This paper was cleared by ASC- 03-2147 on 14 August 2003

TERRAIN AWARENESS & PATHWAY GUIDANCE FOR HEAD-UP DISPLAYS (TAPGUIDE); A SIMULATOR STUDY OF PILOT PERFORMANCE

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Abstract

This study was conducted to determine the flight technical performance, workload, and situation awareness of pilots flying a low-level curved approach to an austere airfield. This low-level ingress was flown under simulated night IMC with occasional breakouts into VMC. A total of 13 USAF pilots participated in this study. The simulated flights were performed in AFRL's Transport Aircraft Cockpit (TRAC) flight simulator. The simulator was configured using a C-17 aeromodel, and the head-up display showed either conventional commercial symbology (baseline) or one of two synthetic vision pathway configurations with wire-frame terrain. One of the synthetic vision configurations used rectangular pathway elements (pavers) and the other configuration used a square wire-frame tunnel. Speed and altitude information was provided either in the form of tapes or dials in all three configurations. A secondary task was introduced to test the displays under increased levels of workload. The secondary task involved authentication of a 5-digit code. In addition, the pilots had to deal with traffic targets to which they were alerted on the head-down display. The flight technical data clearly indicated that both pathway formats (paver and tunnel) are superior to the baseline symbology format. For all practical purposes the paver and tunnel formats performed equally well. Head-up guidance with terrain and pathway information provided much tighter flight technical performance than conventional head-up guidance. Thus, we conclude that the mission capability of the potential military users could be substantially increased.

Introduction

While perspective flight display concepts have been around for decades [1,2], it wasn't until fairly recently that computer and display technologies have become sufficiently powerful to support real-time perspective displays and terrain database depictions. Touted as potential benefits of perspective flight displays are economy, efficiency, noise abatement, safety, and reduced minimums. These last two benefits motivated the current study.

Safety and reduced minimums are related in that it is concern for Controlled Flight Into Terrain (CFIT) mishaps that drive flight minimums higher. As visibility declines due to weather, pilots are held to more conservative flight parameters with respect to altitude and spacing, presumably because in such reduced visibility conditions the pilot has lower situation awareness concerning both the terrain and air traffic. Conventional primary flight displays are not designed to take into account either the terrain or traffic when providing aircraft state information or flight guidance.

Recent technologies have improved the flow of terrain and traffic data to the flightdeck. Frequently, however, the additional data are provided on displays that are not integrated with the primary flight instruments, requiring that pilots scan several displays to obtain all of the relevant data. Using that data pilots must then generate and update their mental model of the aircraft attitude, geolocation, and relationship to other aircraft. While pilots do this all the time, they rely heavily on the strong percepts received through the visual channel. Lacking these percepts of the real world, the workload for mental model maintenance increases.

As indicated previously, perspective flight displays have been proposed to help compensate for the loss of situation awareness that comes with reduced visibility. One form of perspective presentation, synthetic vision, consists of a virtual world that is constructed from a database. Such a synthetic view possesses several desirable features, such as an infinite field of regard, a field of view limited only by display hardware, range up to and beyond the visible horizon, and the ability to depict surrounding terrain regardless of visibility conditions.

The Air Force Research Laboratory (AFRL) demonstrated significant improvements in flight performance for complex precision approaches [3]. This research compared a perspective display format with the MIL-STD HUD [4]. Further research has shown that pilot situation awareness (SA) is significantly increased with a perspective flight display [5]. At the same time, significant decreases in pilot workload while using perspective displays were reported. These improvements to SA and workload were associated with significant improvements in flight technical error [5]. Such improvements result from the similarities between the synthetic image and the real-world image that the pilot would have if there were no restrictions to visibility. Figure 1 provides an example of an image (in negative grayscale for print clarity) used in the present study.

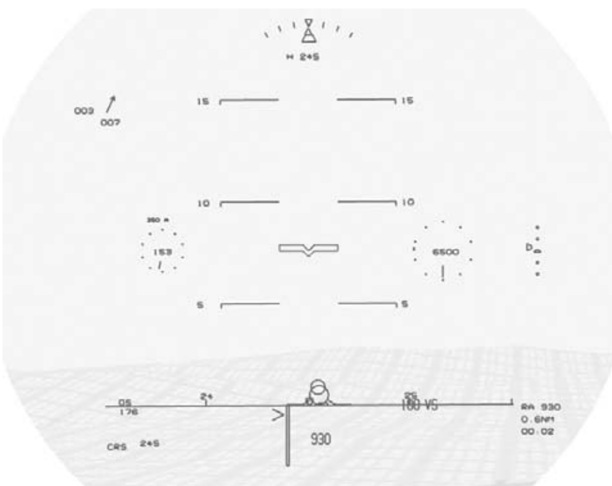

Figure 1. Baseline HUD Symbology with Synthetic Terrain

Not only does the perspective display provide a more intuitive presentation, but it also affords a "look ahead" (preview) much like a road does for an automobile driver. When approaching a turn, pilots see the direction and magnitude of the turn without having to interpret and chase a flight director symbol or consult a head-down moving map. "The presence of preview on the future trajectory and its constraints provide the pilot with the opportunity to anticipate changes in requirements, and thus allow him to stay ahead of the situation" [6]. By maintaining awareness of the "future trajectory and its constraints", pilots may more effectively evaluate errors and their impact on overall flightpath goals, correcting some errors and neglecting others.

Another element of the tunnel is flight guidance. To correct errors, traditional flight directors require pilots to track the symbol as it deviates from the center of the display. In a perspective flight display, a predictive flight path vector may be coupled with a speed-based predictor that is constrained to the pathway. The control activity consists of placing and keeping the flight path predictor symbol inside the speed-based predictor symbol. Where the two symbols meet is where the aircraft will be on path.

This study was the second of two simulation efforts. The two best formats from the first study (pavers and tunnel formats) were retained along with the better of the two baseline formats. The two pathway formats were modified slightly based on the findings of the first study [7].

Method

Participants

Thirteen pilots volunteered to participate in the study. All were Air Force pilots and 8 had HUD experience. Pilot experience ranged from 3650 hours to 21,130 hours with an average of 7086 hours. All pilots were male.

Experimental Design

Independent Variables. The study used a 3 x 2 x 2 within-subjects design. The three factors were HUD Symbology (HGS4000, Pavers, Tunnel), Synthetic Terrain (on/off), and Gauge type (dials/tapes). All scenarios were conducted under simulated IMC with 0' ceiling and 700' visibility. Figures 2 through 4 show the baseline symbology with tapes and synthetic terrain on, Pavers with tapes and no synthetic terrain, and Tunnel with tapes and synthetic terrain on, respectively. All of the levels of the factors, though not in all combinations are reflected in Figures 1-4.

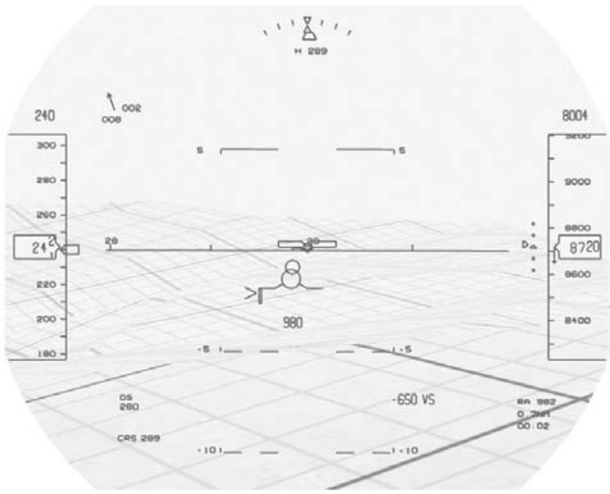

Figure 2. HGS 4000 with Synthetic Terrain

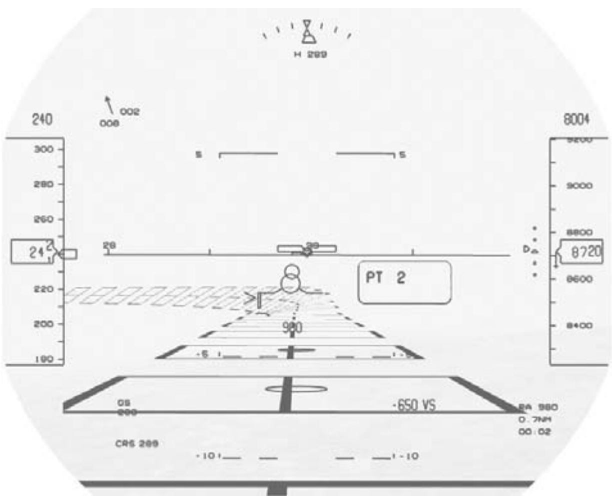

Figure 3. Pavers without Synthetic Terrain

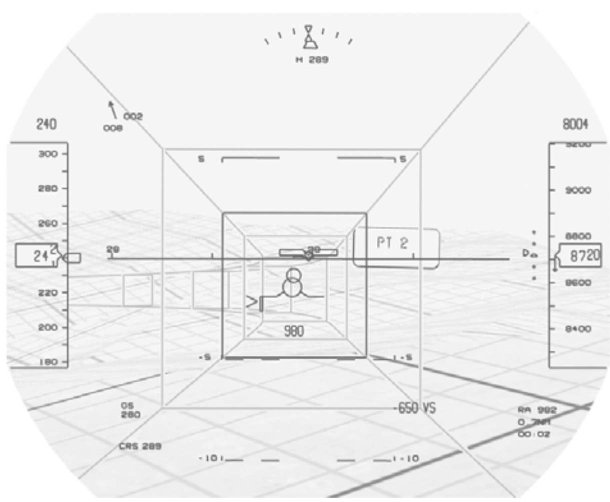

Figure 4. Tunnel with Synthetic Terrain

Dependent Variables. The dependent variables included flight technical error (lateral, vertical, and airspeed deviation) and situation awareness and workload measures. Derived from the FTE data were measures of the percentage of time spent flying off-path (total, lateral, and vertical). Percentage of time spent off path refers to the amount of time outside of the 300'x300' corridor that defined the commanded path. In the cases of the lateral and vertical measures, only the lateral and vertical components of the corridor were considered.

The situation awareness measure used was the Situation Awareness adaptation of the Subjective Workload Dominance technique (SA-SWORD), which is a subjective paired-comparison technique.

Two workload measures were used NASA TLX (NASA Task Load Index) and SWORD (Subjective Workload Dominance technique) [8]. The former is a rating technique with six subscales while the latter is a paired-comparison technique. NASA TLX ratings were taken during each trial, while SWORD and SA-SWORD measures were taken at the conclusion of the experiment.

Procedure

Participants received an introductory briefing, simulator and symbology familiarization, and then flew six practice flights of 8 minutes each to become familiar with the aircraft handling characteristics and the test procedures. Data collection consisted of 12 trials, one for each condition. In each trial, participants flew a low-level ingress scenario to a landing on an austere landing strip (60' x 3000'). Trials lasted approximately 9 minutes apiece, and NASA TLX was administered after each trial. Upon completion of all trials participants completed the SWORD and SA-SWORD instruments followed by a subjective questionnaire.

Participants were given a chance to study the route prior to each trial. The route was also displayed on a head-down moving map throughout the trial. A sample route is shown in Figure 5.

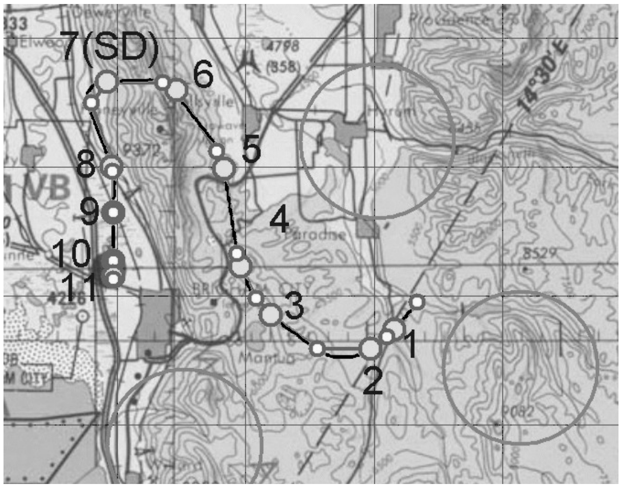

Figure 5. Sample route.

Apparatus

The Transport Aircraft Cockpit (TRAC) is a reconfigurable, three seat (pilot, copilot, flight engineer) transport aircraft cockpit research simulator (Figure 6). Only the pilot station was used in this study. Wide-angle collimating windows are used for displaying out-the-window scenes. The HUD formats were painted on the out-the-window scene and subtended a visual field of 30 degrees horizontal by 20 degrees vertical from the pilot eye point. Head down instrument formats were displayed using three 21" flat panel AMLCDs across the front of the cockpit. The head-down displays were 6" horizontal by 8" vertical. For this study, TRAC was configured with a C-17 aeromodel and the center C-17-style flight control stick.

Figure 6. Transport Aircraft Cockpit (TRAC)

Silicon Graphics Onyx Reality Engine 2 graphics computers generated out-the-window scene graphics and cockpit display formats. Visual scene generation occurred at rates varying from 25Hz to 30Hz depending upon scene complexity. Visual scene rendering was accomplished via in-house class libraries based on Paradigm's Vega library using Iris Performer, and Multigen-ModelGen was used for visual database development. Graphics programming was accomplished in C/C++ and Fortran languages.

Results

Flight Technical Error (FTE)

The flight technical error data collected consisted of airspeed, lateral, and vertical deviation from commanded values. Root Mean Square Error (RMSE) was calculated from the raw FTE values for statistical analysis.

The data were subjected to a repeated measures ANOVA. Both RMS Lateral and Vertical Track Error were significant ($\alpha = .05$) for HUD Symbology with F = 43.83 and F = 10.84, using the Geisser-Greenhouse conservative F test. Figures 7 and 8 show the RMS medians for lateral and vertical track error, respectively. No FTE variables were significant for the Gauge type or Synthetic Terrain factors.

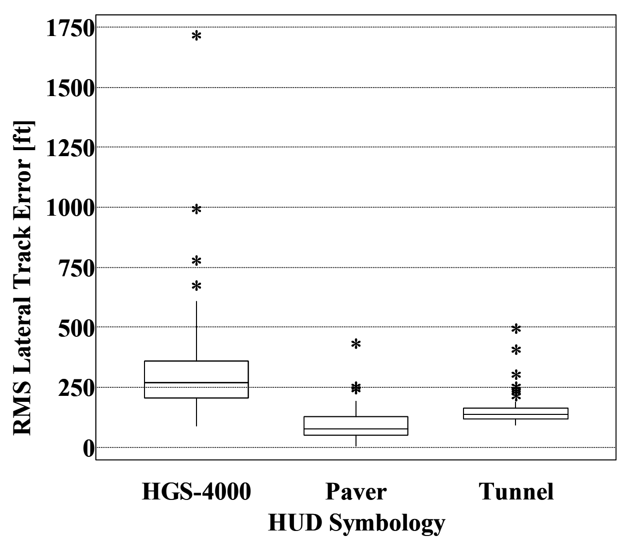

Figure 7. RMS Lateral Track Error

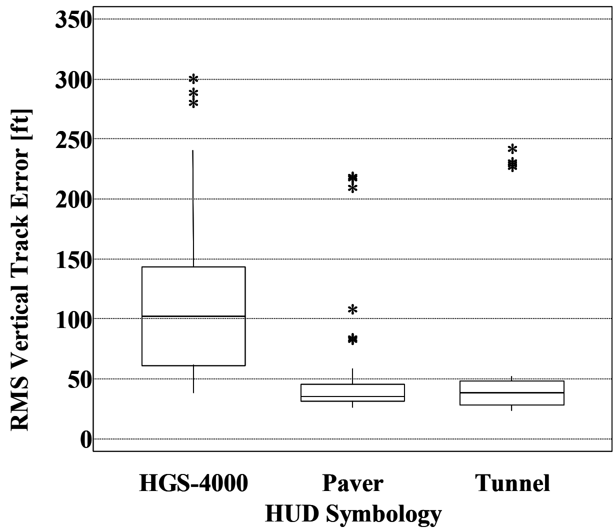

Figure 8. RMS Vertical Track Error

The percent of time spent off path was also significantly lower in the two pathway formats. Total percentage off path, percentage off lateral, and percentage off vertical were all significant at F = 103.35, F = 71.89, and F = 105.39, respectively. As expected, post hoc analysis showed that the differences were between the baseline and each of the two perspective formats. Figure 9 shows the medians for percentage of time off path for each HUD format. There were no significant differences between the two perspective formats on any of the FTE measures. As with the RMS variables, none of the derived off path variables were significant for the Gauge type or the Synthetic Terrain factors.

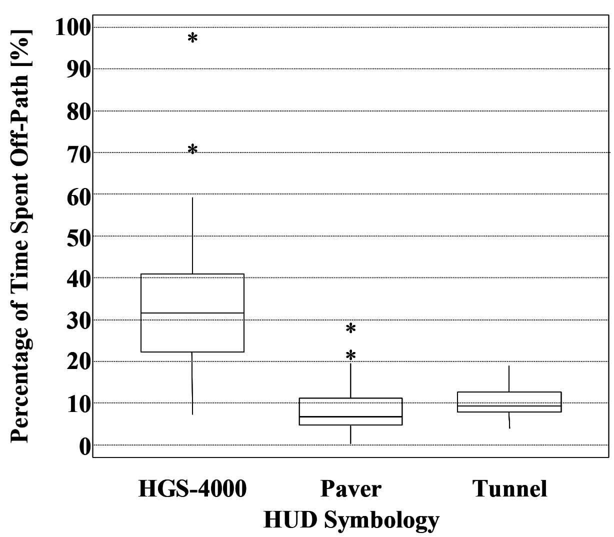

Figure 9. Percentage of Time Spent Off-Path

Situation Awareness (SA) and Workload

A repeated measures multivariate analysis of variance (MANOVA) was conducted for SA-SWORD, SWORD, and NASA-TLX scores. The multivariate F tests were significant for HUD Symbology and Synthetic Terrain. Gauge type was not significant. There were also no significant interactions.

Pairwise comparisons revealed that the significant mean differences on SA-SWORD, SWORD, and NASA-TLX occurred between the baseline symbology and each of the two perspective formats, with higher SA and lower workload associated with the perspective formats. Figures 10-12 show the medians by HUD format and Synthetic Terrain condition, for SA-SWORD, SWORD, and TLX, respectively. As with FTEs, there were no significant differences between the two perspective formats on any of the SA or workload measures.

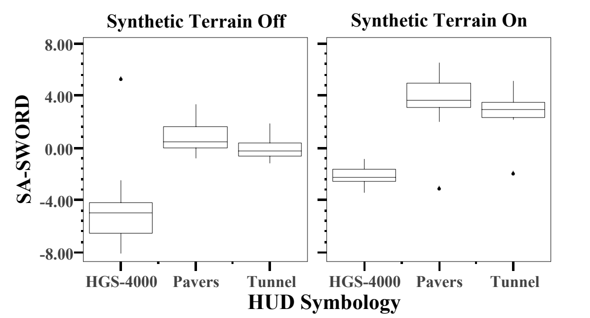

Figure 10. SA-SWORD Scores by HUD Symbology and Synthetic Terrain conditions

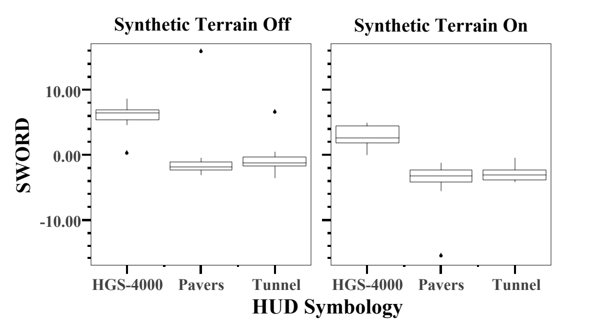

Figure 11. SWORD Scores by HUD Symbology and Synthetic Terrain conditions

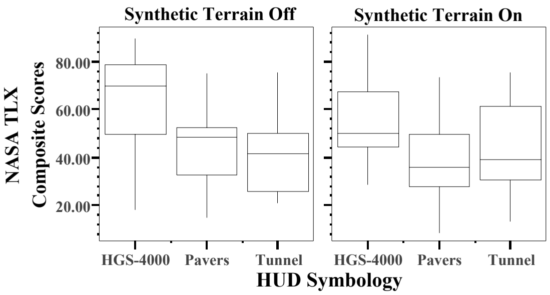

Figure 12. NASA TLX Scores by HUD Symbology and Synthetic Terrain conditions

For Synthetic Terrain, mean differences were significantly different for only SA-SWORD and SWORD. Higher SA and lower workload were associated with the 'on' condition of synthetic terrain.

Discussion

The flight technical error results replicated those of previous comparisons between traditional flight directors and perspective flightpath displays. Pilots were able to fly complex profiles using all three primary flight displays, but flew much more accurately with a perspective presentation. For lateral accuracy, errors were 1/3 (pavers) to ½ (tunnel) that of the baseline symbology and for vertical accuracy, errors were just under ½ (pavers and tunnel) that of the baseline symbology. In terms of time outside of the commanded corridor, the perspective presentations, as expected, allowed pilots to spend more time inside the corridor. The time outside the corridor ("off-path") using the baseline symbology was 4 times that of the paver format and 3 times that of the tunnel.

One interesting result was the seemingly equivalent performance of the two perspective presentations with respect to vertical error. The tunnel format completely defines and depicts the commanded corridor with precise perspective lateral and vertical guidance, while the pavers provide precise perspective lateral guidance and only general perspective vertical guidance. However, both formats provided the same glideslope deviation-style vertical deviation indicator. If pilots used the vertical deviation indicator to maintain the vertical aspect of the profile as effectively as the tunnel walls and ceiling, perhaps HUD clutter can be reduced by removing the walls and using a more traditional glideslope deviation-style indicator in conjunction with the reduced pathway format.

The synthetic terrain results replicated similar studies wherein the terrain had no significant effect on the flight technical errors, but did affect the self-report of SA and workload. As indicated, the synthetic terrain showed differences on SWORD and SA-SWORD, but not TLX. The two SWORDs were administered after all trials, while the TLX was administered after each trial. Thus, differences in the SWORD and TLX results may be due to changes in perceived workload over time, they may measure different facets of workload, or one may be more sensitive than the other.

The subjective questionnaire asked pilots to rate the utility of the baseline symbology, pavers, and tunnel formats, and the synthetic terrain on a scale of 1-7. "1" was "of no use" while "7" was "extremely useful". The average ratings for baseline symbology, pavers, tunnel, and synthetic terrain were 4.4, 6.8, 6.3, and 6.0, respectively. A number of pilots commented that the synthetic terrain was useful under many circumstances, but not "mission essential" when perspective flightpath guidance was present. As shown in prior research, and confirmed here, the synthetic terrain presentation does not appear to affect a pilot's ability to maintain the commanded flightpath, even though it appears to affect pilots' reported SA and workload. This performance result may be the source of pilots' opinions that terrain imagery is useful, but not essential.

Where pilots indicated that the terrain would be most useful is during large deviations from the commanded flightpath. In these cases, some commented, the terrain would allow for "instantaneous" SA about aircraft proximity to terrain as well as the rate of closure with terrain. That is, when they were outside of the "safe" corridor pilots expressed a need to expand the scope of their SA to include terrain so they could fly [virtually] visually, much as they would fly in Visual Meteorological Conditions (VMC).

These comments do not confirm the results of some studies wherein cognitive capture was reported [9,10] for pilots using some form of perspective display. Nor do they gainsay other studies that report no differences between on- and off-path SA [11, 5]. Rather, these comments highlight the strong trust that pilots place in the command guidance when flying in IMC. This trust is only likely to grow as the computing and display capabilities installed on flight decks increase.

The flight technical data clearly indicated that perspective formats (in this case, pavers and tunnel) are superior to the baseline symbology format. For all practical purposes the two perspective formats performed equally well. Head-up guidance with synthetic terrain and pathway information provided much tighter flight technical performance and improved SA and workload than conventional head-up guidance. Thus, we conclude that mission capability and terminal area operations could be substantially improved.

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