Running Head: Advanced Avionic Display Dimensionality

Evaluating the Effects of Dimensionality in Advanced Avionic Display Concepts for Synthetic Vision Systems

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ABSTRACT

Synthetic vision systems provide an in-cockpit view of terrain and other hazards via a computer-generated display representation. Two experiments examined several display concepts for synthetic vision and evaluated how such displays modulate pilot performance. Experiment 1 (24 general aviation pilots) compared three navigational display (ND) concepts: 2D coplanar, 3D, and split-screen. Experiment 2 (12 commercial airline pilots) evaluated baseline “blue sky/brown ground” or synthetic vision-enabled primary flight displays (PFDs) and three ND concepts: 2D coplanar with and without synthetic vision and a dynamic “multi-mode” rotatable exocentric format. In general, the results pointed to an overall advantage for a split-screen format, whether it be stand-alone (Experiment 1) or available via rotatable viewpoints (Experiment 2). Furthermore, Experiment 2 revealed benefits associated with utilizing synthetic vision in both the PFD and ND representations and the value of combined ego- and exocentric presentations.

Evaluating the Effects of Dimensionality in Advanced Avionic Display Concepts for Synthetic Vision Systems

Synthetic vision system (SVS) technologies have the potential to improve aviation safety by reducing the number of accidents caused by conditions of challenging terrain and/or low visibility. Through the combination of on-board terrain and obstacle databases and advanced navigation guidance, SVS technologies provide a computer-generated, real-time presentation of the surrounding terrain and other obstructions, regardless of the actual weather conditions. While the majority of SVS research to date has focused on the primary flight display (PFD) (Alexander, Wickens, & Hardy, 2005; Prinzel, Comstock, Glaab, Kramer, Arthur, & Barry, 2004; Schnell, Kwon, Merchant, & Etherington, 2004), SVS implementations are generally proposed as comprising multiple panels or displays – an important one being a navigational display (ND).

Technology is now emerging whereby situation awareness (SA) for the surrounding terrain, obstacles, traffic, planned flight paths, and possibly weather information can be portrayed on the ND. The optimal presentation methods (including content, viewing perspective, and dimensionality) by which to present this ND information are still under investigation. Past research has shown that both two-dimensional (2D) and three-dimensional (3D) exocentric renderings are useful for portraying a 3D environment, and that the most appropriate display for a given context is generally dictated by the task (St. John, Cowen, Smallman, Oonk, 2001; Wickens, 2000). With this in mind, the overall goal of the present research is to guide development of the optimal ND format within an SVS context, focusing specifically on dimensionality. Three alternative ways of rendering the three dimensions of space necessary to support airborne navigation are discussed here.

A 2D coplanar ND consists of a top-down view of the flight environment in the top panel, as well as a side-view depiction in the bottom panel (the bottom panel is often referred to as a vertical situation display or VSD). Both display panels of a 2D coplanar ND are characterized as providing faithful axis representations (St. John et al., 2001; Wickens, 2003) of the lateral and vertical planes. 2D displays are generally good for supporting tasks requiring precision for navigation, distance estimation, or hazard localization. Within an aviation context, 2D coplanar displays support better performance than 3D displays for flight path tracking tasks (Wickens & Prevett, 1995), conflict avoidance maneuver choices (Alexander, Wickens, & Merwin, 2004), and a number of spatial judgment tasks (e.g., Wickens & Prevett, 1995; Wickens, Liang, Prevett, & Olmos, 1996).

3D displays have been advocated due to their “natural,” integrated representation of the 3D world (Wickens, 2003). Such an integrated representation is beneficial as it matches the users’ “perspective expectation,” and thus may immerse the viewer in the display, thereby supporting a better understanding of the nature of the 3D space and shape. However, these displays often yield less precise navigation than that offered by 2D displays (St. John et al., 2001; Wickens, Merwin, & Lin, 1994). Other costs include spatial awareness biases and distortions which are inherent to a 3D representation due to the “2D to 3D effect” (McGreevy & Ellis, 1986). The 2D to 3D effect leads pilots to subjectively rotate vectors in depth more parallel to the viewing plane than their actual orientation, leading to compression and ambiguity along the line-of-sight.

A third alternative format - the “split-screen display” - may resolve the tradeoffs between 3D and 2D coplanar displays. The split-screen display consists of a 3D view to support global awareness in one panel and a side-view VSD of the 2D coplanar format to support precise hazard localization and avoidance in the other panel. Two studies have compared 2D coplanar with split-screen NDs, one of them also including just a 3D display. Alexander and Wickens (2004) compared traffic position estimation performance across all three display formats and found that, overall, the 2D coplanar display best supported both vertical (compared to 3D) and lateral (compared to split-screen) traffic position estimation performance. Alexander and Wickens (2005) examined flight path tracking and change detection performance and found that the 2D coplanar display was slightly better in supporting flight path tracking and change detection performance when compared to the split-screen format. However, these experiments used piloting tasks which required focused attention to specific locations within the 3D environment, rather than requiring divided attention among other displays or duties. Tasks more integrative in nature might be better served by a split-screen display due to its realistic depiction of all three airspace axes in a single, integrated panel.

The present research, involving two flight simulations, examined several display concepts for synthetic vision and evaluated how such displays modulate pilot performance related to situation awareness, mental workload, and off-nominal event detection and avoidance. Across both experiments, pilots flew step-down approaches (Experiments 1 and 2) or departures (Experiment 2), and were required to complete a number of non-flying tasks (Experiment 1).

EXPERIMENT 1

In Experiment 1, the three ND formats (2D coplanar, 3D, and split-screen) were compared as traffic, terrain, and flight parameter awareness were periodically assessed by the Situation Present Assessment Methodology (SPAM; Durso & Gronland, 1999) and Situation Awareness Global Assessment Technique (SAGAT; Endsley, 1995) probes. The experiment design was expected to modulate SA based on the presence or absence of critical display attributes that feed information processing. For example, the top-down view in the 2D coplanar display allows for a faithful (i.e., non-compressed) depiction of the horizontal airspace situation. The side-view VSD of both the 2D coplanar and split-screen displays provides a faithful vertical axis representation, but also introduces an additional display panel leading to increased visual scanning demands. The 3D view, provided in the 3D display and the top panel of the split-screen display, depicts the 3D airspace in a realistic, integrated fashion, but subject to 3D compression and ambiguity. From this, four hypotheses are offered:

1. The absence of an unambiguous VSD in the 3D display should hinder traffic vertical position estimation performance, probed by SPAM traffic location questions. The mental effort necessary to resolve this ambiguity is expected to be associated with higher mental workload ratings.
2. The presence of an integrated 3D representation of the external scene in the 3D and split-screen displays should help maintain global awareness, probed by SAGAT terrain questions.
3. Residual attentional capacity should be reduced by scanning between panels of the ND, which is mandatory in the 2D coplanar and possible (but less essential) in the split-screen format. Increased scanning demands in the 2D coplanar ND will draw attention away from the PFD, whose content is probed by SAGAT flight parameter questions.
4. Off-nominal event detection should be degraded with the 3D display, relative to the 2D coplanar and split-screen displays, to the extent that display ambiguity increases the demands associated with the traffic position estimation task, and therefore reduces residual attentional capacity.

METHOD: EXPERIMENT 1

Pilot Participants

Twenty-four certificated flight instructors (experience: M = 982 flight hours; age: M = 23 years) from the University of Illinois Institute of Aviation participated in the experiment. All pilots had normal or corrected-to-normal vision and were paid for their participation.

Simulation

This experiment was conducted in a full mission Frasca Model 142 dual control FAA-approved flight simulator configured as a Piper Archer III single engine aircraft. The fixed-base, yoke-controlled simulator was positioned in front of an approximately 180° view of the outside world. Three projectors with 1280 x 1024 pixels of resolution projected Yosemite National Park terrain images onto three separate 7.5 ft x 10 ft (2.3 m x 3 m) screens. The cockpit LCD SVS display was a 14.1 in x 11.2 in (35.8 cm x 28.4 cm) screen with a resolution of 1280 x 1024 pixels.

Experimental Display Concepts

All display concepts (see Figure 1) contained an egocentric PFD in the upper left corner of the screen. The PFD was 3.9 in x 4.7 in (10 cm x 12 cm) and portrayed the command flight path using a tunnel format. The tunnel was depicted by a series of connected 200 ft x 75 ft (61 m x 23 m) green boxes, spaced 300 ft (91.4 m) apart in depth. Ownship was represented as a green "W" (i.e., boresight), and a white 3D perspective predictor portrayed the pilot's estimated position five seconds ahead of ownship. Altitude and airspeed were presented as round dials on the right and left of the display, respectively. A horizon line was provided and the exact heading of ownship was displayed directly above the boresight.

The ND top panel, in all cases, was 8.4 in x 8.4 in (21 cm x 21 cm). The VSD shown for the two dual-panel display concepts (2D coplanar and split-screen) was 3.3 in x 8.4 in (8.4 cm x 21 cm). All displays contained a 30-second predictor vector.

Insert Figure 1

2D Coplanar Display. The coplanar display consisted of a top-down map view in the top panel, with terrain altitude color-coded relative to ownship, and a VSD in the bottom panel presenting a side-view depiction of 4 nm (7.4 km) ahead of ownship and 1 nm (1.8 km) behind (see Figure 1a). The top-down map terrain color-coding closely resembled that used in a standard Terrain Awareness Warning System (TAWS) display (FAA, 1999), where red represented terrain above ownship's altitude, yellow represented terrain up to 1000 ft (305 m) below ownship, and black represented terrain greater than 1000 ft (305 m) below ownship.

3D Display. The 3D display (see Figure 1b) presented a photorealistic, "tethered" view. An elevation angle of 45° was chosen to optimize judgments within the longitudinal and vertical dimensions (Boeckman & Wickens, 2001) with an azimuth offset of approximately 10° in the clockwise direction (Ellis, McGreevy, & Hitchcock, 1987). The ambiguity of judgments in the vertical direction was further reduced by attaching a "drop line" from ownship and other aircraft to the terrain below (St. John et al., 2001: Wickens, 2003).

Split-Screen Display. The split-screen display was comprised of a 3D view in the top panel and a side-view VSD in the bottom panel (see Figure 1c).

Task and Experimental Design

The experiment utilized six low-level flight paths. Airspeed was fixed at 100 knots until the final approach leg to ensure that all SA probes (described below) were encountered at the same point in each scenario across all participants. Manual control of airspeed resumed upon crossing a final approach fix for landing.

Pilots made traffic location judgments on a total of 60 aircraft targets across the three ND formats. Pilots flew scenarios containing between one to four aircraft within the display view at any given time. Using a variant of SPAM, pilots were periodically asked, during simulation freezes, to estimate the location of the nearest aircraft in the outside world. Visibility was adjusted so that these aircraft were not visible in the outside world. However, the outside world did present the corresponding mountainous terrain that was visible on the display, so connections between locations in the outside world and the display could be easily established.

When the simulation froze, pilots used a knob on the control yoke to move a white ball in the outside world to the position where they estimated the location (relative elevation and azimuth) of the closest aircraft, and then pressed a button on the yoke to continue to the next trial. This type of response essentially mimicked direct pointing to inferred locations in the outside world of display-depicted aircraft. Pilots were instructed to perform the location estimation task as quickly and accurately as possible. No feedback was provided at any time during the actual experiment, although aircraft icons were present in the outside world for the first practice trial so pilots could establish a connection between the display and outside world representations.

Six out of ten scenario freezes also contained a second question, a SAGAT probe, which either probed terrain (e.g., “on which outside world screen was the highest terrain?”) or general situation awareness, consisting of flight parameter queries (e.g., heading, altitude, path direction). Success in accurately identifying these flight parameters was dependent on the amount of attention deployed to the PFD, given that primary flight information was only provided within that display. The PFD, ND, and outside world were blank during the terrain or general SAGAT probes.

A within-subjects manipulation of ND format was used to create six flights. The presentation of ND format was counterbalanced across pilots so that all six combinatory orders of the formats were used, and then repeated for each pilot in reverse order.

Off-Nominal Event

The second-to-last trial involved an off-nominal event for which the pilots were not briefed. This unexpected event was erroneous PFD pathway guidance which directed the pilots to fly through a man-made communication tower visible in the outside world but not on the ND. The event allowed the determination of which display best supported an appropriate response (i.e., verbally acknowledging the presence of the hazard, flying an evasive maneuver) to the uncharted obstacle.

Procedure

Each pilot first read experiment instructions explaining the task and was shown illustrations of the SVS displays while the experimenter read descriptions. After completing two practice scenarios, pilots flew six experimental scenarios. A modified (scale of 1-20, un-weighted) NASA-TLX subjective mental workload rating scale (Hart & Staveland, 1988) was completed at the end of each experimental trial.

RESULTS: EXPERIMENT 1

All analyses consisted of a series of three planned comparisons: (1) 2D coplanar vs. 3D, (2) 2D coplanar vs. split-screen, and (3) 3D vs. split-screen. Because only three *a priori* comparisons were made, family-wise error rates were not adjusted (see Keppel, 1982, for more details). A criterion p value of .05 was used for statistical significance, and a criterion p value of .10 was used for effects approaching significance. Fewer than 5% of the data were removed as outliers greater than two standard deviations from the mean.

SPAM Situation Awareness Probes: Traffic Awareness

The amount of time needed to complete the SPAM traffic awareness probe was analyzed. There were no display effects on response times to the traffic awareness probes (all $p > .10$).

To evaluate the accuracy of traffic position estimation, the difference between the pilots' positioning of the symbol, and the true location of the closest traffic aircraft was partitioned into lateral and vertical estimation errors as measured by degree of visual angle. There were no display effects on absolute or signed lateral position estimation errors (all $p > .10$). For absolute vertical estimation errors, the planned comparisons between the 2D coplanar display and the 3D and split-screen displays showed no significant differences (both $p > .10$). The planned comparison between the 3D and split-screen displays did, however, reveal a significant effect such that vertical estimation errors were about 1.2 degrees greater with the 3D ($M = 5.78$ degrees) than the split-screen ($M = 4.63$ degrees) display ($t(23) = 2.53$, $p < .05$, $d = 1.05$). Signed vertical estimation errors showed that pilots exhibited an overall bias to estimate aircraft positions as lower than they actually were by about 2.3 degrees of visual angle. This bias, however, was not influenced by display type.

SAGAT Situation Awareness Probes: Flight Parameter and Terrain Awareness

The terrain awareness and flight parameter probe data by display type are shown in Figure 2. The planned comparison between the 2D coplanar and 3D displays revealed no significant difference ($p > .10$); however, an effect approaching statistical significance with a medium effect size was found between the 2D coplanar and split-screen displays, where the overall accuracy was about 7% greater with the split-screen ($M = 59.2\%$) than the 2D coplanar ND ($M = 52.3\%$; $t(23) = 1.90$, $p = .07$, $d = 0.79$). Examining this effect in terms of probe type (terrain vs. flight parameter) revealed no significant effects; thus, the split-screen advantage was reflected in both awareness of terrain and flight condition.

Insert Figure 2

Mental Workload

No statistically-significant differences in mental workload were revealed in the planned comparisons between the 2D coplanar ($M = 9.08$) and either the 3D or the split-screen displays (both $p > .10$). However mental workload was rated lower with the split-screen ($M = 7.97$) than the 3D ($M = 9.28$) display, an effect approaching statistical significance with a medium effect size ($t(23) = 1.83$, $p = .08$, $d = 0.76$).

Off-nominal Event Detection

Ten of twenty-four pilots flew directly through the tower not represented on the ND; four of those ten made a comment regarding the tower as they flew through it while the other six made no comment at any time, and therefore it might be inferred that they did not notice it. A breakdown of which ND format was being used at the time of the fly-through, and whether or not they acknowledged the tower verbally is given in Table 1. Low power due to there being only one event per pilot precluded formal statistical analyses. However, the data do show a trend such that the pilots were more likely to make no comment of the tower's presence when using the 3D ND than when using the 2D coplanar or split-screen displays.

Insert Table 1

DISCUSSION: EXPERIMENT 1

Traffic Awareness

Our first hypothesis, that ambiguity costs within the 3D display would hurt traffic position estimations in the vertical dimension, was confirmed. Position estimation error within the vertical dimension, in fact, was poorest with the 3D display, and this display was associated with higher mental workload ratings (of marginal significance) when compared to the split-screen display. In this regard, it is important to note that 3D ambiguity is invited in the compressed vertical axis, but not the uncompressed lateral axis. Interestingly, the split-screen display somewhat helped vertical estimations compared to the 2D coplanar display given that there was not a significant difference in performance between the 2D coplanar and 3D displays. This is possibly due to the greater ease of use and naturalness of the integrated 3D representation in the top panel of the split-screen display, which allowed more attentional capacity to be directed to precise estimation from the VSD.

Terrain Awareness

Hypothesis two predicted that the 3D representation in the 3D and split-screen displays would help maintain global awareness, as measured by SAGAT terrain probes. This hypothesis was partially supported by the marginally significant effect of greater accuracy with the split-screen than the 2D coplanar ND. The specific nature of these probes supports this interpretation given that shape-understanding tasks, requiring an overall spatial understanding of the environment, are best supported by information integration via 3D displays (St. John et al., 2001). An inference from these results is that a benefit to the 3D display was not found because greater attention demands associated with resolving ambiguity necessary for other SA-related tasks presumably offset the benefits of integration.

Flight Parameter Awareness

It was hypothesized that flight parameter awareness would be indirectly affected by the attenuated demands of the ND in that the flight parameter probe data differences reflect attention demand differences for the ND concepts. These data showed that the visual scanning demands inherent to the 2D coplanar display compelled pilots to allocate visual attention to the ND, at the cost of attention to the PFD containing the information needed to answer those probes accurately. Performance on these probes indicates a greater amount of residual attention was available with the split-screen relative to the 2D coplanar display, given the reduced (although not eliminated) need in the split-screen display for between-panel scanning as the only way to integrate lateral and vertical axes. Relative to the 3D display, there is a greater ease of resolving ambiguity in the split-screen display given the faithful vertical representation in the VSD.

Off-nominal Event Detection

One finding of considerable interest is the failure of ten out of 24 pilots to avoid colliding with the tower shown in the outside world but not on the ND, a manipulation of attentional tunneling reported elsewhere with tunnel-supported SVS displays (Wickens & Alexander, submitted). Of most importance are those six pilots who failed to even verbally acknowledge the presence of the tower whatsoever. Out of those six, four were flying with the 3D ND, one with the 2D coplanar, and one with the split-screen. It may be inferred that the lowered difficulty of performing the traffic position estimation task with the two unambiguous, dual-panel displays relative to the ambiguous, single-panel 3D display allowed for more attentional resources to be devoted to scanning the outside world, increasing the likelihood of detection of the tower, thus supporting our fourth hypothesis. More discussion of this issue is contained in Wickens and Alexander (submitted).

Experiment 1 Summary

The greater vertical position estimation error, higher mental workload ratings, and higher number of unexpected tower collisions found with the 3D display lead us to conclude that this format would not be ideal as a stand-alone display for an SVS navigational concept. The results further point to the importance of an accurate vertical axis representation such as that shown in the bottom panel, side-view VSD of the 2D coplanar and split-screen displays. Furthermore, our results generally suggest that pilots are doing an effective job of exploiting the “best of both worlds” offered by the split-screen display, taking advantages of its benefits (3D integration, VSD unambiguous altitude) without suffering its costs (scanning demands induced by two panels, one of which is ambiguous).

EXPERIMENT 2

Experiment 2 expanded upon the findings of Experiment 1 regarding synthetic vision ND formats. The experiment had three objectives: (1) to compare the 2D coplanar display against an alternative format to this split-screen display; (2) to incorporate the presence or absence of photo-realistic terrain information, both within the PFD and the ND; and (3) to move the research toward a commercial and business aircraft focus. The alternative ND format used multiple viewpoints in a dynamic sequence, achieved by zoom and rotation, rather than as a static pair. This concept of dynamic, rotatable multi-viewpoints has been shown elsewhere to mitigate many of the costs of 3D ambiguity (Sollenberger & Milgram, 1993; Thomas & Wickens, 2005).

In total, six display combinations were evaluated, consisting of two PFDs combined with one of three NDs (2 x 3). The PFD was either: (1) a baseline PFD; or (2) an egocentric SVS PFD. The ND concepts were: (1) a baseline 2D coplanar ND with TAWS and VSD; (2) a SVS 2D coplanar ND; or (3) “multi-mode SVS ND” which was the 2D coplanar SVS ND with two additional dynamic, rotatable 3D exocentric modes.

Given the above configurations, the following four hypotheses are offered:

1. Research has demonstrated that the addition of synthetic terrain information on cockpit displays significantly enhances situation awareness, lowers mental workload, and rates higher in pilot preference (Arthur et al., 2004; Kuchar & Hansman, 1993; Prinzel et al., 2004; Schnell, Kwon, Merchant, & Etherington, 2004). It was therefore hypothesized that global situation awareness and pilot preference will be rated higher and mental workload

lower for display formats with SVS on the PFD and 3D multi-mode SVS ND displays compared to the baseline PFD and ND displays.

2. Kuchar and Hansman (1993) and Arthur et al. (2004) reported the significant efficacy of an egocentric view of terrain coupled with a non-SVS plan-view display with TAWS and VSD for recognition and prevention of CFIT accidents compared to the same display suite without terrain on the PFD. Therefore, it was hypothesized that pilots would be better able to recognize and proactively respond to potential CFIT situations when pilots flew the scenarios with synthetic vision than with baseline displays.
3. Because the multi-mode SVS ND retains the advantages of both 2D plan-view and 3D exocentric perspectives (Sollenberger & Milgram, 1993; Thomas & Wickens, 2005) - without the limitations found when either is a single fixed viewpoint - it was hypothesized that the multi-mode SVS ND would afford the highest level of situation awareness for recognition and avoidance of CFITs when the ego- and exocentric displays were considered independently.
4. Additionally, the coupling of precise navigation guidance information with an egocentric terrain display and multiple exocentric viewpoints would enable the highest overall level of situation awareness for recognition and avoidance of CFITs compared to other PFD and ND combinations.

METHOD: EXPERIMENT 2

Pilot Participants

Twelve Airline Transport Pilots (experience, *M* = 8,500 flight hours), who fly for major US commercial airlines, participated in the experiment. All participants were type-rated in the B-757, and had head-up display (HUD) and “glass cockpit” experience, which ensured familiarity with a velocity vector and guidance symbology.

Simulation

The experiment was conducted in the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III simulator at NASA Langley Research Center. The single-pilot, fixed-based simulator consists of a 144° by 30° out-the-window (OTW) scene, a graphical research display (SVS-RD), and simulated large commercial transport aircraft controls. The OTW scene was presented with unlimited visibility during training and was reduced to ¾ nm for the experimental runs. The synthetic terrain database for all SVS concepts was 95 nm by 95 nm (176 km by 176 km) in area, centered at the Eagle-Vail Regional County Airport (EGE) airport in Colorado. The SVS-RD was 18.1 in (46 cm) diagonal, with dual-glass XGA LCD monitors, closely abutted to give a seamless impression of two ARINC Size D (6.7 in x 6.7 in {17 cm x 17 cm} viewing area) displays. The aircraft model was a B-757-200 and typical landing and departure configurations (e.g., flap settings, reference speeds) were used. All scenarios were flown with moderate turbulence and autothrottles engaged.

Experimental Display Concepts

Primary Flight Displays. Two PFDs were evaluated, identical to one another with the exception of the presence or absence of synthetic vision terrain information (Figure 3a and b). The PFDs had symbology typical of integrated PFDs with the addition of a flight path marker with acceleration/deceleration and reference airspeed error indicators (see Prinzel et al., 2004).

Insert Figure 3 here

Neither PFD presented tunnel (i.e., pathway) information. However, flight path control and positioning information was available through path deviation indications and guidance cue information. The vertical and horizontal path deviation scales provided “fly-to” indication relative to a 600 ft wide by 350 ft tall (183 m x 107 m) desired path by 1 dot lateral and 2 dots vertical deflection, respectively. An integrated “tadpole” guidance symbol driven by a modified pursuit guidance control law (Merrick & Jeske, 1995; Prinzel et al., 2004) was used for the PFDs. The vertical and horizontal pursuit command was based on the path centerline positioned 30-seconds ahead of ownship. The tail on the tadpole cue indicates the direction and magnitude of the path track change.

Navigation Display Concepts. Three ND concepts were evaluated: (a) baseline, (b) SVS ND, and (c) multi-mode SVS ND. Each ND included TAWS terrain visual alerts, TAWS peaks’ mode information, and a VSD. The baseline ND concept mirrored present-day commercial and business aircraft equipage (Figure 3c, a 2D coplanar ND in map-centered mode). The SVS ND was identical, with the addition of terrain information (Figure 3d). The SVS multi-mode ND was identical to the 2D SVS ND concept with the exception that the pilot could also initiate additional viewing modes that changed the display frame-of-reference from 2D “god’s-eye view” to dynamic 3D exocentric perspective views.

Under the SVS multi-mode ND condition, two 3D exocentric ND modes were available. The first mode was termed “animate” and is designed to give the viewer a sense of being part of the action or being “immersed.” When the pilot initiated the “animate” mode, the viewpoint of the ND automatically implemented seven steps, as illustrated in Figure 4. The ND slewed from the (a) SVS 2D coplanar view to a (b) 20 degree right offset view at a distance of 5000 ft (1.5 km) that zoomed out to (c) 10000 ft (3 km) then (d) panned to the left, stopping at (e) 20 degrees azimuth on the other side of the viewpoint, and then zoomed in to (f) 5000 ft (1.5 km) viewing distance and then, rotated up to a (g) 90 degree view look-down to ease the transition from the 3D to the (h) 2D perspective. At each viewpoint, the view would hold from 1 to 3 seconds requiring a total time of 30 seconds to complete. The pan and zoom functions were smooth, with visual momentum principles enforced.

Insert Figure 4 here

A second pilot-initiated mode was called “perspective” and is illustrated in Figure 5. When the pilot initiated this mode, the view would change from the 2D SVS coplanar view to a (a) 3D 20 degree right offset view at 10000 ft (3 km); hold for 5 seconds, and the switch to a (b) 3D 20 degree left offset view at 10000 ft (3 km); hold for 5 seconds, and then back again to 2D SVS coplanar view. This mode took approximately 10 seconds to complete and visual momentum in the design was “implied”, not explicit.

Insert Figure 5 here

The objective of both modes was to provide pilots with multiple viewpoints to resolve 3D ambiguity. An important feature of the display concept was that these views would “time-out,” or go back to the SVS 2D coplanar mode. “Time-out” precluded the possibility that a pilot might use it for primary navigation. The pilot could chose when to initiate either the perspective or animated panning modes based on each individual’s preference or strategy developed during the training session. Pilots were briefed on various strategies that could be employed, but they were not required to employ any particular strategy.

Tasks and Experimental Design

Each pilot flew thirteen approach and six departure tasks for a total of nineteen runs. The experimental runs combined one of eight initial starting positions with one of five pre-entered flight management system (FMS) flight paths (3 approach paths, 2 departure paths). Each pilot flew twelve nominal (i.e., non-CFIT) approaches that varied in initial stating position and flight path flown. A thirteenth "rare event" approach task was flown, consisting of an initial starting condition and flight path that guided the aircraft toward terrain and a possible CFIT. Pilots flew five nominal departure tasks and a "rare event" CFIT departure scenario. Response to CFIT was calculated as the delta from pilot control input response to aircraft-terrain collision.

The experimental design was a 2 (experimental task: approach vs. departure) x 6 (display conditions) x 2 (nominal, rare event) x 12 (pilots) mixed-subjects experimental design. All pilots flew each approach and departure nominal scenario with all six display conditions. There was one replicate of each of the six nominal approach scenarios (2 runs each of nominal approach tasks). For the CFIT scenarios, each pilot was randomly assigned one approach and one departure CFIT scenario yielding two data points for each of the six display combinations across CFIT scenarios and pilots.

Procedure

After completing a statement of consent form, the pilots were given a detailed briefing of display concepts and scenarios. The briefing was followed by 8 practice approaches and departure procedures. After training, pilots performed thirteen approaches and six departures for a total of nineteen experimental runs. After each run, pilots completed a run questionnaire (7-point Likert Scale) and the Revised Workload Estimation Scale (Ames & George, 1993). Upon completion of all experimental runs, pilots filled out the SWORD and SA-SWORD (Vidulich & Hughes, 1991). Usability exercises and a final debriefing questionnaire were also administered.

RESULTS: EXPERIMENT 2

Data was analyzed using non-parametric and parametric statistics as well as Student Newman-Keuls (SNK) post-hoc tests. A criterion p value of .05 was used for statistical significance.

Situation Awareness

Subjective measures of situation awareness are shown in Table 2. There was a significant main effect for display conditions for SA ($F(5, 55) = 17.8$, $p < .01$). Pilots rated their SA significantly higher with the SVS PFD + SVS multi-mode ND compared to the other five display combinations. The baseline PFD + baseline ND was rated significantly lower in SA than all other display conditions. No other significant effects were found. This same pattern of effects was revealed with the SA-SWORD measure ($F(5, 55) = 60.8$, $p < .01$).

Insert Table 2 here

Mental Workload

As shown in Table 2, an ANOVA revealed a significant main effect for Revised Workload Estimation Scale ratings for mental workload ($F(5, 55) = 2.70$, $p < .05$). The SNK showed that pilots rated the SVS PFD + SVS multi-mode ND to be significantly lower in mental workload than the baseline PFD + baseline ND. No other displays were significantly different from each other. The SWORD analysis also found a significant effect for mental workload ($F(5, 55) = 8.78$, $p < .01$), revealing the same general pattern of effects.

Controlled-Flight-Into-Terrain

All pilots avoided terrain for the approach and departure CFIT scenarios. However, there was a significant difference in the time before the pilot's recognized the potential CFIT, depending upon the display configuration for both the approach and departure tasks (F (5, 11) = 26.6, $p < .05$), as shown in Table 3. A SNK post-hoc revealed that pilots responded significantly sooner in the two SVS multi-mode ND conditions (baseline PFD M = 184 s; SVS PFD M = 237 s), and of these, the multi-mode ND, coupled with the SVS PFD, was earliest. A similar pattern of data was observed with the departure data.

Insert Table 3 here

The results also showed that both pilots who flew the baseline PFD + baseline ND concepts only avoided the terrain by an average of 273 ft vertically and 0 ft laterally. While not technically a CFIT, this result was a CFIT "incident" or near-miss. In contrast, when synthetic vision was presented on the PFD, pilots were much more proactive and were able to execute both lateral maneuvers often well before TAWS and/or VSD alerts on the ND.

3D Exocentric Modes

Pilots initiated the perspective mode (M = 4.83) significantly more times than the animate mode (M = 1.58) during the approach (z = -3.089, $p < .05$). During the departure, the usage did not significantly differ (z = -1.406, $p > .05$) between animate (M = 2.25) and perspective (M = 1.16) modes. Most pilots (83%) reported that the perspective mode, which required 10 seconds to complete a full cycle, provided the greatest SA regarding flight path and terrain awareness with minimum cognitive and attentional investment. However, pilots felt that that the animate mode, which required 30 seconds to complete a full cycle, would be useful to brief and rehearse an approach, missed approach, etc. All pilots reported that both modes were highly useful and complemented each other.

DISCUSSION: EXPERIMENT 2

Experiment 2 evaluated whether the limitations of 3D display formats could be mitigated through a 2D coplanar display with 3D dynamic **rotatable** view options, supporting motion parallax as a depth cue. Experiment 2 also evaluated the effects of cockpit display formats for both ego- and exocentric views because synthetic vision technology will most likely be developed for the PFD and PFD/ND combination (e.g., Ramsey, 2004; Schiefele, Howland, Maris, & Wipplinger, 2004; Schnell et al., 2004; Scott, 2001; Smietanski, Lenhart, Kranz, & Mayer, 2000).

Situation Awareness and Mental Workload

Overall, the egocentric view of the external scene topography presented on the SVS PFD was found to be the significant source of terrain information for pilots. The enhanced SA reported for the SVS PFD was largely due to the egocentric view which gave the pilots an immersed sense of the terrain around them. Conversely, synthetic vision presented on the 2D coplanar ND was not found to have efficacy due to the lack of a 3D, or immersed, view.

Significantly lower mental workload ratings were given for the SVS PFD. The presence of terrain information on the PFD lessened the pilot's need to interpret the ND for task-critical terrain information or to invoke the 3D multi-mode exocentric display, when it was available.

Although the SVS 2D coplanar ND alone was not found to be significantly better than the baseline 2D coplanar ND, the SVS multi-mode ND substantially enhanced pilot SA regardless of PFD concept; however, the cost for this SA enhancement was a modest increase in pilot workload associated with invoking and interpreting the multi-mode ND. Moreover, when the SVS multi-mode ND was paired with the SVS PFD, the SVS cockpit displays complemented each other, mitigating the costs typically associated with each independently. The experimental data confirmed our hypothesis that an exocentric SVS multi-mode ND effectively and significantly enhanced pilot SA with the greatest benefit witnessed when paired with the egocentric SVS PFD.

Controlled-Flight-Into-Terrain

Pilots experienced several CFIT incidents while flying with the baseline displays during both the departure and approach CFIT scenarios. Overall, pilots were effective at managing the CFIT situation when synthetic vision was presented on the PFD. However, when pilots also had the SVS multi-mode ND display available to them, they were able to execute *proactive* evasive maneuvers, often well before the terrain presented a danger to the aircraft. This contrasted with pilot response to the CFIT with the baseline PFD paired with either a baseline or SVS 2D coplanar ND. In those cases, pilots were ill-equipped to recognize the hazardous situation and instead were *reactive* to TAWS and VSD alerts, significantly limiting reaction time and options to avoid terrain.

Experiment 2 Summary

Table 4 shows a summary of the SA, workload, and CFIT response results across PFD/ND display combinations. Importantly, a summation down rows can assess the PFD effect, or a summation across columns can assess the ND effect. Overall, results clearly show that the SVS PFD + SVS multi-mode ND was the best display combination for all three dependent variables (i.e., SA, workload, CFIT response), while the SVS multi-mode ND with conventional PFD was also significantly better for CFIT response. Furthermore, as far as SA is concerned, the two displays lacking any 3D representation (on the PFD or ND) were inferior.

Insert Table 4 here

The general agreement of SVS/multi-mode superiority across all measures is helpful, and reveals a synergy between the 3D representations in both displays. Importantly, however, the 3D ND in the multi-mode configuration is coupled, in series, with a 2D coplanar view. But such a view alone is not adequate, since the 2D coplanar ND did not provide the best performance. This is inferred to be due to the lack of a 3D view, or immersed sense of the surrounding terrain, in the 2D coplanar ND. Interestingly, by far the most preferred multi-mode configuration was the 2-view "perspective" rather than the 7-view "animate" display. This is inferred to be the result of the greater speed (10 s vs. 30 s) to cycle through all views, to provide an unambiguous picture.

GENERAL CONCLUSIONS

The current research examined display dimensionality within an important context for aviation safety—a navigational display within a synthetic vision system. Furthermore, this research addresses a relatively new design concept which brings the "best of both worlds," in terms of 2D and 3D displays, together in a split-screen format. Overall, the results pointed to a general advantage for the split-screen ND, whether it be static stand-alone (Experiment 1 as assessed by objective SA measures) or available via rotatable viewpoints (Experiment 2 as assessed by subjective measures of SA and workload). Both experiments pointed to split-screen display benefits for off-nominal event detection. While there was no direct comparison between the static split-screen and rotatable multi-mode display formats, research on 2D and 3D displays points to the inherent tradeoffs in utilizing either format alone given the variety of tasks required in aviation (St. John et al., 2001; Wickens, 2000), implying that multiple viewpoints may be necessary to support all possible tasks (Hollands, Ivanovic, & Enomoto, 2003). Other research also points to the benefits of interactive viewpoints in reducing spatial ambiguities associated with 3D displays (Sollenberger & Milgram, 1993; Thomas & Wickens, 2005) and providing visual momentum between consecutive displays (Hollands et al., 2003). Suggestions for future research include direct comparisons between the static split-screen and rotatable multi-mode display formats.

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REFERENCES

Alexander, A. L., & Wickens, C. D. (2004). Measuring traffic awareness in an integrated hazard display. *Proceedings HFES 48th Annual Meeting* (pp. 171-175). Santa Monica, CA: HFES.

Alexander, A. L., & Wickens, C. D. (2005). Flightpath tracking, change detection, and visual scanning in an integrated hazard display. *Proceedings HFES 49th Annual Meeting* (pp. 68-72). Santa Monica, CA: HFES.

Alexander, A. L., Wickens, C. D., & Hardy, T. J. (2005). Synthetic vision and the primary flight display. *Human Factors, 47*, 693-707.

Alexander, A. L., Wickens, C. D., & Merwin, D. H. (2004). Perspective and coplanar cockpit displays of traffic information. *International Journal of Aviation Psychology, 15,* 1-21.

Ames, L., & George, E. J. (1993). *Revision and verification of a seven-point workload estimation scale.* (Air Force Technical Publication AFFTC-TIM-93-01). Wright Patterson AFB, OH: Air Force Flight Technical Center.

Arthur, J. J., Prinzel, L. J., Kramer, L. J., Parrish, R. V., & Bailey, R. E. (2004). *Flight simulator evaluation of synthetic vision display concepts to prevent controlled flight into terrain* (NASA Technical Publication TP-2004-213008). Hampton, VA: NASA Langley Research Center.

Boeckman, K. J., & Wickens, C. D. (2001). *The resolution and performance effects of three-dimensional display rotation on local guidance and spatial awareness measures* (Technical Report ARL-01-4/NASA-01-3). Savoy, IL: University of Illinois, Aviation Research Laboratory.

Durso, F. T., & Gronlund, S. (1999). Situation awareness. In F. T. Durso (Ed.), *Handbook of applied cognition* (pp. 283-314). New York: John Wiley & Sons.

Endsley, M. R. (1995). Measurement of situation awareness in dynamic systems. *Human Factors, 37*, 65-84.

Federal Aviation Administration (FAA) Aircraft Certification Service (November, 1999). *Terrain awareness and warning system* (Technical Standard Order TSO-C-151a). Washington, D.C.: U.S. Department of Transportation.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index). In Hancock, P. A. & Meshkati, N. (Eds.), *Human mental workload* (pp. 139-183). Oxford, England: North-Holland.

Hollands, J. G., Ivanovic, N., & Enomoto, Y. (2003). Visual momentum and task switching with 2D and 3D displays of geographic terrain. *Proceedings HFES 47th Annual Meeting* (pp. 1620-1624). Santa Monica, CA: HFES.

Keppel, G. (1982). *Design and analysis: A researcher's handbook* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall, Inc.

Kuchar, J. K., & Hansman, R. J. (1993). Part-task simulation study of candidate terrain alerting displays. *SAE Aerotech '93 (paper 932570).* Costa Mesa, CA: SAE.

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

Merrick, V. K., & Jeske, J. A. (1995). *Flight path synthesis and HUD scaling for V/STOL terminal area operations*. (NASA Technical Memorandum 110348). Hampton, VA: NASA Langley Research Center.

Prinzel, L. J., Comstock, J. R., Glaab, L. J., Kramer, L. J., Arthur, J. J., & Barry, J. S. (2004). The efficacy of head-down and head-up synthetic vision display concepts for retro- and forward-fit of commercial aircraft. *International Journal of Aviation Psychology, 14*, 53-77.

Ramsey, J. W. (February, 2004). Synthetic Vision: No longer futuristic. *Avionics*, 12-20.

Schnell, T., Kwon, Y., Merchant, S., & Etherington, T. (2004). Improved flight technical performance in flight decks equipped with synthetic vision information system displays. *International Journal of Aviation Psychology, 14,* 79-102.

Schiefele, J., Howland, D., Maris, J., & Wipplinger, P. (2004). Human factors flight trial analysis for 2D/3D SVS. In J. G. Verly (Ed.), *Enhanced and Synthetic Vision 2004 (pp. 50 -60).* Bellingham, WA: International Society for Optical Engineering.

Scott, W.B. (2001, October 29). Synthetic vision systems: Ready for prime time? *Aviation Week & Space Technology*, 78-80

Smietanski, G., Lenhart, P. M., Kranz, S., & Mayer, U. (2000). In J. G. Verly (Ed.), *Enhanced and synthetic vision 2000 (pp. 87 -95).* Bellingham, WA: International Society for Optical Engineering.

Sollenberger, R., & Milgram, P. (1993). Effects of stereoscopic and rotational displays in a three-dimensional path-tracing task. *Human Factors, 26*, 33-48.

St. John, M., Cowen, M. B., Smallman, H. S., & Oonk, H. M. (2001). The use of 2D and 3D displays for shape-understanding versus relative-position tasks. *Human Factors, 43*, 79-98.

Thomas, L. C., & Wickens, C. D. (2005). *Effects of display dimensionality, conflict geometry, and time pressure on conflict detection and resolution performance using a cockpit display of traffic information* (Technical Report AHFD-05-04/NASA-05-1). Savoy, IL: Aviation Human Factors Division.

Vidulich, M. A., & Hughes, E. R. (1991). Testing a subjective metric of situation awareness. *Proceedings HFES 35th Annual Meeting* (pp. 1138-1142). Santa Monica, CA: HFES.

Wang, W., & Milgram, P. (2002). Viewpoint optimization for navigation using dynamic tether. *Proceedings HFES 46th Annual meeting* (pp. 2164-2168). Santa Monica, CA: HFES.

Wickens, C. D. (2000). The when and how of using 2-D and 3-D displays for operational tasks. *Proceedings of the IEA 2000/HFES 2000 Congress* (pp. 3-403-3-406). Santa Monica, CA: Human Factors and Ergonomics Society.

Wickens, C. D. (2003). Pilot action and tasks: Selection, execution, and control. In Tsang, P. S. & Vidulich, M. A. (Eds.), *Principles and practice of aviation psychology* (pp. 239-263). Mahwah, NJ, US: Lawrence Erlbaum Associates, Publishers.

Wickens, C. D., & Alexander, A. L. (submitted). Attentional tunneling and task management. *International Journal of Aviation Psychology*.

Wickens, C. D., Liang, C. C., Prevett, T., & Olmos, O. (1996). Electronic maps for terminal area navigation. *International Journal of Aviation Psychology, 6*, 241-271.

Wickens, C. D., Merwin, D. H., & Lin, E. L. (1994). Implications of graphics enhancements for the visualization of scientific data. *Human Factors*, *36*, 44-61.

Wickens, C. D., & Prevett, T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays. *Journal of Experimental Psychology: Applied*, *1,* 110-135.

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

Table 1

Experiment 1 Distribution of Events Where Pilots Failed to Avoid the Unexpected Event(Tower)

	ND Display Concept		
	2D Coplanar	3D Exocentric	Split-Screen
Total Events	4	4	2
Verbal Acknowledgment	3	0	1
No Response	1	4	1

Table 2

Experiment 2 Situation Awareness and Mental Workload Ratings by PFD and ND Format.

	Post-Run Subjective Ratings[1]		Paired Comparison Ratings[2]	
Display Combination	SA	WL	SA	WL
Baseline PFD + Baseline 2D Coplanar ND	4.04	2.96	0.022	0.2523
Baseline PFD + SVS 2D Coplanar ND	4.69	2.81	0.042	0.249
Baseline PFD + SVS Multi-Mode ND	5.46	2.77	0.1245	0.2319
SVS PFD + Baseline 2D Coplanar ND	5.5	2.58	0.1369	0.0888
SVS PFD + SVS 2D Coplanar ND	5.88	2.54	0.2297	0.076
SVS PFD + SVS Multi-Mode ND	6.35	2.27	0.4438	0.1005

Note. SA = situation awareness; WL = mental workload; PFD = primary flight display; ND = navigation display; SVS = synthetic vision system.

[1] = 7-point Likert scale. [2] = Geometric means.

Table 3

Experiment 2 Average Time Before Terrain Impact When Pilot Recognized CFIT Situation

	CFIT Scenario	
Display Combination	Departure (sec)	Approach (sec)
Baseline PFD + Baseline 2D Coplanar ND	14 (5.657)	62 (5.155)
Baseline PFD + SVS 2D Coplanar ND	27 (5.657)	54 (4.243)
Baseline PFD + SVS Multi-Mode ND	184 (26.870)	168 (15.556)
SVS PFD + Baseline 2D Coplanar ND	85 (1.414)	138 (8.485)
SVS PFD + SVS 2D Coplanar ND	72 (12.728)	122 (0.707)
SVS PFD + SVS Multi-Mode ND	237 (55.154)	342 (67.882)

Note. PFD = primary flight display; ND = navigation display; SVS = synthetic vision system.

Table 4

Experiment 2 Rank Order Summary for Situation Awareness, Mental Workload, and Controlled Flight Into Terrain Results

	PFD Condition		
ND Condition	Baseline	SVS	Total ND Score
Baseline 2D Coplanar ND	[6, 6, 6][1]	[3, 2, 3]	[9, 8, 9]
SVS 2D Coplanar ND	[5, 4, 5]	[2, 2, 4]	[7, 6, 9]
SVS Multi-Mode ND	[3, 4, 2]	[1, 1, 1]	[4, 5, 3]
Total PFD Score	[14, 14, 13]	[6, 5, 8]	

Note. PFD = primary flight display; ND = navigation display; SVS = synthetic vision system.

[1] = Rank order for each of the dependent variables (SA, workload, CFIT response). Thus, a [6, 6, 6] indicates that the display condition was worst on all variables out of all 6 possible display combinations. Conditions essentially equivalent to one another have been assigned the same rank.

FIGURE CAPTIONS

Figure 1. Experiment 1 navigational display formats: (a) 2D coplanar, (b) 3D exocentric, and (c) split-screen views. Screenshots show the actual experimental set-up consisting of the tunnel-in-the-sky PFD in the upper left and the ND on the right. PFD = primary flight display; ND = navigation display.

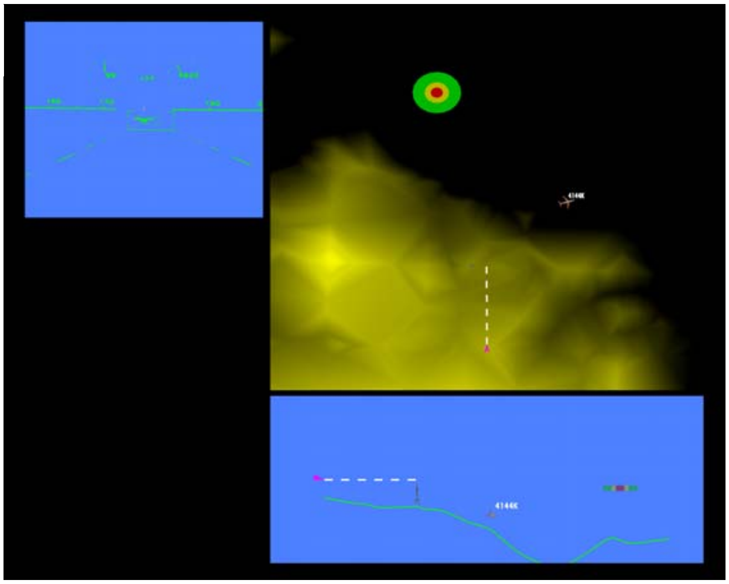
Figure 2. Experiment 1 mean accuracy of terrain and flight parameter probes by display type.

Figure 3. Experiment 2 display formats: (a) non-SVS PFD, (b) SVS PFD, (c) SVS 2D coplanar ND, and (d) non-SVS 2D coplanar ND. SVS = synthetic vision system; PFD = primary flight display; ND = navigation display.

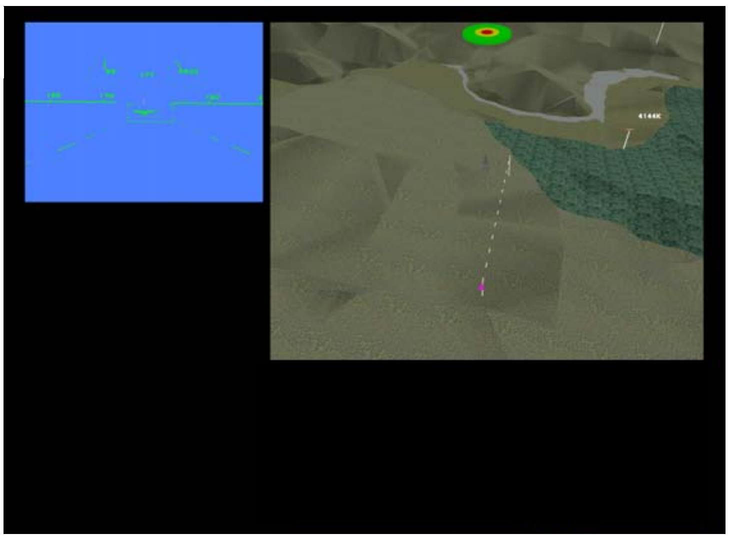
Figure 4. Experiment 2 SVS 3D Multi-Mode ND concept for “animate.” SVS = synthetic vision system; ND = navigation display.

Figure 5. Experiment 2 SVS 3D Multi-Mode ND concept for “perspective.” SVS = synthetic vision system; ND = navigation display.

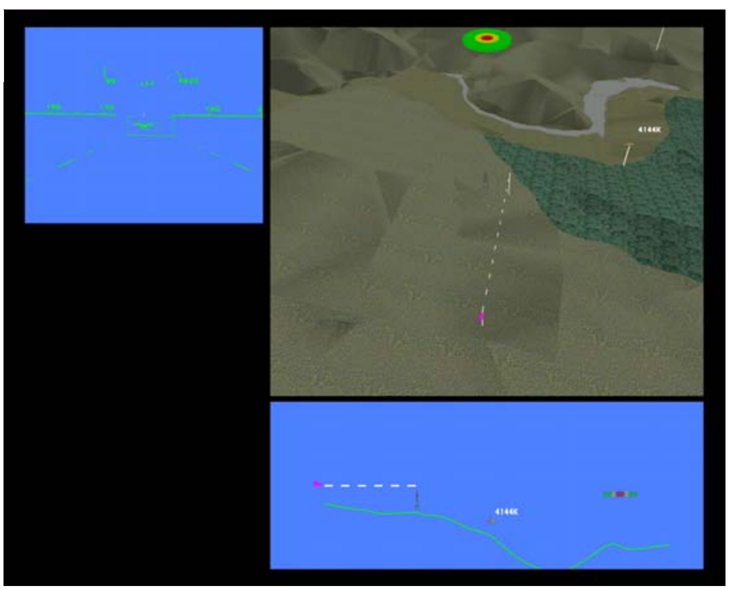
(a)

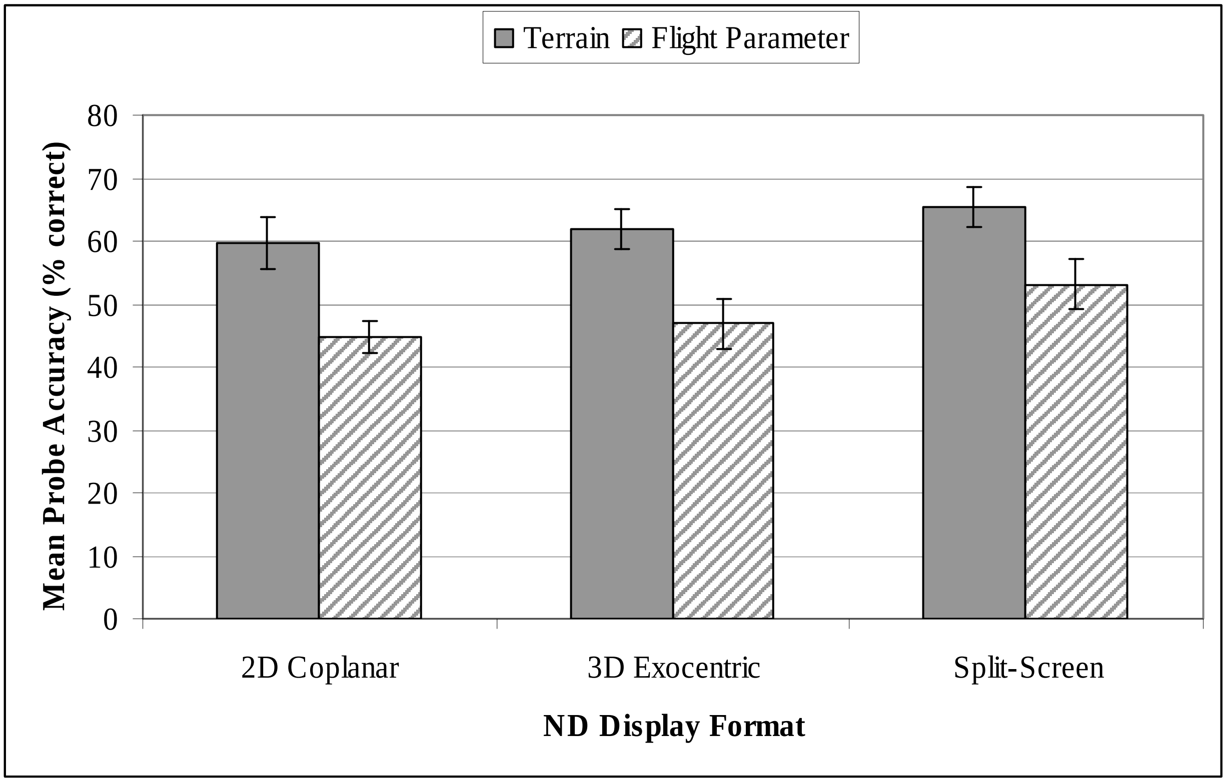


(b)

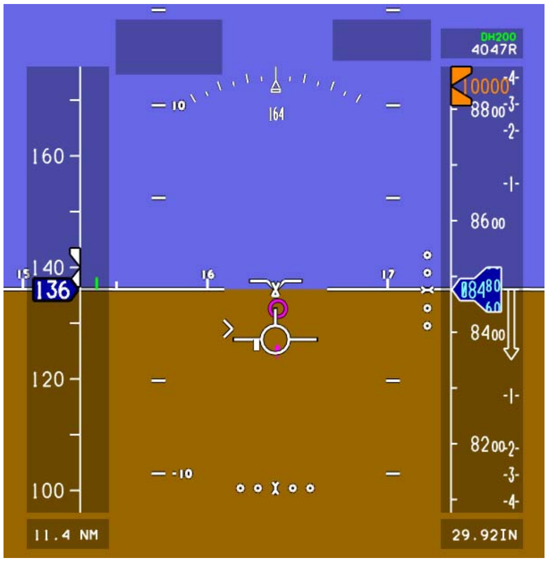


(c)




Terrain
Flight Parameter
Mean Probe Accuracy (% correct)
80
70
60
50
40
30
20
10
0
2D Coplanar
3D Exocentric
Split-Screen
ND Display Format

(a)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140
136
120
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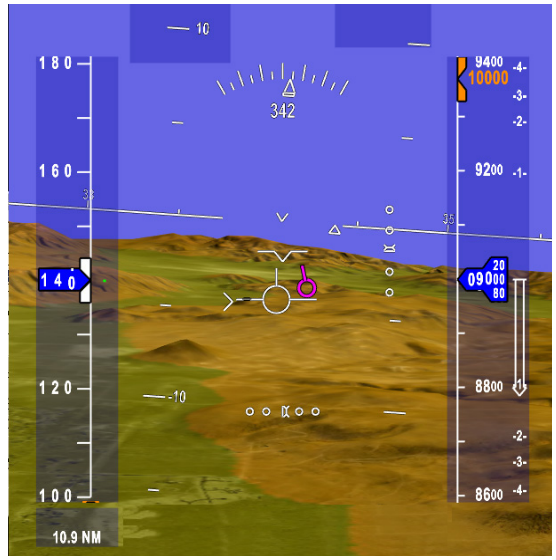
29.92IN

(b)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140
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100
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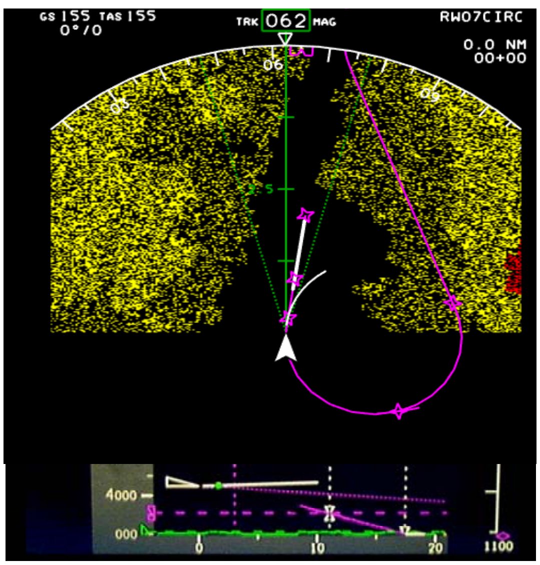
9400
10000
9200
8800
8600

(c)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RW07CIRC
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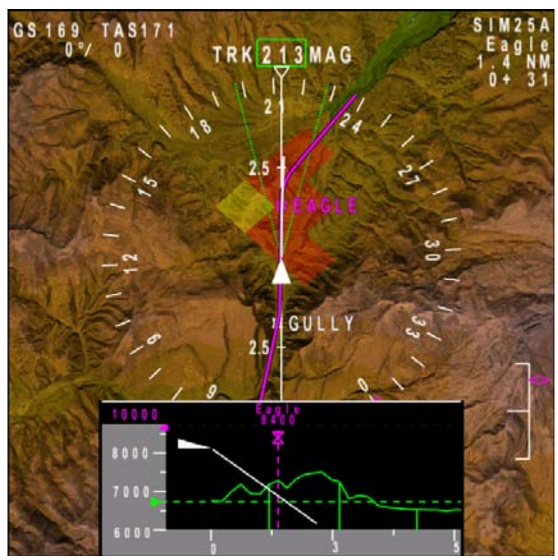
00+00
4000

(d)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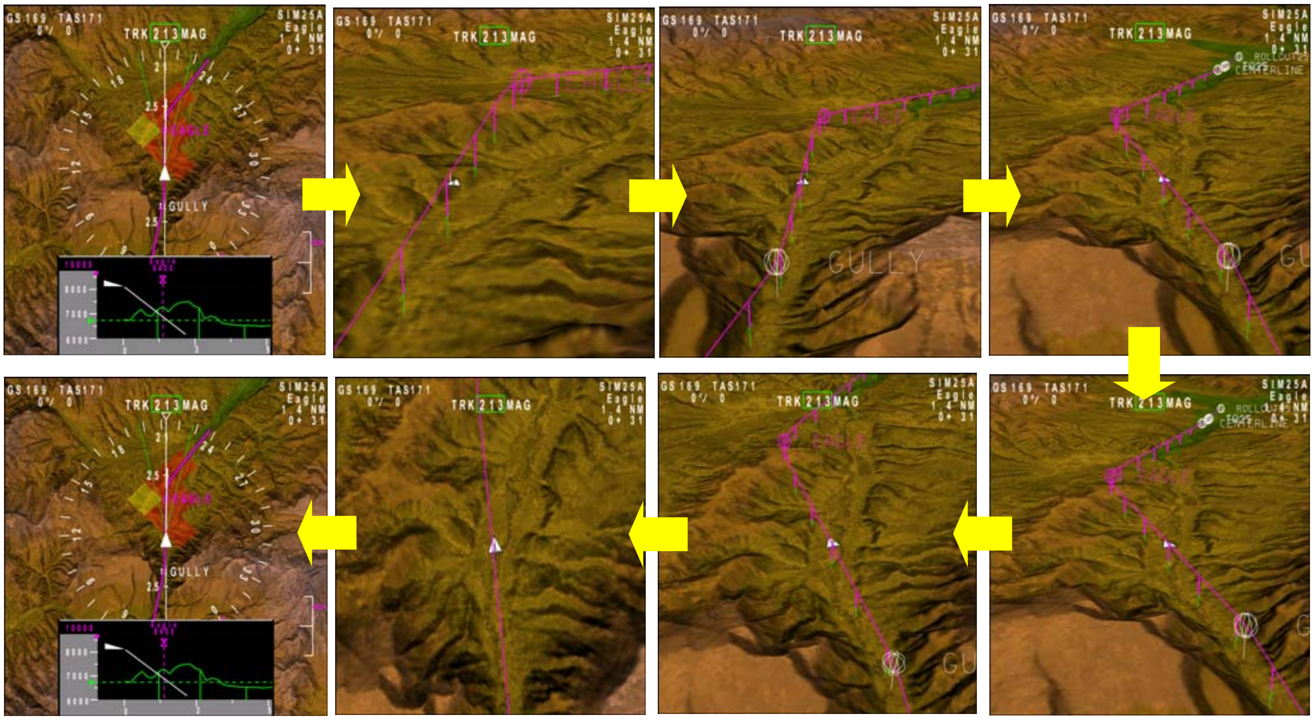
10000
8000
7000
6000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Eagle
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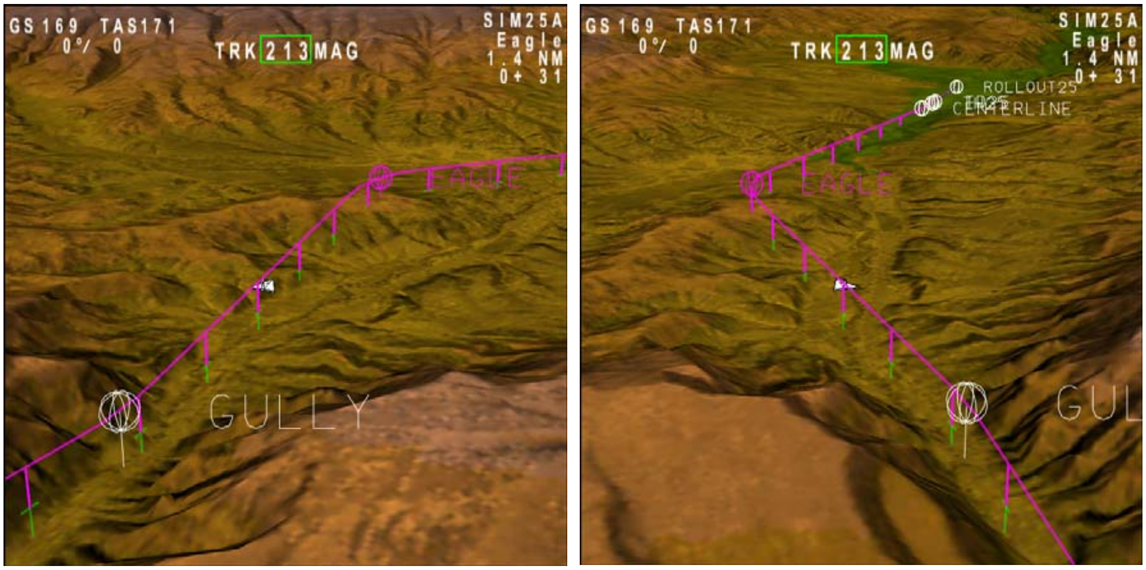
GS 169 TAS171
0°/ 0
TRK 213 MAG
SIM25A
Eagle
1.4 NM
0+ 31
EAGLE
GULLY
GS 169 TAS171
0°/ 0
TRK 213 MAG
SIM25A
Eagle
1.4 NM
0+ 31
ROLLOUT25
CENTERLINE
EAGLE
GUL

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