SYNTHETIC VISION SYSTEM COMMERCIAL AIRCRAFT FLIGHT DECK DISPLAY TECHNOLOGIES FOR UNUSUAL ATTITUDE RECOVERY

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A Commercial Aviation Safety Team (CAST) study of 18 worldwide loss-of-control accidents and incidents determined that the lack of external visual references was associated with a flight crew's loss of attitude awareness or energy state awareness in 17 of these events. Therefore, CAST recommended development and implementation of virtual day-Visual Meteorological Condition (VMC) display systems, such as synthetic vision systems, which can promote flight crew attitude awareness similar to a day-VMC environment. This paper describes the results of a high-fidelity, large transport aircraft simulation experiment that evaluated virtual day-VMC displays and a "background attitude indicator" concept as an aid to pilots in recovery from unusual attitudes. Twelve commercial airline pilots performed multiple unusual attitude recoveries and both quantitative and qualitative dependent measures were collected. Experimental results and future research directions under this CAST initiative and the NASA "Technologies for Airplane State Awareness" research project are described.

Recent accident and incident data suggests that Spatial Disorientation (SD) and Loss-of-Energy State Awareness (LESA) for transport category aircraft are becoming an increasingly prevalent safety concern in all domestic and international operations (Bateman, 2010). SD is defined as an erroneous perception of aircraft attitude that can lead directly to a Loss-Of-Control (LOC) event and result in an accident or incident. LESA is typically characterized by a failure to monitor or understand energy state indications (e.g., airspeed, altitude, vertical speed, commanded thrust) and a resultant failure to accurately forecast the ability to maintain safe flight. The leading consequence of LESA is aircraft stall.

A CAST study of 18 loss-of-control accidents determined that a lack of external visual references (i.e., darkness, instrument meteorological conditions, or both) was associated with a flight crew's loss of attitude awareness or energy state awareness in 17 of these events. The Airplane State Awareness Joint Safety Analysis (JSAT) and Implementation Team (JSIT) reports (CAST, 2014a; CAST, 2014b) recommended that, to provide visual cues necessary to prevent LOC resulting from a flight crew's SD/LESA, manufacturers should develop and implement virtual day-VMC display systems, such as synthetic vision systems. In support of this implementation, CAST requested the National Aeronautics and Space Administration (NASA) to conduct research to support definition of minimum requirements for virtual day- VMC displays to accomplish the intended function of improving flight crew awareness of airplane attitude; see CAST Safety Enhancement 200 (SE-200) entitled, "Airplane State Awareness – Virtual Day-VMC Displays".

Airplane State Awareness – Virtual Day-VMC Displays

A NASA project, entitled Technologies for Airplane State Awareness (TASA), has been developed which, in part, addresses the CAST request for research to support manufacturer design and implementation of virtual day-VMC displays that will enable the necessary visual cues to prevent SD/LESA and aid in detecting unusual attitude and performing recovery. In large transport aircraft, an unusual attitude is operationally defined as a nose-up pitch attitude greater than 25 degs, a nose-down pitch attitude greater than 10 degs, a bank angle greater than 45 degs or flight within these parameters but with airspeeds inappropriate for the conditions.

Virtual Day-VMC Displays

Virtual day-VMC displays are intended to provide similar visual cues to the flight crew that are available when outside visibility is unrestricted (i.e., observed under VMC). Their intended function is improve continuous attitude, altitude, and terrain awareness, reducing the likelihood of unstable approach, inadvertent entry into an unusual attitude, spatial disorientation, and/or collision with terrain through the use of a synthetic vision display; that is, a computer-generated image of the external scene topography from the perspective of the flight deck, derived from aircraft attitude, high-precision navigation solution, and database of terrain, obstacles and relevant cultural features. Virtual day-VMC display standards are not currently in effect for this intended function and the NASA research will inform the development of minimum aviation system performance standards under RTCA Special Committee (SC)-213, Enhanced Flight Vision Systems and Synthetic Vision Systems (EFVS/SVS).

Experimental Method

Technologies for Airplane State Awareness

SE-200 defined areas of research needed for design and implementation of virtual day-VMC displays to prevent loss-of-control accidents due to loss of attitude awareness and lack of external visual references. NASA research has been completed that evaluated virtual day-VMC display design characteristics, such as image minification, optical flow cues, and field-of-view for attitude awareness (Nicholas, 2016). The present paper describes high-fidelity, large commercial transport simulation research that evaluated various types of synthetic vision system displays and a symbology concept termed, “background attitude indicator”, as they may promote aircraft attitude awareness as evident from pilot recognition of and in their ability to recovery from unusual attitudes.

Research Pilots

Twelve active major commercial airline pilots participated in the research. The average experience was 22,000 hours. All pilots had been trained on large transport aircraft unusual attitude recovery procedures.

Research Simulator

The research was conducted in the Research Flight Deck at NASA Langley Research Center, which is a high-fidelity, 6 degree-of-freedom motion-based large commercial aircraft simulator with full-mission capability and advanced glass, Boeing 787-like flight deck displays.

Unusual Attitude Recovery Scenarios

The research employed four unusual attitude (UA) initial conditions based on FAA training scenario guidance. The four UA scenarios were: (a) Nose-up 30 degrees, 90 degrees right roll; (b) Nose-up 30 degrees, 90 degrees left roll; (c) Nose-down 30 degrees, 60 degrees right roll; and (d) Nose-down 30 degrees, 60 degrees left roll. The initial starting altitude was 22,000 ft. mean sea level and each trial lasted an average of 30 seconds.

Unusual Attitude Recovery Trial Method

Twenty trials were conducted such that all display concepts (five) were evaluated in each of the four UA scenarios. Prior to data collection, pilots were provided detailed briefings on Boeing and FAA-recommended UA recovery techniques with subsequent discussion on each pilot’s airline specific training; it was observed that there were not any substantive differences across pilots (US air carriers) in terms of UA recovery technique training. Training in the simulator followed with specific instruction and practice and with the display concepts, performing UA recoveries until the pilots demonstrated an asymptotic level of performance.

Each data collection trial began with the pilot being briefed on the display concept. When ready, the displays were blanked and real motion cueing was used while flying the simulator to the UA initial condition to keep the pilots unaware of the actual attitude. (Post-experimental briefings validated that the method was successful and all pilots confirmed they had no awareness of attitude prior to start of each trial.) Once the simulator reached the UA condition, a tone was sounded followed by the front panel displays unblanking and pilots were instructed to move from hands-in-lap, open their eyes, recognize the UA condition, and perform a successful UA recovery. Pre-experimental briefings provided instructions and training including FAA- (FAA, 2016) and Boeing- (Boeing, 2004) recommended UA recovery techniques (all pilots had been trained by their respective airlines), followed by in-simulator practice. Once the pilot judged the aircraft had been recovered (criteria being wings-level attitude; zero vertical speed), the trial ended and post-trial ratings and pilot comments were solicited.

Display Concepts

The 5 experimental display concept conditions are shown in Figure 1 below. The first concept was a baseline display emulating a Boeing 787 primary flight display; this display does not include SV. Two virtual-day VMC (SV) display concepts were used – one was representative of the minimum aviation system performance standards, as defined by RTCA under DO-315A, for a synthetic vision display intended for *terrain* awareness (i.e., the so-called "MASPS SV"). The other SV concept was representative of virtual-day VMC (SV) in operational use today (i.e., the so-called "Industry Standard SV"). The fourth display concept - Advanced virtual-day VMC (SV) display - added an innovative optical flow cue when the aircraft entered into an unusual attitude, that aided situation awareness in proper execution of recovery. The optical flow cue consisted of a series of yellow ball symbols that moved in the direction of the aircraft attitude (e.g., when nose-up and climbing, the cues would depict movement in direction of up in the primary flight display). Finally, the Industry Standard + BAI condition uses the Industry Standard SV but extended the presentation of the SV scene beyond the primary flight display (PFD) window across the entire display panel (see Bailey et al, 2013) using the Captain's PFD as the BAI reference point.

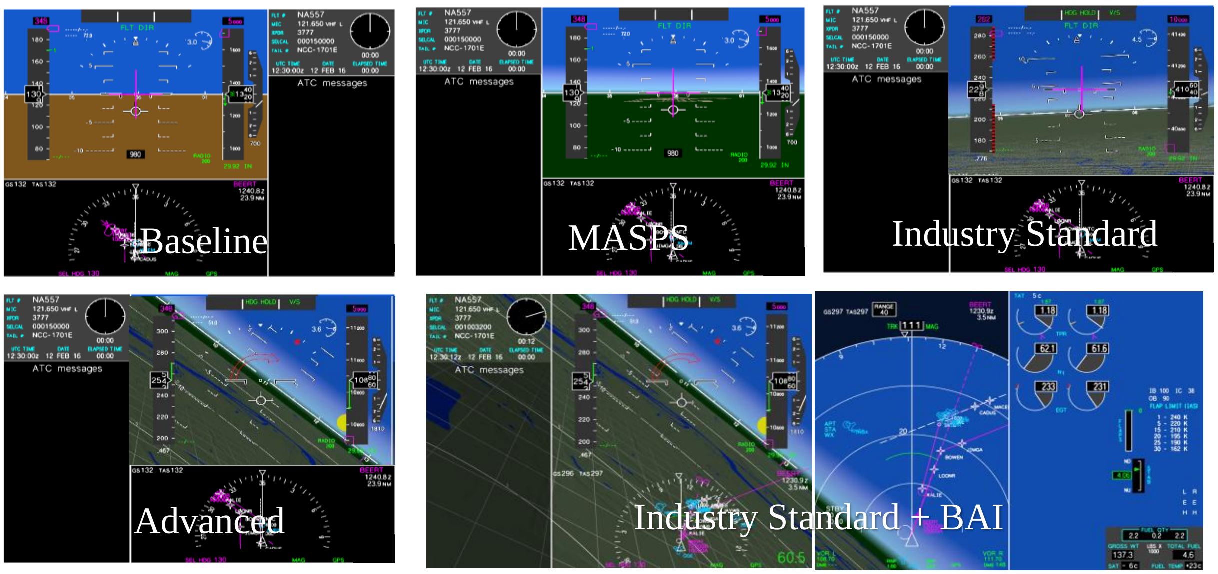


Figure 1. Experimental Display Conditions

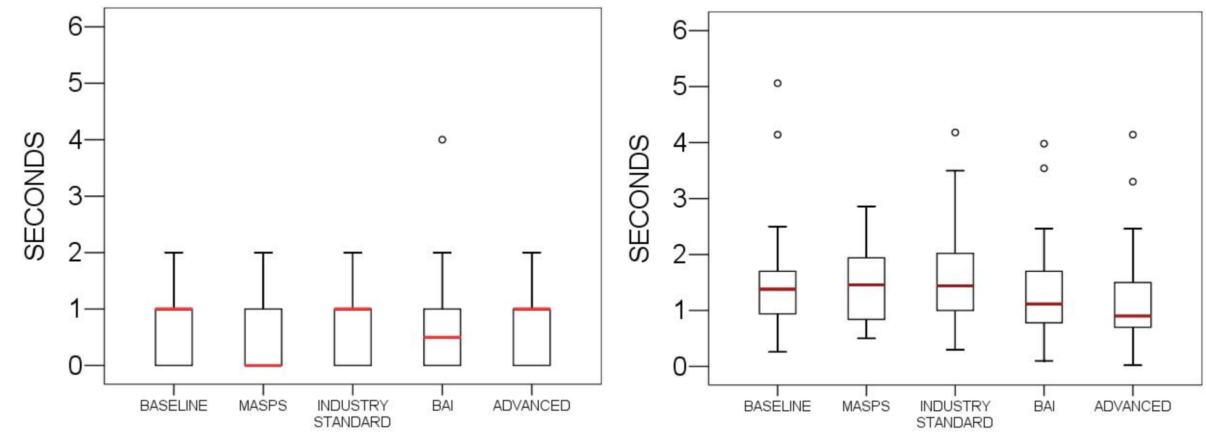
Experimental Results

A number of dependent measures were collected and analyzed for attitude recognition and unusual attitude recovery. A UA recovery (UAR) score was also calculated based on whether the correct, incorrect, or neutral pitch, roll, and throttle input was made (using a score of +1, -1, or 0, respectively) for a total score that ranged from -3 (poor) to + 3 (excellent).

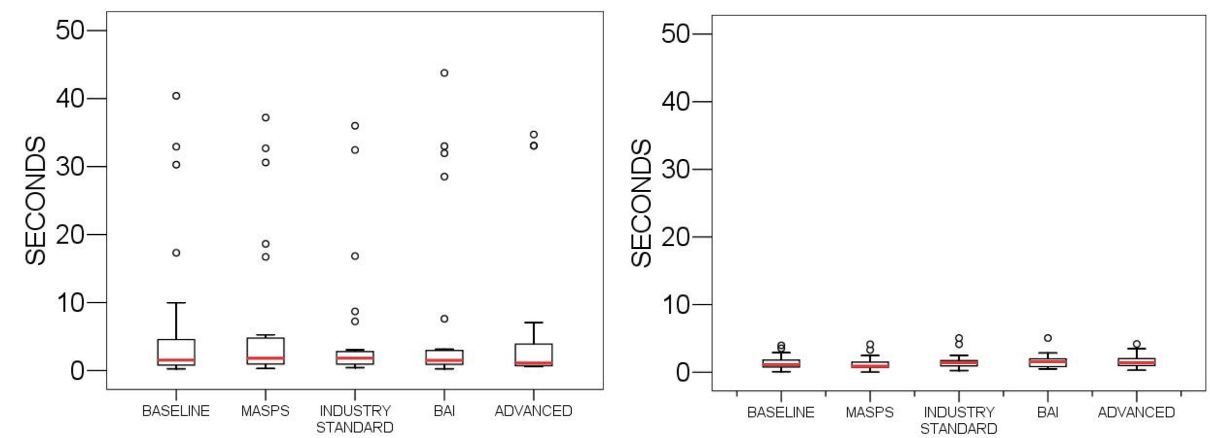
Quantitative Results

Scenarios. For scenario, the four UA scenarios were combined into either a pitch-up or pitch-down condition for analysis. The results showed significant main effect for time-to-first pitch input, $F(1, 23) = 37.599$, $p < 0.01$; time-to-first correct pitch input, $F(1, 23) = 9.130$, $p < 0.01$; time-to-first roll input, $F(1, 23) = 5.479$, $p < 0.05$; and time-to-first correct roll input, $F(1, 23) = 24.951$, $p < 0.01$. A significant main effect was found for UAR score for scenario, $F(1, 23) = 61.408$, $p < 0.01$. The 30 degree pitch-up UAR scenario condition was significantly poorer for dependent measures compared to the 30 degree pitch-down UAR scenario condition. No significant effect was found for number of control reversals, $F(1,23) = 0.04$, $p > 0.05$.

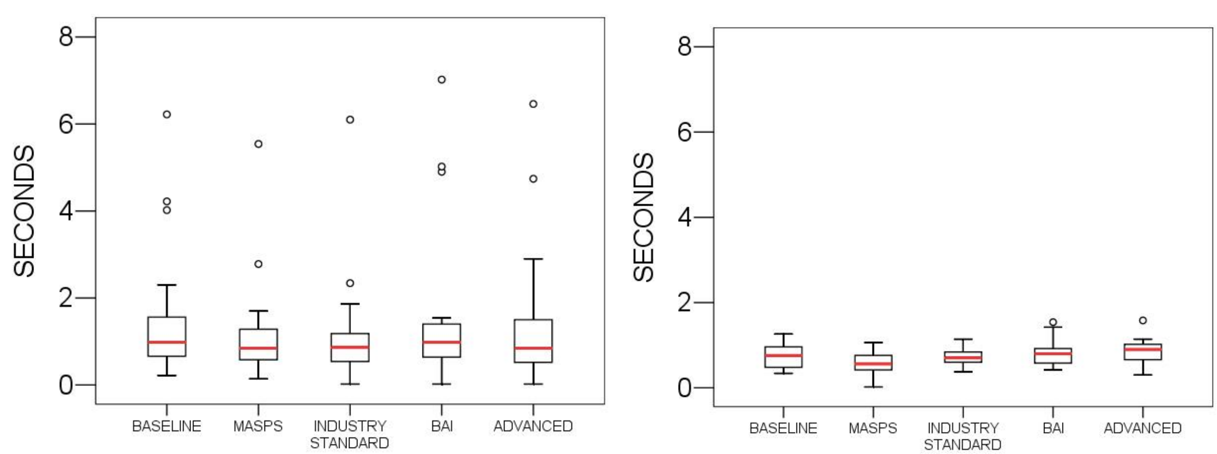
Displays. No significant differences were found for time-to-first pitch input, $F(4, 92) = 1.407$, $p > 0.05$; time-to-correct first pitch input, $F(4, 92) = 0.145$, $p > 0.05$; time-to-first roll input, $F(4, 92) = 2.131$, $p > 0.05$; time-to-first correct roll input, $F(4, 92) = 0.345$, $p > 0.05$; number of control reversals, $F(4, 92) = 1.100$, $p > 0.05$; and UAR score, $F(4, 92) = 0.063$, $p > 0.05$. The scenario *display interaction effects for all quantitative dependent measures were also not significant. Figure 2 presents boxplots of each of the quantitative dependent measures for the pitch-up (left side of figure) and pitch-down UAs (right side of figure) for each display concept. The boxes indicate the median value and $25^{th}/75^{th}$ percentiles with the whiskers extending to 1.5 times the height of the box or to the minimum or maximum values. The points beyond the whiskers are extreme values or outliers and are indicate by circles.



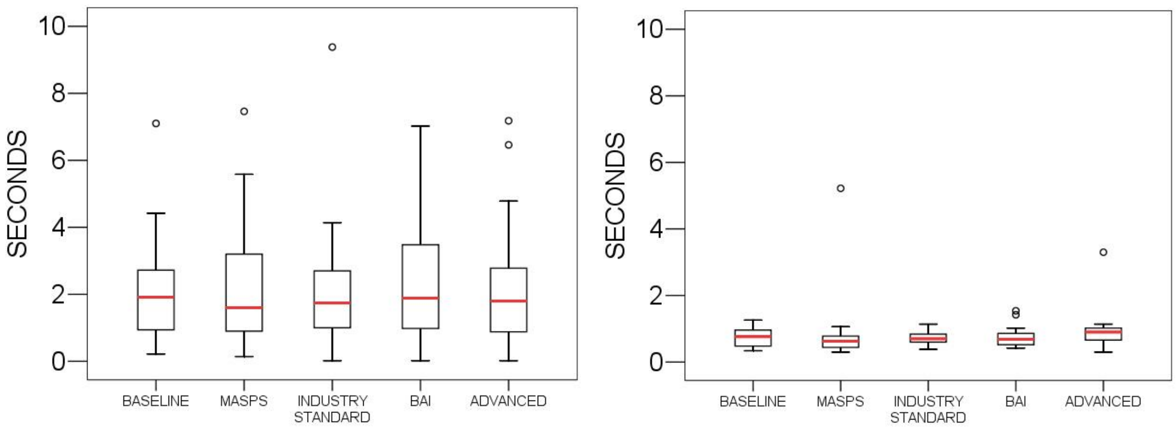
Time-to-First Pitch Input



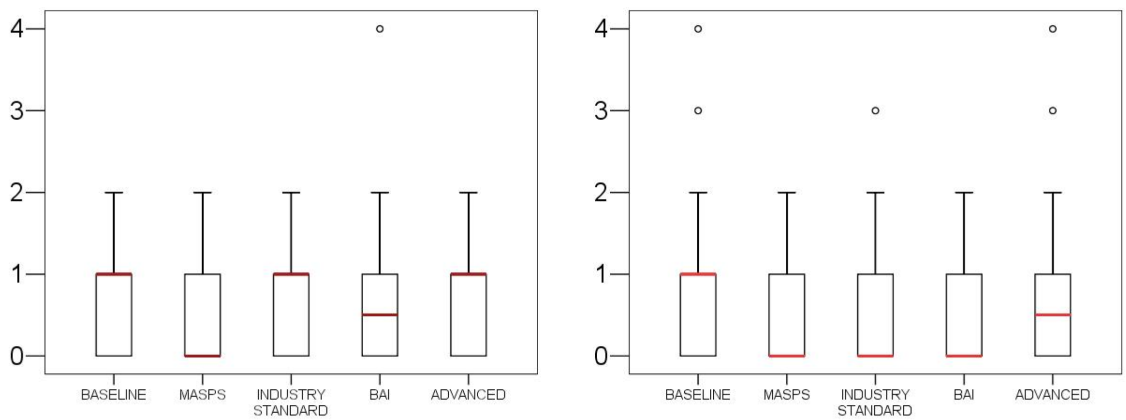
Time-to-First Correct Pitch Input



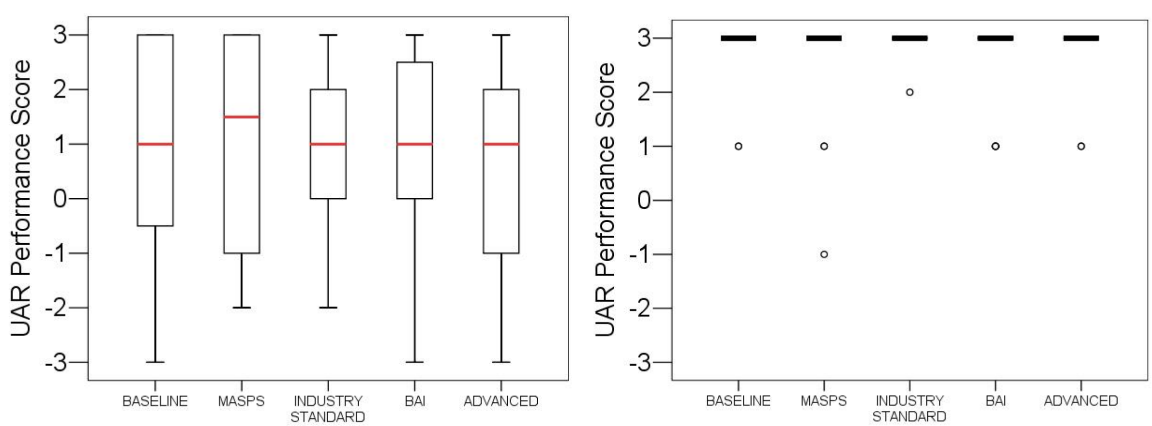
Time-to-First Roll Input



Time-to-First Correct Roll Input



Number of Control Reversals



UAR Score

Figure 2. Boxplots of Quantitative Dependent Measures (left – 30 degrees up; right – 30 degree down)

Qualitative Results

Scenarios. Post-experimental analyses revealed that the nose-down, 60 degrees right roll UA had highest workload (using NASA-Task Load Index, TLX), $F(3, 177) = 26.15$, $p < 0.01$ and lowest situation awareness (using Situation Awareness Rating Technique, SART), $F(3, 177) = 26.15$, $p < 0.01$.

Displays. No significant differences were found across display concepts for NASA-TLX, $F(4, 204) = 0.565$, $p > 0.10$. No significant differences were found across display concepts for SART, $F(4, 204) = 0.847$, $p > 0.10$. The ANOVA revealed a significant main effect for paired comparison geomeans for display, $F(4,48) = 24.033$, $p < 0.0001$. Pilots rated the Industry Standard + BAI (0.34) as significantly higher for SA than all four other display concepts. The BAI was reported to significantly enhance attitude awareness. The results also showed that the Advanced (0.19) and Industry Standard (0.21) virtual day-VMC displays were not significantly different from each other. These concepts were significantly different from Baseline (0.13) and MASPS (0.12) concepts, and pilots reported that their enhanced synthetic vision presentations provided better situation awareness and more intuitive interpretation of aircraft attitude than the baseline (no SV) or MASPS (minimal SV).

Conclusions

The subject pilots had substantial experience and training in recognizing and recovery from UAs. This pilot population was conservatively selected because, if significant differences were found across displays, it would be even more significant with less experienced commercial pilots - the identified risk group in the CAST report. Although the pitch-up scenarios were found to be significantly different than nose-down, the differences are associated with the difficulty of quantifying nose-up transport aircraft UAR performance (see Gawron, 2009); no quantitative performance differences for displays were found and all pilots were well adept to recover from the UA conditions. The pilots subjectively rated the nose-down conditions as being the most difficult scenarios.

Although no performance differences were found, pilot comments revealed that the added situation awareness provided by the background attitude indicator and the terrain visual cues of the Industry Standard and Advanced virtual day-VMC (SV) displays was substantial (compared to Baseline and MASPS concepts). The BAI concept was rated significantly better than all other display concepts and will be further researched. The Advanced virtual day-VMC concept with optical flow cues was not found to be quantitatively or qualitatively different compared to Industry Standard, but pilot feedback suggests that modifications to the cues would substantially improve efficacy. Furthermore, pilots stated that the optical flow cues, as implemented, may not provide useful information for recovery but would be of value to help them recognize an impending unusual attitude.

In general, the results posit that virtual day-VMC displays have potential benefit to aid in recognition of, and recovery from, unusual attitudes. The next steps are to evaluate the SV display concepts with low-hour (< 1200 hours) international pilot populations and continue research and development of the BAI and optical flow cues.

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