



Synthetic Vision Systems General Aviation (SVS-GA)

Terrain Portrayal for Head Down Displays (TP-HDD) - Simulation

SVS-GA/FAA Workshop

October 2002

SVS-GA Team

PI – Monica Hughes



TP-HDD Objectives and Products

Aviation Safety Program: Synthetic Vision Systems – General Aviation

- Objectives
 - Establish the relationship between terrain depiction fidelity and:
 - Terrain situation awareness (SA)
 - Pilot performance (control and navigation)
 - Low-Visibility Loss of Control (LVLOC) prevention
 - Further establish the overall benefit of SVS for GA pilots
- Products
 - Information to establish DEM resolution and texturing requirements for tactical HDDs, based on phase of flight
 - Data to enable SVS design tradeoffs (performance vs. fidelity) that currently does not exist
 - Support the FAA Capstone-2 certification (workload/stress issues)
 - Develop integration of tactical HDDs with baseline strategic displays
- All products are highly valuable to the SVS Project, industry, and the FAA



TP-HDD Displays

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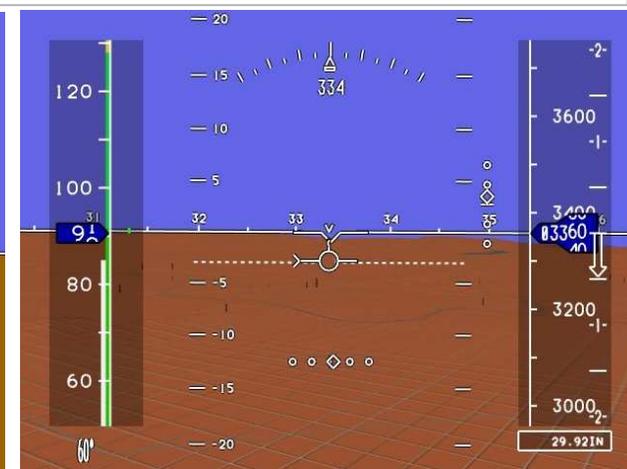
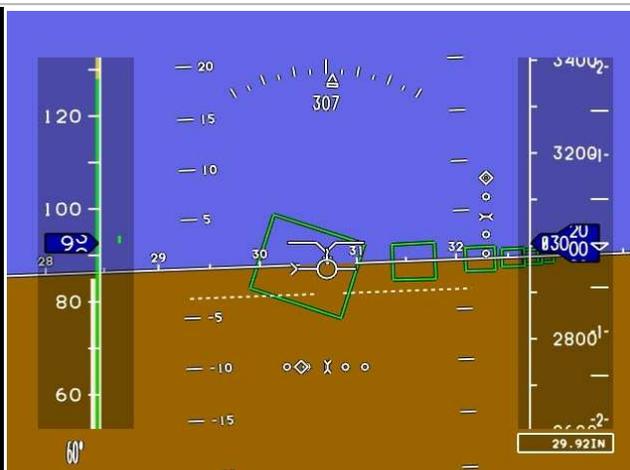
Baseline Round Dials



Blue Sky/ Brown Ground PFD



SVS PFD



- Airspeed, attitude, altitude, turn coordinator, directional gyro, and vertical speed indicator
- For approach scenario
 - Localizer/Glide slope deviation indicators
 - No tunnel

- Integrated Information on PFD
 - Velocity vector with sideslip flag and acceleration caret
 - Air data tapes
 - FOV= unity, 30, 60, 90
 - Horizon line, pitch grid, roll scale with sideslip wedge and a digital heading
 - Tunnel for approach scenario

- Terrain Portrayed
 - FOV= unity, 30, 60 and 90
 - DEM= 1, 3 and 30 arc-sec
 - Various texturing
 - Otherwise same as BSBG
 - Tunnel for approach scenario
 - With and without tunnel on CCFN30 for approach scenario



Display Concept Elements

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- Baseline concept: Blue sky/brown ground standard Primary Flight Display (BSBG-PFD) (i.e. no terrain data) or basic baseline C-172 round dials (BRD)
- SVS-PFD concepts
 - Tunnel on/off
 - Selectable FOV
 - Multi-resolution, multi-texturing

Digital Elevation Models

- | | | |
|----|-------|-----------------------------|
| 1. | Low: | 30 arc-second (900m/2953ft) |
| 2. | Med: | 3 arc-second (90m/295ft) |
| 3. | High: | 1 arc-second (30m/98ft) |

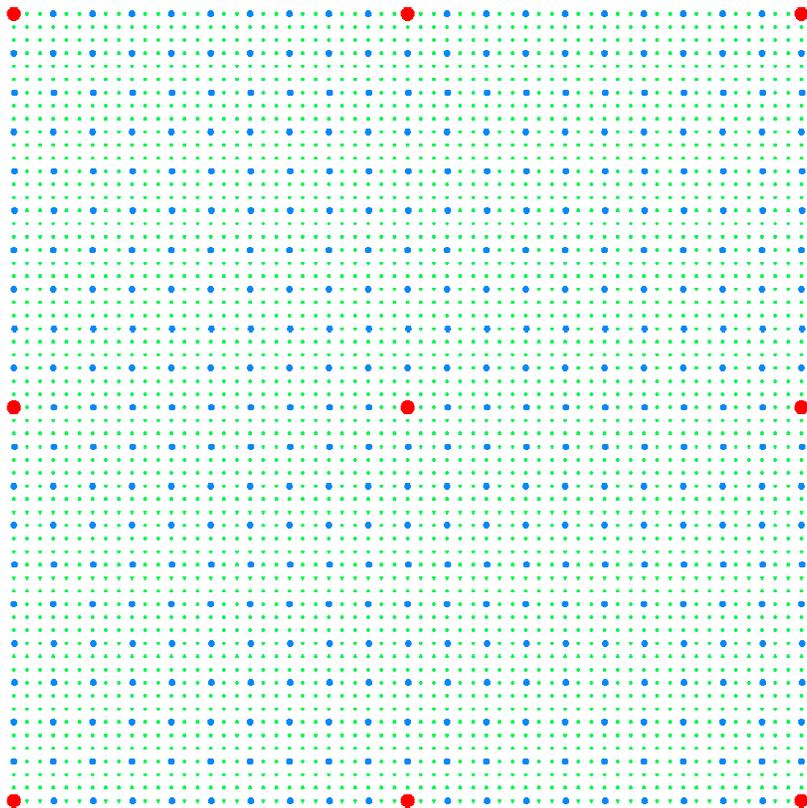
Terrain Texturing

1. Constant color w/fishnet overlay
2. Terrain elevation-based generic texturing
3. Terrain elevation-based generic texturing w/fishnet overlay
4. Photo Realistic texturing
5. Photo Realistic texturing w/fishnet overlay



Digital Elevation Models - DEMs

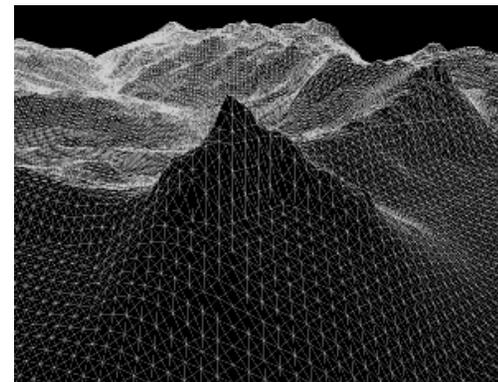
Aviation Safety Program: Synthetic Vision Systems – General Aviation



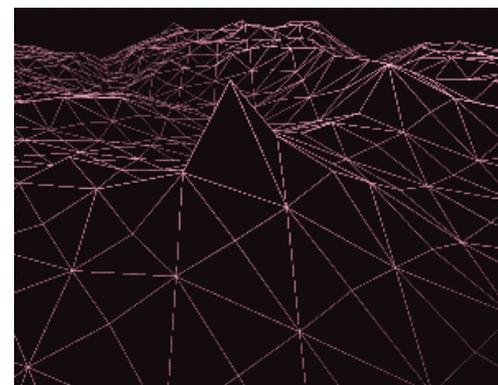
Green Dots: 1 arcsec ~ 30m

Blue Dots: 3 arcsec ~ 90m

Red Dots: 30 arcsec ~ 900m

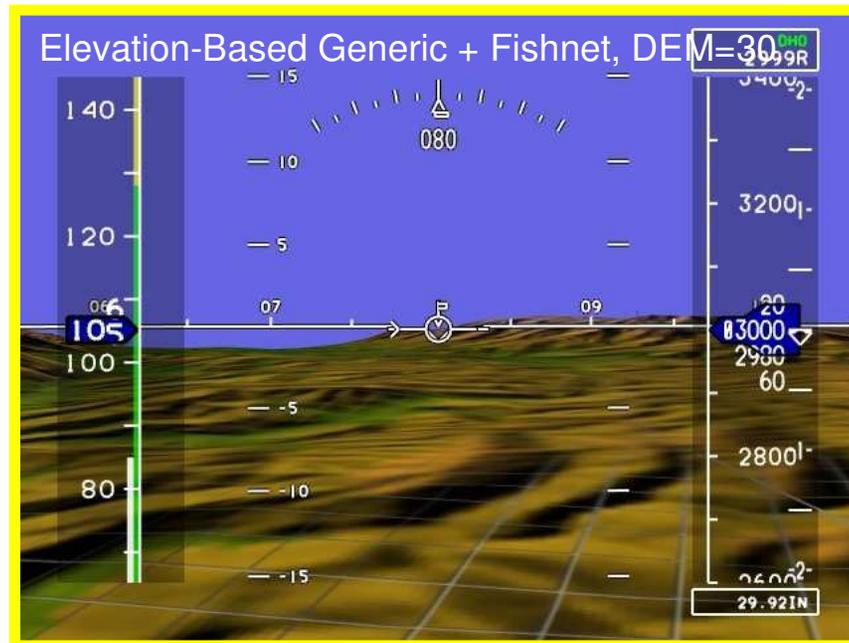
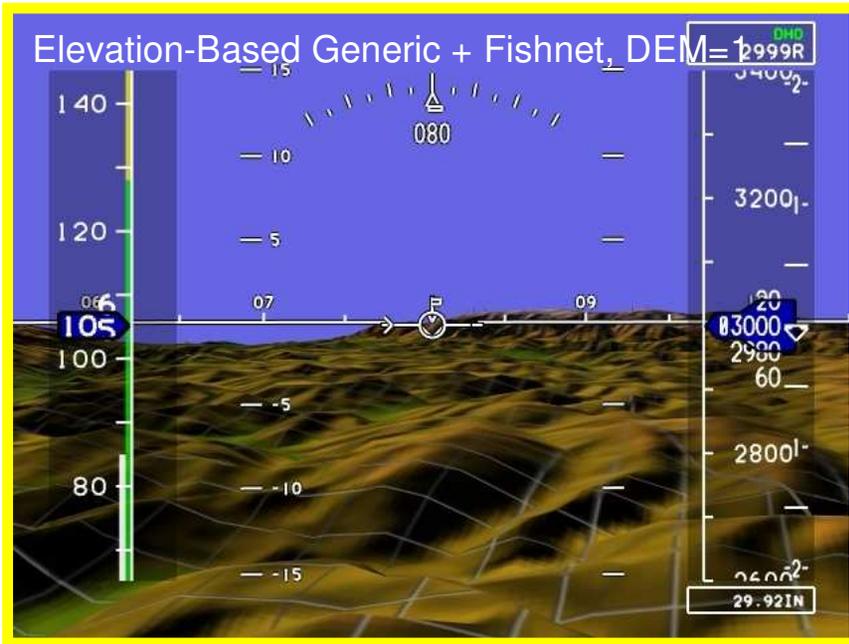


3 arcsec

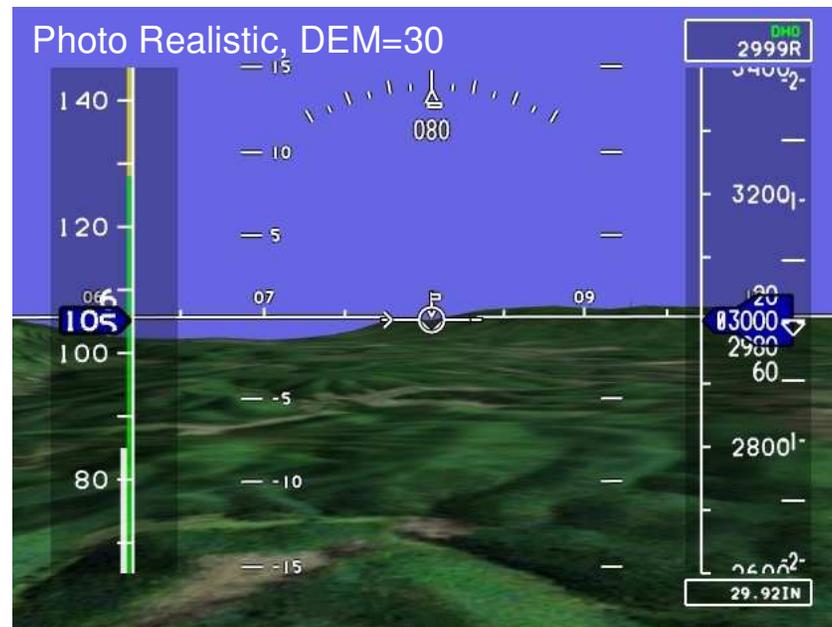


30 arcsec

Source: Darmstadt Technical University



Display Concepts
Tested



Display Concepts
Tested



Display Concepts
Tested

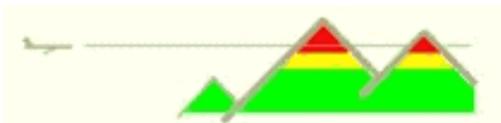
MX20 Strategic Display With Terrain Awareness Function



Aviation Safety Program: Synthetic Vision Systems – General Aviation

Color	Terrain (wrt ownship)
Red	At or above
Yellow	W/in 500ft
Green	W/in 2000ft
Black	More than 2000ft below

- Provided
 - Strategic terrain display
 - Integration with tactical SVS terrain presentation
 - Additional lateral path guidance (approach)
 - Terrain advisory if the aircraft is within two minutes of a close encounter with the ground.
- Range scale set to 10nm





Experiment Development

Aviation Safety Program: Synthetic Vision Systems – General Aviation

- Usability Study
 - All 18 SVS display concepts
 - Five subjects
 - Purpose: Parse down 18 SVS display concepts into manageable amount for the simulation (10 concepts)
- Pre-Testing
 - Several display concepts derived from usability
 - Three subjects
 - Purpose: Validate scenarios and pilot qualifications are appropriate for simulation
 - Dress-rehearsal to ensure team is ready for actual study
- Final Experiment
 - Twelve display concepts derived from usability study
 - 10 SVS
 - 1 Baseline (either BSBG, or basic round dials (BRD), blocked by pilots)
 - 1 Tunnel on/off evaluation
 - Twenty-seven pilots participated (1.5 days, each)



Experimental Test Matrix

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Texturing Concepts

DEM (arc-sec)

	<i>EBG</i>	<i>PR</i>	<i>CC+</i> <i>FN</i>	<i>EBG+</i> <i>FN</i>	<i>PR+F</i> <i>N</i>
<i>30</i>			√	√	√
<i>3</i>				√	√
<i>1</i>	√	√	√	√	√

Legend for Texturing Concepts:

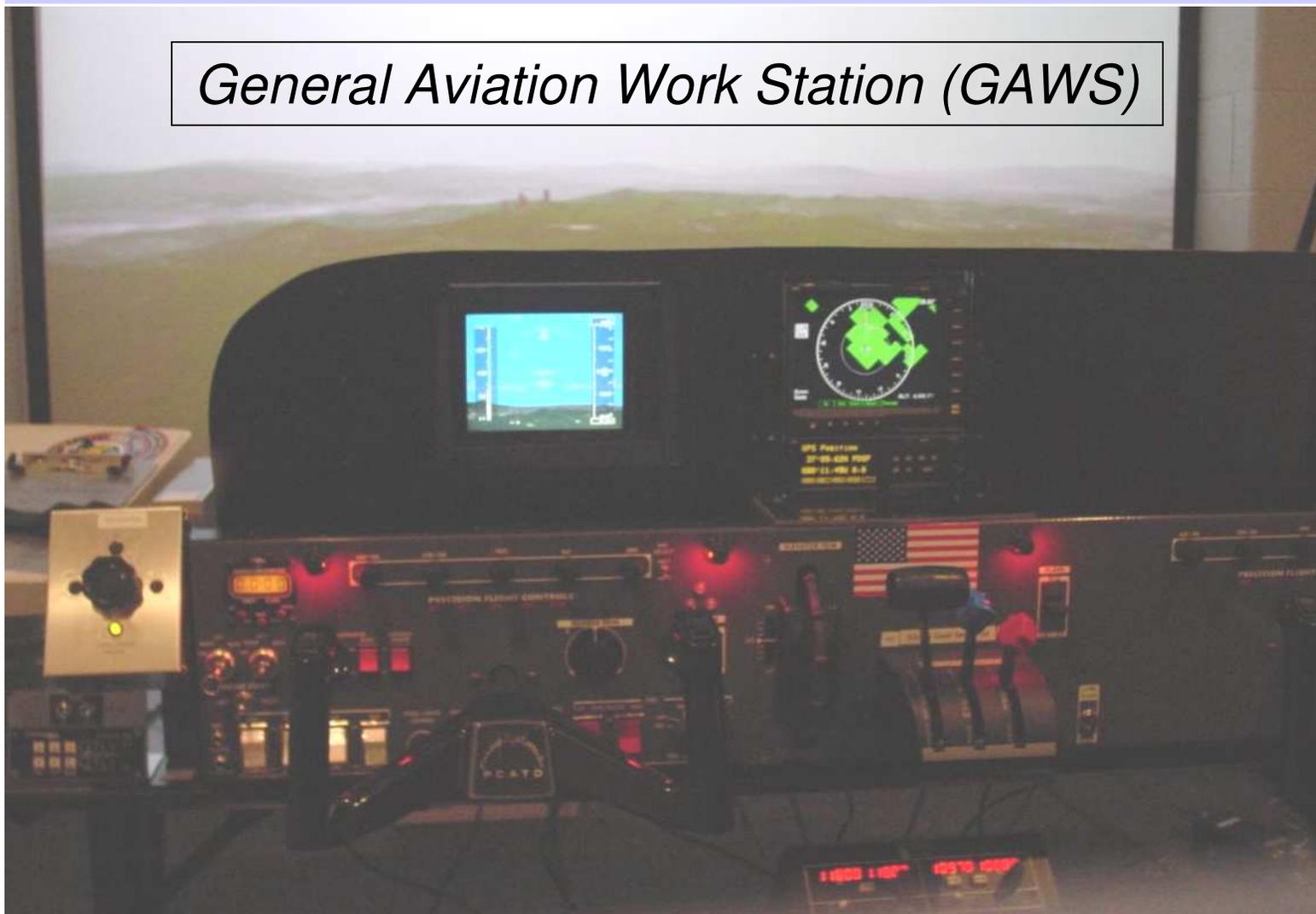
CC = Constant Color, EBG = Elevation-Based Generic, PR = Photo Realistic, FN = Fishnet



Experiment Apparatus

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General Aviation Work Station (GAWS)



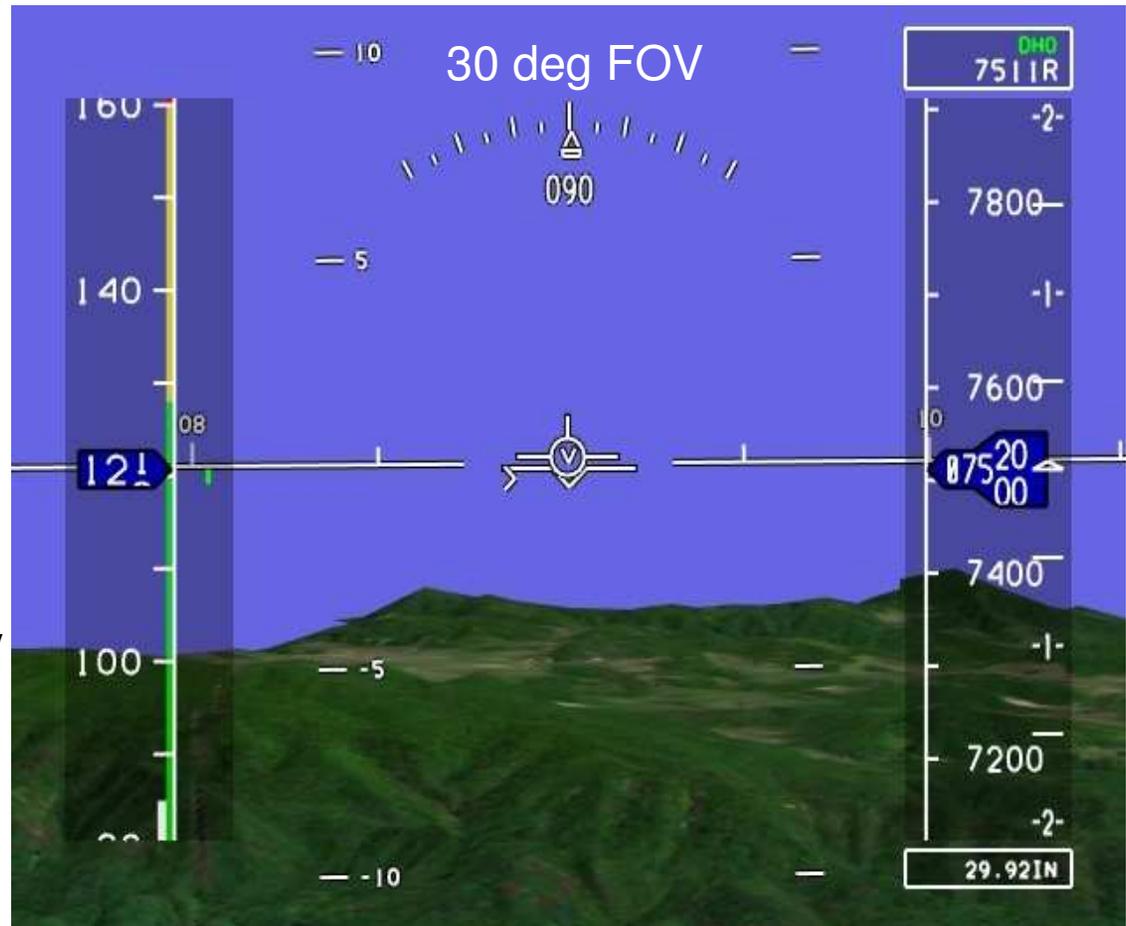
- C172R Simulation Model
- Modified Precision Flight Control PC-Based Aviation Training Device, Model PI-142 instrument procedure trainer

Field Of View (FOV)



Aviation Safety Program: Synthetic Vision Systems – General Aviation

- Pilot selectable
- Previous research data indicate that a single fixed FOV could significantly limit SVS effectiveness
- Possible FOV use
 - 60 deg FOV for cruise and approach (MF=4)
 - 30 deg FOV for low-crosswind/calm approach conditions
 - Higher FOVs help keep VV on the screen in crosswinds and to see into turns
- Larger FOV's exaggerate range and altitude values

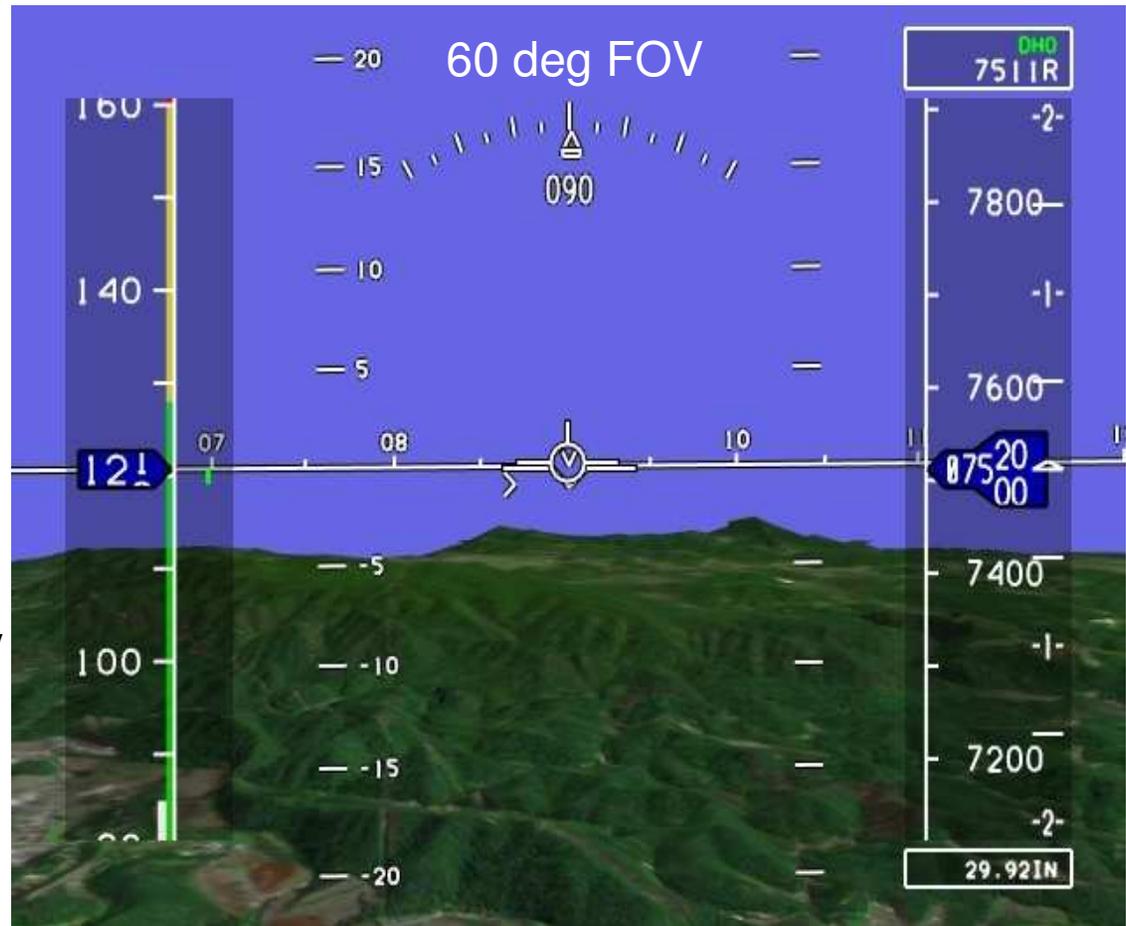


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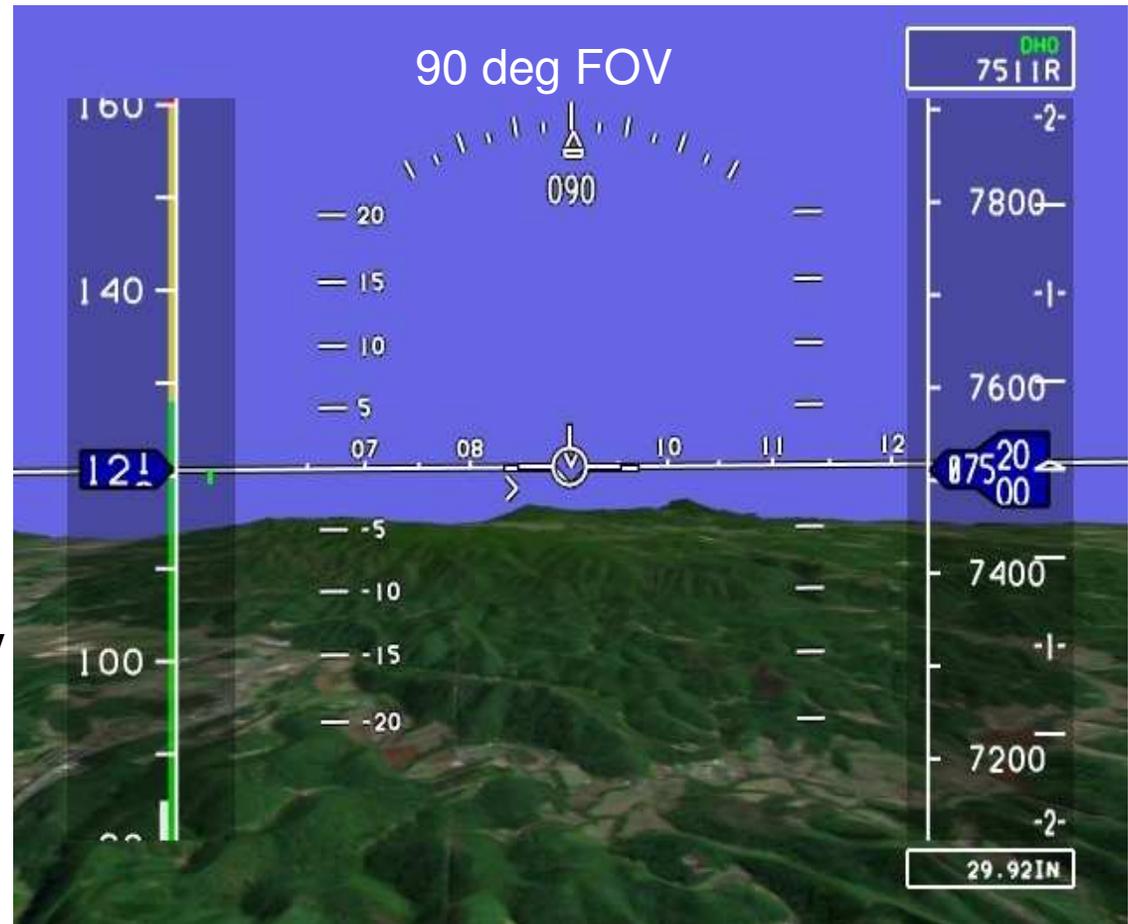


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Subject Pilots

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- Two groups of pilots (general and extended pool) totaling 27 subjects
- General pool (14 subjects) met the following criteria
 - Private Pilot Certificate
 - Less than 400 hours (Low-Time)
 - No instrument training (beyond requirements for private pilot certificate)
 - No appreciable experience with desk-top simulators (i.e., Microsoft Flight Simulator)
- Extended pool of subjects (13 subjects):
 - Low-time Instrument-rated pilots (6 subjects)
 - Remaining pilot pool: Capstone-2 operators (3 subjects) and NASA and FAA Test Pilots (4 subjects)

Simulation Conduct



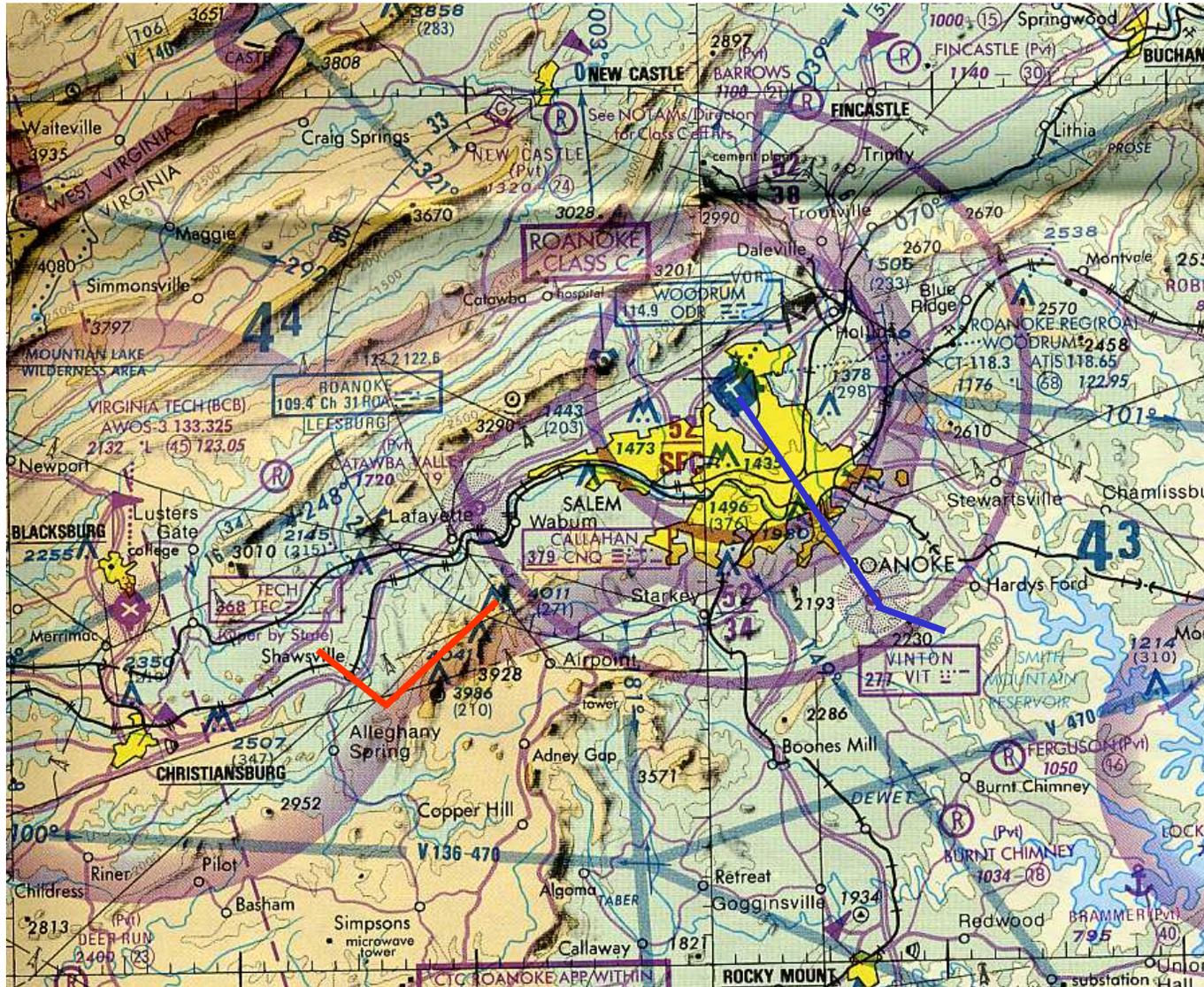
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- Pilot pre-brief
- Training
 - Approximately an hour of simulation time with CFII
- Runs
 - 3 blocks: High Altitude (11 Runs), Low Altitude (11 Runs), Approach (12 Runs), Plus Rare Event
- Questionnaires
 - Run Questionnaire after each run
 - Block Questionnaire after each block
 - Final Questionnaire at the conclusion of experiment



Simulation Area of Operations

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Simulation Operations – Scenarios

Aviation Safety Program: Synthetic Vision Systems – General Aviation

Scenario 1 – High Altitude Enroute

Initial Conditions: Straight and Level at 9,500 ft MSL (approximately 7,000 ft AGL), 100 KIAS.

Path: Straight and level for 2 minutes, then make a specified left turn and descend 1,500 ft (ending at 8,000 ft MSL or approximately 4,000 ft AGL).

Weather: Visibility will decrease from VMC to IMC between first and second minute of flight. Moderate turbulence for duration of flight.



Simulation Operations – Scenarios

Aviation Safety Program: Synthetic Vision Systems – General Aviation

Scenario 2 – Low Altitude Enroute

Initial Conditions: Straight and Level at 6,500 ft MSL (approximately 4,000ft AGL), 100 KIAS.

Path: Straight and level for 2 minutes, then make a specified left turn and descend 1,500 ft (ending at 5,000 ft MSL or approximately 1,000ft AGL).

Weather: Visibility will decrease from VMC to IMC between first and second minute of flight. Moderate turbulence for duration of flight.



Simulation Operations – Scenarios

Aviation Safety Program: Synthetic Vision Systems – General Aviation

Scenario 3 – SVS RWY 33 Approach

Initial Conditions: On 30° intercept heading RWY 33, at 2,600 ft MSL, 90 KIAS.

Path: Fly heading 300° to join the localizer, intercept glide slope at approximately 4.5 miles.

Weather: Visibility will decrease from VMC to IMC within first minute of flight. Winds 030° at 15 kts, decreasing to 5 kts by the end of approach. Moderate turbulence at the start, decreasing to light turbulence on final. Flight ends at 200 ft AGL.



Simulation Operations – Scenarios

Aviation Safety Program: Synthetic Vision Systems – General Aviation

Scenario 4 – Rare Event (Low Altitude)

- One event per subject
- Disguised to look like the low altitude scenario
- Initial conditions - at the same lat/lon position, but actual altitude was 1500ft lower.
- Incorrect Altimeter setting (Altitude tape and the MX20 showed the incorrect altitude. But terrain on PFD displayed the correct altitude)
- Display concepts were randomized within pilots
- Occurred on the subject's last run, repeating one of the display concepts that subject has already flown
- Rare event and non-rare event scenario not flown back to back
- Only 27 data points



Dependent Variables

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- Control of aircraft to stated parameters
 - Pitch, bank, speed, altitude, heading, etc.
- Workload
 - Analysis of Control Inputs
- Questionnaires
- Physiological data (measures of stress)
 - Skin temperature (similar to LVLOC)
 - Pulse rate (similar to LVLOC)
 - Muscle activity (similar to LVLOC)



Run Questionnaire (front)

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MENTAL DEMAND



Low High

PHYSICAL DEMAND



Low High

TEMPORAL DEMAND



Low High

PERFORMANCE



Good Poor

EFFORT



Low High

FRUSTRATION



Low High

DEMAND ON ATTENTIONAL RESOURCES



Low High

SUPPLY OF ATTENTIONAL RESOURCES



Low High

UNDERSTANDING OF THE SITUATION



Low High

LEVEL OF TERRAIN AWARENESS



Low High

STRESS



Low High

Workload:

TLX – Blue

Stress – Purple

Situational Awareness:

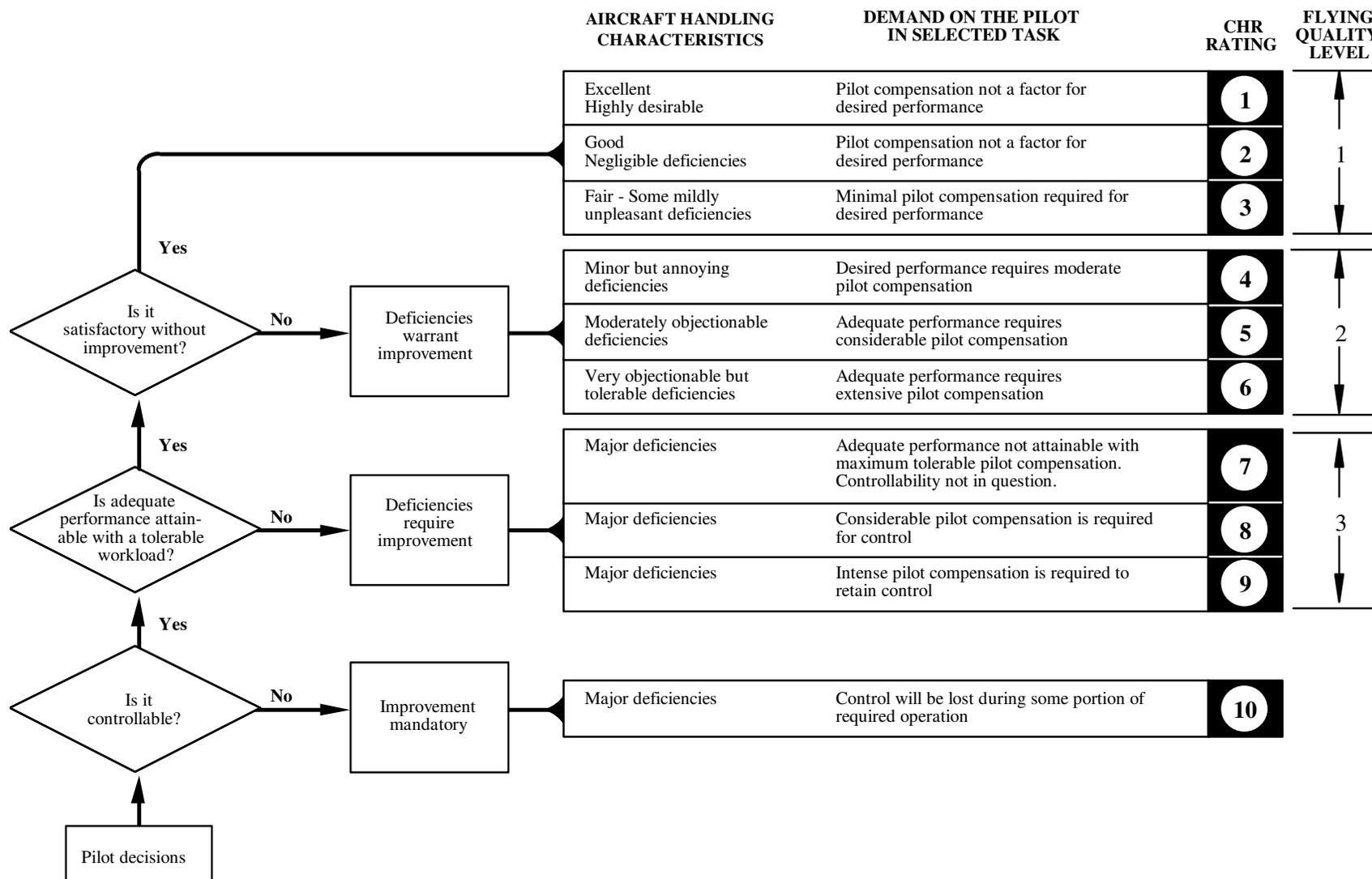
SART – Red

TA - Green



Run Questionnaire (back –Cooper Harper)

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Pilot Performance Metrics

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- Desired performance (keep within these parameters ~90% of the time) when appropriate:
 - Airspeed error $\leq \pm 10$ knots
 - Altitude error $\leq \pm 100$ ft
 - Heading error $\leq \pm 10^\circ$
 - Bank Angle error $\leq \pm 10^\circ$
 - Localizer error $\leq \pm 1$ dot
 - Lateral path error $\leq \pm 1$ dot
 - Glideslope error $\leq \pm 1$ dot
 - Vertical path error $\leq \pm 1$ dot
- Adequate performance (~90% of time between PTS and twice PTS) when appropriate:
 - Airspeed error between $\leq \pm 20$ knots
 - Altitude error between $\leq \pm 200$ ft
 - Heading error between $\leq \pm 20^\circ$
 - Bank Angle error between $\leq \pm 20^\circ$
 - Localizer error between $\leq \pm 2$ dots
 - Lateral path error $\leq \pm 2$ dots
 - Glideslope error $\leq \pm 2$ dots
 - Vertical path error $\leq \pm 2$ dots
- Below adequate performance (beyond twice PTS).



Results – Quantitative: Approach

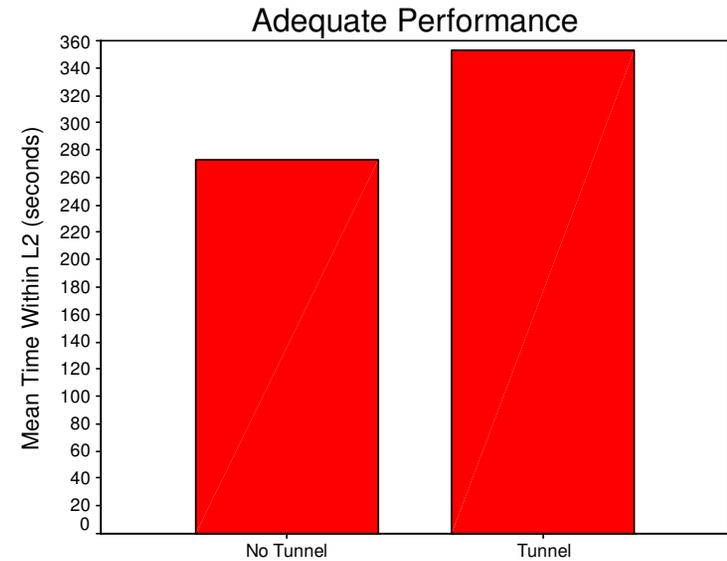
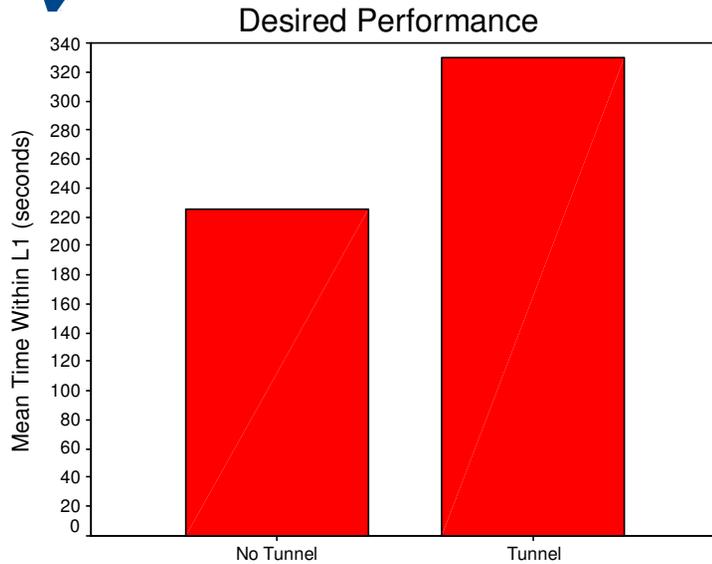
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- Texture: No statistically significant differences in performance
- DEM: No statistically significant differences in performance
- Fish Net: No statistically significant differences in performance



Results – Quantitative: Approach, Tunnel

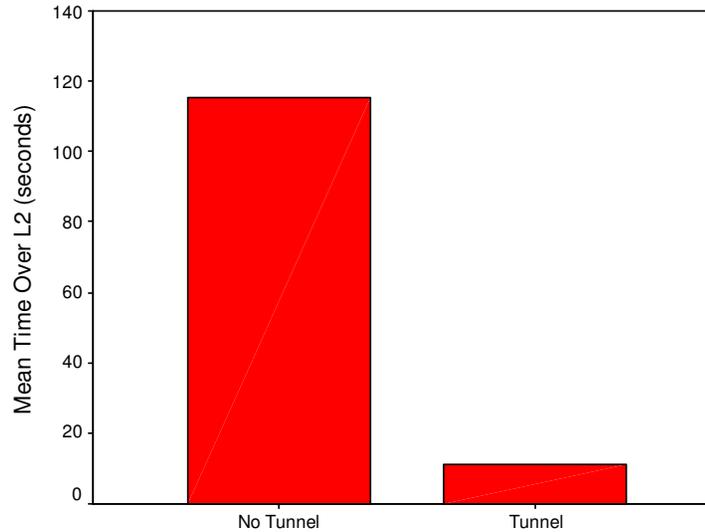
Aviation Safety Program: Synthetic Vision Systems – General Aviation



p=.000

Display Concept CCFI

Below Adequate Performance



Display Concept CCFN30

p=.000

p=.000

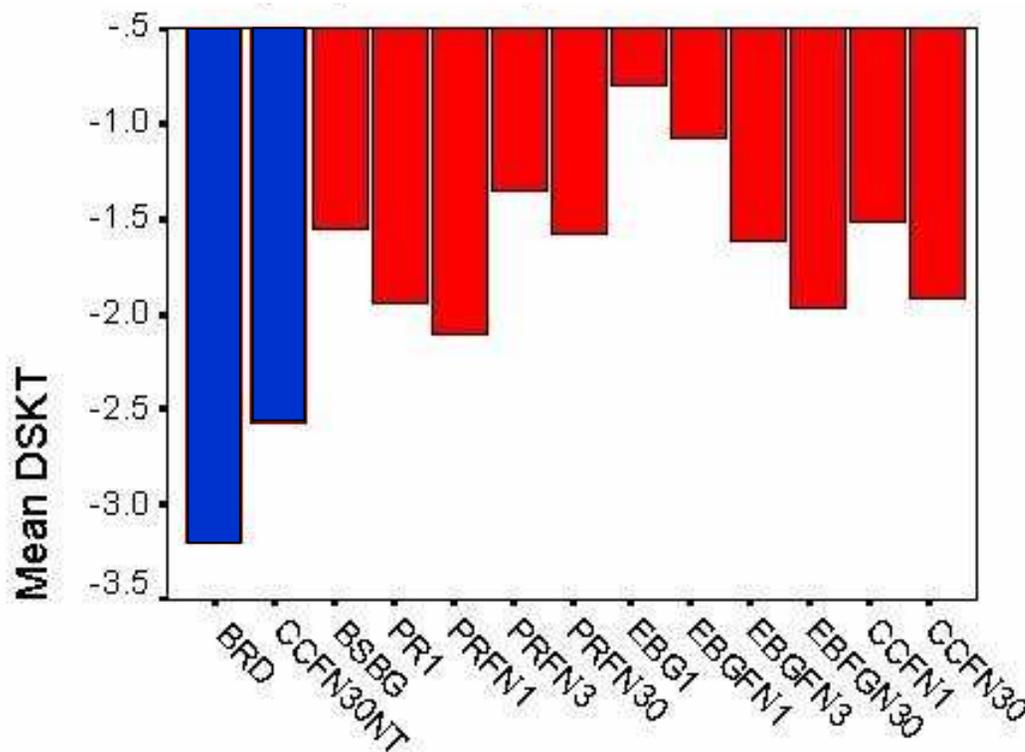
Display Concept CCFN30



Results - Physiological

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Display Configs vs. Mean Delta Skin Temperature



- Legend:
- BSBG – Blue Sky/Brown Ground
 - BRD – Basic Round Dials
 - PR – Photo Realistic
 - EBG – Elevation Based Generic
 - CC – Constant Color
 - FN – Fish Net
 - NT – No Tunnel
 - 1 – DEM = 1 arc-sec
 - 3 – DEM = 3 arc-sec
 - 30 – DEM = 30 arc-sec
 - Blue Bar = No Tunnel
 - Red Bar = Tunnel



Results – Qualitative

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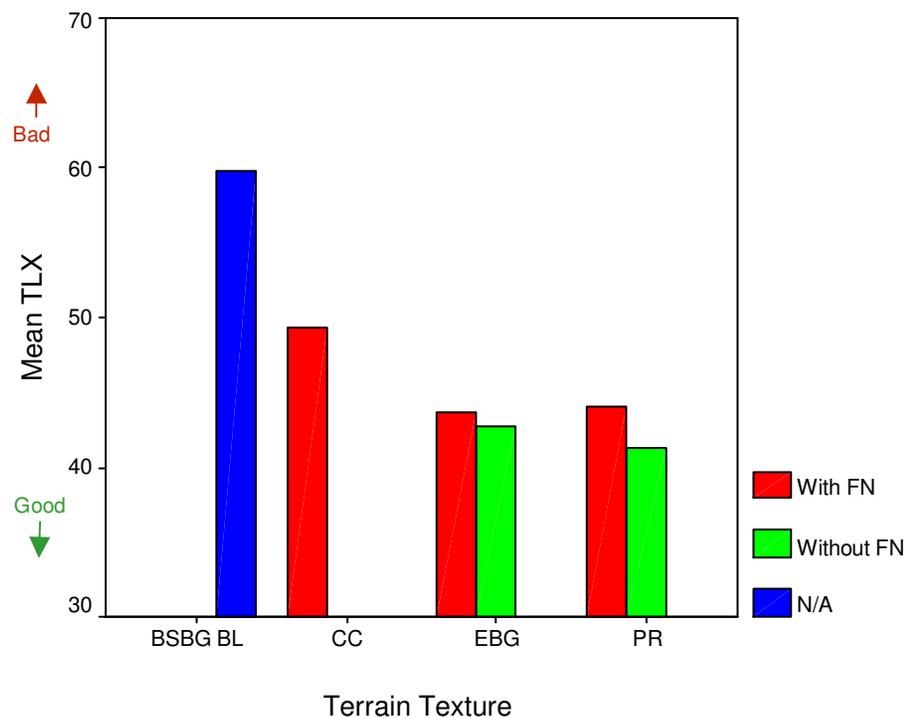
- SART - situation awareness subjective measure
- TLX - analyzing mental workload
- Terrain Awareness Rating
- Stress Rating
- Cooper-Harper Rating
- SA-SWORD
 - Modified Subjective Workload Dominance (SWORD) technique
 - Applied to Situational Awareness (SA)
 - Collect raw judgment data assessing SA
 - Construct judgment matrices
 - Calculate SA-SWORD ratings
- Pilot Comments (during and after)



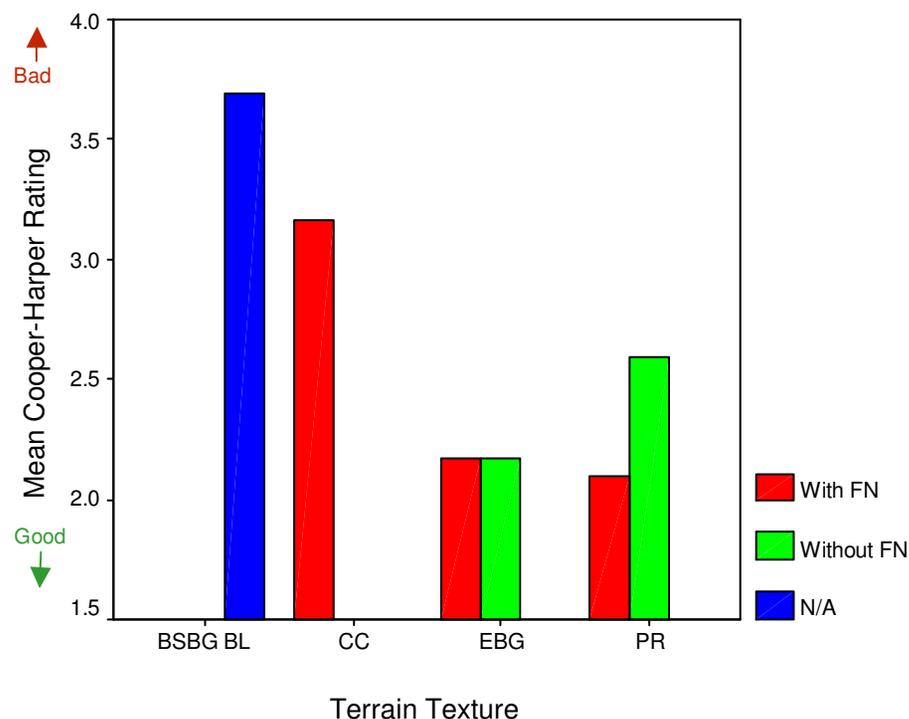
Qualitative: Approach, Texture

Aviation Safety Program: Synthetic Vision Systems – General Aviation

TLX



CH



Univariate ANOVA:

$p=.045$

SNK Post-Hoc:

EBG, PR, CC ($p=.495$)

CC and BSBG ($p=.076$)

Univariate ANOVA:

$p=.000$

SNK Post-Hoc:

EBG and PR ($p=.601$)

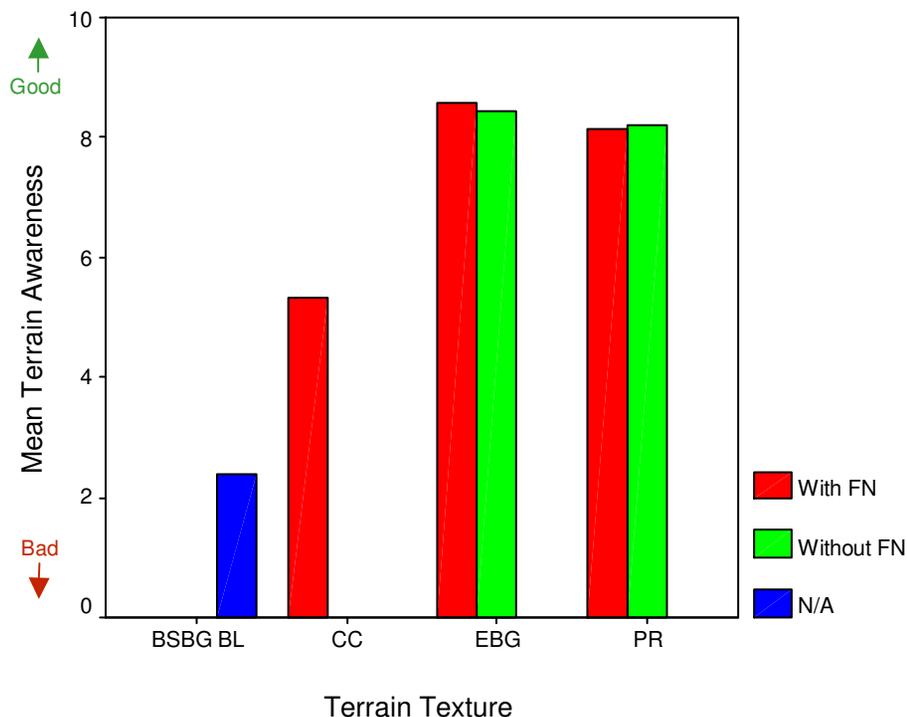
CC and BSBG ($p=.120$)



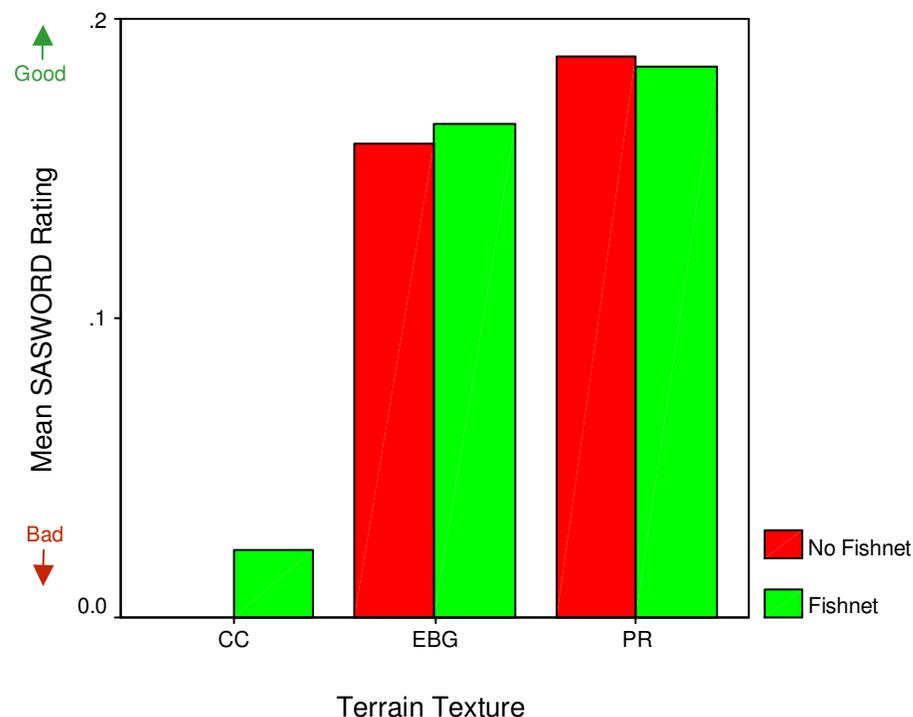
Qualitative: Approach, Texture

Aviation Safety Program: Synthetic Vision Systems – General Aviation

TA



SASWORD



Univariate ANOVA:

$p=.000$

SNK Post-Hoc:

EBG and PR ($p=.475$)

CC ($p=1$)

BSBG ($p=1$)

Univariate ANOVA:

$p=.000$

SNK Post-Hoc:

EBG and PR ($p=.190$)

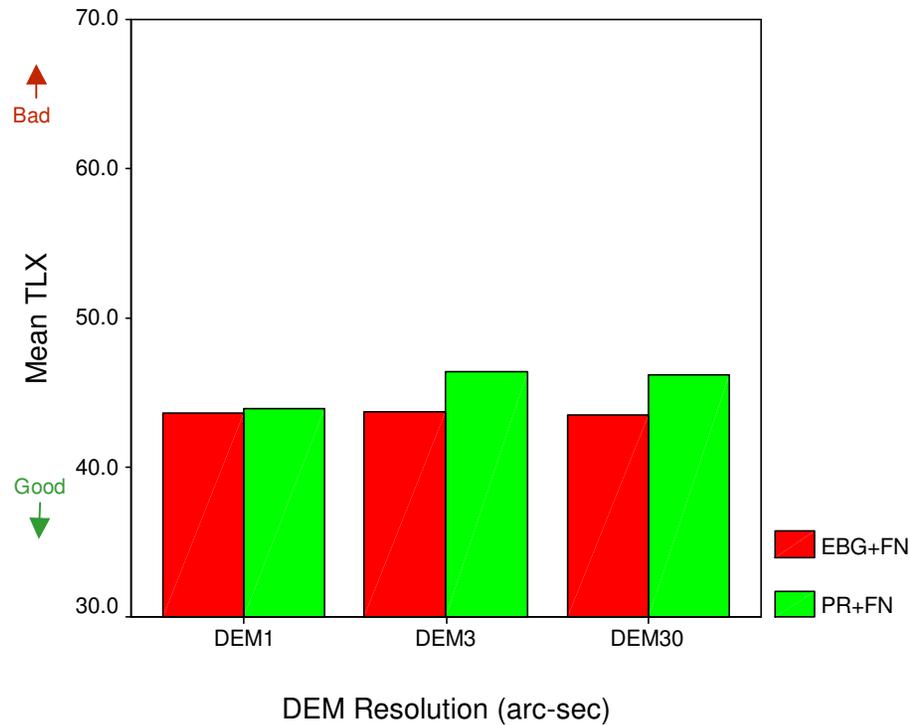
CC ($p=1$)



Qualitative: Approach, DEM

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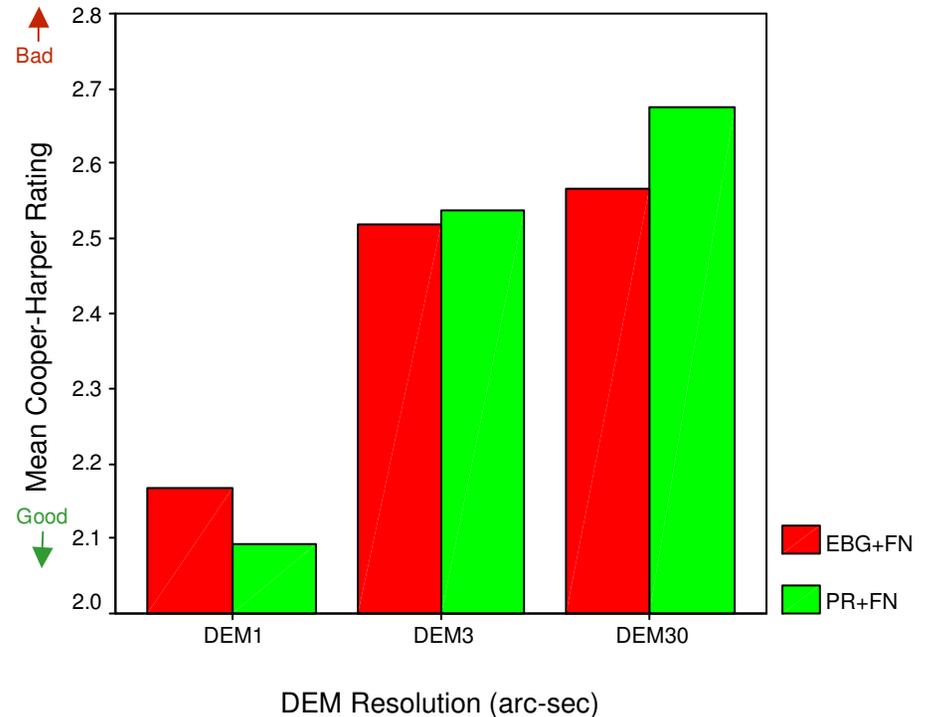
TLX



Univariate ANOVA:
 $p=.946$

No statistical significance

CH



Univariate ANOVA:
 $p=.090$

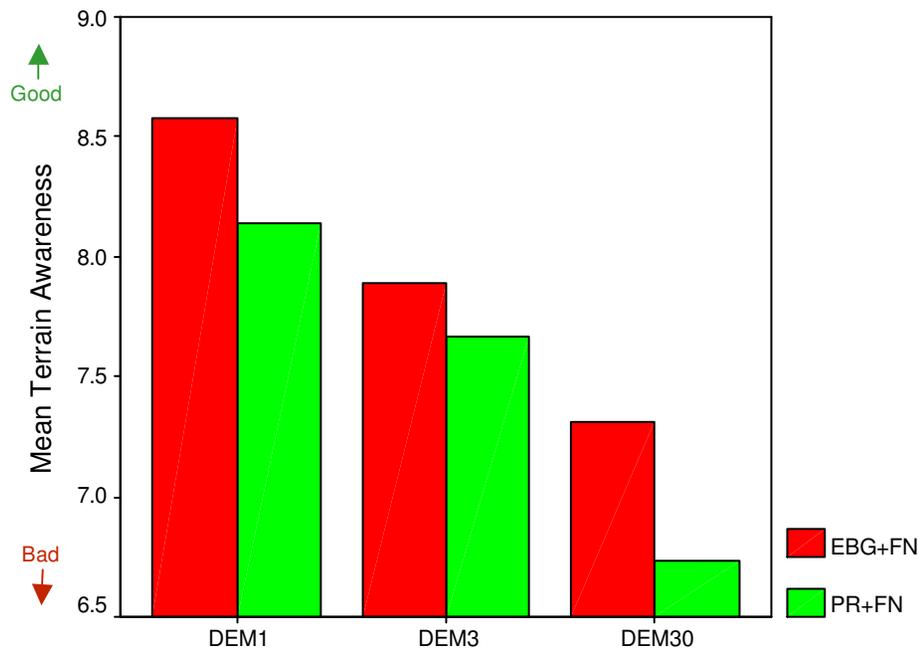
No statistical significance



Qualitative: Approach, DEM

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TA



DEM Resolution (arc-sec)

Univariate ANOVA:

DEM: $p=.000$

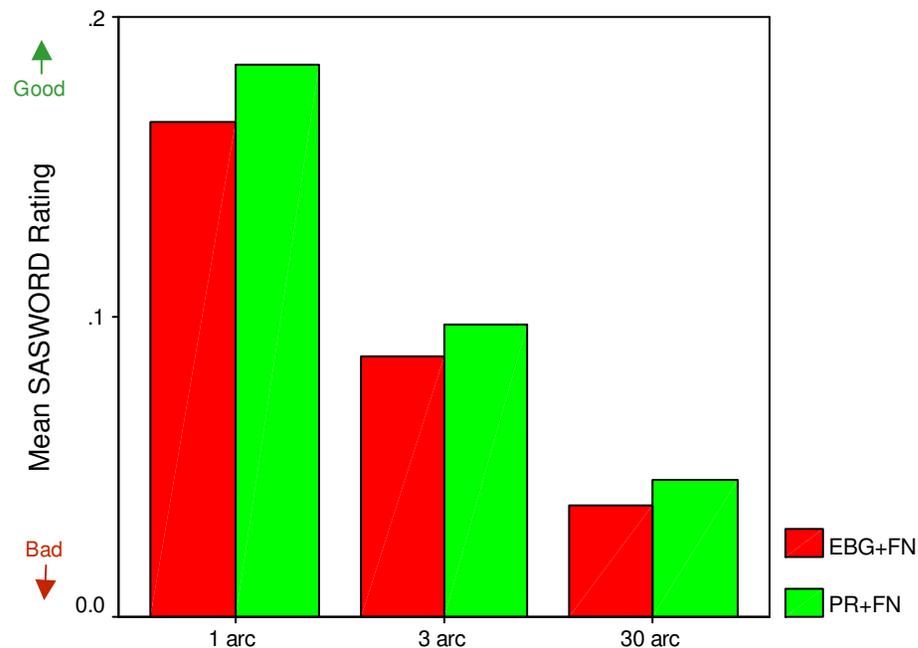
SNK Post-Hoc:

DEM1 and DEM3 ($p=.079$)

DEM30 ($p=1$)

Texture effect and interaction not significant

SASWORD



DEM Resolution (arc-sec)

Univariate ANOVA:

DEM: $p=.000$

SNK Post-Hoc:

DEM1 ($p=1$)

DEM3 ($p=1$)

DEM30 ($p=1$)

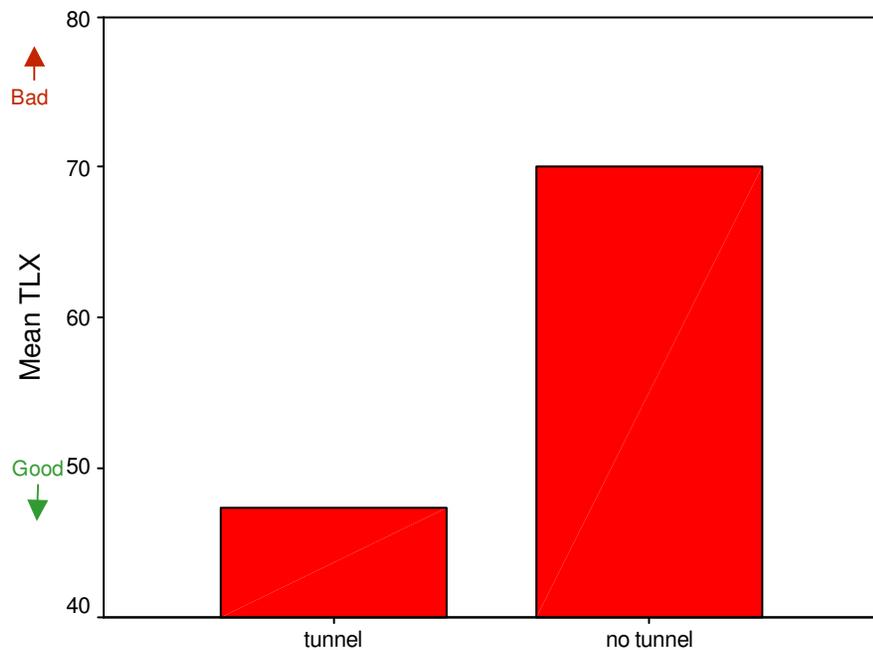
Texture effect and interaction not significant



Qualitative: Approach, Tunnel

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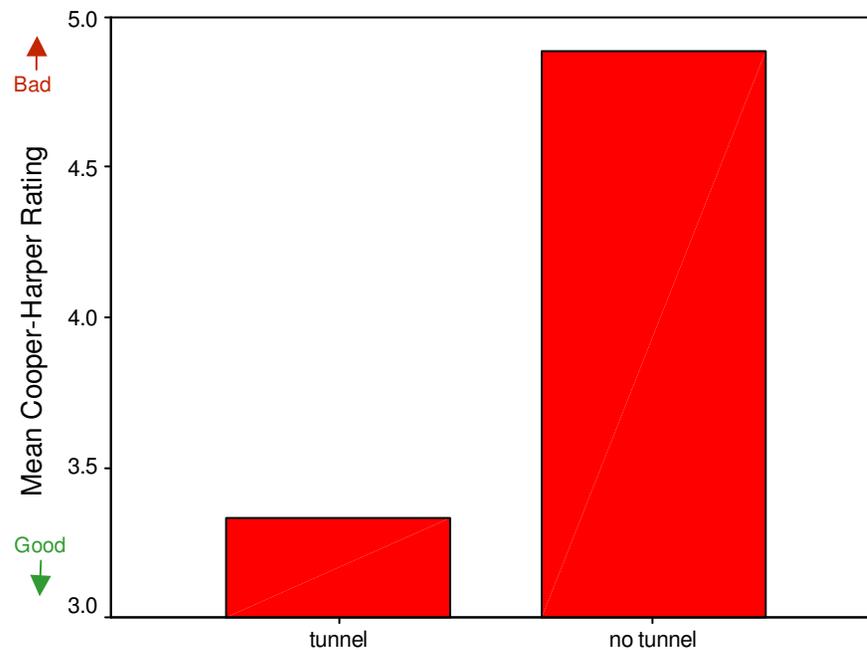
TLX



Tunnel Selection for CCFN30

Univariate ANOVA:
 $p=.001$

CH



Tunnel Selection for CCFN30

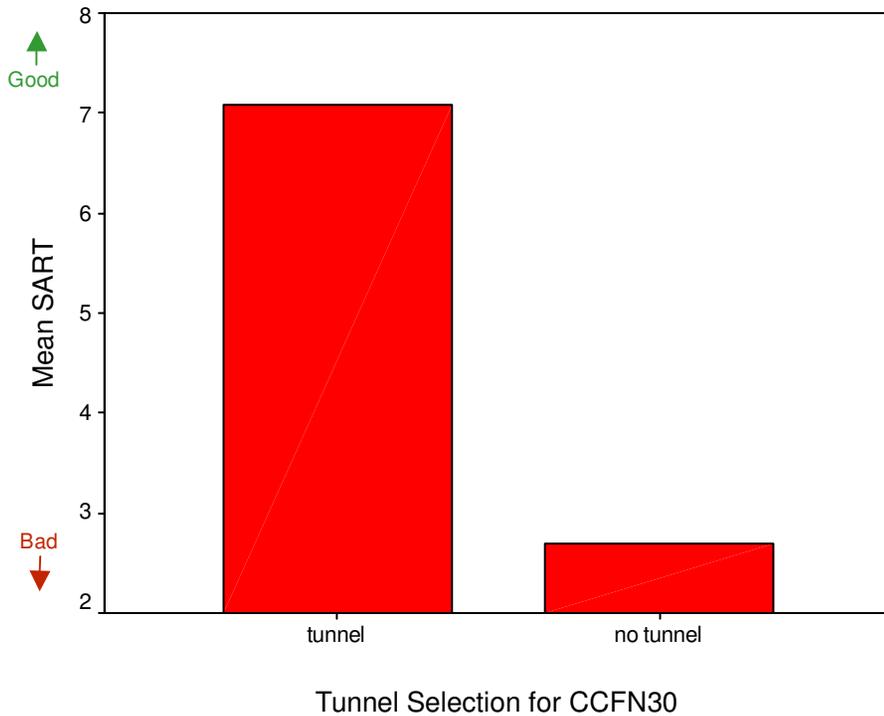
Univariate ANOVA:
 $p=.001$



Qualitative: Approach, Tunnel

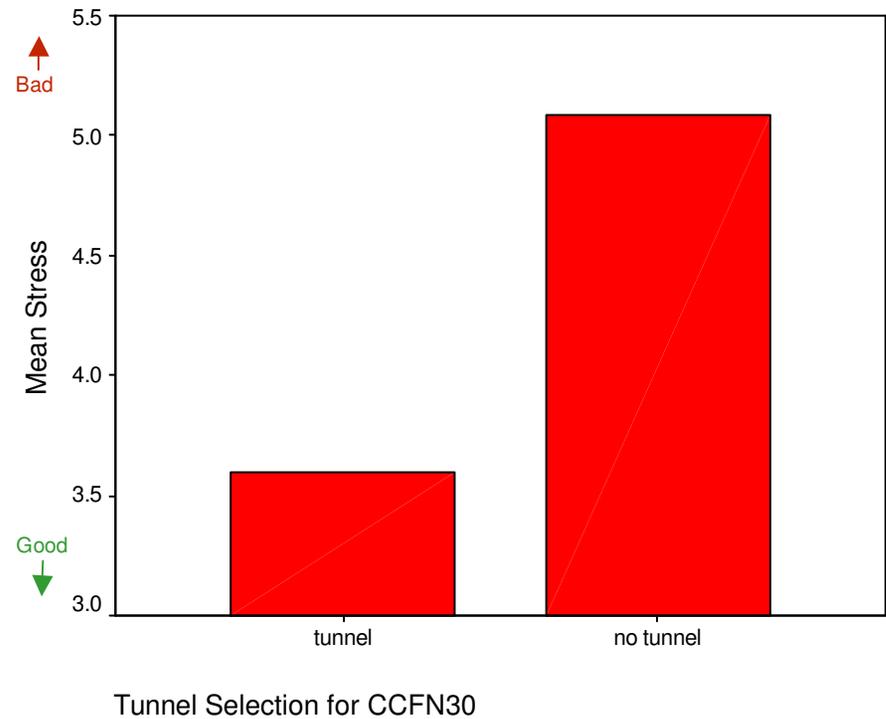
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SART



Univariate ANOVA:
 $p=.001$

Stress

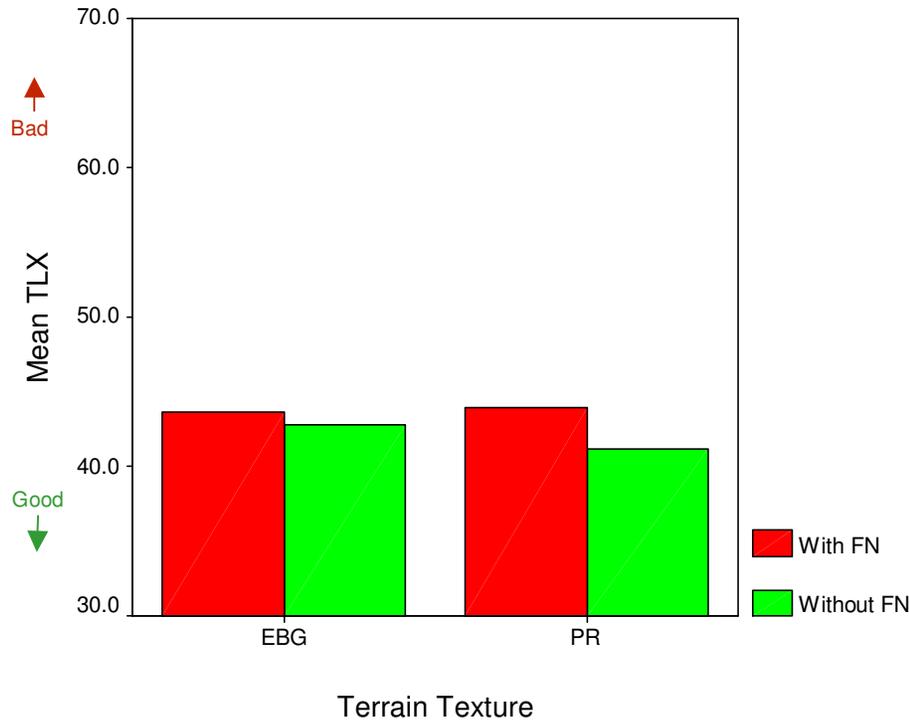


Univariate ANOVA:
 $p=.018$

Qualitative: Approach, FN



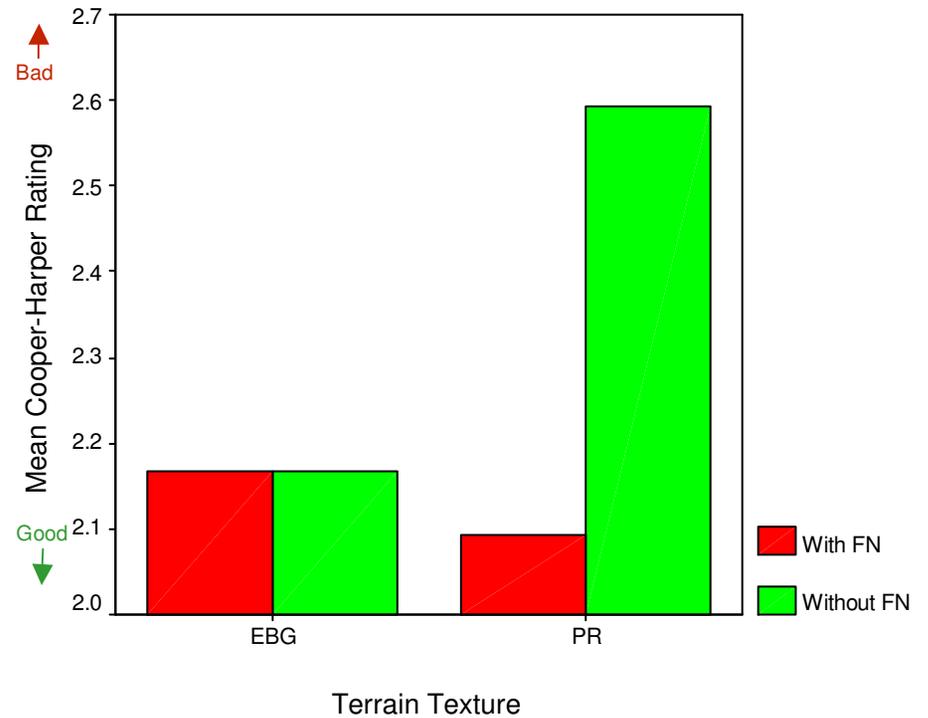
TLX



Univariate ANOVA:
 $p=.658$

No statistical significance

CH



Univariate ANOVA:
 $p=.311$

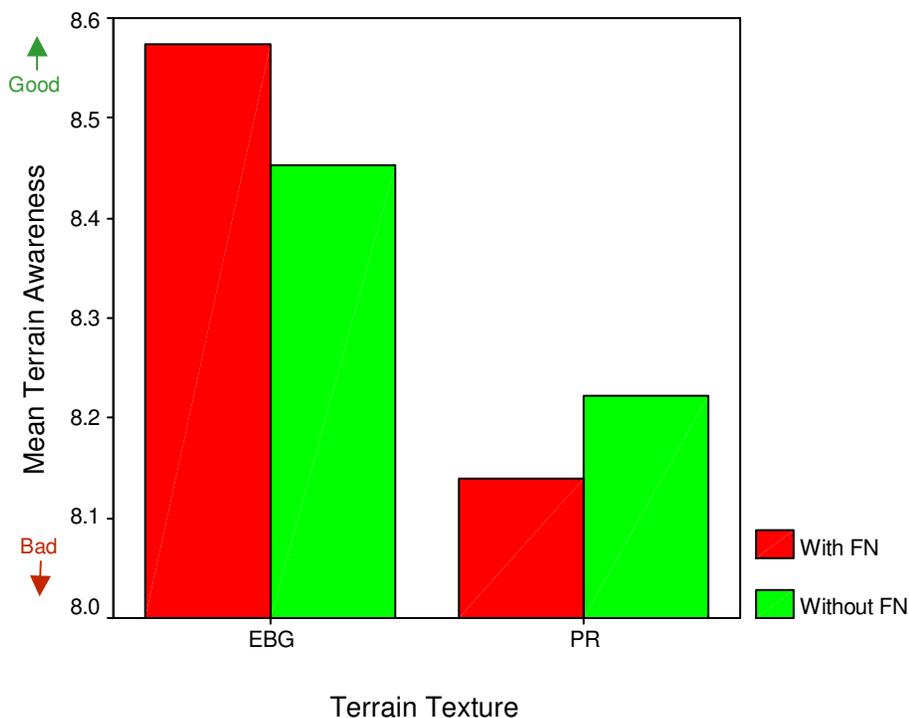
No statistical significance



Qualitative: Approach, FN

Aviation Safety Program: Synthetic Vision Systems – General Aviation

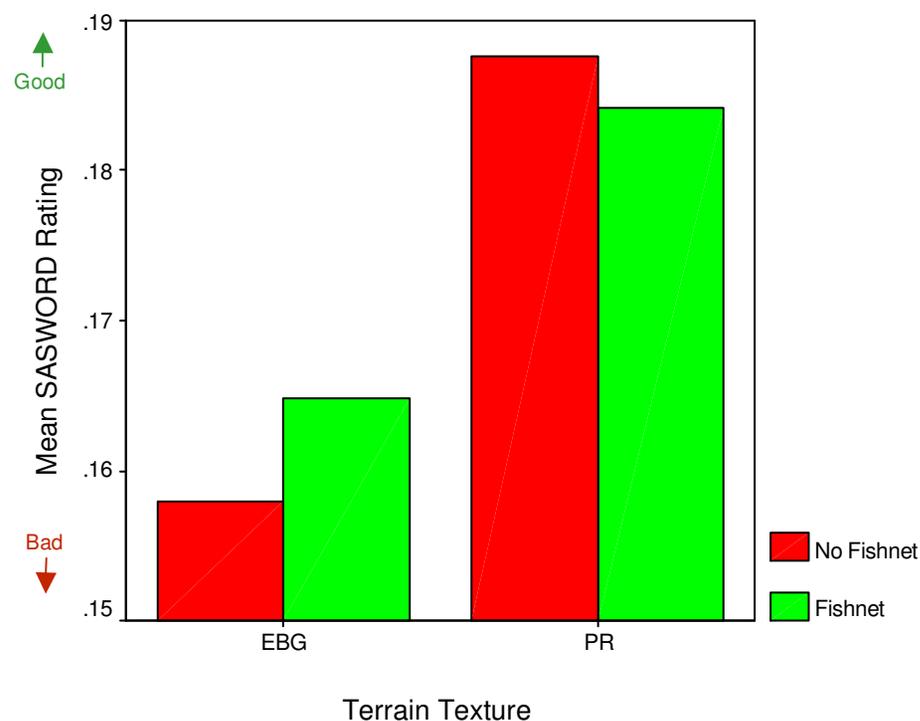
TA



Univariate ANOVA:
 $p=.946$

No statistical significance

SASWORD



Univariate ANOVA:
 $p=.927$

No statistical significance



Qualitative: Rankings From Exit Interview

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Overall Rankings, texture and resolution

Rank	<i>Approach (rank)</i>	<i>En Route (rank)</i>	<i>Emergencies (rank)</i>
1	EBG1 (2.7)	PR1 (2.6)	PR1 (2.4)
2	PR1 (2.7)	EBG1 (2.7)	EBG1 (2.9)
3	PRFN1 (3.1)	PRFN1 (3.0)	PRFN1 (2.9)
4	EBGFN1 (3.3)	EBGFN1 (3.4)	EBGFN1 (3.5)
5	EBGFN3 (5.0)	EBGFN3 (5.1)	PRFN3 (4.9)
6	PRFN3 (5.1)	PRFN3 (5.1)	EBGFN3 (5.2)
7	EBGFN30 (7.2)	PRFN30 (7.1)	PRFN30 (7.1)
8	PRFN30 (7.3)	EBGFN30 (7.3)	EBGFN30 (7.3)
9	CCFN1 (8.6)	CCFN1 (8.7)	CCFN1 (8.9)
10	CCFN30 (10.0)	CCFN30 (10.0)	CCFN30 (10.0)
11	BL (10.9)	BL (10.9)	BL (10.9)



Qualitative Rankings: Overall (cont.)

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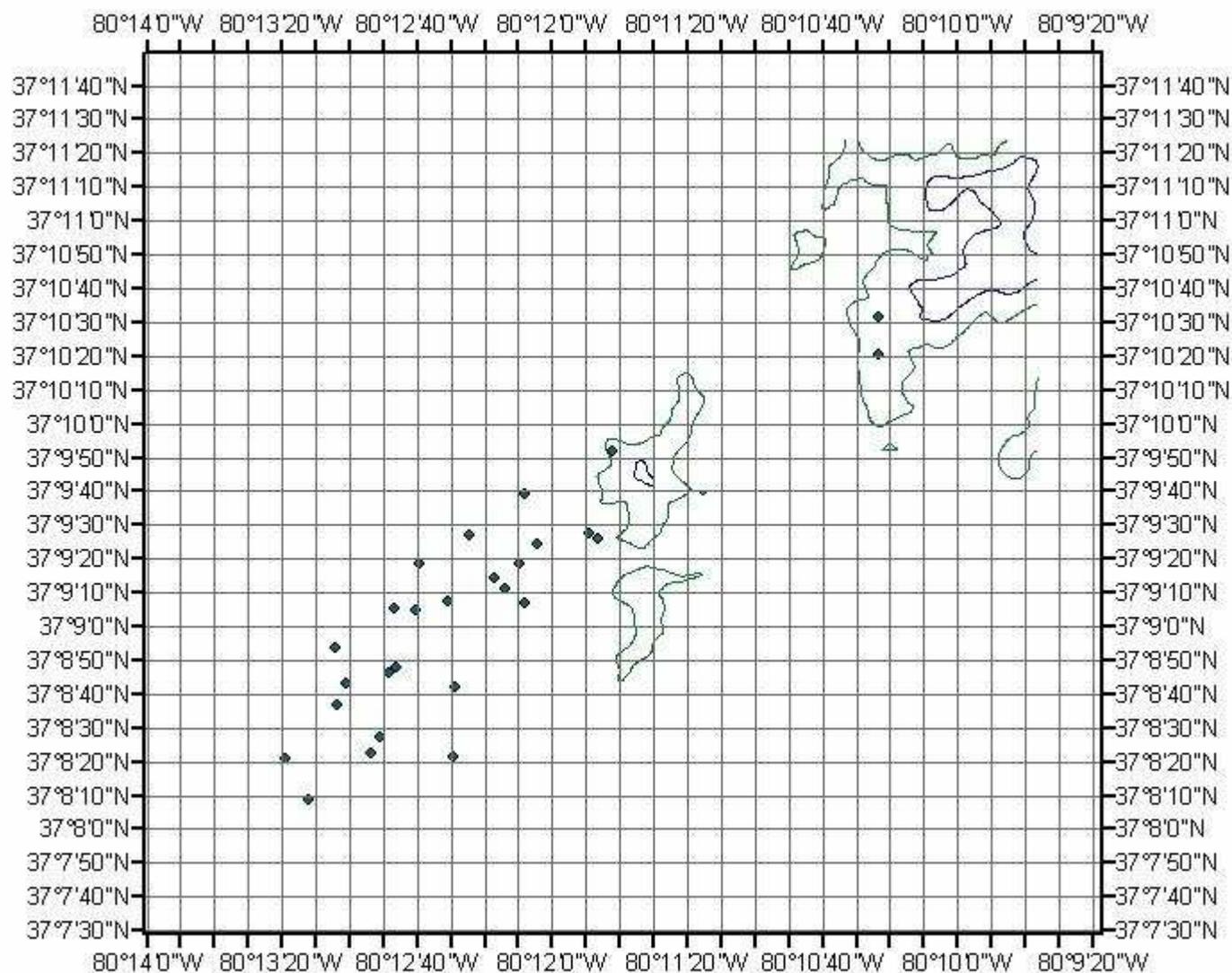
- All SVS concepts preferred over baselines
- Higher resolution DEMs preferred over lower resolution DEMs
- For the more advanced concepts, FN is not preferred
- No strong preference between EBG and PR
- For CCFN, an increase in DEM resolution is not as effective with regard to preference as changing texture



Rare Event

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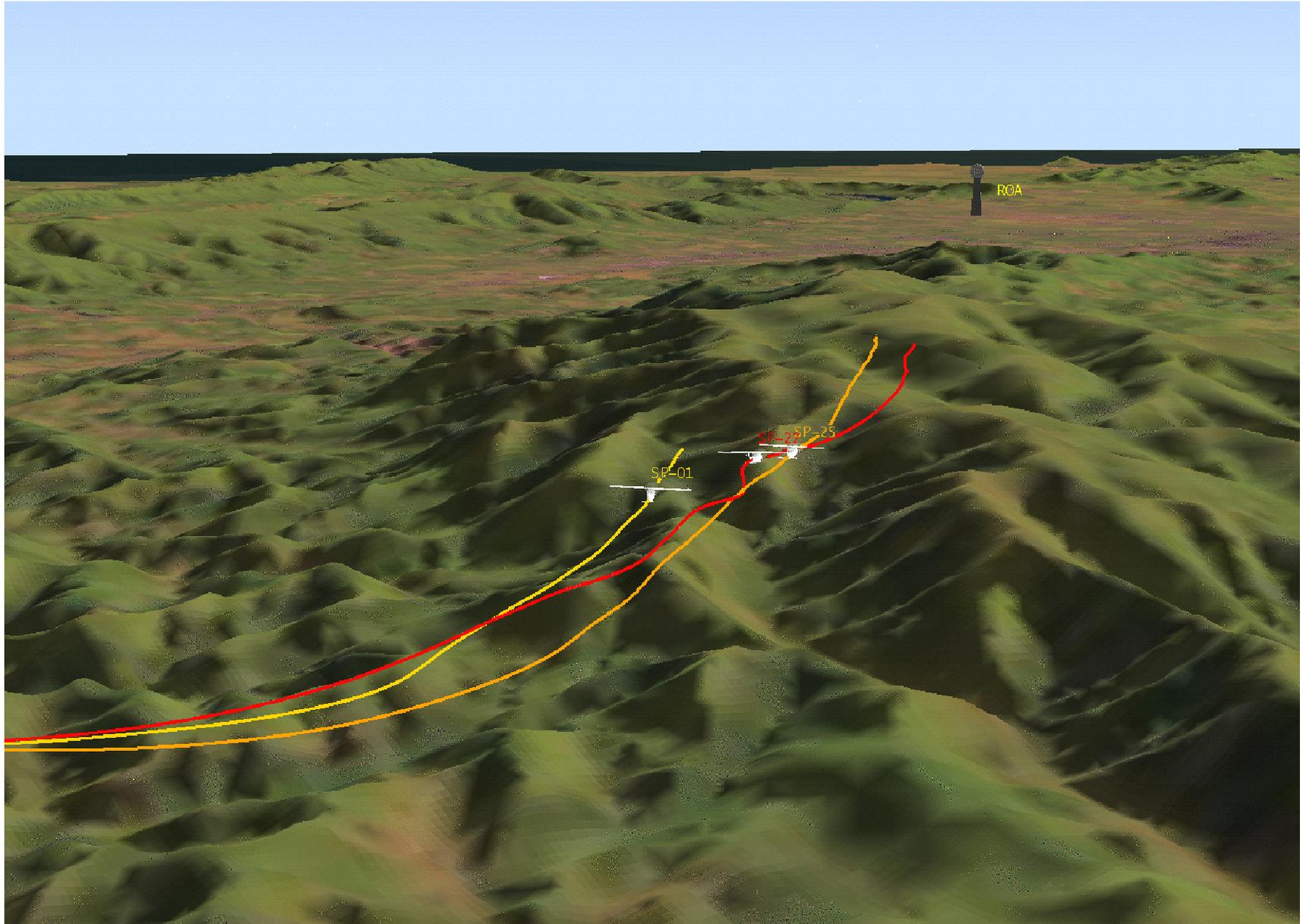
Scale: 0 1 mile



Rare Event



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Rare Event

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Subject Pilot	Display Concept	Pilot Qualification	CFIT Category
1	CCFN1	Test Pilot	A
2	PRFN3	VFR	A
3	EBGFN30	VFR	A
4	EBG1	IFR	B
5	CCFN30	Test Pilot	A
6	PRFN1	Test Pilot	B
7	EBGFN3	VFR	A
8	EBGFN1	VFR	A
9	PRFN30	VFR	A
10	PR1	IFR	A
11	CCFN30	Capstone	A
12	EBG1	IFR	A
13	EBGFN1	Capstone	B
14	PR1	Test Pilot	A
15	PRFN1	VFR	A
16	EBGFN3	IFR	A
17	PRFN3	IFR	A
18	EBGFN30	VFR	A
19	PRFN30	IFR	A
20	CCFN1	Capstone	C
21	CCFN30	VFR	C
22	EBG1	VFR	D
23	EBGFN1	VFR	C
24	PR1	VFR	C
25	PRFN1	VFR	D
26	EBGFN3	VFR	A
27	PR3	VFR	A

- Only 27 Data Points
- CFIT Category:
 - A: Safe – Terrain no factor
 - B: Safety of flight concern – “incident”
 - C: Cued by out the window visual, first
 - D: Terrain impact

	Totals	VFR	IFR (Low Hour)	IFR (Test Pilots)	Capstone User
Cat. A	18	9	5	3	1
Cat. B	3	0	1	1	1
Cat. C	4	3	0	0	1
Cat. D	2	2	0	0	0

Green: VFR
Blue: IFR

Test Characteristics



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- Simulation effort completed 6/14/02
- Data was generated for 27 pilots
- Total number of data runs: 945
- Total number of simulation hours: 324



Summary of Preliminary Results - Quantitative

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For approach task only:

- In terms of performance data –
 - Texture is not statistically significant
 - DEM is not statistically significant
 - FN is not statistically significant
 - Tunnel: Performance increase when using tunnel (versus no tunnel) is statistically significant
- In terms of physiological data –
 - Indicates less workload is associated with the tunnel, in general



Summary of Preliminary Results - Qualitative

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For approach task only:

- Texture (both awareness and workload measures):
 - CCFN is better than BSBG
 - EBG and PR is better than CCFN
 - Textured SVS is better than no texture
- DEM:
 - Awareness measures (EBGFN and PRFN, only)
 - DEM30 always rated lower than 1 or 3
 - When there was a difference between 1 and 3, 1 was better
 - Workload measures (EBGFN and PRFN, only)
 - No difference in DEMs
- Tunnel (both awareness and workload measures)
 - Significant improvement for tunnel vs. no tunnel, on CCFN30
- FN (both awareness and workload measures)
 - No significance observed (EBG and PR, only)



Summary of Preliminary Results

Aviation Safety Program: Synthetic Vision Systems – General Aviation

- All SVS concepts tested increased pilot performance and were preferred over traditional round dials
- Higher resolution DEMs were preferred, but did not show significant pilot performance improvements
- EBG and PR were rated similarly, but PR is computationally more intensive
- Low-hour, VFR pilots received “desired performance” ratings on en route and precision approach maneuvers (with tunnel present)
- Without training, all subjects but two avoided rare event CFIT (terrain impact)

Plan



- Continued Data Analysis
 - Correlate Qualitative and Quantitative
 - En Route Data
- Report Findings in Publications
- Utilize Findings in Subsequent Planned Experiments

Back-Up Slides

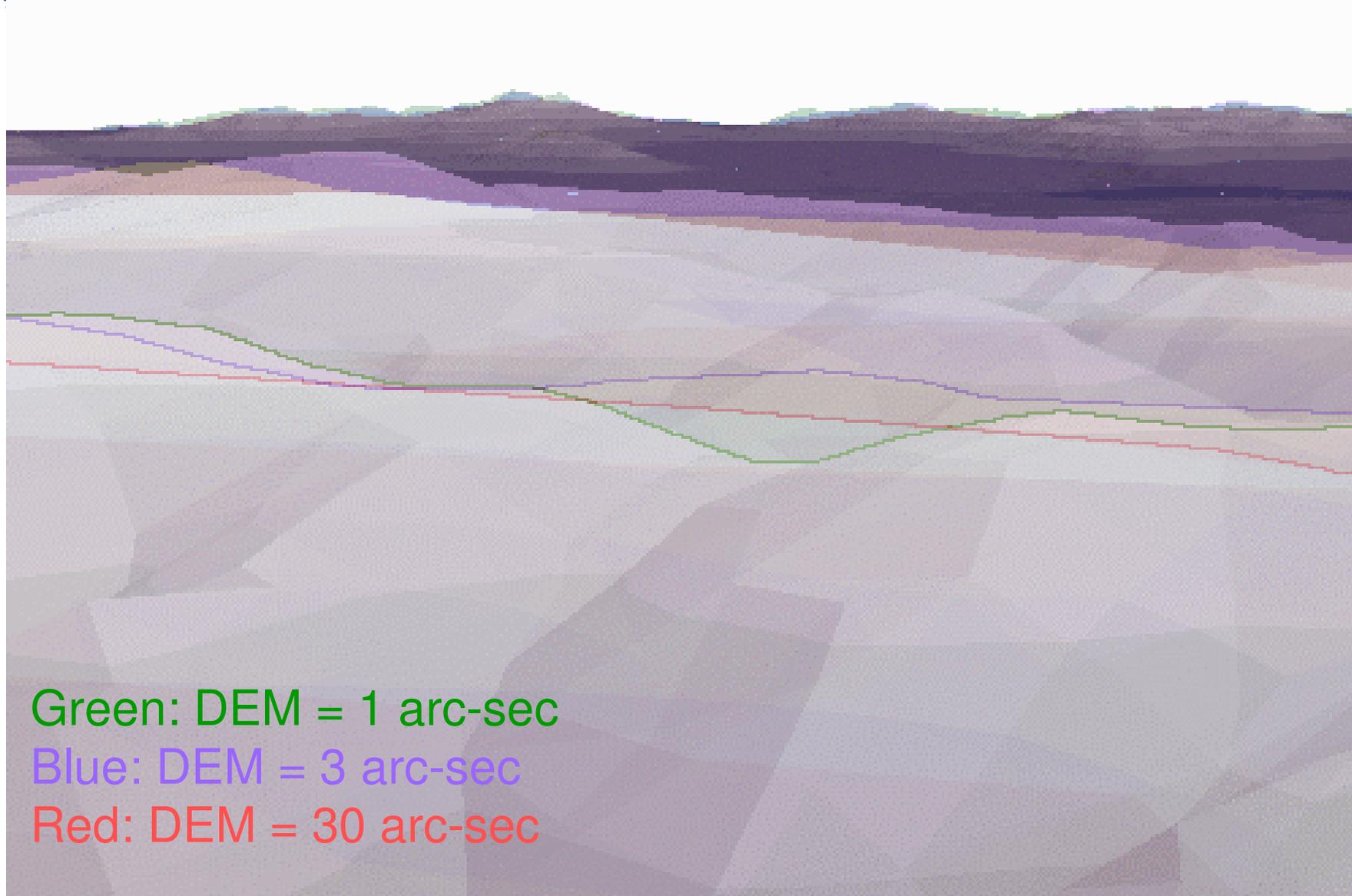


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Database Discussion



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Green: DEM = 1 arc-sec

Blue: DEM = 3 arc-sec

Red: DEM = 30 arc-sec

Selected Pilot Comments



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- While PR may be more “comforting” because it’s familiar (looks like what you see out the window), the terrain relief is so much more evident on EBG.
- Populated areas show up better on PR.
- EBG is more intuitive because you don’t have to interpret what the colors mean – if something is light on the PR, it could be dirt, building, etc.
- Cultural features (roads, rivers, towers) show up better on EBG.
- While DEM1 is the best, DEM3 is enough to do the job. DEM30 is questionable.
- Having a tunnel during the approach is a life-saver.
- Focused so much on tunnel and other symbology, that terrain was secondary during approach tasks.
- FN really helps define the terrain undulation.
- It’s easy to confuse the FN with roads and rivers.
- CCFN is better than standard gages.



Rare Event

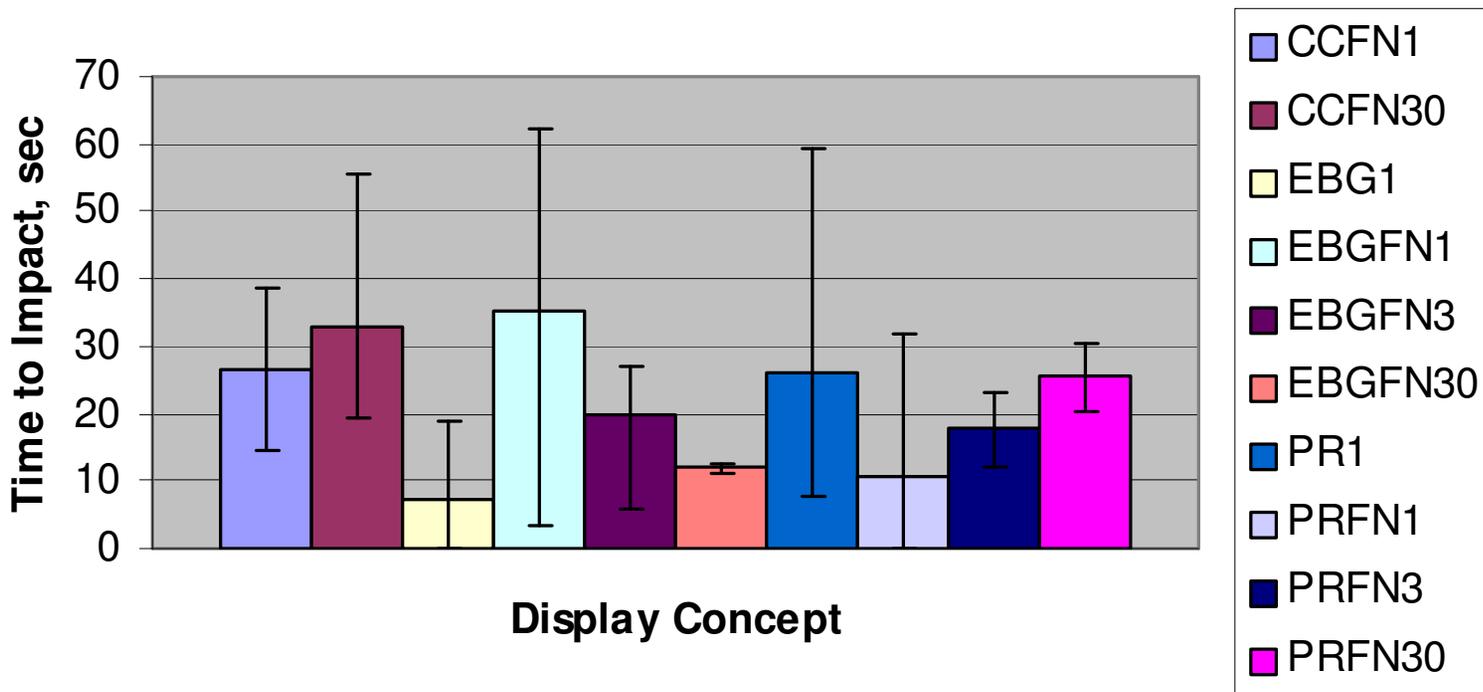
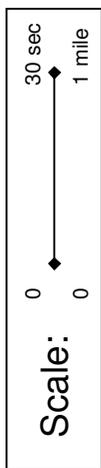
Aviation Safety Program: Synthetic Vision Systems – General Aviation

Subject Pilot	Display Concept	Pilot Qualification	CFIT Category
1	CCFN1	Test Pilot	A
2	PRFN3	VFR	A
3	EBGFN30	VFR	A
4	EBG1	IFR	B
5	CCFN30	Test Pilot	A
6	PRFN1	Test Pilot	B
7	EBGFN3	VFR	A
8	EBGFN1	VFR	A
9	PRFN30	VFR	A
10	PR1	IFR	A
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13	EBGFN1	Capstone	B
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15	PRFN1	VFR	A
16	EBGFN3	IFR	A
17	PRFN3	IFR	A
18	EBGFN30	VFR	A
19	PRFN30	IFR	A
20	CCFN1	Capstone	C
21	CCFN30	VFR	C
22	EBG1	VFR	D
23	EBGFN1	VFR	C
24	PR1	VFR	C
25	PRFN1	VFR	D
26	EBGFN3	VFR	A
27	PR3	VFR	A



Rare Event

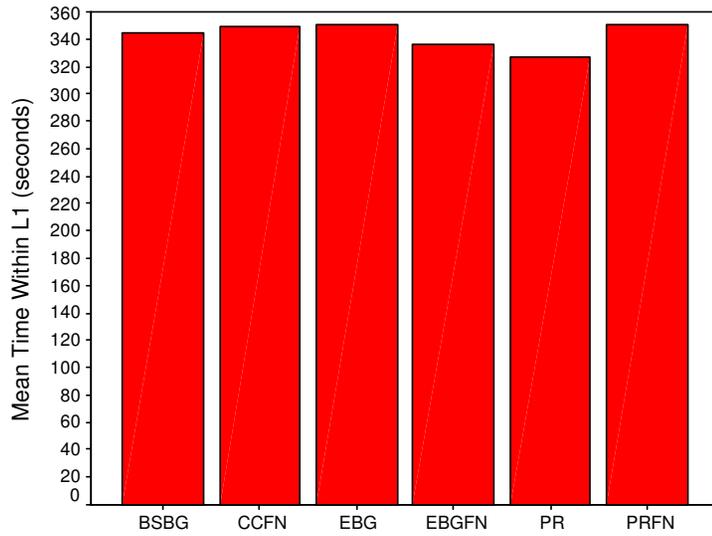
Rare Event Maneuver Estimated Average Time to Impact, with Max/Min Values





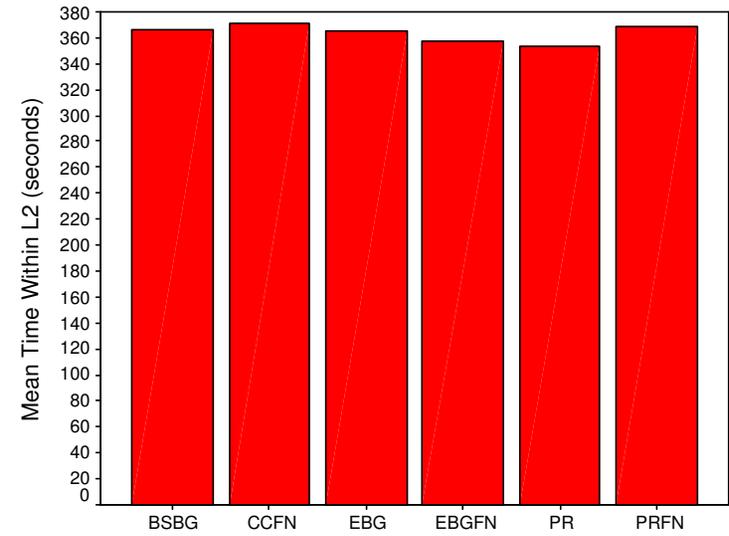
Results – Quantitative: Approach, Texture

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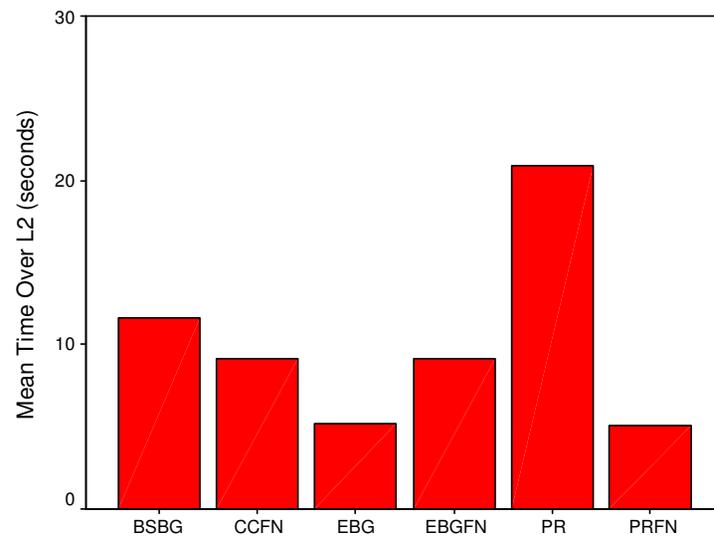
p=.510

Display Concept



p=.631

Display Concept



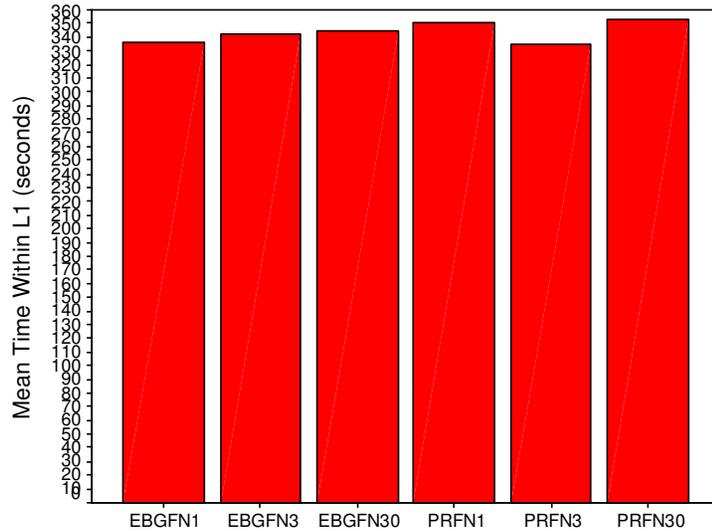
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Display Concept



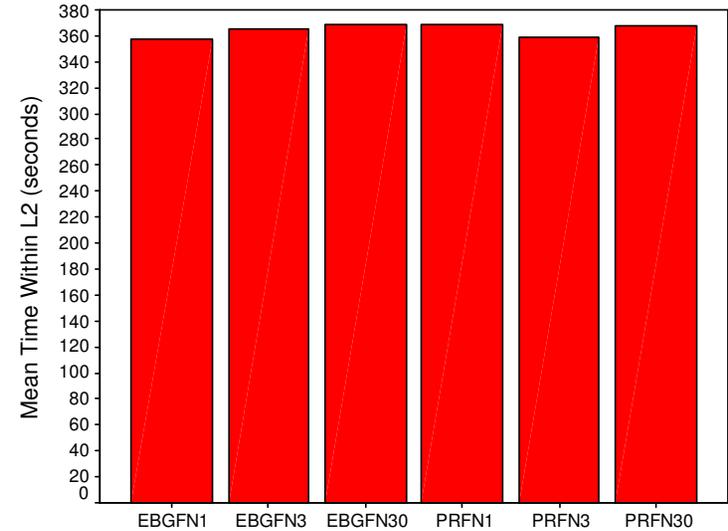
Results – Quantitative: Approach, DEM

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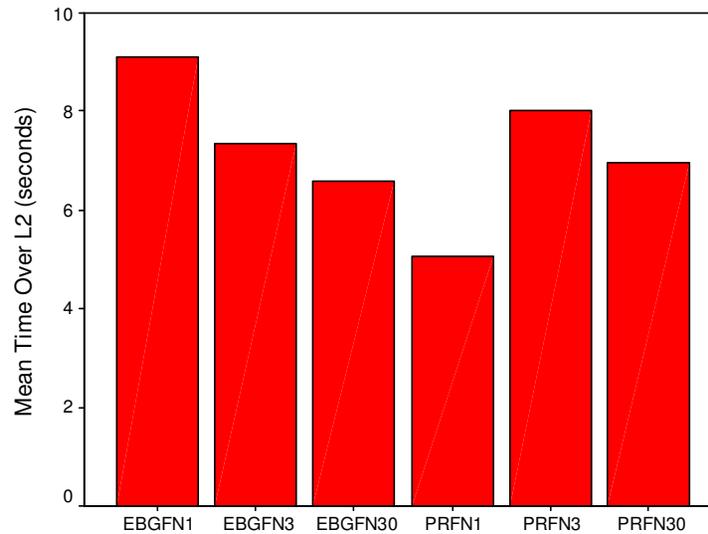
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Display Concept



$p=.782$

Display Concept



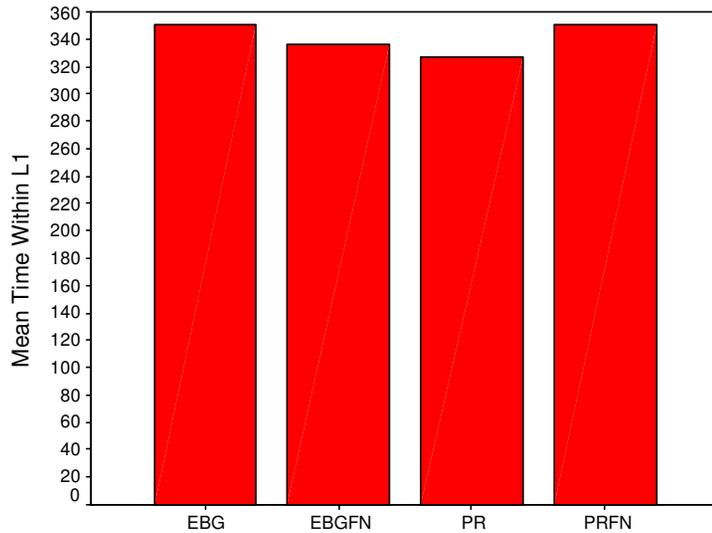
$p=.883$

Display Concept



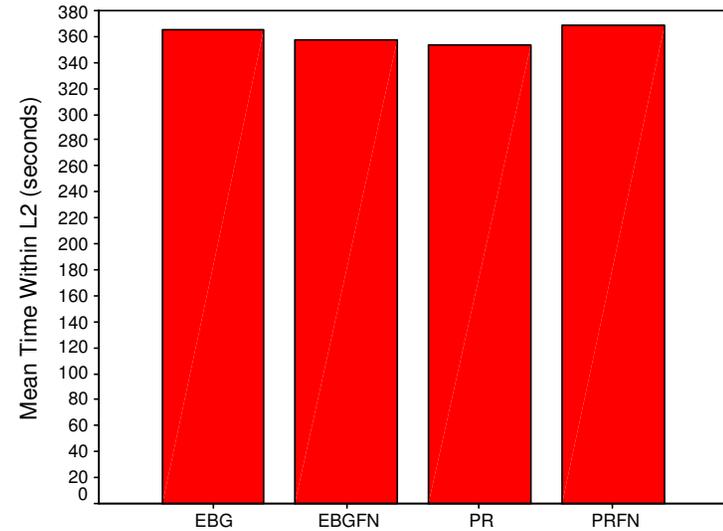
Results – Quantitative: Approach, FN

Aviation Safety Program: Synthetic Vision Systems – General Aviation



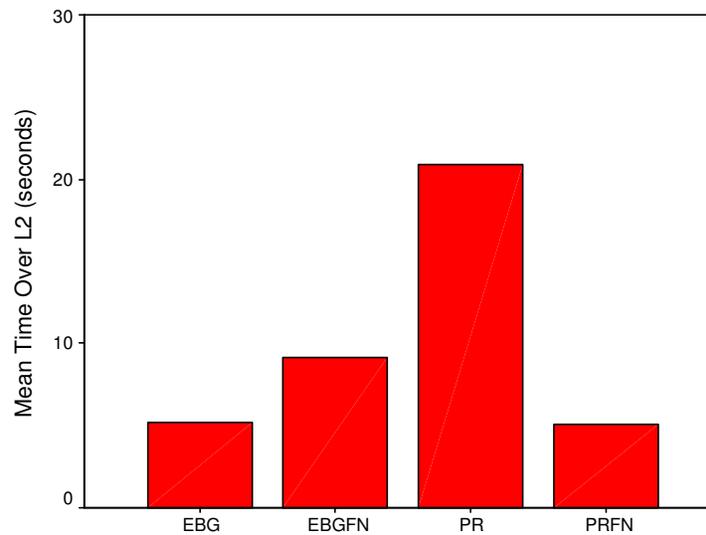
$p=.387$

Display Concept



Display Concept

$p=.644$



Display Concept

$p=.060$