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The Effect of Terrain-Depicting Primary-Flight-Display Backgrounds and Guidance Cues on Pilot Recoveries from Unknown Attitudes

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THE EFFECT OF TERRAIN-DEPICTING PRIMARY-FLIGHT-DISPLAY BACKGROUNDS AND GUIDANCE CUES ON PILOT RECOVERIES FROM UNKNOWN ATTITUDES

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A study was conducted to evaluate the effects of primary flight display (PFD) terrain depictions on pilots' performance of recoveries from unknown attitudes. Forty pilots participated in the study, each group of eight using a different display format. The five conditions consisted of combinations of terrain depiction (none, full-color terrain, brown terrain) and guidance indications (pitch and roll arrows). Participants flew baseline trials in the Advanced General Aviation Research Simulator using a common electronic attitude indicator and then performed recoveries from unknown attitudes (UARs) using one of the PFD formats. Performance measures included initial response time, total recovery time, primary reversals, and secondary reversals. No significant effects of the primary independent variables were found on any of the performance measures. Posttest interviews indicated the participants preferred the directional-arrow indicators and had no preference for or against the presence of terrain depictions during UARs, focusing primarily on the zero-pitch line as a reference. It was concluded that the specific terrain representations examined did not pose a hazard to the identification of and recovery from unknown attitudes as long as a zero-pitch line of sufficient discriminability (contrast and size) to all backgrounds was present.

Background

Electronic Flight Instrumentation Systems (EFIS) are becoming more available daily, and a major component of this type of system is the Primary Flight Display (PFD). While PFDs initially depicted attitude and flight-guidance information, they evolved to include forward-looking perspective-views of both guidance information (Beringer, 2000) and of the outside world (Wickens, Haskell, & Hart, 1989; Alter, Barrows, Jennings, & Powell, 2000), often generated from terrain databases. This type of display is presently appearing in systems submitted for certification in general aviation (GA) aircraft, and a number of questions have been raised regarding the effects of various design features on different aspects of pilot performance. In lieu of empirical data on the effects of manipulations of specific design parameters, certifiers have had to rely upon general guidelines. This has sometimes resulted in the adoption of very conservative criteria for the certification and use of these particular displays.

Some data relevant to the GA environment have become available that may be useful for determining what the allowable range of variation in design parameters can be. The parameters that are of present interest include: size of the display, angular representation of the outside world (field of view), display resolution, terrain-feature resolution, use of color, style of terrain representation, definition of display clutter, and effects of the above on the performance of both routine and non-routine flight tasks.

A series of studies was performed at the NASA Langley Research Center examining the use of various terrain representations and pilot preferences for various fields of view and styles of depiction (Prinzel et. al., 2003; Arthur, Prinzel, Kramer, Parrish, & Bailey, 2004). Some agreement was found with previous studies concerning preference for field of view (30 degrees), and some assessment was made of pilot navigation performance and basic precision maneuvers, concluding that fewer errors were committed and terrain awareness was enhanced with the displays. One issue that was not addressed, however, was the recovery from unknown or unusual attitudes. This specific concern was addressed in one certification process by requiring that the terrain depiction be removed from the PFD when the aircraft exceeded certain pitch or roll criteria because of a concern that the presence of the terrain might cause confusion or somehow interfere with a successful recovery. However, there were no empirical data to indicate what role, positive or negative, the terrain depiction might play in the recoveries.

Thus, a study was conducted to examine how terrain depiction might either impede or enhance recoveries from unknown attitudes, including the display content (type of terrain; flat, mountainous) at the time of the recovery as well as the possible ameliorating effect of providing recovery guidance arrows (Gershzohn, 2001). Questions of specific interest were: (1) would pilots recover to the terrain horizon rather than the zero-pitch line if the two were different, as would be seen in mountainous terrain; (2) if this behavior were observed, could it be ameliorated by positive guidance cues; and (3) would the coloration of the terrain presentation affect performance?

Method

Experimental Display Formats

The five display formats consisted of combinations of terrain depiction (none, full-color terrain, brown terrain) and guidance indications (pitch and roll arrows).

Baseline ADI. The no-terrain display consisted of a traditional attitude indicator (blue sky, brown ground) with airspeed, altitude and vertical speed presented in tape format along the left and right edges of the display with a compass card at the bottom of the display (Figure 1).

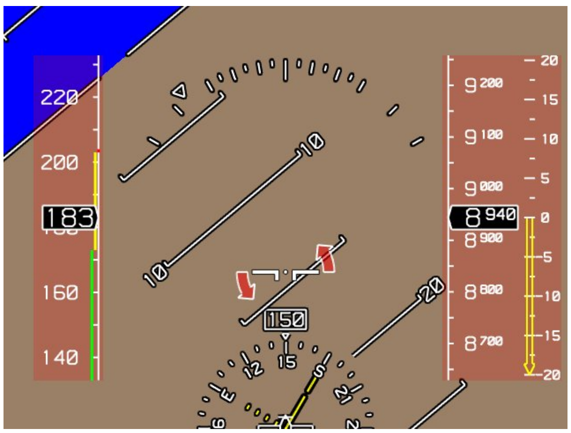

Figure 1. *EADI with roll-recovery arrow shown.*

Guidance Arrows. The second display was identical to the first but had guidance arrows for pitch and roll recovery. Pitch arrows were linear (Figure 2) and appeared when the aircraft attitude was greater than 13 degrees up or down and disappeared when the aircraft was within 5 degrees of zero pitch, pointing from the aircraft symbol to the horizon. Roll arrows (Figure 1) were curvilinear (arc form) and appeared when the aircraft exceeded 25 degrees of bank and disappeared when the aircraft was within 10 degrees of zero bank, pointing from the plane of the wings to the horizon line. For pitch-down attitudes, the roll-command arrow took precedence over the pitch-command arrow. For pitch-up attitudes, the priority was reversed.

Full-color terrain. The third display was similar to the first except that the brown portion of the display was replaced with photo-realistic terrain (full-color; shown in both Figures 2 and 3). The terrain was generated using variable-sized polygons that had photo-realistic texture applied to them to create the out-the-window scene. This is somewhat different from the terrain-creation methods used by other terrain-depicting displays, where equal-sized polygons, or even squares, are used to create the terrain skin and a more generic type of texture is applied. The fourth display was the same as the third display, but it included the guidance arrows.

Figure 2. *PFD with pitch-recovery arrow shown.*

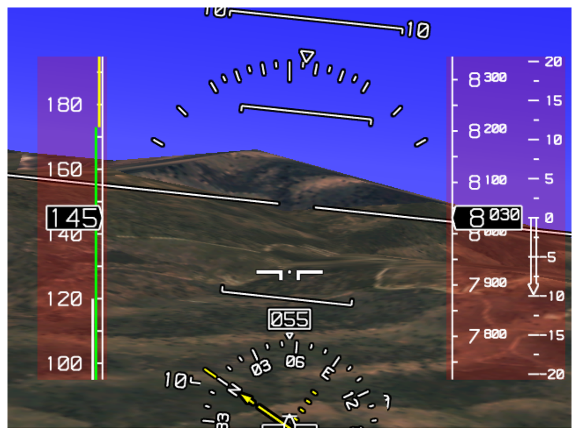

Figure 3. *PFD full-color terrain depiction with mountain in view.*

Brown terrain. The final display was similar to the first, but the "ground" portion of the display was replaced with brown (polygon-based) terrain imagery (Figure 4). The variable-sized-polygon structure im-

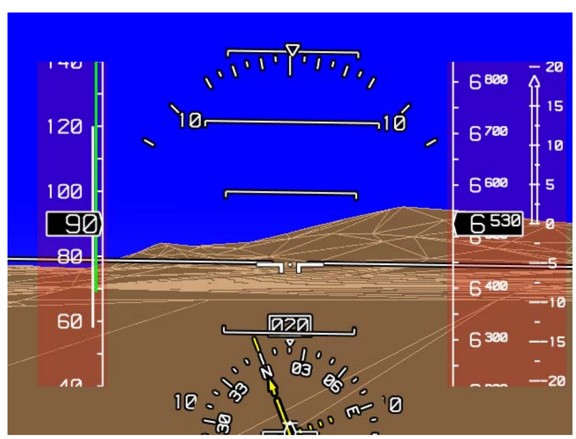

Figure 4. *PFD brown-only terrain depiction with mountain in view.*

parted more apparent texture to this uniform-brown depiction than one sees in brown-only depictions using a uniformly sized polygon/square as the basis for terrain-contour construction. Figures 3 and 4 show similar views of a mountain in the full-color (Figure 3) and the brown-only (Figure 4) modes for comparison.

Horizon line. The horizon line was constructed such that it would have high contrast against the vast majority of possible backgrounds. This is not normally an issue with traditional head-down attitude direction indicators (ADIs), as the horizon on these displays is represented as the boundary between differently colored filled areas, often with a line of a different color between them. It is also possible to use a single-color line (as long as it conforms to MIL-STD-1787C, 5.1.2.1; Horizon reference; the standard does not deal specifically with terrain-depicting PFDs, nor does the soon-to-be-released SAE Aerospace Recommended Practice document on perspective displays deal specifically with this horizon-line issue) in terrain-depicting displays where the ground and sky representations are of known uniform colors (i.e., the Chelton display uses a uniformly brown ground and blue sky).

However, displays expected to portray a realistically colored terrain representation or an enhanced depiction having multiple, albeit unrealistic, hues require a horizon line having components (bands) that will contrast against many hues. To this end, a horizon line was employed consisting of three two-pixel bands alternating black-white-black. This was consistent with horizon lines used in other full-color terrain display experiments and with recommendations made to a certification applicant who was submitting a colored-terrain PFD for consideration.

The original display was created at a resolution of 640 by 480 pixels but presented on a 1280 by 1024 flat-panel display in the cockpit using 800 by 600 pixel resolution inset in the upper right portion of the display. This produced a PFD image approximately 7.5 inches wide by approximately 5.6 inches tall (a 9.38 diagonal) and increased the apparent horizon-line thickness from 6 pixels to about 8 pixels. Seen from the pilot's viewing distance of 26 inches, the active display subtended 16.4 degrees horizontally and 12.3 degrees vertically, with the three-banded horizon line subtending approximately 9.85 minutes of arc vertically (each band about 3.3 minutes of arc).

Experimental Design

A two-factor crossed design was employed, with terrain background (full-color; present or absent) and guidance arrows (present or absent) as the *independent variables*. The supplemental condition, brown-only terrain, was added after contribution of guidance arrows had been assessed. Dependent variables included initial response time (IRT; time to first control input), total recovery time (TRT), primary control-input reversals (first response in wrong direction), and secondary control-input reversals (subsequent response in wrong direction).

Two *sampling variables* were added to obtain more representative data from across a wider range of display indications. *Terrain depiction at roll-out* was planned using lead headings based upon expected roll-out times (obtained in pretest) and presented terrain either (1) higher than the zero-pitch reference line (mountainous background) or (2) terrain lower than the zero-pitch reference line (level terrain). *Attitude at recovery onset* was also varied so that trials included combinations of pitch (+20, 0, and –15 degrees) and bank (60 degrees left, 0, 60 degrees right) excepting, of course, the zero-zero condition.

Three supplemental trials were also added for approximately the last 7 pilots in each group. These trials included a near-mountains trial (terrain horizon significantly above zero-pitch line), an inverted trial (by sponsor request), and a 40-degree displayed field-of-view trial (to assess whether previously expressed pilot preferences for a wider displayed field of view was linked with any improvement in performance with a wider field).

Equipment and Participants

Data were collected using the Advanced General Aviation Research Simulator (AGARS) in the CAMI Human Factors Research Laboratory. The simulator was configured to represent a Piper Malibu; the participants all flew in the left seat. The PFD was represented on a flat-panel, high-resolution LCD mounted on the instrument panel directly in front of the participant. The PFD was presented at the size of an approximately 7-inch diagonal measurement within a larger hardware-display area, and the image showed approximately 30 horizontal degrees of the outside world.

The display layout was similar in many respects to one already certified for GA use. The experimenter-pilot (EP) flew from the right seat with a repeater display of the PFD mounted atop the glare shield. The out-the-window view represented a hard-IFR situation with no environmental visual cues visible in the uniformly gray fields. Performance data were recorded digitally, with supplemental audio and visual data recorded on DVD from two video sources (cockpit-wide view and PFD inset) and all audio sources (participant, EP, data-collection experimenter).

Participants were 40 GA pilots (38 male, 2 female) recruited from the local community, 8 assigned to each of the 5 display conditions. Age and overall flight hours were balanced across groups as participants entered the experiment (not assigned a priori from a known sample). Ages ranged from 19 to 57 years. All were at minimum certified as Private Pilot, while many were instrument-rated and a number were flight instructors; initial license year ranged from 1972 to 2004. Each group had a similar distribution of pilot categories and hours of experience represented, with total pilotage time (as PIC in VMC) ranging from 11 to 11,700 hours. Total flight times ranged from 50 to 13,000 hours.

Procedures/tasks

After completing the informed consent form and filling out a brief pilot experience questionnaire, participants were briefed concerning the display they would be using and instructed that recoveries would be from unknown attitudes. Their task was to recover to a zero-pitch, zero-bank attitude, regardless of altitude or airspeed, as the EP would configure the aircraft such that performance was usually within the operating envelope (primary interest was in participant ability to interpret the display and determine when a level attitude had been restored). They were then ushered into the AGARS, where they were further familiarized with the display and with the simulator. They then donned a headset and a visor so that direct vision of the display would be obscured when they were in the head-down preparatory position for the recovery.

Each pilot then took off from Albuquerque (ABQ) and climbed out to the north into IFR conditions. All pilots performed 8 warm-up (baseline) recovery maneuvers, using the basic electronic attitude-direction indicator (EADI) on the PFD, to familiarize them with the performance of the AGARS and with the dynamic functioning of the PFD. Each trial began with the participant in the head-down position and hands off of the controls. The EP then placed the simulator into the required attitude and heading for that trial, using predetermined airspeed, altitude, and heading criteria that had been rehearsed (the same EP performed all unknown-attitude entries for all participants). The EP gave a preparatory "Ready" about two seconds before handing over the controls, "and" about one second before, and "Go!" at the transfer of controls to the participant. After completing the warm-up trial, the participant flew the simulator back to ABQ and performed a full-stop landing. At this time, the display format was changed and the procedure repeated.

Experimental trials consisted of 16 recovery maneuvers (defined by combinations of the sampling variables described earlier), using the PFD that was assigned to the participant. Two different orders of the combinations of sampling variables (attitude at onset and terrain seen at roll-out) were used and balanced across the groups. Accordingly, half of the headings were selected to end the recovery facing mountainous terrain higher than the aircraft altitude and half were selected to end the recovery facing terrain lower than aircraft attitude. Pilot recovery times and initial response times were recorded for each trial. A recovery was considered complete when the aircraft reached ±2.5 degrees of pitch and ±5.0 degrees of bank and was able to maintain those values for 3 seconds, although trials were generally allowed to continue for a few seconds after these criteria had been reached to guarantee stability in the recovery.

The supplemental trials described earlier in the Methods section were added to the end of the session in the order of (1) near-mountains trial, (2) inverted trial (the nose slightly above the horizon and a bank angle of approximately 165 degrees), and (3) expanded FOV trial. The participant then flew the simulator back to ABQ for a full-stop landing. Participants completed a posttest set of questionnaires regarding their subjective assessment of the displays (one was also administered after the warm-up trials), went through a posttest interview, and provided both solicited and unsolicited responses/opinions.

Results

Group Equivalence

Demographic variables. Groups were compared both on the basis of the distributions of experience (hours), categories of license/ratings, and age. Mean age by group ranged from 26 to 28 years of age with no significant differences between groups. The distributions of hours of experience and licensing/rating categories were also similar enough between groups that any differences found in performance were unlikely to be a result of those variables.

Baseline performance. Analysis of recovery times for the baseline trials showed that the groups initially differed in their performance but were performing equivalently (no significant differences) by the last two trials (see Figure 5). This finding suggests that all groups had attained a roughly equivalent level of performance prior to entering the experimental trials.

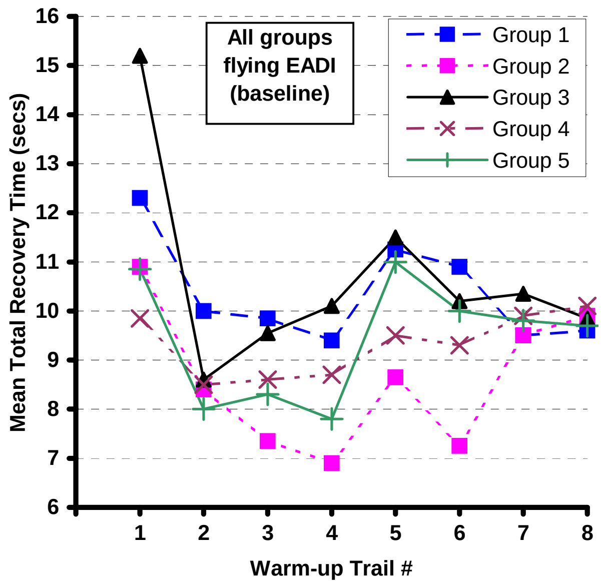

Figure 5. *Mean recovery time by group and serial trial for baseline warm-up using the basic electronic attitude direction indicator (EADI).*

Performance Variables

Recovery times. Multivariate Analysis of Variance indicated there were no significant differences between the display configurations for either (IRT, TRT) of the response-time variables. Figure 6 presents mean TRTs by maneuver and display format.

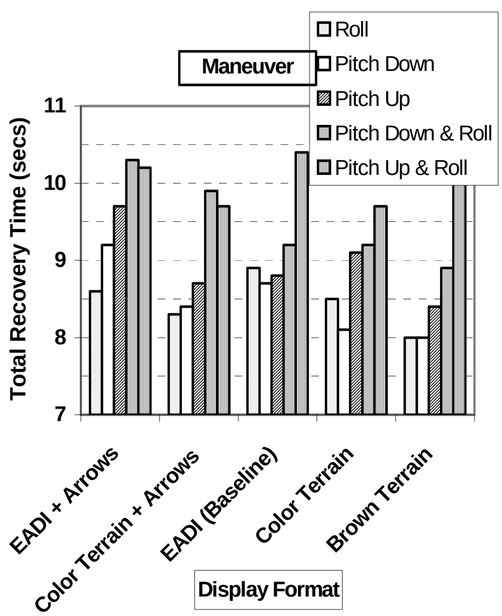

Figure 6. *Mean TRT (seconds) by maneuver and display format.*

To illustrate times actually required to complete a recovery, pitch-roll TRTs averaged around 10 seconds, whereas roll-only recoveries averaged about 8.5 seconds. Pitch-only recoveries averaged approximately 8.6 to 9.0 seconds. Univariate analyses were conducted to determine if type of maneuver resulted in any significant differences between display types. Again, no significant differences were found between displays and type of maneuver for either of the response-time measures. (Means by maneuver and display format are presented in Figure 6.)

Control reversals. Examination of control reversals, defined as movements in the opposite direction of that required for the recovery, indicated that were only three clearly identifiable primary control reversals in the nearly 800 trials. There were no secondary reversals (initial response in correct direction; subsequent control movement opposite to input required). Recovery times for the three reversals were not notably different from those of other trials. Thus, reversals did not appear to be a factor, regardless of the format of display used.

Supplemental trials. Analyses were conducted for performance variables on each of the three supplemental trials. No significant differences were found for the 40-degree FOV trials, the inverted trials, or the near-mountains trials. Only one of the participants showed any indication of holding the nose of the aircraft above the zero-pitch line in the near-mountain trial rather than completing the recovery.

Questionnaires and Posttest Interviews

Pilots indicated, when interviewed, that they were focusing their attention on the relatively prominent zero-pitch line, and did not regard the terrain depictions as significant contributors to their recovery task. The directional-guidance arrows produced a positive qualitative response from the participants, although there was no apparent performance difference. Participants also expressed a relatively uniform preference for the terrain-depicting displays in general. A few individuals expressed a preference for the 40-degree FOV, stating that it allowed them to "see more." The one individual who had kept the nose of the simulator slightly higher than zero pitch for the near-mountain trial clarified, in the posttest interview, that he had been concerned about the mountain and had kept the nose a little high in preparation for a possible climb over the mountain, having no indeterminacy about the zero-pitch line location.

Summary and Conclusions

It appears, for this specific task, that the presence of a zero-pitch line of the contrasting components specified (white with black borders) and of the thickness and extent specified (9 minutes of visual arc and running the entire width of the display area) allows pilots to adequately discern the zero-pitch reference from other features on the display and to perform recoveries from unknown attitudes without regard to the specific format of perspective terrain display used. It also appears that the directional-guidance arrows, despite being positively received by the participants and having been demonstrated to be useful in a previous experiment, did not have an appreciable effect on recovery times. The frequency of occurrence of reversals was too low to allow any conclusion to be drawn about the possible effectiveness of guidance arrows in that regard.

Given the previous findings (indicating enhanced terrain awareness attributable to terrain depictions), combined with the lack of detrimental effects found in this study relative to recoveries from unknown attitudes, there would appear to be few significant obstacles to the implementation of this type of PFD for general aviation use. Caveats to be observed, however, would be that (1) similarly constructed terrain depictions are used, (2) the zero-pitch line is clearly differentiable from the terrain and sky depictions regardless of the type of background and (3) that the direction of off-display pitch-line locations are clearly indicated.

Acknowledgments

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