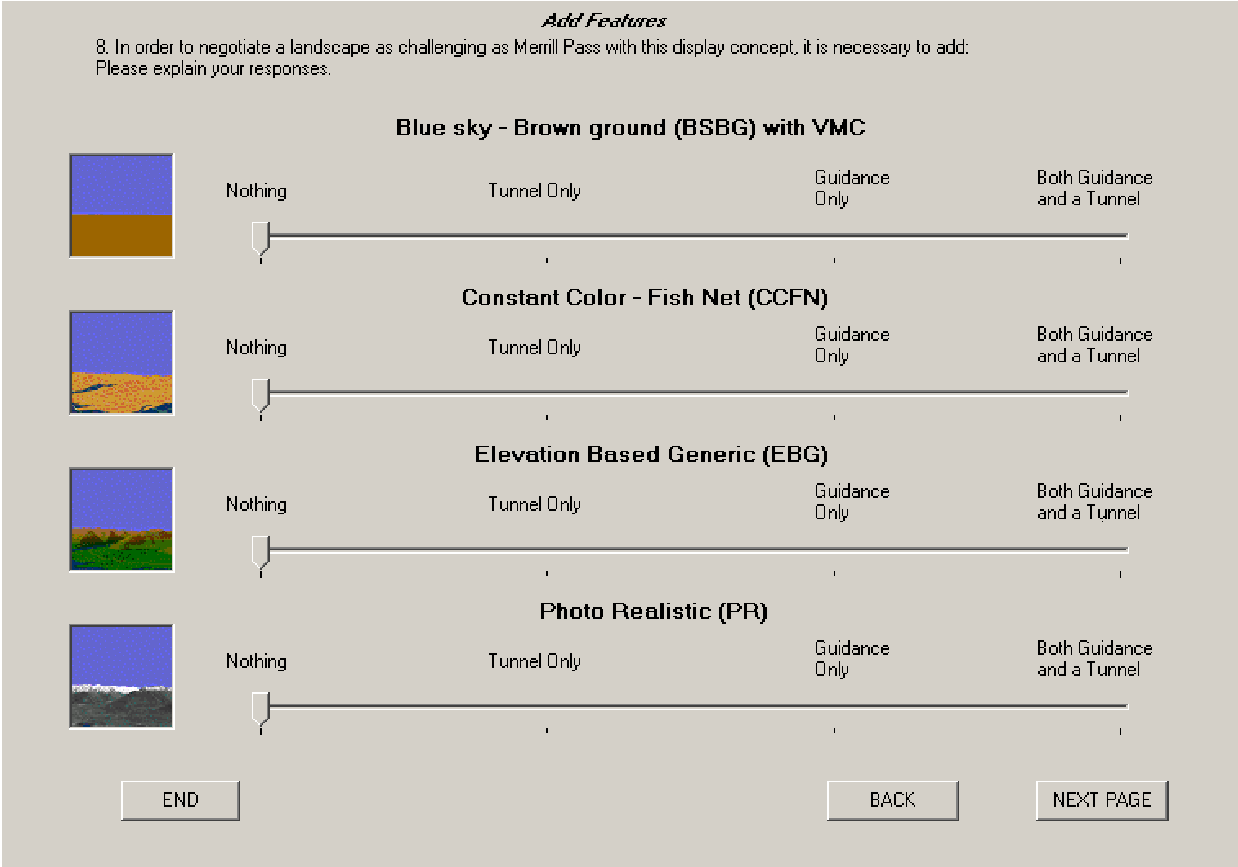

Figure D.8: Block Two, NGNT, Added Features Desired

Next, following questions were posed to the EP that relate to Block Two runs, discussing all runs with guidance and tunnel, see Figures D.9-17:

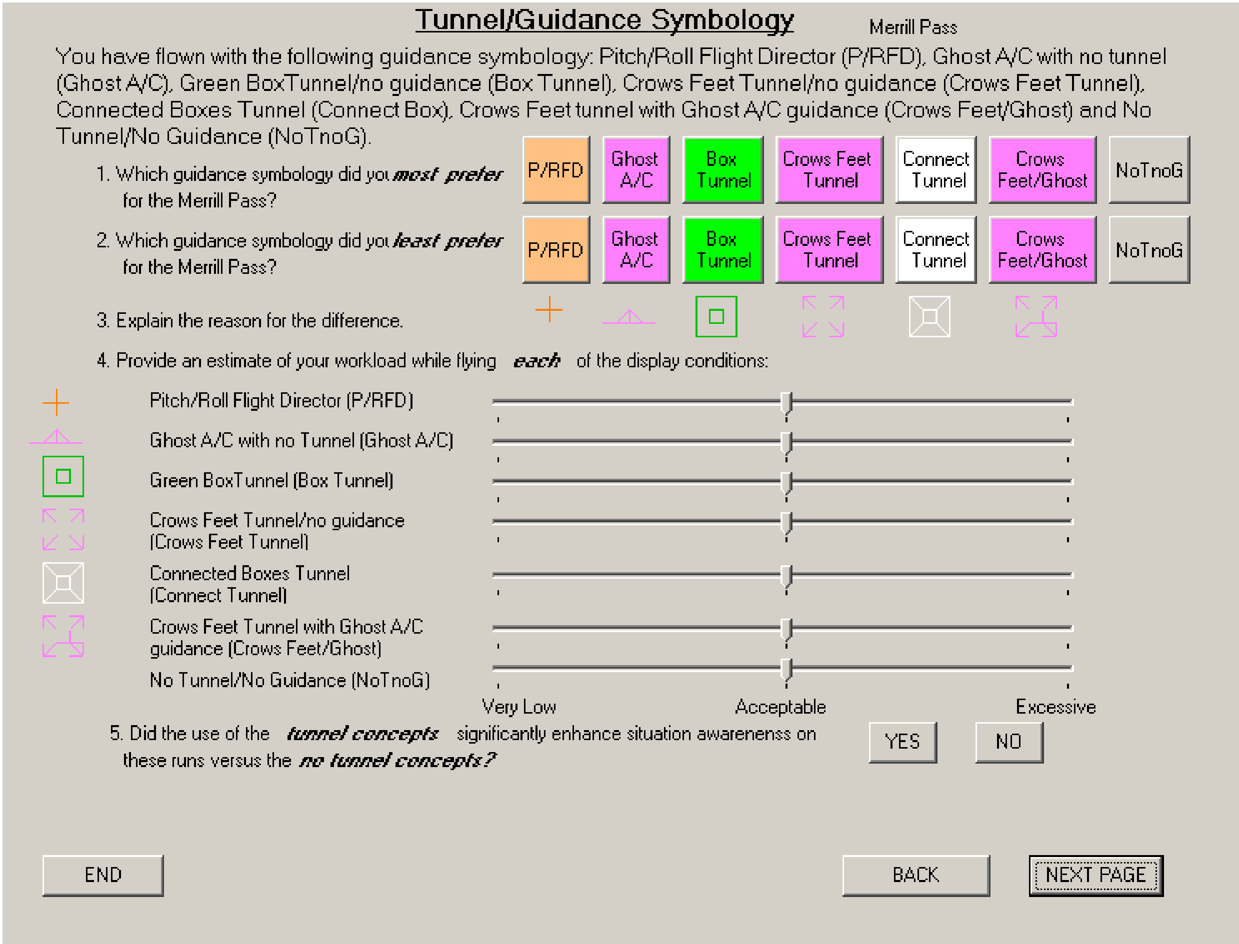

Figure D.9: Block One, Tunnel/Guidance, Preferences for GSC

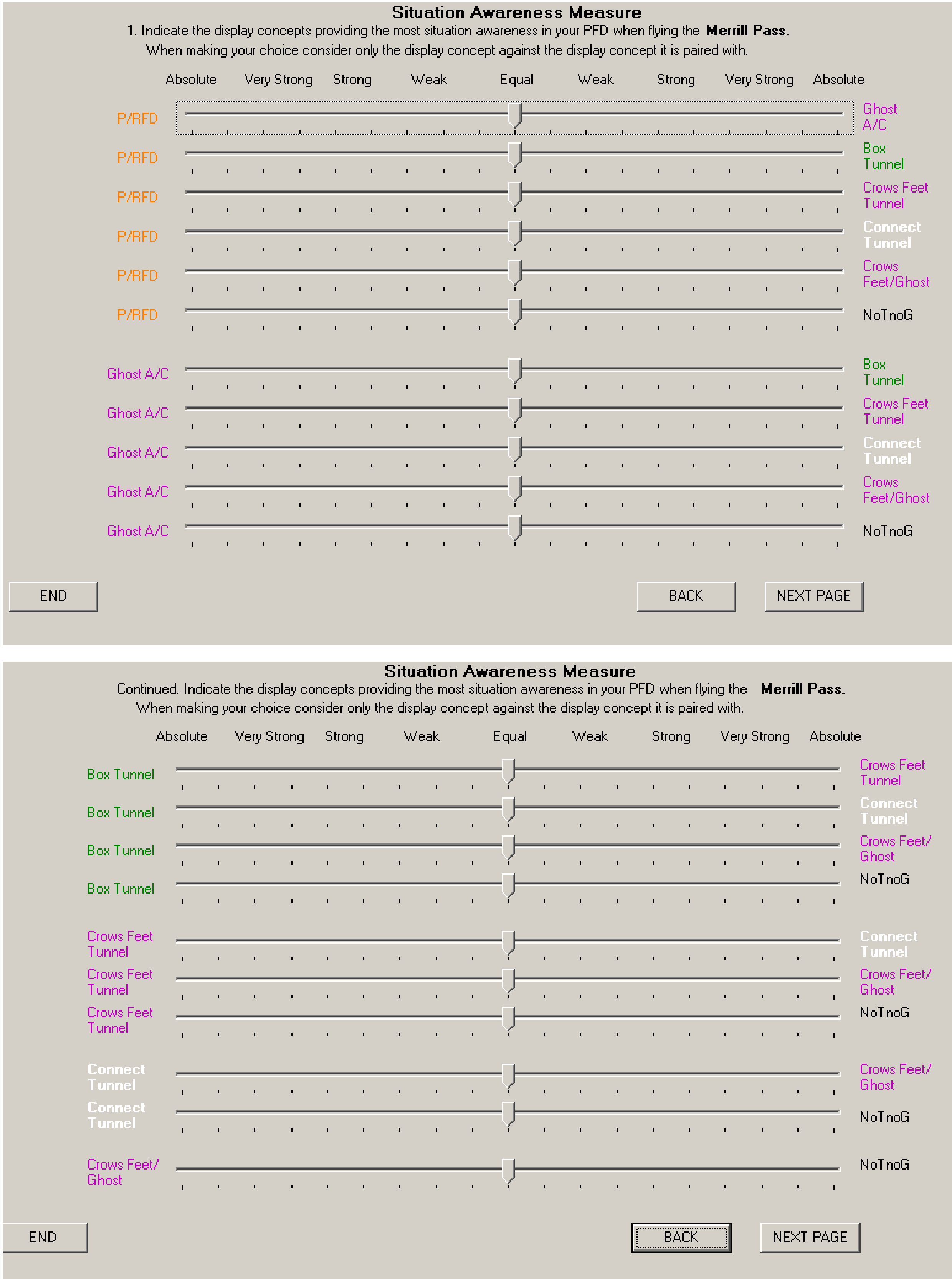

Figure D.10: Block One, Tunnel/Guidance, Situation Awareness for All Combinations

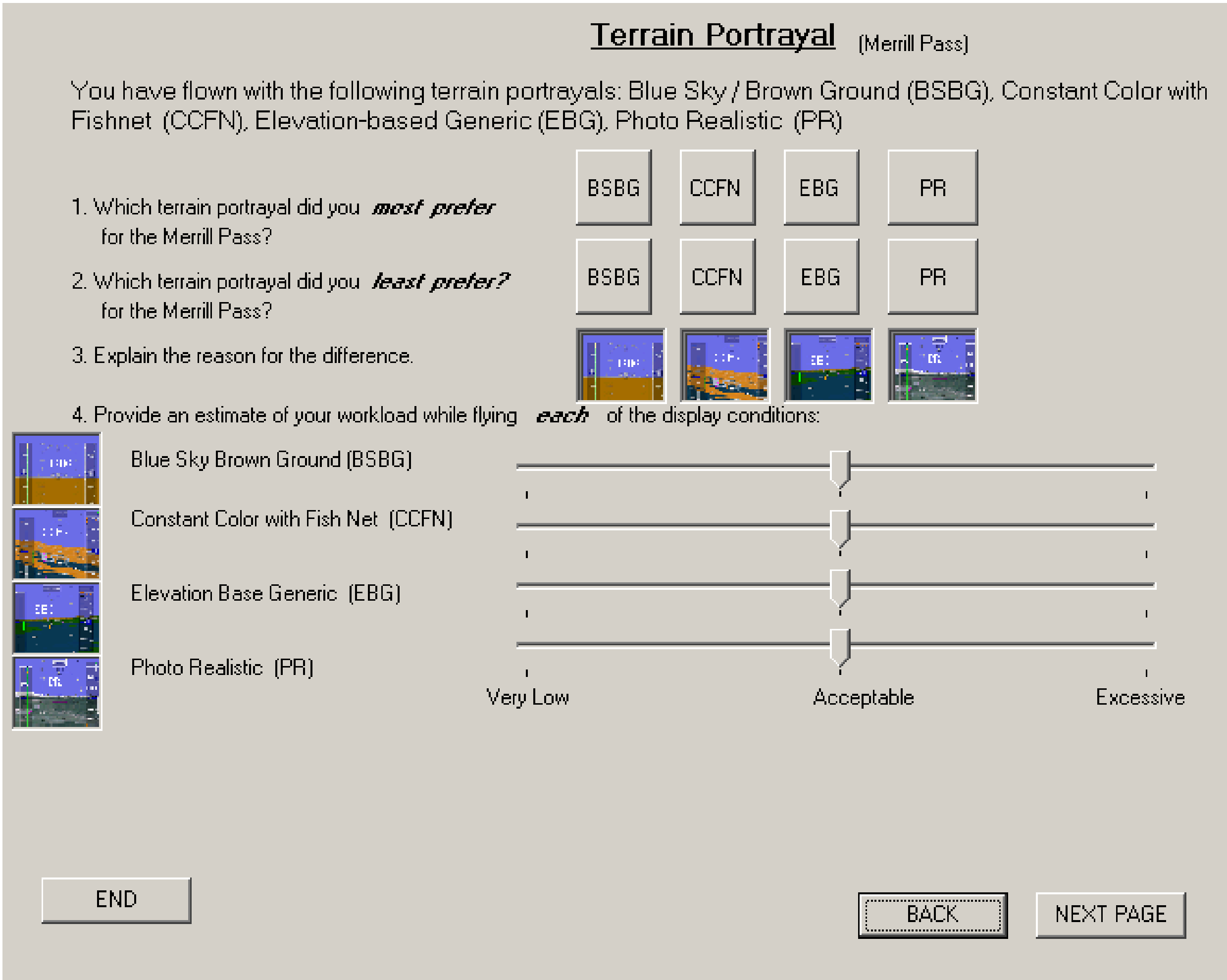

Figure D.11: Block One, Tunnel/Guidance, Preferences for TPC

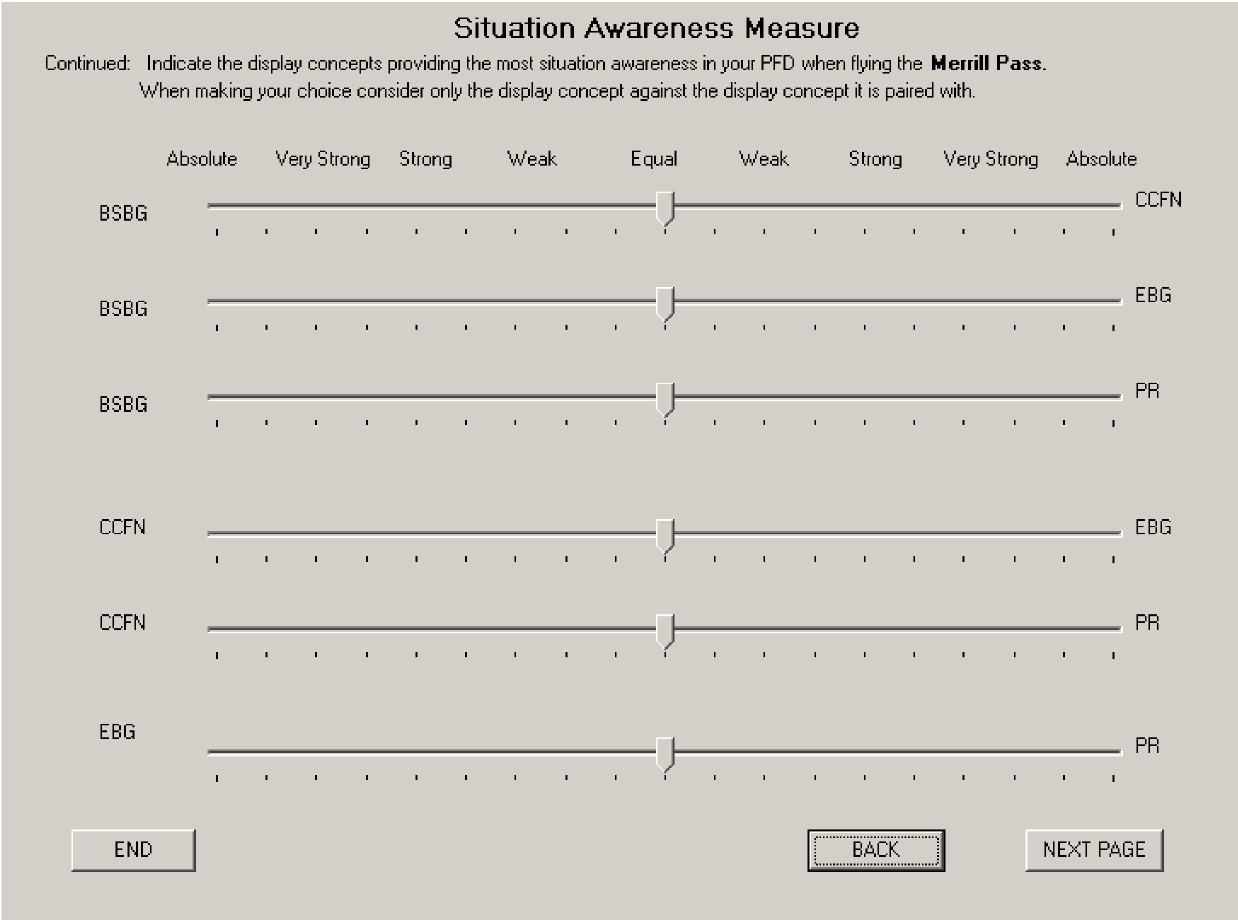

Figure D.12: Block One, Tunnel/Guidance, Situation Awareness for TPC

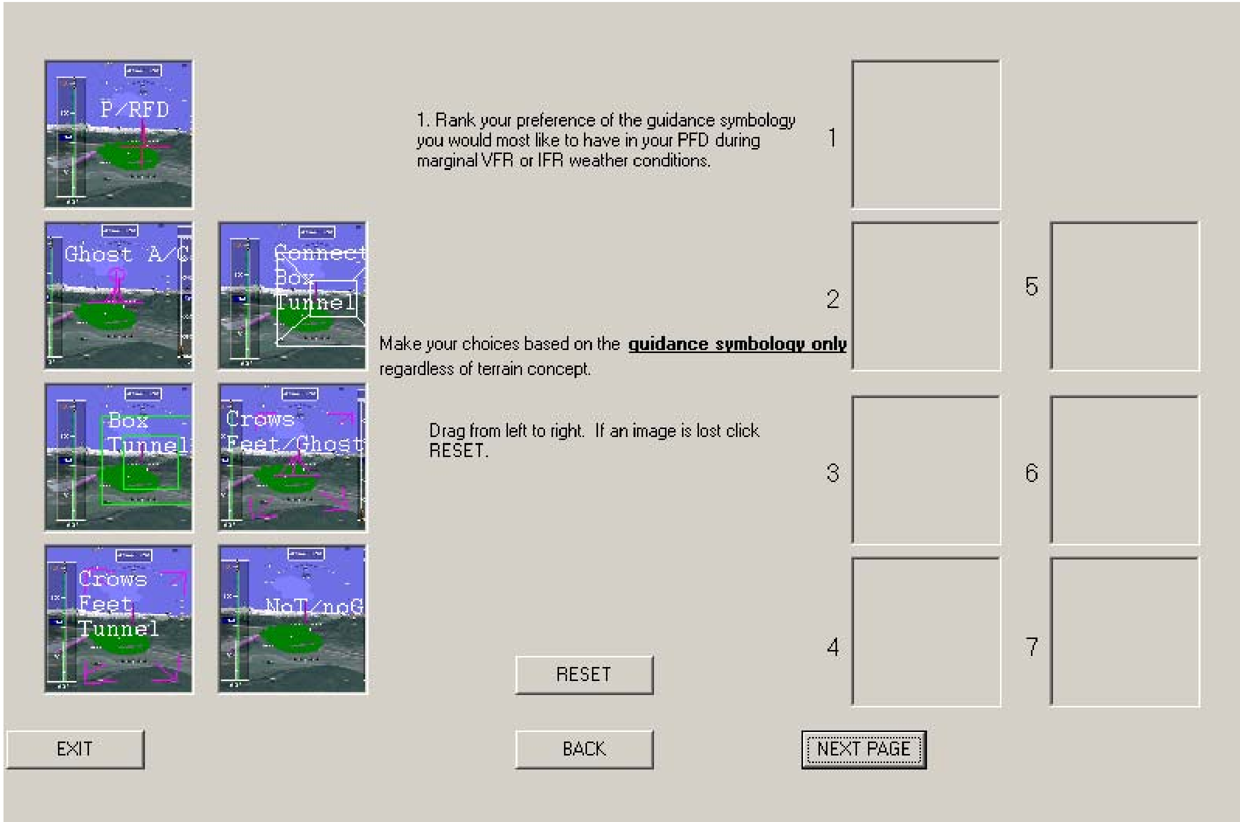

Figure D.13: Block One, Tunnel/Guidance, Preferences for GSC

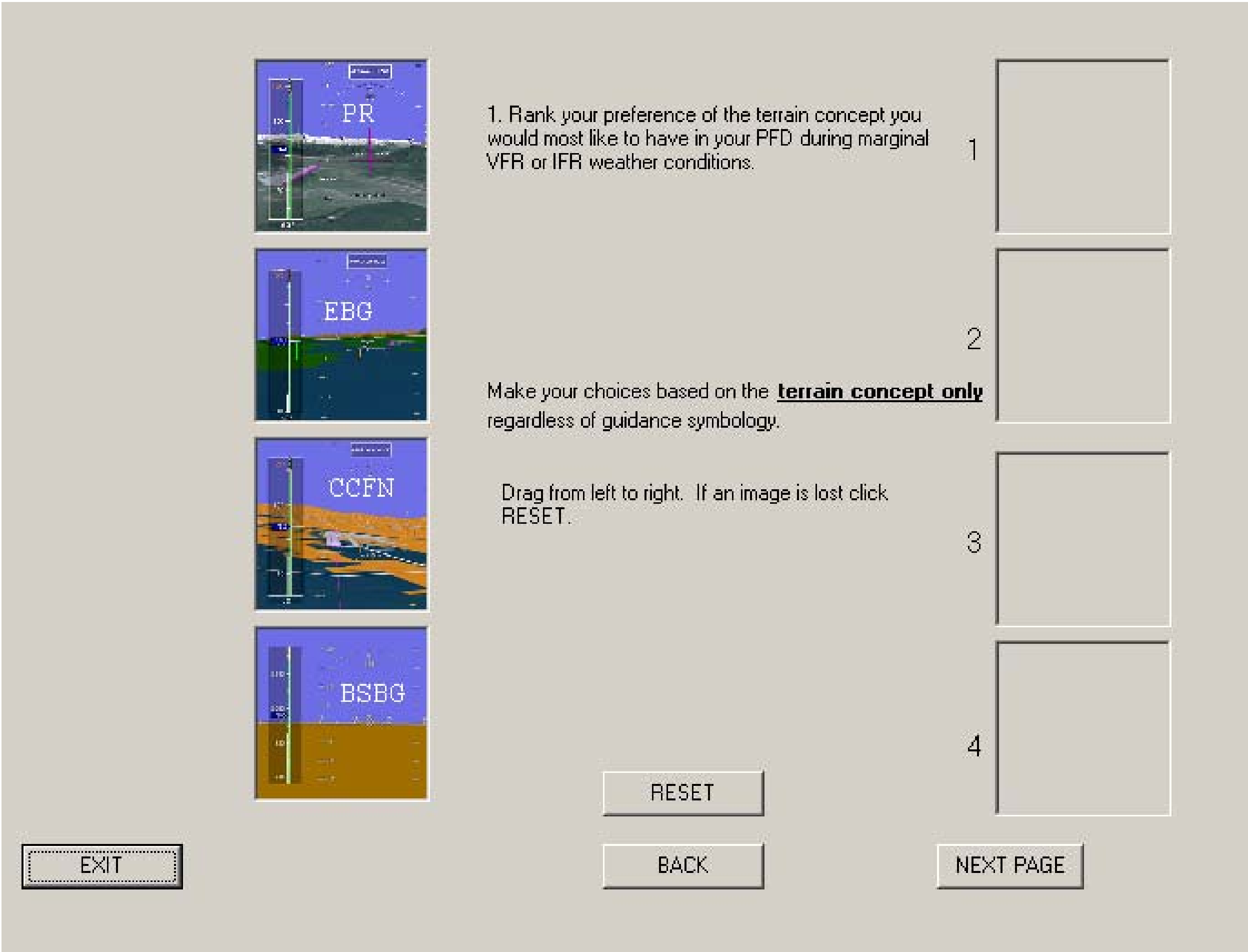

Figure D.14: Block One, Tunnel/Guidance, Preferences for TPC

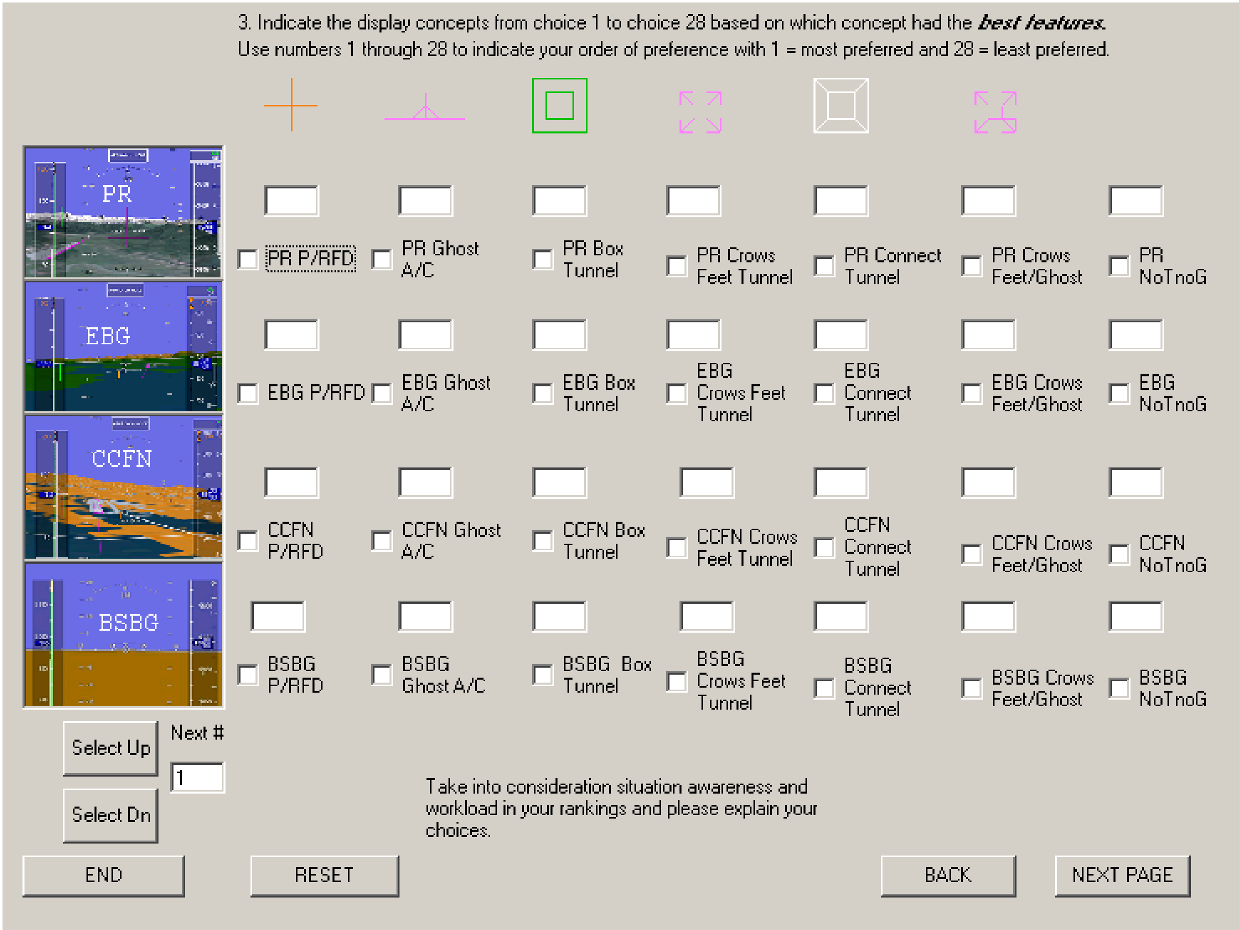

Figure D.15: Block One, Tunnel/Guidance, Ranking for All Combinations

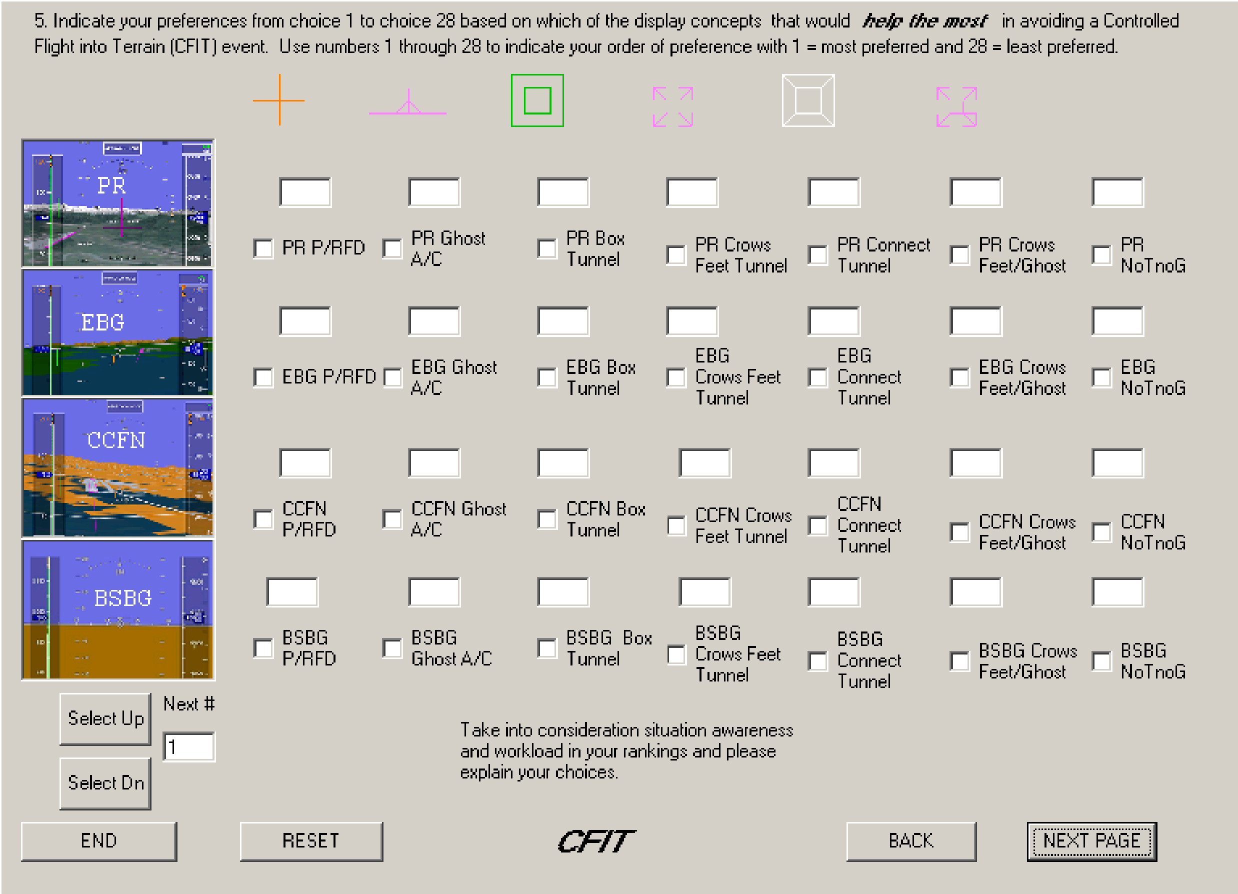

Figure D.16: Block One, Tunnel/Guidance, Ranking for All Combinations for CFIT Avoidance

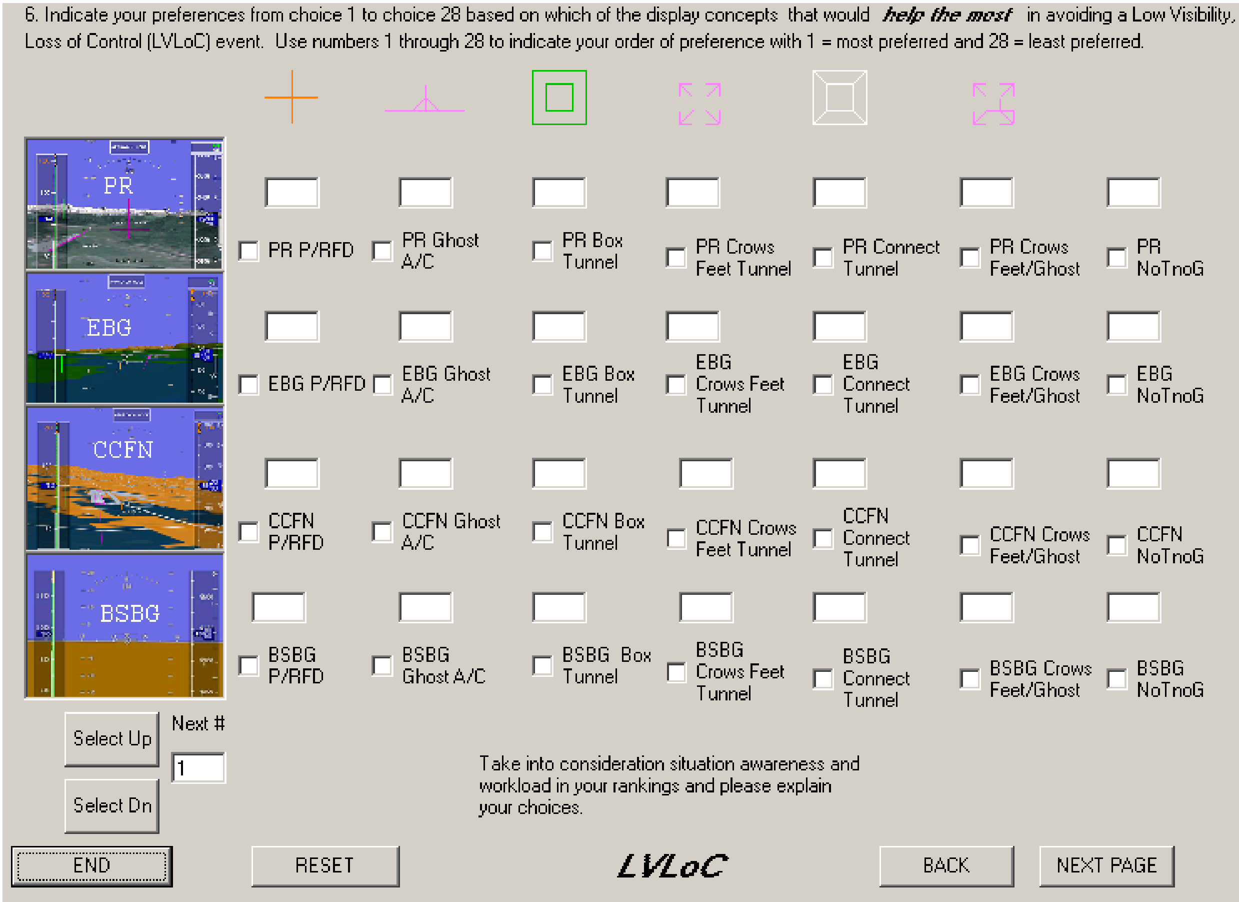

Figure D.17: Block One, Tunnel/Guidance, Ranking for All Combinations for LVLOC Avoidance

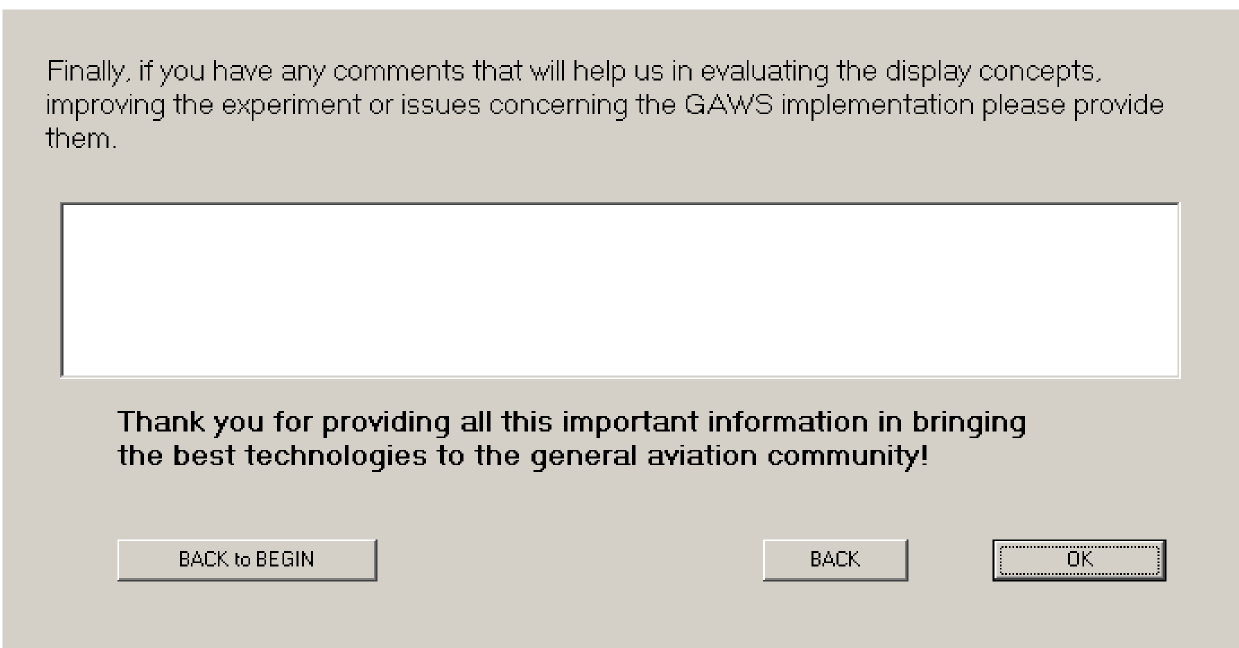

Figure D.18: Final Question

APPENDIX E: Unusual Runs and Outliers

A total of 48 runs, (6 GSC) X (4 TPC) X (2 Replicates) = 48, were conducted in the block one group, i.e. runs using the display combinations with GSC. There were 4 actual CFIT incidents and 8 runs where the evaluation pilots encountered temporary loss of SA without loss of control or CFIT. Table E.1 shows the details of these unusual runs, including comments recorded by the experiment Principal Investigator (PI). The table indicates that, among terrain portrayal concepts tested here, there were no unusual runs for the EBG. However, there were 6 unusual runs for BSBG, 4 for CCFN, and 3 for PR. Among the guidance and symbology concepts, one can see that evaluation pilots had problems with PRFD (5 unusual runs), 5 for CFT, 3 for GP, and none for UBT, CBT or CFTGP. As it will be shown in the next sections UBT, CBT and CFTGP were also the most favored guidance and symbology concepts by the pilots. Consistently, Elevation Based Generic was most favored terrain portrayal concept by evaluation pilots.

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TPC	GSC	Rating	Comments by EPs from PI Notes. *PI Comments in Italic. Runs with GSC*	Source
BSBG	CFT	VFR	Can't tell where the boxes are. Lost this one. It's difficulty flying wings level.	SA
BSBG	PRFD	VFR	Had a hard time. Was looking at the FD and tried to stay with it and than lost the CDI and the other way. Would not be able to fly this one well. Quite frustrating and stressful. *PI= EP almost lost it before the turn but recovered.*	SA
BSBG	PRFD	IFR	VMC, I looked outside more and lost the track of PRFD.	SA
BSBG	PRFD	VFR	(I was) Using the ND to try to fly the path. Chased one needle and lost the other. SA was all OTW and ND. Zoomed in ND to fly the path closer thought that is not supposed to be the guidance. Pretty difficult situation even OTW, the bowl of valley especially.	SA
BSBG	CFT	IFR	Went very high for 15 sec and then came back. Difficult to stay in the center. Lost the tunnel reference could be due to the on set of fatique. Needed to stay on top all the time and it was difficult to make a turn.	SA
BSBG	PRFD	IFR	Chasing needles all over the place. Very sensitive. Guidance lost and got real closed to the wall. Most difficult by far. Seemed to be very sensitive and difficult to anticipate. Had a hard time following it.	SA
CCFN	CFT	IFR	No bad but seems would have been easier with the ghost plane. Got lost in the turn because of the colors of the tunnel.	SA
CCFN	GP	IFR	*PI=He didn't pay attention to the terrain and crashed in .6 minutes, CFIT*	CFIT
CCFN	GP	HIFR	FOV=30 is useless for CFT. *PI=CFIT in the middle of the turn.*	CFIT
CCFN	CFT	VFR	got to side and lost the tunnel. Tried to get back had CFIT at WP3, I can see the symbology but I just couldn't get cought up to it.	CFIT
PR	PRFD	HIFR	Struggling to stay and was correcting in the wrong direction. CFIT right before the turn. (Turned around 180 then crashed. Lost elevator control.)	CFIT
PR	CFT	IFR	Still hard today on the CFT. Lost in the corner and had some spatial disorientation. It is okay in a straight line. It was the turn that was difficult.	SA+SD
PR	GP	IFR	Lost the ghost a couple of times.	SA

Table E.1: Loss of SA and Controlled Flight into Terrain Cases for Runs with GSC

Unusual No Guidance No Tunnel Runs

Table E.2 shows the list of the unusual runs among the 144 NGNT runs (4 terrain portrayal concepts * 2 Replicates * 18 evaluation pilots). Here, there were 4 CFIT runs with CCFN and 2 with EBG. Among the unusual NGNT runs, there were not any cases with PR (in IMC) or BSBG in VMC.

TPC	GSC	Rating	**Comments by EPs from PI Notes.** ***PI Comments in Italic. No Guidance No Tunnel Runs***	Source
CCFN	NGNT	VFR	Not able to determine my distance above ground caused the CFIT. *PI= CFIT in 3:51 minutes.*	CFIT
CCFN	NGNT	IFR	*PI= too low. Stopped 2.4 into flight.*	CFIT
CCFN	NGNT	IFR	Finding the pass with this concept is difficult. SA was low due to lack of depth cue on the CCFN. *PI= CFIT in 3:40 minutes into the flight.*	CFIT
CCFN	NGNT	HIFR	*PI= CFIT before WP4.*	CFIT
EBG	NGNT	IFR	Looking outside doesn't help much. *PI= CFIT in 3:40 minutes*	CFIT
EBG	NGNT	HIFR	*PI= CFIT during the turn.*	CFIT

Table E.2: Controlled Flight into Terrain Cases for Runs with No Guidance and No Tunnel

Segmented Treatment

During the segmented treatment of FTE there were few unusually large values of FTE for some of these segments. A careful examination of these values showed that the second tier unusual data were based on a single run. In this particular run, the EP lost his lateral SA as he was "distracted" by the ND. For the analysis of segmented treatment of FTE, any data with an outlier larger than 10 times the standard deviation of the measures were treated as an outlier and removed from the data bank. Figures E.1 - E.12 show the data distribution for lateral and vertical path deviations before and after the outlier removal process.

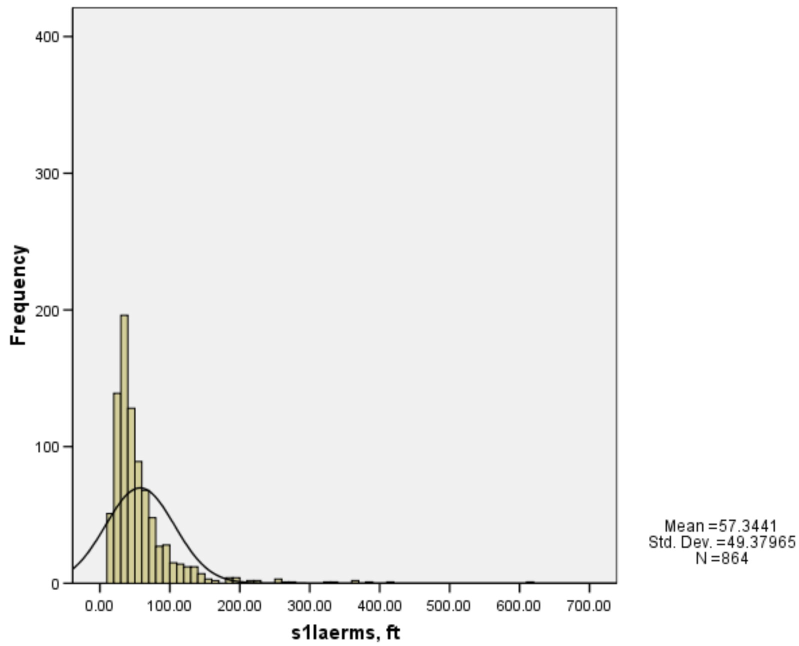

Figure E.1: Distribution of Lateral Deviation Values for segment 1 before outlier removal

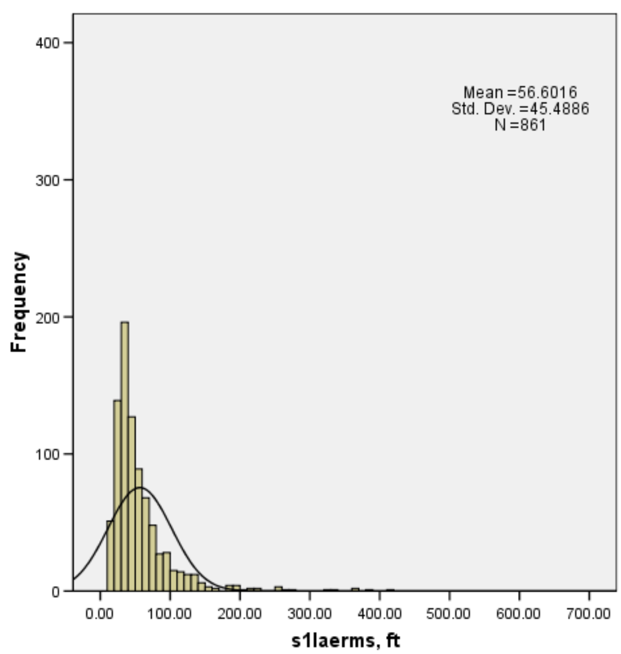

Figure E.2: Distribution of Lateral Deviation Values for segment 1 after outlier removal

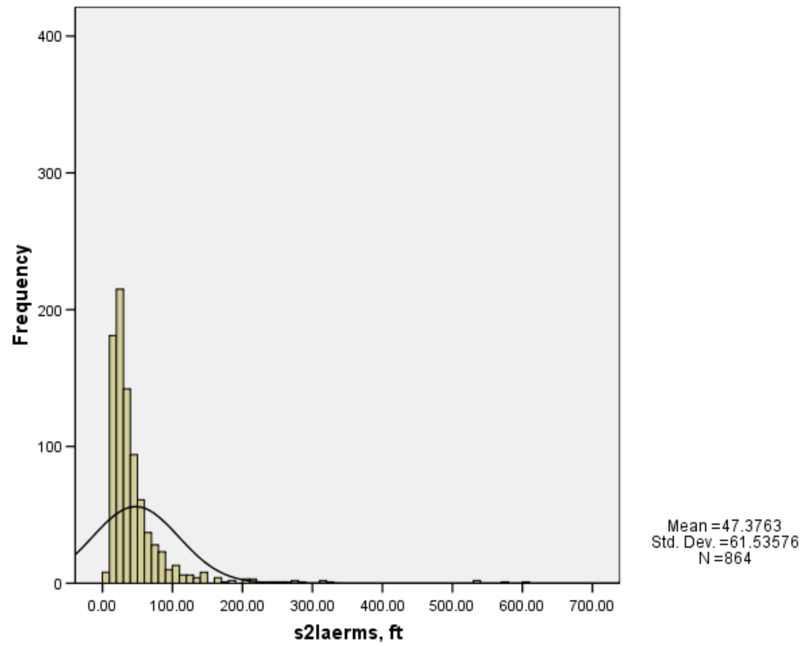

Figure E.3: Distribution of Lateral Deviation Values for segment 2 before outlier removal

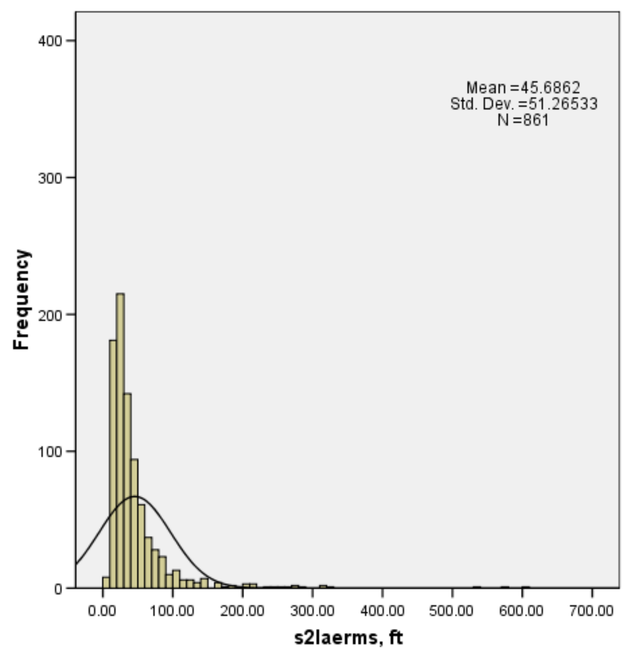

Figure E.4: Distribution of Lateral Deviation Values for segment 2 after outlier removal

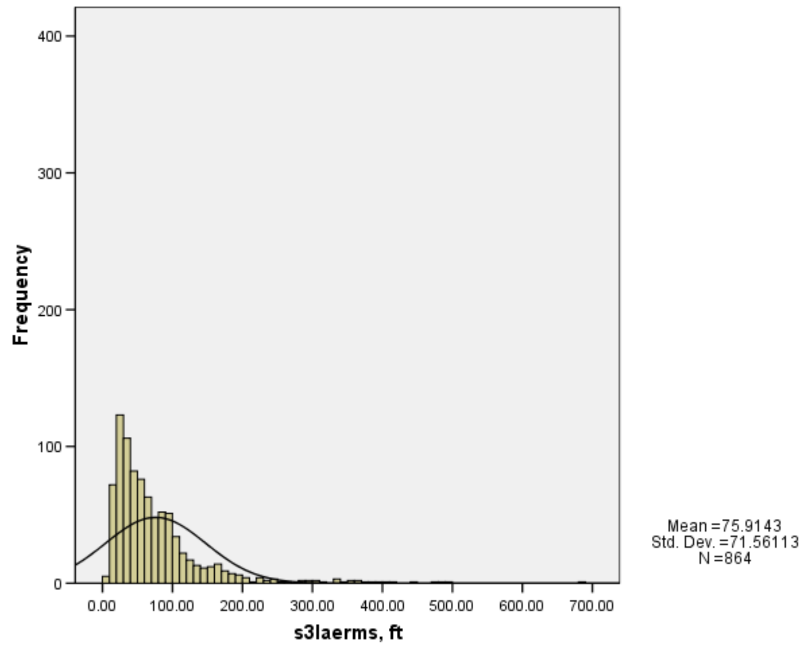

Figure E.5: Distribution of Lateral Deviation Values for segment 3 before outlier removal

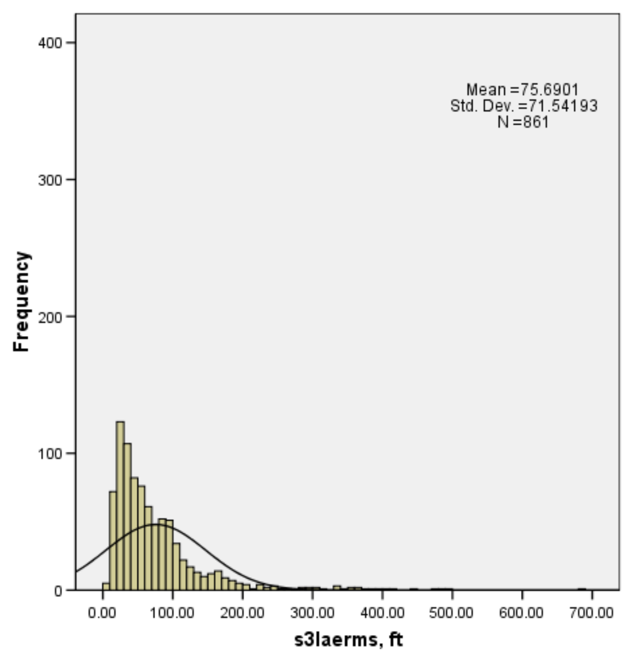

Figure E.6: Distribution of Lateral Deviation Values for segment 3 after outlier removal

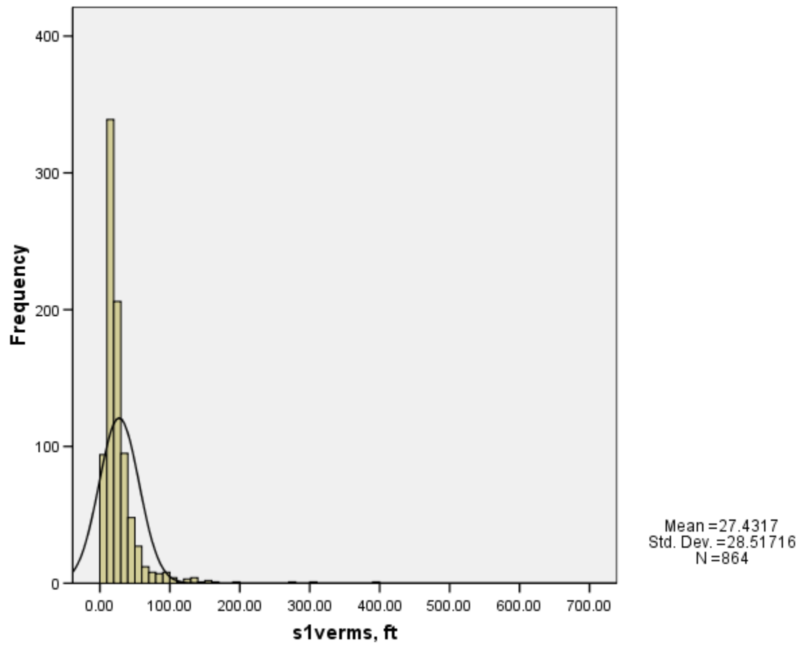

Figure E.7: Distribution of Vertical Deviation Values for segment 1 before outlier removal

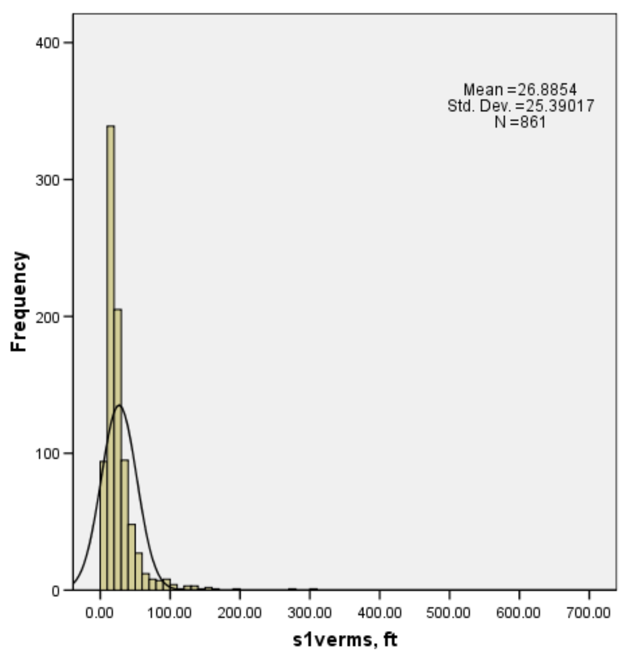

Figure E.8: Distribution of Vertical Deviation Values for segment 1 after outlier removal

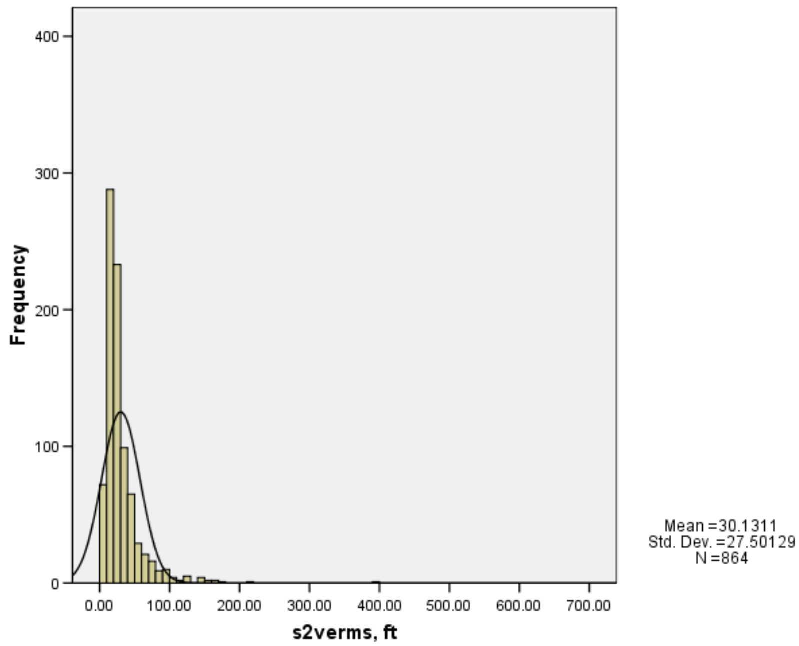

Figure E.9: Distribution of Vertical Deviation Values for segment 2 before outlier removal

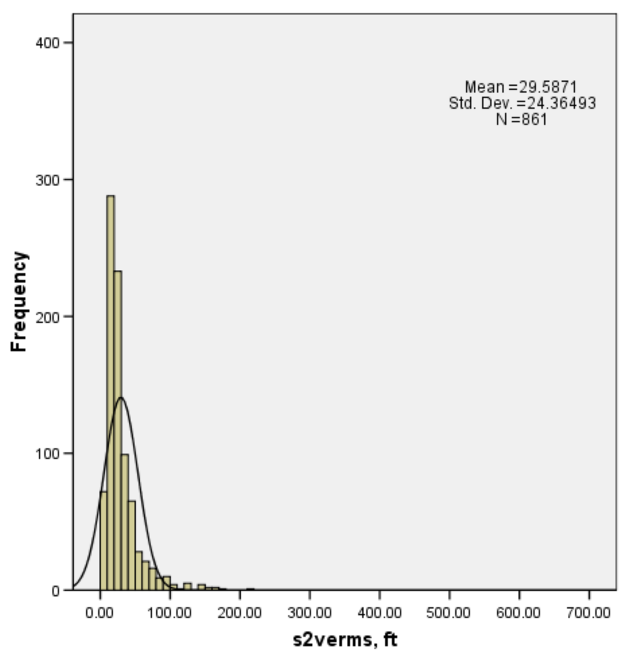

Figure E.10: Distribution of Vertical Deviation Values for segment 2 after outlier removal

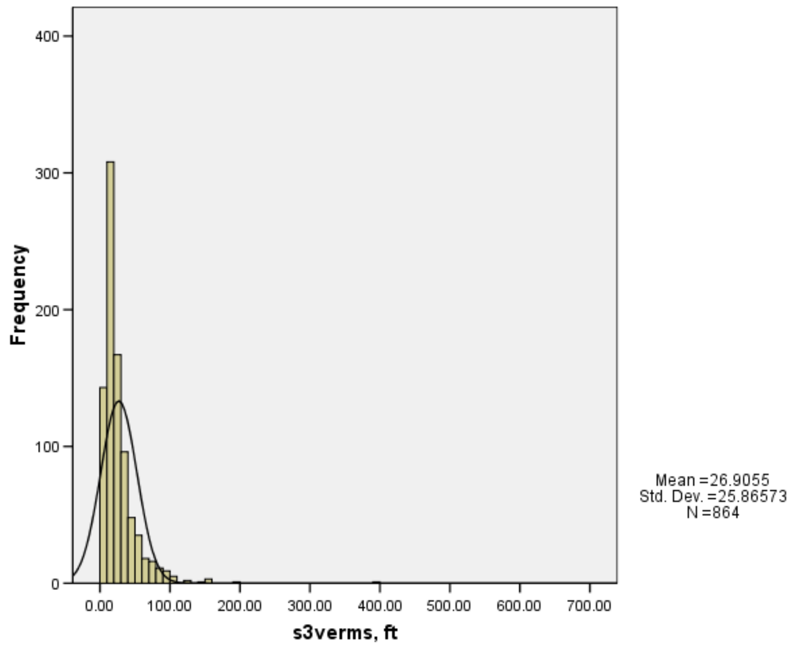

Figure E.11: Distribution of Vertical Deviation Values for segment 3 before outlier removal

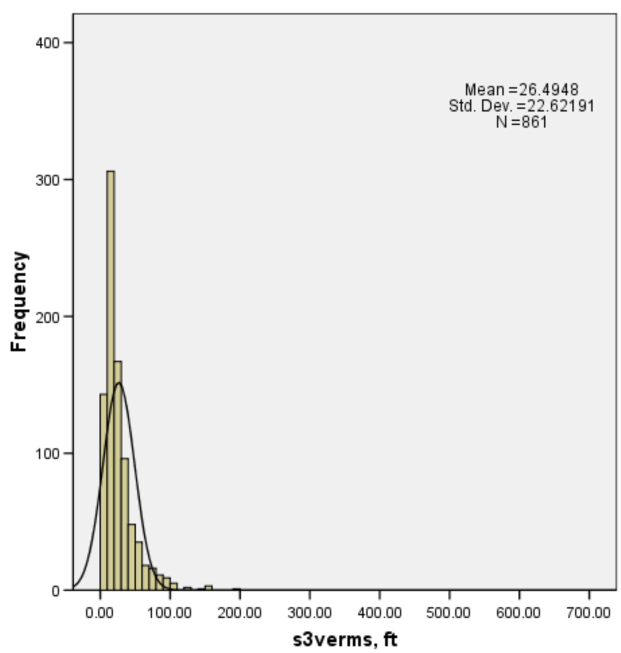

Figure E.12: Distribution of Vertical Deviation Values for segment 3 after outlier removal

APPENDIX F: Samples of Evaluation Pilot Comments

Samples of EP comments, as extracted from PI notes during the runs, are shown in tables F1-14. The first group of tables shows the comments of H-IFR evaluation pilots, followed by comments of IFR and finally VFR pilots. In each group of tables, the comments are grouped by the blocks of terrain portrayal concepts followed by the NGNT runs.

As mentioned earlier the full transcripts of the audio taped EP comments will be (possibly) published as a separate document, however, these are readily available to the reader upon request from the authors.

TPC	GSC	Comments
HIFR		
BSBG	PRFD	I tend to over-control quite a bit. No terrain information, that is not helpful. Hard to anticipate the turn but looked at the ND an noticed the turn. Don't like these things. Over-controlling could be due to the turbulence. No terrain awareness. It takes a lot of concentration to stay centered up. It jumps a lot. Turns are not easy on this one. Even a small turn is hard to tell where to focus. It helps to stay on target once you are on.
BSBG	GP	Better than the last display. GP tends to jump a lot and may be it is because I am trying to anticipate too much. The lateral is the worst. Hard to fly smoothly with the GP, I am just chasing it. I need to do a lot of physical work to chase the GP. I feel like over-controlling. Advantage of this display is very little clutter. GP requires a lot more control movements to center. Hard to be smooth on the control but is also fairly accurate. As long as you keep up with the GP, you are doing okay but very busy.
BSBG	CBT	Would have been helpful to have a center marker on the tunnel. Other than that, the guidance is pretty good. Turbulence was pushing him around and hard to stay smooth. Could see outside a little for the ground and that is it. Easy to over-control this. No TA. Tunnel looks good. The background is less cluttered and can see the background very well. Tunnel allows me to see what is coming up ahead and that is helpful. Turbulence really gives some physical demand. I can see the turn coming up.
BSBG	UBT	No terrain awareness except the outside. Still I like the balloon and the green boxes; it is hard to know where the center is. The boxes are smaller and makes it easier than the CFT to find the center. Feel like over controlling a little bit. No TA. I like the balloons. It helps to see where I am without the ND. Fairly good guidance. Easy to see the center of the tunnel and the balloons also help. For the green boxes you have to stay left in the box for right turn and right in the box when turning left. VMC, my tendency is to fly VFR instead of flying the boxes. I have to stay outside the boxes around the corner.
BSBG	CFTGP	FOV 30 is not helping much. I am chasing it too much. Try to go to the center of the box to reduce over controlling and chasing the GP. I don't care for BSBG it doesn't tell me much about terrain. I seems to be high workload with this and no terrain.
BSBG	CFTGP	Little clutter on the background and thus good contrast with the CFT. CFT helps me to see where the future path is. Lot of physical control manipulation needed to stay with the it.
BSBG	CFT	CFT is hard to tell where the center is. No TA. Gives good understanding of where the path is but is not very accurate. Easy to get off course. I am getting off but not realized until it happened. The active CFT disappears behind the tapes. Without the GP, the CFT alone makes it harder to fly and hard to judge the center. Better than nothing but not too great. *EP scanned the CDIs more than GP* .
BSBG	NGNT	*VMC* ; I am learning MFD better, the altitude is a wild guess.

Table F.1: A Sample of EP (H-IFR) Comments for the Combination of BSBG and GSC.

TPC	GSC	Comments
HIFR		
CCFN	NGNT	It is hard to judge 500 ft. I try to stay in touch with the ground. I don't know what altitude it is suppose to be but I still try to keep close to the ground.
CCFN	GP	In the first turn it gets hard to tell how high you are, it seems relatively low. It is the way the CCFN is building up, which make you look closer to the ground. It is actually not a bad thing. Once I learned to fly the GP, it is little bit easier to anticipate where it is going.
CCFN	CFTGP	CFT helped somewhat knowing where the path leads. With the GP, I tend to move the control yoke more than the others but it is more accurate. With 30 FOV this gives pretty good TA but not as good as the EBG and the PR. It is not bad.
CCFN	PRFD	A lot more demand on my scan work and I need to look at the ND more. TA was moderate. Once getting the cross-hair lined up it is okay. The issue is when making the turn, ND is needed. The bars jump quite a bit. The noodle on the ND makes it look like you need to turn all the time.
CCFN	CFT	Some terrain awareness. Don't like the CFT by themselves; it is hard to see where the center of the boxes is. Hard to see where you are in space. TA is decent. Usable but not very good compared to the others. Hard to tell when you are drifting.
CCFN	GP	There is some TA with this. It takes some physical manipulation to keep the GP in the center. It is too sensitive. Turbulence makes the thing jump around. Hard to stay with the GP. Really I feel like over-controlling the airplane with the GP.
CCFN	CFT	Hard to see the CFT corners. It would have been helpful to have some kind of marker at the center of the Crows Feet Tunnel. There is some TA though not as good as the other TPCs. Hard to see the Crows Feet center also. Kind of confusing on where the velocity vector is going to go.
CCFN	CFTGP	Moderate TA. The CFT makes it easy to know where the path is but use the GP to stay in the center. CFT helps to see the turn. The terrain display makes me feel I was too low; may be because of the lines. TA with this CCFN is not as good as with the others.
CCFN	PRFD	Good TA. The FD seems somewhat easier on this combination but it jumps around and hard to be smooth. It is not as physically and as intensive as GP but it is awfully sensitive. Got to cross-reference with the ND but still it is better than the previous display.
CCFN	UBT	Probably leaving FOV at 60 when flying all the time. Balloons allow you to see the center of the tunnel. It would be nice to have some sort of marker at the center of the tunnel. I tend to stay outside of the boxes during a turn. Relatively easy to fly.
CCFN	CBT	Moderate terrain information. Not much cue on the terrain and it appears lower than actually it is. Magenta box sometimes disappears behind the tapes and makes it more difficult to see th center of the tunnel. Hard to see center of the magenta box when it is obscured by the tapes.
CCFN	UBT	Moderate terrain awareness. Like the balloon. Staight and leve is easy, turns are more difficult. I like the heading information, it is easy to read. I need to stay on the outside of the box during the turns. Tendency is to cut inside to much.
CCFN	CBT	Turbulence really bounced me around. Hard to tell where is the exact center of the boxes. Good awareness of the terrain. Feel like I was over-controlling just to keep up with it. Easy to fixate on the white box ahead and thus not targeting at the right point.

Table F.2: A Sample of EP (H-IFR) Comments for the Combination of CCFN and GSC.

TPC	GSC	Comments
HIFR		
EBG	GP	Good TA; especially the 30 FOV is pretty accurate compared to the OTW. I like this terrain. It is good. I like the 30 FOV at least in the first turn. It is impossible to see with the 30 FOV on the other displays. Tougher to stay with the plane at 60 FOV.
EBG	CBT	I like this display, FOV=30 is good for terrain clearance. Wind and turbulence makes it harder to follow the box, I killed the terrain and white boxes. It is hard to see the center of the box, a cross-hair would have been nice in the center of the box.
EBG	CBT	I like this terrain it gives me visual of outside and terrain elevation. There is a tendency to cut through the tunnel but the guidance box helps to stay on it. FOV30 terrain is better but I need 60 to stay in the box. The OTW is not enough I am relying on PFD.
EBG	CFTGP	Crows Feet helped me to get back inside the box. I am still learning to follow it with the help of ND. I go to FOV of 30 which I like for terrain but I tend to over control with 30. I try to fly smooth but I can't because I am trying to stay out of terrain.
EBG	GP	Good TA. A lot of physical movements to keep the ghost plane in the center. Hard to be smooth but seems to be very accurate. 30 FOV is too sensitive to follow the plane well. Easy to visualize the turn. Tend to over-correct after the turn.
EBG	UBT	I like the balloons; don't have to look at the ND. The terrain awareness is good. I like this kind of terrain display. So far, when going straight, the system is pretty good. I could see the boxes ahead. Some tendency to shoot for far away boxes than the one in front of me.
EBG	UBT	Do like the waypoint balloons. Like the green boxes though it is hard to tell when it is the transition to the next green box. Tendency is to cut the corners on this one. As you need to visually stay to the outside of the boxes as it comes towards you.
EBG	CFTGP	Good terrain. Seems like still have to over control a little but perhaps due to a new day; not too bad. This is not a bad concept. The terrain awareness is pretty good. 30 FOV feels like really know where the mountains are. I see the big turn coming up.
EBG	CFT	I don't like the CFT as guidance. It is hard to tell where you are. Contrast between the CFT and the terrain makes it hard to see *(corners)* them. They do help to see the turn coming up. Tendency is to cut the corners especially during the turns.
EBG	PRFD	Good TA. This 30 FOV is quite comfortable for PRFD. The lateral guidance is a lot more jumpy than the vertical guidance. Cross-checking the ND quite a bit. Pretty good TA. With 30 FOV I can see how close the mountains are. Tendency to pull up.
EBG	PRFD	Lateral FD seems to be overly sensetive. You have to rely on ND for turn information. I like this terrain presentation.
EBG	NGNT	I am more comfortable about this terrain still difficult to say hight above the ground.

Table F.3: A Sample of EP (H-IFR) Comments for the Combination of EBG and GSC.

TPC	GSC	Comments
HIFR		
PR	CFTGP	Good TA. The airplane is easy to follow once you get to the middle of the CFT. Takes a little effort to get used to it. The PR helps to some extend. It gives better orientation awareness. A lot of physical effort to keep the GP centered but once centered it works good.
PR	PRFD	I normally don't like FD but here it is nice.
PR	UBT	Good TA. Easy to stay in the center during the straight path. Like the balloon which helps to stay on path. Tendency to cut the turns again. Overall it is a pretty good display; good PR, good control. But during the turn it was hard to figure out where it is.
PR	PRFD	Good TA. The cross-hairs are pretty sensitive. Turbulence is hard to follow. PR display makes it more comfortable, knowing where the terrain is. Cross hairs are jumpy and I need to use ND. Needle does not help much. Too much turn indications then what is needed.
PR	GP	It is a little bit difficult to pick the altitude from the display so I have a hard time to get started right. I have to cross-check with ND to see if the turn is coming up. It is hard to stay with ghost plane. With visual cues of PR, I can anticipate what they are.
PR	CFT	Good TA because of the PR. Don't like the CFT by themselves very much. It is hard to tell where the center of the CFT is, plus the other symbolgys also clutter the center of the tunnel. The ND noodle seems to be more than it should be.
PR	CBT	Excellent terrain awareness. The TA is good for 30 FOV but I can't see the magenta box thus switching back to 60. Good display probably the nicest combination so far at least for the straight and level. Still hard to see where the center is.
PR	CBT	Good TA. This is a decent display with the tunnel. Pretty compelling view and give a good security on where you are along the flight path. Pretty good set up and still know where the terrain is, even though the 60 FOV distorts the reality. The tunnel let you know where you are going.
PR	CFT	Advantage is the magenta contrast well with the PR and you can see the magneta much better than the other terrain. It is still not as accurate to follow as the other GSc. It does give you an idea where you are going and good TA.
PR	GP	Like the 30 FOV but GP jumps around too much. 60 is not bad. Pretty good SA but need to look at the ND to anticipate the turns. Once getting used to the idea that the plane will have to make a violent turn, it becomes easier.
PR	NGNT	Good realism; I am confident in where I am. Green boxes still let me stay to the outside of the turns. I like this display. One needs to get used to it. it seems like the box shows one is in the middle but not the CDIs.
PR	NGNT	Good TA. Great for terrain awareness for sure without the guidance.

Table F.4: A Sample of EP (H-IFR) Comments for the Combination of PR and GSC.

TPC	GSC	Comments
IFR		
BSBG	CBT	I stay with FOV60,
BSBG	UBT	I used 30 of FOV because boxes were slower. The BSBG made me look out the window more even though there was not much to see. Seeing outside gave me a more secure feeling. I focused more on the second rather than the first box in front of me.
BSBG	CFT	FOV of 60 had more clutter and a lot of disconnected lines all over. The CFT lines lead to less SA because it is hard to see where I was going and I started to go way off. It was better, less clutter, with BSBG than other TPCs but more risky.
BSBG	CFTGP	It is not bad with the CFT to assist the GP. With just the CFT, I don't like to zoom-in but with this one the zoom-in helps me to keep closer track with the GP and with less clutter.
BSBG	CFTGP	The background requires glancing out the window more. The OTW made me think I was closer. I wasn't quite ready for some quick changes in time. I tried to look outside more. I was lagging behind the GP a little and was not aware of what is outside.
BSBG	CFT	Without the background (*terrain*), I had to worry more how close to the mountain I was. I felt like chasing the CDI more. I wasn't totally sure without glancing the ND to see where I was. The CFT not connected, especially in the turn, It was hard to see where to turn.
BSBG	UBT	I try to keep focus on the immediate box in front of me. I need to glance over to the ND to see the waypoint numbers. The green box is unconnected and thus harder to get an idea on where you are going. It is harder to notice the boxes. They don't give much speed change.
BSBG	CBT	With tunnel I can see what is happening and allowed me to see and control the speed better. I could see the tunnel going up. Not having the background it was more disconcerting.
BSBG	GP	Without the background (*terrain*), I looked more at the ND and took attention away from the PFD. Chase plane required a lot of chasing especially during the turn and right after it. The GP made a lot of directional changes at that point and made me work harder.
BSBG	GP	It is a little more difficult to anticipate the GP. The initial setup took a little bit to get on. I could see the (*ghost)* plane but still it took a little to get on at the beginning. Not having the background *(terrain)* I needed to rely on GP.
BSBG	PRFD	With no background (*terrain)* I needed to look at the ND more but was not able to do it because I was too busy. I had a tough time especially at the sharp turn. Too focused on the FD and I was not able to know what is happening. Very little anticipatted.
BSBG	PRFD	VMC, I looked outside more and lost the track of PRFD.
BSBG	NGNT	VMC, I was looking at OTW more and used my airspeed for my altitude indicator.

Table F.5: A Sample of EP (IFR) Comments for the Combination of BSBG and GSC.

TPC	GSC	Comments
IFR		
CCFN	CBT	30 FOV doesn't help much. That makes me put velocity vector through the white boxes instead. When getting real close to the ground, the CCFN appears closer than it actually is. The guidance part feels good to me with 60 FOV.
CCFN	CBT	It was better with the CCFN. It was easier to see. I like the boxes and it is easier to keep up with the boxes and see where to go. Once I was in the box, attention was okay. I can see the lines going up and down on the terrain. I took focus away from ND.
CCFN	CFT	When you get close to terrain they merge and you can't see the contour lines. With the CFT, it is easy to go off the CDI and thus it required more work. You loose a little bit of what is going on due to the blending of the terrain.
CCFN	PRFD	This is simlar to the GP because it is decluttered a little more. I felt close to the ground. Everything was alright, contours were okay.
CCFN	CFTGP	CCFN was fine, good background info just more difficult with the depth perception but you can see the mountains; that helped. GP is a small target but helped to keep it right on the target. Toggled between 30 and 60 to keep things straight.
CCFN	PRFD	Without indication on where to go it was a little difficult. I am all over with this one. When two hill are together it is difficult to distinguish them and is confusing. I needed to catch up with the FD.
CCFN	GP	The contour map (*CCFN*) was fine and getting more used to it. I am not 100% sure about depth perception. GP was hard to anticipate and did not give me enough bank and speed information. I say below normal in understanding of the situation.
CCFN	CFTGP	I looked at the CFT and GP together to help anticipate; little depth perception with this background (*Terrain)*. I used ND to verify but it was hard to tell how close the mountains were. I was looking mostly at the chase plane (*GP)* but did not worry too much on the precision.
CCFN	CFT	Sometimes the left side of CFT was visible but the right side wasn't; perhaps due to the clutters with the tape and CDI. The background *(terrain)* was not really a huge factor and I had a good idea where I was.
CCFN	UBT	With the contour mapping was fine. I felt comfortable with the guidance box and it was nice to know where the walls were. Reassuring knowing where things were. Trying to get to the center of the next box could get into an unusual attitude.
CCFN	NGNT	With the CCFN it is very hard to get your eyes off of PFD.

Table F.6: A Sample of EP (IFR) Comments for the Combination of CCFN and GSC.

TPC	GSC	Comments
IFR		
EBG	CFTGP	30 degrees FOV during the turn seems to be helpful for the turn. With chase plane (*GP) you* can see the small adjustments you need to make; The contour on the terrain helped me anticipate where to go.
EBG	CFT	The CFT corners were dragging me out of the CDI. Though I was off just a little but the CDI showed a lot. The CFT let him know where the turn was and thus I was able to anticipate it. It requires huge correction with CFT.
EBG	CBT	Better this time in keeping predictor on the magenta box. The background was good to have. No need to use 30 FOV to see the white boxes because I was not looking at the white boxes anymore for lining up the predictor.
EBG	CFTGP	I cut the corners to catch up with GP. I like FOV of 30 here better because it gets me closer to GP (on the straight leg).
EBG	CBT	I put the noodle on the first waypoint (on the ND) and that works quite well. I saw a lot of space around me on the ND and made me feel comfortable. Compared this with GP, the GP is more precise and that keeps you on your toes; the magenta box is not as hard as others.
EBG	GP	I was checking more the ND but sometimeswhen I was looking at the ND and I would lose track of the GP quickly. I was more aggressive on keeping up (*with guidance*) because I was not sure what the GP will be doing next. It was good with the background. Good depth perception with light shadows.
EBG	NGNT	this time I was using the terrain to get to the way point.
EBG	NGNT	I had a better depth perception. It might be due to FOV 30.

Table F.7: A Sample of EP (IFR) Comments for the Combination of EBG and GSC.

TPC	GSC	Comments
IFR		
PR	PRFD	FD does not allow you to prepare how far off you will be to the next waypoint and set up for it. Thought I followed the FD quite closely but the CDI shows I was off. The PR background gives good depth perception. The FD was difficult to set up at the beginning.
PR	PRFD	With this GSC it was hard to know how far the cross-hair will move and I started chasing it around. Good to have the terrain but during the turn, I could not see where the cross-hair was going go and thus I put a lot of attention on the cross-hair and did not get the chance to look at the terrain.
PR	UBT	30 degrees of FOV made more emphasis on the balloons and thus I decided to stick with the 60. The balloons sometimes appear to be at a different place until one is right in front of me and I had to ignore it. The PR helped when I was making a harder turn.
PR	CFTGP	I like the 30 FOV because it declutters things a little but that makes the control more jerky. It is easier to toggle between 30 and 60 than the other GSCs. Sometimes there were too many CFT; it was confusing. Too many lines sometimes it gets confusing.
PR	GP	It was useful to have the GP. More exact with FOV of 30. But I was not sure what is the best strategy fto anticipate the turn. PR was better in judging how far/high I was. It was easier to see how close I was the the terrain. I spent more time chasing the plane.
PR	CFT	The PR was more relaxing and I did not go much far off course and it didn't cause the CDI to deviate more because I did not apply jerky control efforts instead of a calmer control inputs. The PR helped the attentional resource and not making too many sharp control inputs.
PR	CBT	It is good with the PR; i am more comfortable to what is around me and it is more realistic. The other terrains look fake. PR feels more accurate and comfortable. Boxes show what is coming up and the white boxes give you good constrast and depth.
PR	UBT	The PR was good kept me aware of where everything was especially with the green box. I aimed at the balloons with the velocity vector and threw me off. Waypoint balloons help to know when the waypoints are coming.
PR	CFTGP	With PR terrain you can see the river and the slope of the mountains; it gives better depth perception, similar to the corners of the terrain on the OTW. I am more confident seeing things outside. I was chasing the GP and was not watching what was around.

Table F.8: A Sample of EP (IFR) Comments for the Combination of PR and GSC.

TPC	GSC	Comments
VFR		
BSBG	UBT	With BSBG I had no idea where is the terrain. More unnerving. It is less likely to anticipate the change and thus less stable. I had to concentrate quite a bit on the box and had problem picking out which box to point to.
BSBG	UBT	In straight flight demand on attention was low but it was harder to stay in the center during a turn. I had time to look at ND. Boxes provided good guidance by aiming several boxes ahead.
BSBG	CBT	Tunnel laid out the course in front of you, no guess work. Plenty of time to plan ahead. It lacked specific terrain detail.
BSBG	PRFD	PRFD needed a lot of attention as you had to go back and forth to try to center the FD. I thought it was centered but the CDI showed it was off course. I stuck with the FD since there were no terrain. Demand on attention was thus high.
BSBG	PRFD	It takes some effort to follow FD especially with no terrain. It is difficult to follow terrain with no terrain on PFD. Quite a bit of work. I did not have much chance to look at ND. It took a lot of concentration to follow FD.
BSBG	CFTGP	It was easy to follow the GP. I tried to look OTW as much as possible because there was no terrain on ND. There was attention to spare due to the GP. I had time to look at the ND. FOV of 30 and 60 were both usable for the GP.
BSBG	CFT	I did have spare attention because of the boxes. During the turn it was more difficult because the boxes were more difficult to interprete. Only terrain cue I had was from OTW but it was limited. Boxes don't have sides and tops made them more difficult to interpret.
BSBG	CFT	Demand of attention was high due to the box which caused my deviations several times. Determining the angle of the boxes from the CFT was difficult. It took more thought process to evaluate the CFT. You needed to figure out where the CFT (*corners)* were.
BSBG	GP	GP was easy to follow but the terrain was not visible except hte OTW. You needed to look over ND and that caused the situation to change suddenly. I looked outside to check for terrain. GP kept me on track but I did not have time to do other things.
BSBG	CFTGP	I could look around without drifting too far from the ghost plane. Understanding the orientation of the plane in roll is easier for BSBG.
BSBG	CBT	BSBG gave better horizon or plane roll orientation.

Table F.9: A Sample of EP (VFR) Comments for the Combination of BSBG and GSC.

TPC	GSC	Comments
VFR		
CCFN	CFT	CCFN gave good impression on the terrain. CFT was hard to interprete during a turn. Hard to predict the trajectory because the CFT (*corners)* piled up and it was hard to distinguish the boxes thus there was less time for other tasks. CCFN gave no problems for terrain clearance.
CCFN	UBT	The display (PFD) was a little jerky at the beginning. The unconnected boxes tunnel was a lot easier than the CFT to tell where you are going. I could prepare for the next box and had time to look at the CDIs.
CCFN	PRFD	Demand on attention was high especially in sharp turns. It was hard to stay on the lines. CCFN helped to get an idea where the terrain was without solely relying on the FD. The FD lines move quickly especially when they move away from each other, can cause confusion.
CCFN	GP	CCFN generally gives good TP. TA was high but at some locations it is hard to figure out how high you are. GP provided everything I needed, combined with the CCFN.
CCFN	UBT	Guidance box was easy to follow. CCFN gave plenty of idea on terrain except in a few locations. Turns required more mental demand to judge the center of the boxes. Steep turn made it difficult to judge the boxes.
CCFN	CBT	Having guidance box always in front plus CCFN, they made the demand on attention low. Tunnel laid out the course ahead, which is good. I was not worried about the quality of the CCFN becaue the guidance information was good. Magenta box in front helped out a lot.
CCFN	CFTGP	CCFN gave enough terrain information. CFT indicated it was clear of terrain. GP stayed right on the course. GP does not require too much thought.
CCFN	CFTGP	When close to the terrain with CCFN is difficult to judge distance to it.
CCFN	CFT	This display combination was rather difficult.
CCFN	CBT	Easy to follow the tunnel and never had any lapse on guidance information.

Table F.10: A Sample of EP (VFR) Comments for the Combination of CCFN and GSC.

TPC	GSC	Comments
VFR		
EBG	PRFD	Similar to the previous one. EBG gave plenty of terrain information. Turns took more effort to keep the FD on course. EBG allowed you to see the direction with the PRFD. FD was less forgiving than the other guidances.
EBG	CFTGP	Easy to follow the GP. CFT helped understand the tunnel. EBG gave clear terrain. No problem with the guidance. Easy to see the CFT with EBG. I could look at the ND too.
EBG	UBT	There was not much instability. I had time to look at the ND. TP was fine and the box was clear in the zone. There wasn't any terrain issues, especially with the boxes. At the turn, if you aim at the center of the box early, it will be fine.
EBG	GP	I had time to look at the ND.
EBG	GP	Ghost plane was easy to follow, EBG was easy to see. Sometimes the plane would make a turn, but I did not have to contcentrate on flying the ghost too much and could watch the CDIs too. Ghost does not take too much mental demand at all.
EBG	CBT	It was obvious as to where to go. With EBG I always knew where the terrain was. The tunnel was extended and showed the trajectory making me understand what to do before it happened. It allowed time for other tasks. 30 degrees FOV was hard to use and made Guidance Box unviewable.
EBG	CFTGP	CFTGP gave good guidance and EBG gave good preception on terrain. GP plane required more attention, especially for VFR. But the combination overall gave enough capacity for other tasks. EBG is a good representation of the terrain.
EBG	CBT	Easy to fly through the tunnel and thus easy to prepare for the maneuvers. I had a better perception of the tunnel due to the lines between them. The combination was good. I like the 30 degrees FOV quite a bit. The tunnel seemed to approach slower and easier to fly.
EBG	PRFD	Following the FD required some workload. It was easier to follow the needle since EBG displays terrain well and made the turn to anticipate easier. I had less time to look at the ND. Terrain was observable but it was hard to keep track of it since you needed to concentrate on the FD.
EBG	CFT	It is hard to see the CFT during a turn. With EBG it was clear to see the terrain. CFT was difficult at the corner. Glancing between PFD and ND required more time.
EBG	UBT	This was with a tunnel, it was easy except I didn't have a turn rate to help me.

Table F.11: A Sample of EP (VFR) Comments for the Combination of EBG and GSC.

TPC	GSC	Comments
VFR		
PR	GP	Good combination, I knew where I was. GP gave good direction. I wsa able to look often to the ND. The GP ables me to anticipate. No confusion. I understand the orientation of the aircraft and terrain. PR is good for mountain but I am not sure how dirt and grass will look like.
PR	CFTGP	Ghost plane made it easy to follow the tunnel, you just need to concentrate on it and boxes became just the side symbol. CFT gave only little bit of heads up on what will happen but ghost helped a lot and I had time to look at the ND.
PR	GP	GP was easy to follow and it did not take too much attention from other things. With PR I was clear to know exactly where I was. I could look at the ND and see the check points. 30 degrees FOV was good for better resolution.
PR	CFTGP	I had plenty of time to look around and at the ND. If you want to center GP precisely it will take some attention. Situation was clear with the PR, and GP. CFT (*corners)* were a little hard to see. GP provided most information needed.
PR	PRFD	When the FD was centered, there were too much symobolgy and they cluttered in the center, including the water marker and velocity vector. I felt more comfortable not because of the change in terrain but more practice.
PR	CFT	Little higher attention was demaned than green boxes tunnel (*UBT)* but not too bad. PR made a big difference helping CFT (it made it better). Most of the time I could see CFT (corners) but couple of times I couldn't see them due the the color of the CFT. PR helped.
PR	CBT	No instability. you can an see tunnel in front easly and can do other things. No problems understanding the terrain and seeing the obstructions. I like the 60 degrees FOV which let me see the mag box fully.
PR	PRFD	It was easier to follow the FD today; it could be due to practice. It made it a lot easier to stick with the FD. You needed to use the ND for guidance. PR helped on the guidance with FD. If you looked away from FD too long it could deviate quickly from you.
PR	CFT	Similar to the previous one. It takes some effort to use the CFT. The color can get lost in the background. I had time to look at other displays. SA of a PR is high. It was hard to figure out where the boxes are and hard to see the four corners of the boxes.
PR	CBT	Visual cues form the tunnel and magenta box and PR made it easy to track the course.
PR	UBT	Higher attention was demanded than connected boxes. I had no magenta box in front so I had to aim for the further boxes an needed the CDIs to help stay on course. Green boxes made it hard to judge where the aircraft was.

Table F.12: A Sample of EP (VFR) Comments for the Combination of PR and GSC.

APPENDIX G: Results of the Flight Technical Errors for Segmented Treatment

In each one of Figures G.1-9, mean RMS of lateral and vertical path deviations for segments 1, 2, and 3 have been plotted far left, center, and right of the figure, respectively. The letters, s1, s2, and s3 refer to segment 1, segment 2, and segment 3, respectively. The letter combination of 'lae' refers to lateral path deviation and 've' refers to vertical path deviation. Accordingly, s1laerms is the value of the mean RMS of lateral path deviation for segment 1, s2laerms the mean RMS of lateral path deviation for segment2, and s3laerms the mean RMS of lateral path deviation for segment3. Similarly, s1verms refers to mean RMS of vertical path deviation for segments 1 and so on.

Effect of Terrain Portrayal Concepts on Flight Technical Errors for Segmented Treatment

During segment 1 and segment 3 where the maneuver can be considered a level maneuver the trends for the mean RMS of LPDs were similar to the results obtain for the complete scenario, i.e. BSBG and CCFN show higher deviations than the EBG and PR but the results are not (statistically) significant.

Effect of Guidance Symbology Concepts on Flight Technical Errors for Segmented Treatment

The values of the mean RMS of the LPDs for each segment (s1laerms, s2laerms, and s3laerms) are plotted in Figure G.1, below. The values of mean RMS of the VPDs for each segment (s1verms, s2verms, and s3verms) are plotted in Figure G.2, below. These results match the results of FTE for the un-segmented (entire scenario) treatment.

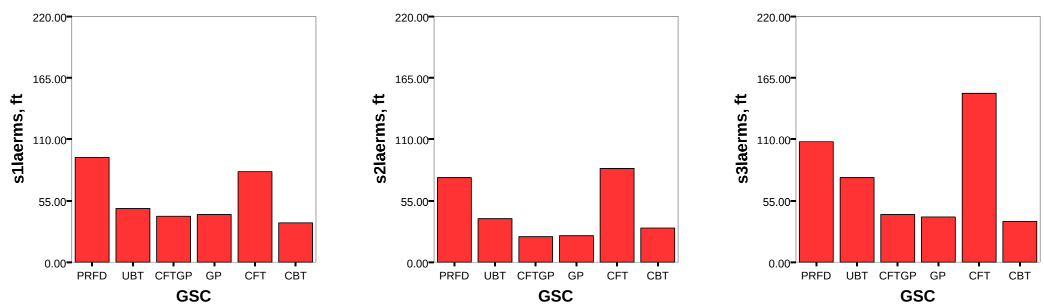

Figure G.1: Mean of Lateral Path Deviations for Segments 1, 2, and 3, by GSC

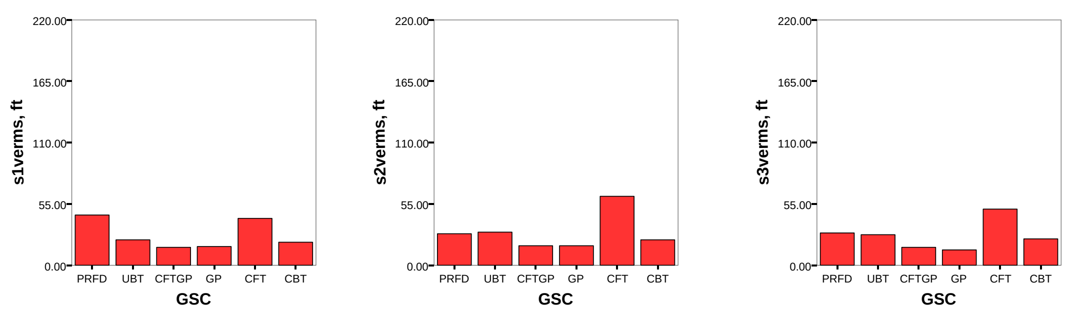

Figure G.2: Mean of Vertical Path Deviations for Segments 1, 2, and 3, by GSC

Effect of Evaluation Pilot Qualifications on Flight Technical Errors for Segmented Treatment

The values of the mean RMS of the LPDs for each segment by EP Rating are plotted in Figure G.3 and the values of the mean RMS of the vertical path deviations for each segment are plotted in Figure G.4 below. Note that the vertical path deviation values by Rating for segment 3 were not (statistically) significant.

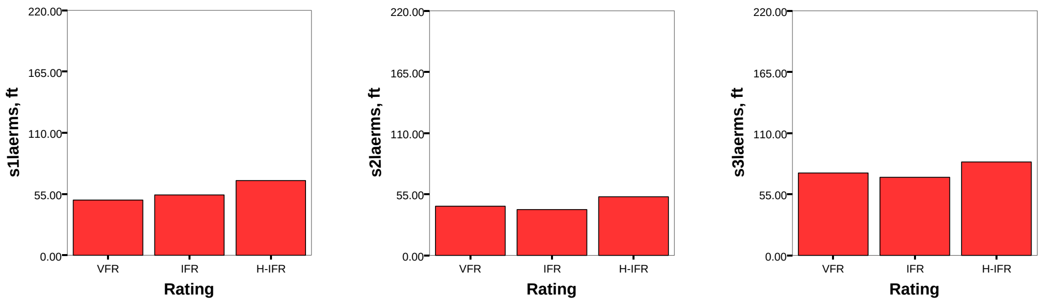

Figure G.3: Mean of Lateral Path Deviations for Segments 1, 2, and 3, by Rating

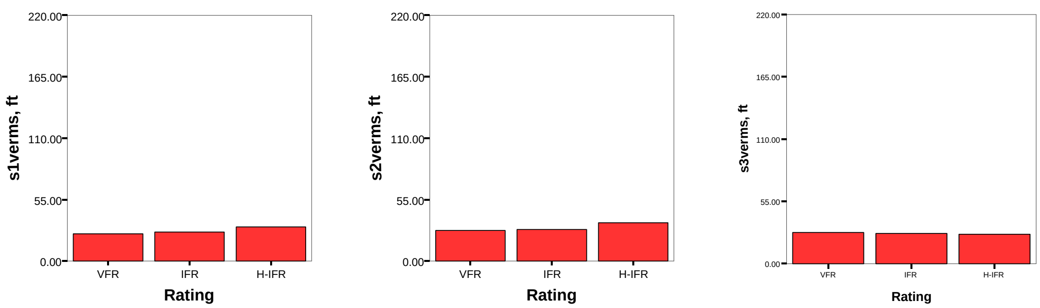

Figure G.4: Mean of Vertical Path Deviations for Segments 1, 2, and 3, by Rating

Interaction Effects of Rating and GSC on Flight Technical Errors for Segmented Treatment

The values of the mean RMS of vertical and lateral deviations are plotted for each TPC and colored by EP Rating, Figure G.5 and G.6. Note that the scale of all of the above figures were expanded to 210 ft since the mean RMS of LPD for CFT guidance by H-IFR pilots, during segment 3, exceeded the scale of 100 ft used in other plots.

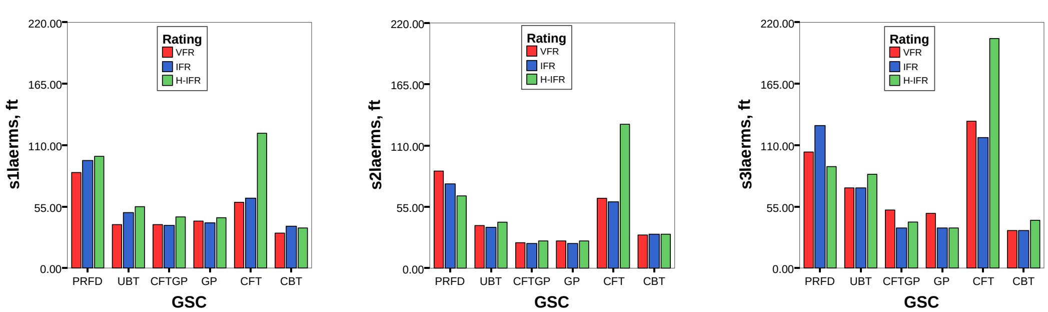

Figure G.5: Mean of Lateral Path Deviations for Segments 1, 2, and 3, by GSC and Rating

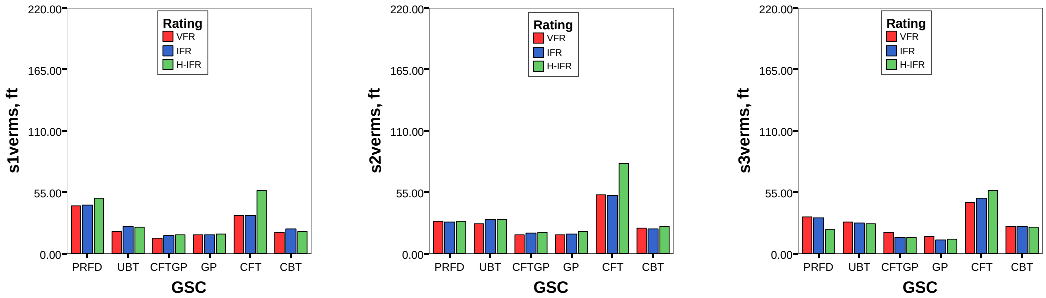

Figure G.6: Mean of Vertical Path Deviations for Segments 1, 2, and 3, by GSC and Rating

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14. ABSTRACT
In support of the NASA Aviation Safety Program's Synthetic Vision Systems Project, a series of piloted simulations were conducted to explore and quantify the relationship between candidate Terrain Portrayal Concepts and Guidance Symbology Concepts, specific to General Aviation. The experiment scenario was based on a low altitude en route flight in Instrument Metrological Conditions in the central mountains of Alaska. A total of 18 general aviation pilots, with three levels of pilot experience, evaluated a test matrix of four terrain portrayal concepts and six guidance symbology concepts. Quantitative measures included various pilot/aircraft performance data, flight technical errors and flight control inputs. The qualitative measures included pilot comments and pilot responses to the structured questionnaires such as perceived workload, subjective situation awareness, pilot preferences, and the rare event recognition. There were statistically significant effects found from guidance symbology concepts and terrain portrayal concepts but no significant interactions between them. Lower flight technical errors and increased situation awareness were achieved using Synthetic Vision Systems displays, as compared to the baseline Pitch/Roll Flight Director and Blue Sky Brown Ground combination. Overall, those guidance symbology concepts that have both path based guidance cue and tunnel display performed better than the other guidance concepts.

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