Regarding Pilot Usage of Display Technologies for Improving Awareness of Aircraft System States

Taumi S. Daniels, Cailin M. Ferguson, Ellen T. Dangtran, Rebecca M. Korovin, Lynda J. Kramer, Emory T. Evans, Yamira Santiago-Espada
NASA Langley Research Center
Hampton, VA 23681
taumi.daniels@nasa.gov

Daniel J. Kiggins — **American Airlines**
Timothy J. Etherington — **Rockwell Collins**
James R. Barnes — **Booz Allen Hamilton**

Abstract— **Avionics-related systems and the procedures for interacting with them appear to be growing in complexity. This trend places a larger burden on pilots to manage increasing amounts of information and to understand system interactions. The result is an increase in the likelihood of loss of airplane state awareness (ASA). One way to gain more insight into this issue is through experimentation using objective measures of visual behavior. This study summarizes an analysis of oculometer data obtained during a high-fidelity flight simulation study that included a variety of complex pilot-system interactions that occur in current flight decks, as well as several planned for the next generation air transportation system. The study was comprised of various scenarios designed to induce low and high energy aircraft states coupled with other emulated causal factors in recent accidents. Three different display technologies were evaluated in this recent pilot-in-the-loop study conducted at NASA Langley Research Center. These technologies include a stall recovery guidance algorithm and display concept, an enhanced airspeed control indication of when the automation is no longer actively controlling airspeed, and enhanced synoptic diagrams with corresponding simplified electronic interactive checklists. Multiple data analyses were performed to understand how the 26 participating airline pilots were observing ASA-related information provided during different stages of flights and in response to specific events within these stages.**

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ACRONYMS

AIME = Automation and Information Management Experiment
AOI = Area of Interest
ASA = Airplane State Awareness
ATC = Air Traffic Control
ATIS = Automatic Terminal Information Service
CAST = Commercial Aviation Safety Team
CMF = Cockpit Motion Facility
EACI = Enhanced Airspeed Control Indicator
EFB = Electronic Flight Bag
EICAS = Engine Indicating and Crew Alerting System
eSyn = Enhanced Synoptics
FMA = Flight Mode Annunciator
FPV = Flight Path Vector
HSI = Horizontal Situation Indicator
MCP = Mode Control Panel
MFD = Multifunction Display
ND = Navigation Display
NOTAM = Notice to Airmen
OTW = Out-the-Window
PF/PM = Pilot Flying / Pilot Monitoring
PFD = Primary Flight Display
QRH = Quick Reference Handbook
RFD = Research Flight Deck
sECL = Simplified Electronic Checklist
SID = Standard Instrument Departure
SIS = System Interaction Synoptic
SRG = Stall Recovery Guidance
STAR = Standard Arrival
VSD = Vertical Situation Display

1. INTRODUCTION

In the period 2010 to 2014, the Commercial Aviation Safety Team (CAST) sponsored a study of 18 commercial aviation events that occurred within ∼10 years prior to the study kickoff [1]. Results identified 12 recurring problem themes involving loss of airplane state awareness (ASA), and suggested a large number of possible intervention strategies. CAST also assessed these strategies for effectiveness and feasibility and recommended several specific Safety Enhancements (SEs) for the industry to implement including:

SE-207 Attitude and energy state awareness
SE-208 Airplane systems awareness

The basis of this study is a flight simulation experiment completed in 2018 called the Automation and Information Management Experiment 2 (AIME2) [2]. AIME2 was a follow-on study [3] and was conducted at the Research Flight Deck (RFD) within the Cockpit Motion Facility (CMF) at NASA's Langley Research Center as shown in Figure 1. The RFD is outfitted similar to a Boeing B-787. The AIME and AIME2 research experiments were conducted to address the two Safety Enhancements, SE-207 and SE-208. The FAA conducted a complementary experiment evaluating

Figure 1: **NASA Langley Cockpit Motion Facility with Research Flight Deck on motion base.**

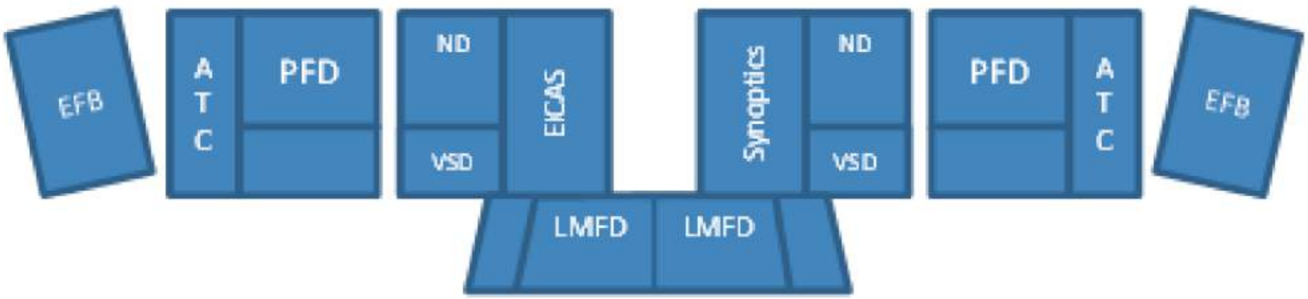

Figure 2: **AIME2 display surface reference layout.**

a subset of the AIME2 ASA technologies on an AirBus A320 simulator at the Mike Monroney Aeronautical Center in Oklahoma City. Two additional AIME experiments are planned to be conducted in the Fall 2018 and Summer 2019 to complete this research. A review of the AIME work to date is presented in [4].

The RFD mimics most of the interfaces provided on the B-787 aircraft while providing a flexible environment for emulating scenarios of interest. As part of AIME2, thirteen two-pilot airline crews participated in the study, where the captains had an average of 24,288 hours and first officers averaged 11,433 hours commercial airline flight experience. Of the 26 crew members, 17 participants had prior military flight experience. The crews completed 180 simulated flight scenarios using the John F. Kennedy International and Ronald Reagan Washington National airports as test sites. Each crew executed a mix of eight different scenarios, some that were based on one or more reference events from past accidents/incidents or studies where loss of airplane state awareness (ASA) was a contributing factor.

Data were collected using an experimental design that allowed for the manipulation of information, operational complexity, system performance and uncertainty across the scenarios. Flight crews were immersed in high density traffic and adverse weather environments that included many concepts either currently emerging in the industry or planned for the near future (e.g. digital data link services, synthetic and enhanced vision systems, and area navigation/required navigation performance operations). In addition, the study emulated off-nominal (and complex) situations such as unexpected weather events, traffic deviations, equipment failures, poor data quality, communication errors, unexpected clearances, and changes to flight plans [2].

One important factor to consider when evaluating new technology concepts is the reference platform into which the new technology will be inserted. Based on guidance from the CAST, it was decided that the B-787 flight deck would be used for this purpose. The B-787 is a highly advanced aircraft, representing in many ways state of the art. However, as most of the relevant B-787 indicators, displays, and functions are also available on other recently developed aircraft, findings should be applicable. Retrofit of these new technologies onto older aircraft may also be possible.

To achieve CAST SE-207/208 objectives, the RFD was equipped with indicators and displays referenced in the CAST report, and of primary interest for this study. Those include: the Primary Flight Display (PFD), the Flight Mode Annunciator (FMA) in the upper center of the PFD, airspeed and altitude "tapes" on the left and right side of the PFD, the Flight Path Vector (FPV) on the PFD, the Navigation Display (ND), the Vertical Situation Display (VSD), the Engine Indicating and Crew Alerting System (EICAS), the synoptic displays (7 types) available on Multi-Function Displays (MFDs), the Lower MFD which serves as the pilot interface to the Simplified Electronic Checklists (sECL), the Electronic Flight Bag (EFB), and the Air Traffic Control (ATC) display that lists ATC data link messages that have been received. These surfaces associated with these displays were organized to mimic the B-787 layout as shown in Figure 2.

2. TEST OVERVIEW AND OBJECTIVES

The facility and environment was set up to fly the defined scenarios within the John F. Kennedy International Airport terminal airspace for arrivals, and at the Washington National Airport for departures. Available independent variables were weather conditions (5); airport configuration (2); traffic conditions (3); flight path/procedure (9); and off-nominal conditions (10). Each scenario had unique settings for each of these variables to cover the selected span of conditions.

For the data presented here, the two pilots were distinguished based on their assigned role and using the terms pilot flying (PF) and pilot monitoring (PM). These roles and terms should not be confused with seat position (left/right). In this study, the Captain took the left seat and the FO took the right seat and each stayed in that seat for the duration of his or her participation. They were, however, asked to change roles (PF/PM) occasionally. Scenarios were randomly sequenced both within and across the crews with the pilot role for each seat position briefed and set prior to each flight.

For arrivals, flights would begin after top-of-descent, but before FL100, and established on the appropriate published standard arrival (STAR) procedure. While holding in position, the crew would conduct an approach briefing and assign PF/PM roles. Pilots were asked to follow normal procedures as if a revenue flight, with caveats discussed during training and induced by the facility's differences from line operations. Pilots were instructed to go-around if unstable or otherwise deemed necessary; but to continue flight until the researcher called for an "End of Run."

For departures, flights would begin holding short of the active (departure) runway awaiting takeoff clearance. While holding short, all relevant checklists would be accomplished as well as briefing NOTAMs and ATIS. Takeoff and climb-out would follow the appropriate published standard instrument departure (SID) procedure. Following each flight, a short questionnaire would be completed by each crew member using a researcher-provided tablet computer.

All of the scenarios incorporated artificially degraded environmental or aircraft state conditions. The goal of these scenarios was to place the aircraft in a low or high energy state, or some other off-nominal condition, often in a manner that was hidden from the flight crew. This research is solely intended to elicit flight crew evaluations of the new technologies, not evaluate flight crew performance.

3. DISPLAY TECHNOLOGIES

As extensions to this reference set of displays and functions, three new technology concepts were evaluated. These are referred to as: (1) EACI - Enhanced Airspeed Control Indicator, visual indication that the automation is no longer actively controlling aircraft speed; (2) SRG - Stall Recovery Guidance, visual cues on the PFD indicating lateral, horizontal control inputs as well as throttle inputs to perform recovery from stall or near stall; and (3) Enhanced Synoptic (eSyn) pages, with associated Simplified Electronic Checklists (sECL). These sECLs are shortened versions of ECLs to be used in conjunction with the eSyn pages.

Enhanced Airspeed Control Indicator

The EACI technology is described in [7]. The concept aims to improve pilot awareness of the energy state of the aircraft.

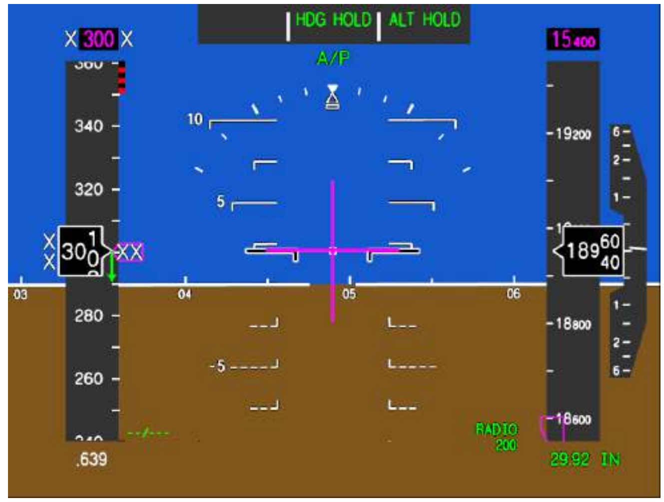

Figure 3: **Primary Flight Display with Enhance Airspeed Control Indicator.**

Figure 4: **Primary Flight Display with Stall Recovery Guidance indicators.**

This is accomplished via a visual indication on the PFD of when the automation (i.e. Autopilot, Autothrottle and Flight Management System) are no longer directly controlling airspeed. An example of this state is when the Autothrottle decouples or the control mode only indirectly controls speed. The indication consists of a three sets of white "X" markers located to the left, right, and top of the airspeed tape. These indicators are shown in Figure 3. Note in this figure that no speed mode is shown in the flight mode annunciator.

Stall Recovery Guidance

SRG is described in [8]. The guidance is shown on the PFD with a repurposed flight director, FMA indicators, "RECOVER" shown below flight director, and commanded throttle settings. These are shown in Figure 4.

When the aircraft reaches the stick shaker angle of attack, the FMA displays three "SRG" indicators in red. Also, the word "RECOVER" is displayed below the flight director also in red font. The flight director is repurposed to show both horizontal and vertical flight guidance to recover from stall towards the reference speed and wings level, while avoiding secondary stalls and excessive load factors. A magenta bar is displayed on the aircraft symbol right wing to indicate the thrust setting target. Two white bars representing the current throttle setting are shown above or below the magenta bar. Also, the flight crew is provided with either up or down magenta arrows indicating the direction (increase or decrease) for the optimum throttle settings. After the pilot advances the throttles and corrects the aircraft attitude, the "RECOVER" message is removed. The SRG condition ends when either crew member selects any MCP automation mode. An angle of attack indicator is not shown, though its use could be an area of future research.

As tested in this study, two different SRG algorithms were evaluated, although results reported here do not differentiate between the two algorithms. In addition, this study evaluated flight crew performance using the SRG, which was activated at stick shaker instead of after the aircraft developed full stall. Comprehensive details of the SRG algorithms and performance are provided in [9] and [10].

Enhanced Synoptic and Simplified ECL

Two types of eSyn pages were evaluated in this study - 1) enhancements to standard B-787 synoptic pages and 2) new synoptic pages for failures in which no relevant synoptic exists. Standard B-787 synoptic displays were enhanced to depict and provide additional information regarding failures and effects. These enhancements enabled the simplification of associated ECLs by removing information now provided on the enhanced synoptic display and providing context-relevant data on the checklists.

For some types of failures, there is no relevant existing synoptic. In these cases, a new synoptic page can be defined. The example used for this research was loss of flight critical data provided by the air data system and inertial reference units.

Unique eSyn pages are associated with specific aircraft faults indicated by an EICAS message. The eSyn color scheme matches that of the other synoptic pages. Basically, data or data paths shown in green indicate valid data, those shown in white indicate operable data but not as accurate, and those in amber indicate invalid data.

For example, an EICAS message "Airspeed Unreliable" resulted in a new eSyn page (referred to as the System Interaction Synoptic, or SIS in this study) indicating bad data from both air data computers and is shown in Figure 5. The impact of this fault is shown on the eSyn as all automation is inoperable (amber text in symbolic MCP near top of figure), alternate altitude and airspeed is derived from GPS and angle of attack, respectively, (amber text near stand-by instrument symbol on left side of figure), and the aircraft is in secondary flight control mode (amber text at bottom of figure).

Associated with the EICAS error and the off-nominal eSyn page is a new simplified electronic checklist (sECL). This shortened checklist is intended to be used with the eSyn to enable the pilot monitoring to determine the fault more quickly. More information on eSyn and sECL is provided in the companion paper [2].

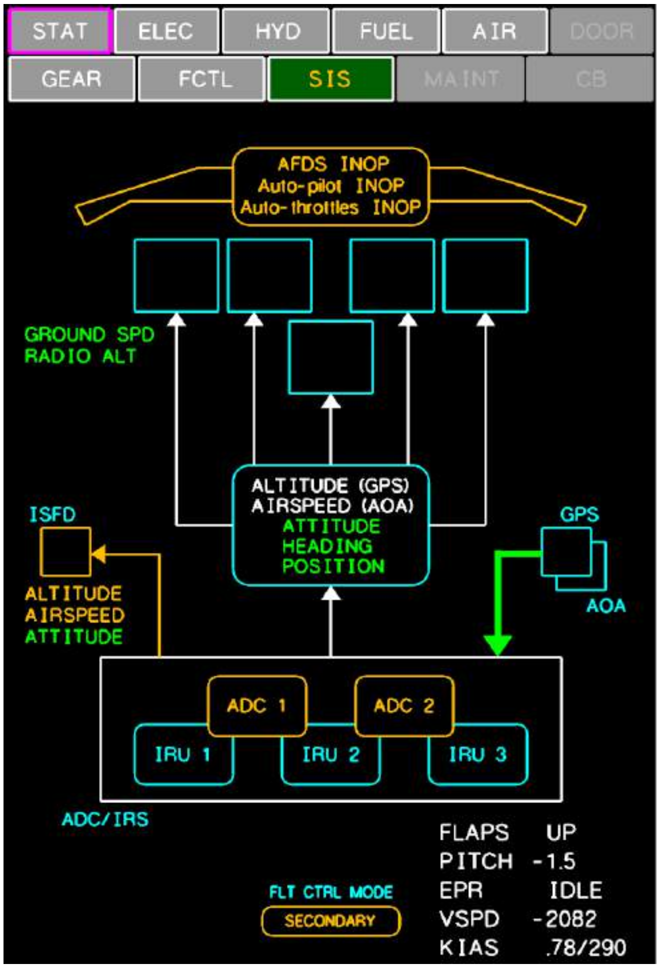

Figure 5: **Enhanced Synoptic for Airspeed Unreliable as shown on left side of MFD.**

4. Oculometer Data

Prior work includes analysis of oculometer or eye-tracker data for two previous experiments as described in [5] and [6]. As in these earlier studies, many types of data were collected, including oculometer data from both crew members. A Smart Eye Pro™ oculometer system has been in use for several years [11] at NASA and has been installed in the RFD for this research. The oculometer consists of ten sets of IR cameras and light sources (five per crew member) in fixed locations within the RFD. These locations determine a reference frame for subsequent measurements.

In order to use the oculometer system, each of the seven flight deck displays (four 17-inch LCD monitors, each split into two display regions, two side-mounted tablet computers or EFBs, and another 17 inch LCD facing upward also split into two) must be located and measured in three dimensional space. Additional measurements were made to locate the MCP. Each display, PFD for example, has known upper left and lower right corners relative to the oculometer reference frame. As the PFD was the primary focus of this experiment, the upper right and lower left corners of the PFD were used as calibration points for the Smart Eye Pro™. In addition, a calibration procedure is required that yields eye vector corrections on a per pilot basis.

Each crewmember has dedicated oculometer data consisting of measurements of head position, eye vectors in three dimensions, and pupil diameters. A gaze point is defined at the intersection between a fixed reference frame (flight deck displays) and one of the eye vectors. Each gaze point has a margin of error in location. There are several possibilities that result in missing data, including oculometer calibration errors, filtering data that may have been good, and crew member motion, blinking, or moving out of position (different posture due to fatigue). The Smart Eye Pro™also provides a measure of the quality of each measured eye vector. This quality value was used to filter or remove bad data.

In addition to the gaze point measurements, the oculometer data includes an estimate of pupil diameter (both eyes for both crew members). Pupil diameter has been reported as an effective measure of surprise [12], and on the impact of performance of flight crews [13]. Other researchers have defined "surprise", as opposed to "startle" in the literature [14]. Here we use pupil diameter to indicate "surprise" from the unexpected absence of autopilot speed control. The surprise may also be indicative of the crew's sudden cognitive awareness possibly due to an unexpected condition or a notification within the flight deck system. In addition, prior research has indicated that pupil diameter can be used as a measure of mental attention [15].

The oculometer data were collected to allow for objective evaluation of the crews' attention to the various displays and areas of interest (AOI), and their respective awareness of airplane state at critical junctures of the flights. The left and right PFDs have equivalent AOIs. An example of PFD AOIs is shown in Fig. 6 as rectangles with yellow borders. These include three AOIs enclosing the "X" characters to the right, left, and above the speed tape. The small AOI rectangle located to the left of the airspeed is denoted as"Left Xs", the rectangle above the speed tape is denoted as "Speedtape Xs", and the tall rectangular AOI to the right of the speed tape is denoted as the "Bug Xs". These three AOIs are specific to the enhanced airspeed control indicator (EACI).

In addition, there are two AOIs below and to the right of the flight director. These two in addition to a third AOI below the flight mode annunciator comprise those AOIs associated with stall recovery guidance (SRG). The altitude tape and vertical speed indicator are also enclosed by another AOI to capture these pilot gaze points.

The entire display comprises an AOI for each of the other non-PFD displays. The eSyn page depicted in Figure 5 was shown on the upper multifunction display (MFD) and the sECL was shown on the lower MFD. These two MFDs comprised additional AOIs.

Other AOIs include two primary flight displays (PFD), two navigation displays (ND), two electronic flight bags (EFB), and the Mode Control Panel (MCP). Both crew members have one each of these AOIs. A final AOI is Out-the-Window (OTW) shared by both of the crew, that is not shown.

5. Results and Analysis

By means of the method described in Section 4, crew member's engagement with the different AOIs was tracked and analyzed across all 180 flights. For this paper we present findings for PF and PM engagement with three ASA

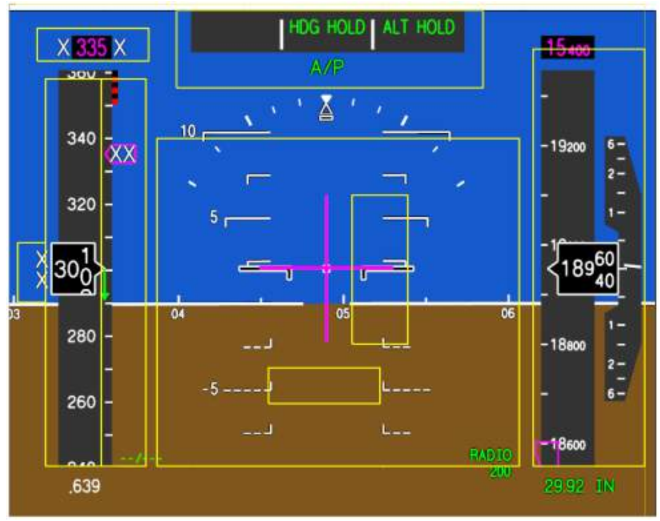

Figure 6: **Primary Flight Display with Areas of Interest shown as yellow rectangles.**

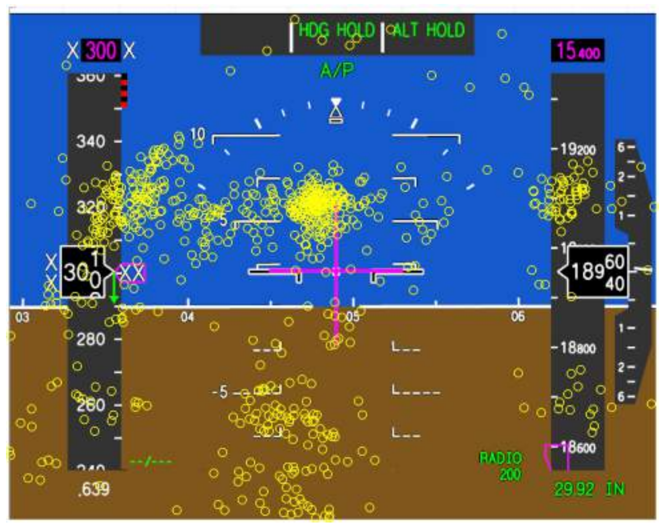

Figure 7: **Example of EACI PF Gaze Point Map on PFD.**

display technologies. The findings include aggregate pilot gaze point distributions, gaze point and heat maps for various phases of flight, gaze point during scenarios involving loss of automation control of airspeed, and pupil diameter plots during loss of airspeed/altitude during scenarios involving unexpected auto-throttle disconnects.

Enhanced Airspeed Control Indicator

In AIME2 overall, and in these EACI scenarios in particular, a high workload was designed to challenge the pilots. Flight crews flew three types of scenarios that were designed primarily to assess usability of the concept. Here usability refers to ease of use, usefulness, and usage. The scenarios included the approach and cruise phases of flight in addition to descending while in a holding pattern. At some predetermined moment, a typical scenario would have an aircraft energy problem as the result of unexpected autothottle disconnect with no aural warning. Following the disconnect, the airspeed began to slowly decrease. The scenario was considered complete when the PF or PM made a verbal

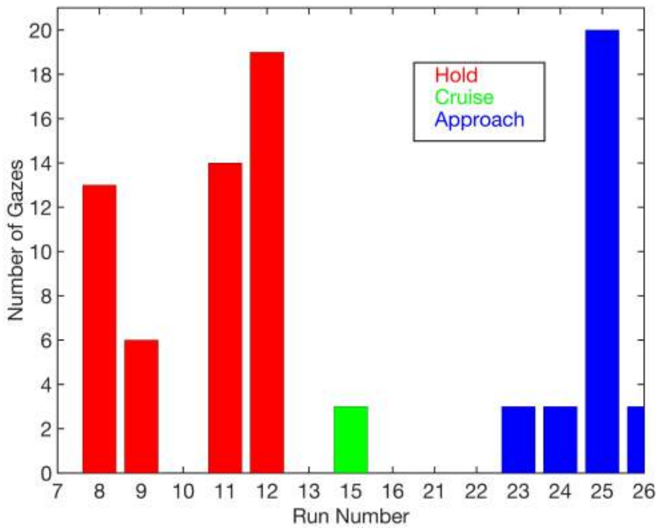

Figure 8: **Gaze Point Counts of PF Combined AOIs by Phase of Flight.**

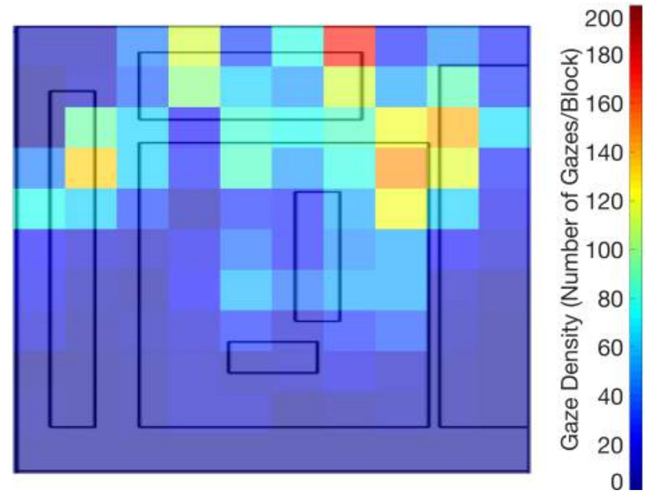

Figure 9: **Aggregate Heatmap for All PF Cases During EACI.**

remark about the airspeed, or the PF applied thrust.

A typical gaze point map for one data collection run is shown in Figure 7. In the figure, all PFD gaze points are shown for the PF during the period from autothrottle disconnect until the problem was acknowledged (49 seconds in this example). The non-sequential gaze points are shown as small yellow circles on a static PFD image, and there is significant time (within the 49 sec) where the PF was looking elsewhere. During the 49 seconds, the accumulated times of PF gazes were: OTW 23 sec, OD 16 sec, and PFD 10 sec. The longest gaze dwell time on the PFD in this case was about 3 seconds. In this example, note that though the EACI "X" markers were observed by the PF (as indicated by the gaze points), the PF did not acknowledge decreasing airspeed (from 225 to 200 knots) during an autothrottle disconnect scenario even with the EACI technology.

This situation is the result of either inadequate training for the experiment or the pilot physically saw the markers but did not mentally process them. In the figure, the background PFD image shows an airspeed of 300 knots. Note that this is a static image and not specific to this particular scenario example. This background image is intended to show the gaze points in relation to other features on the PFD.

Across all EACI scenarios for the PF, the number of times that the oculometer measured a gaze point on any of the three EACI AOIs is shown in Figure 8. Gaze point counts were summed for the three EACI AOIs and are color coded by phase of flight. The x-axis enumerates the only those run numbers where the EACI technology was tested. Baseline data is not shown in the plot since there were no "Xs" on the PFD. The period of time for each count started when the autothrottle was disconnected and ended when the PF or PM verbally announced that there was a problem with the airspeed or the PF applied thrust. If there are no counts shown in the plot, then for that scenario, the PF did not gaze at a particular EACI AOIs. If there are counts shown on the plot, then the PF gazed at one of the EACI AOIs but did not recognize its significance. Finally, in the figure, different scenarios are listed by number, used for scenario identification.

Another type of oculometer data visualization technique is the heatmap. Across all crews, the aggregate gaze point distribution across the PFD can illustrate which regions of the PFD are engaging the flight crew's attention. Shown in Figure 9 is a heatmap for PFs gaze point distribution for all EACI cases. In the figure, the black rectangles are drawn to show the various AOIs on a notional image of the PFD. The gaze point distribution has greatest intensity across the top half of the PFD, an indication that the PFs as a group include airspeed, FMA, and altitude in their gaze pattern.

As an example of PF engagement during an EACI scenario, Figure 10 is a plot of normalized pupil diameter versus time. In the plot, the abscissa is 5 seconds before and after the moment when the PF realizes that the autothrottle is disconnected. The PF was the Captain for this scenario. The AOIs are plotted as colored bars versus time with the color coding given in the legend. Note the distinct change in AOIs before (grey and cyan) and after (yellow and grey) indicating the shift in PF engagement. Finally, note that the normalized pupil diameter remains somewhat constant around 0.9 during the period. This would indicate that the PF was not surprised by the realization.

In this particular scenario, the period of time from autothrottle disconnect to PF noticing the problem was about 102 seconds with a decrease in airspeed of about 84 knots. The realization occurred with the stick shaker onset and the transition to SRG. At that moment, the PF began to focus on the recovery (mostly yellow AOIs). In the plot, "Flt Dir" indicates the central portion of the PFD while "Other" refers to other displays and OTW.

The analysis of other AIME2 data, including a formal usability assessment and pilot feedback, is more revealing regarding EACI. These results are presented and discussed in a companion paper[2].

Stall Recovery Guidance

An example gaze point map for SRG is shown in Figure 11. In the figure, gaze points are small yellow circles plotted onto a static PFD image. The gaze points occur over the period of time from stick shaker onset to PF commanded automation selection. In this example, the First Officer was the PF and

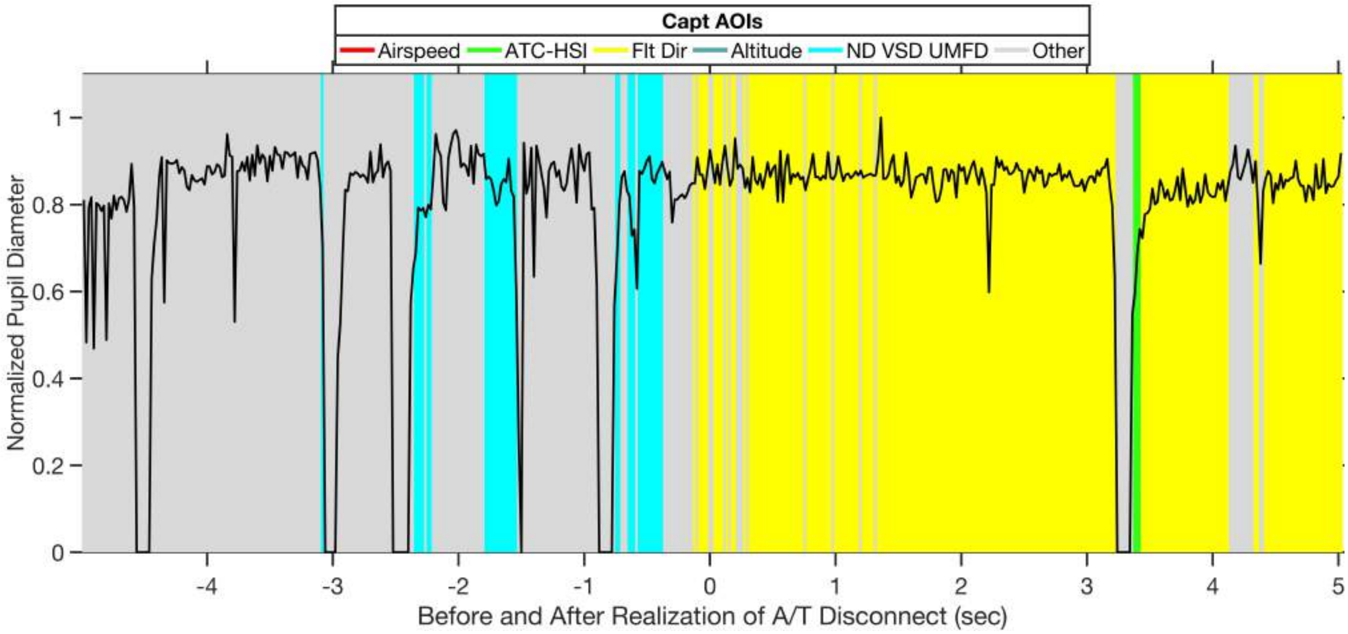

Figure 10: **Example of PF AOIs and Pupil Diameter.**

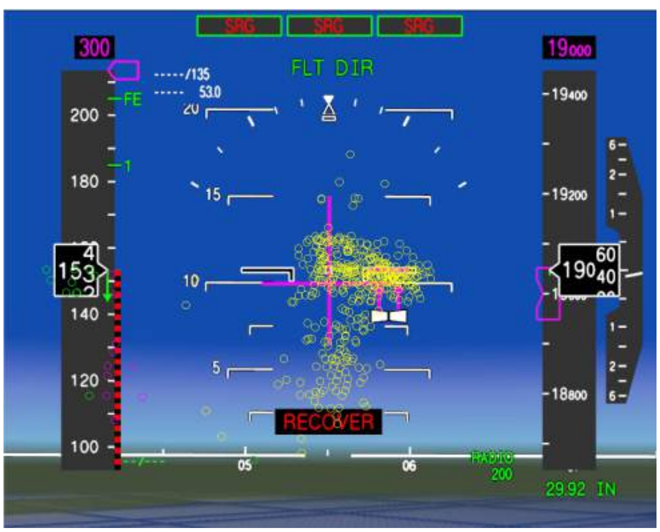

Figure 11: **Example Gaze Point Map for SRG.**

the scenario involved loss of autothrottle soon after takeoff. After stick shaker onset, the PF used the SRG to recover the aircraft in approximately 34 seconds. The total gaze times for the AOIs were 33 sec for SRG / aircraft attitude and less than 1 second for all others (airspeed, altitude, other displays, and OTW) combined.

Figure 12 is an example plot of normalized pupil diameter versus time after stick shaker for an SRG scenario. Also shown in the plot are color coded AOIs drawn as vertical bars versus time. In this case, the PF was the Captain and the time in task of the recovery was about 14 seconds. In this particular cruise scenario, the PF was distracted by an off-nominal while the autothrottle was silently disconnected. After autothrottle disconnect, the airspeed decreased by 95 knots down to the stick shaker speed. At this moment, the PF begins the recovery manuever coinciding with the plot x-axis at time 0. In the plot, pupil diameter increases rapidly from about 0.8 to a maximum of 1, then maintains an enlarged value for the next 4.5 seconds.

We attribute this first 4.5 seconds to an initial surprise followed by an elevated attentional state. The next mental state begins with a blink (zero pupil diameter) and a decrease in the average pupil diameter down to about 0.8 while the PF gazes at other things including out the window (OTW); airspeed, altitude, and automation ("AAA"); and ND, ATC, and HSI. Analysis of other crews to the stick shaker onset revealed a variety of responses. Most crews noticed the impending stick shaker condition and were not surprised.

Other PFs exhibited similar behavior as shown in the example plot of Figure 12, though most did not exhibit surprise because of the scenario design. In particular, the scenario design required a fairly rapid decrease in airspeed to approach stick shaker. The inertia of the Boeing B-757 dynamic model used in this study did not lend itself to this type of response without some non-realistic intervention designed into the scenario.[1] The goal was to achieve stick shaker before the flight crew became aware of the slowly decreasing speed and altitude. As part of the scenario design, the dynamic model was modified to change how it responded in order to achieve the stick shaker condition more quickly. In some of the scenarios, the researcher in the jump seat had to restrain the PF from advancing the throttles before the SRG engaged (at stick shaker onset). The goal of the scenario was to evaluate pilot response to the SRG after achieving stick shaker.

A comparison of oculometer data collected across all scenarios is shown in Figures 13 and 14. From the plots, in the Baseline cases, PFs tended to scan a larger portion of the PFD with an emphasis on determining aircraft attitude. For the SRG Technology cases, the PFs were more focused on the SRG attitude and throttle guidance. This result indicates

[1] In the NASA Langley RFD, the flight deck displays were similar to those in a Boeing B-787 while the underlying dynamic response driving the simulator motion-base was similar to that of a Boeing B757.

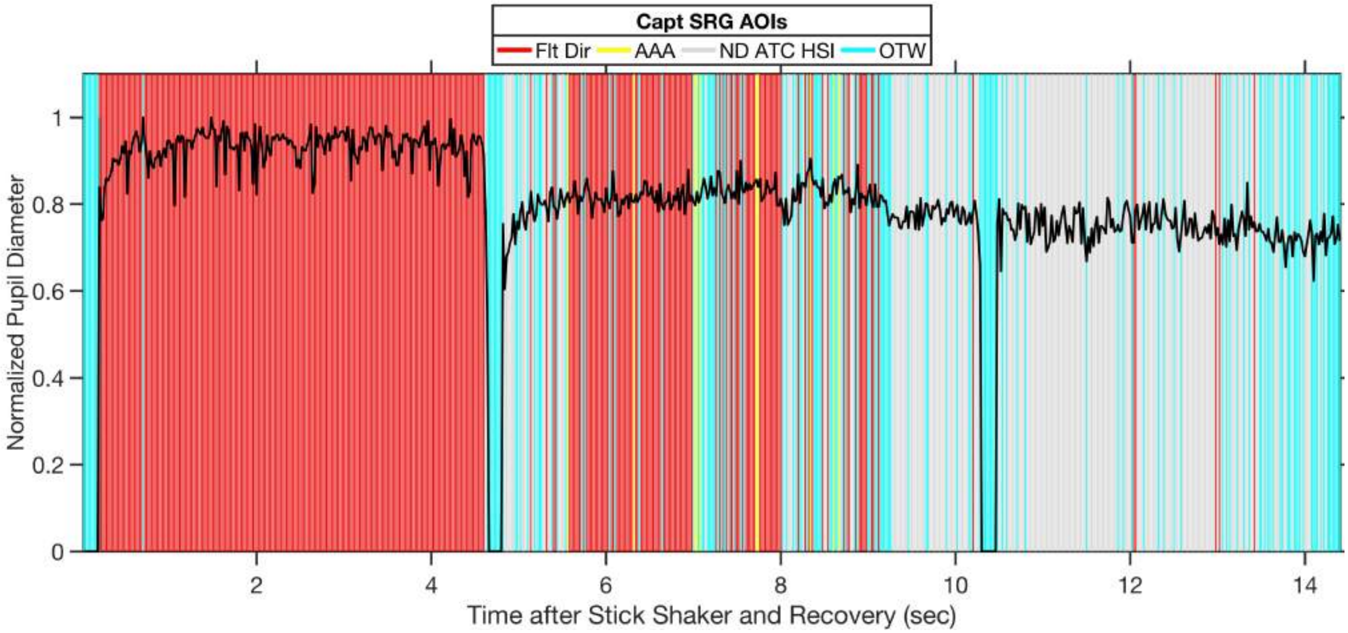

Figure 12: **Example of SRG AOIs and Normalized Pupil Diameter.**

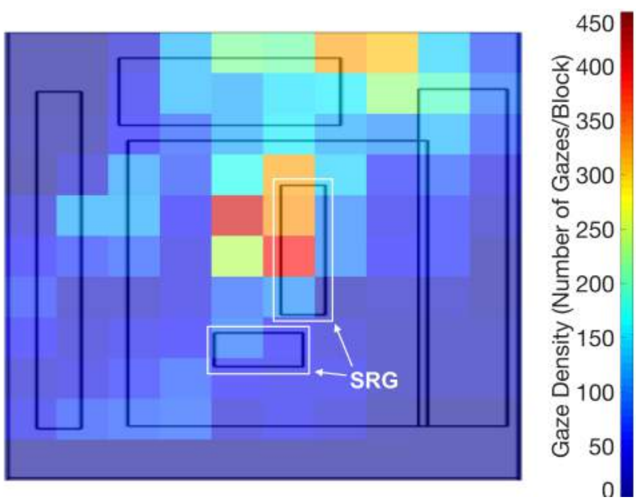

Figure 13: **Aggregate SRG Baseline Heatmap for PFs**

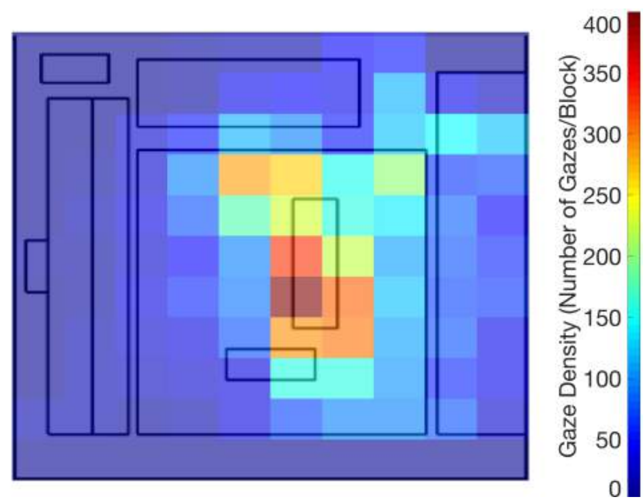

Figure 14: **Aggregate SRG Technnology Heatmap for PFs**

that the crews followed the training to include the throttle guidance in their scan patterns. Further detailed findings regarding SRG from AIME2 are reported in [10] and [9].

Enhanced Synoptic and Simplified ECL

The eSyn / sECL scenarios included off-nominals that required the PF to manually fly the aircraft while the PM used the checklists to determine the aircraft state. The Baseline cases involved the PM, either the Captain or First Officer, to look down onto the LMFD at the standard ECL. For those scenarios that used an simplified ECL, the PM would also look at the eSyn. The flight deck displays for AIME2 were specifically configured such that the synoptics and ECL were in close proximity, for both Baseline and eSyn / sECL scenarios. In some cases, the oculometer system was unable to measure the PM crew member due to his or her head down position when gazing at the LMFD.

The time in task of the sECL scenario begins when the off-nominal error occurred (and an EICAS message appeared) until the PM completed the associated checklist. This time in task across all flight crews in the Baseline cases for the PM focus over specific displays is shown in Figure 15. In other words, the figure shows the temporal distribution of the allocation of cumulative gazes over specific AOIs across all flight crews in the Baseline scenarios.

For comparison, Figure 16 shows the amount of time across all flight crews in the eSyn / sECL technology cases for the PM focus over those same AOIs. The pie charts use the same legend where “Other” refers collectively to the EFB, opposite side ND (OND), and VSD. The significant result is the decrease in sECL time in task from the Baseline case (9%) compared to the eSyn / sECL case (4%).

For the two different off-nominals, the mean time in task

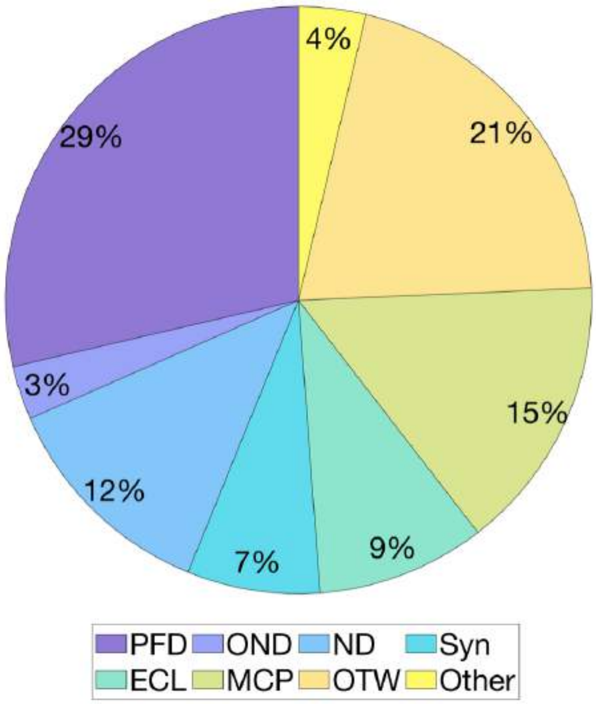

Figure 15: **Aggregate PM Visual Attention Distribution for No Synoptic and with Standard ECL**

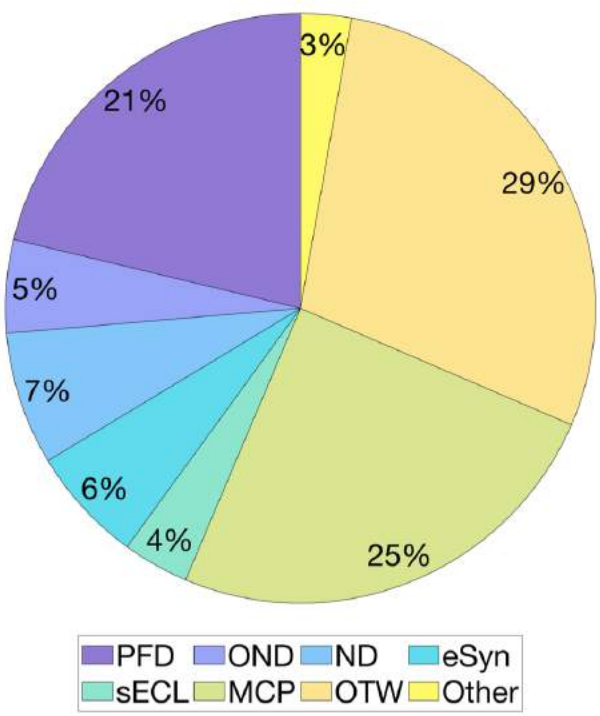

Figure 16: **Aggregate PM Visual Attention Distribution for eSyn and Simplified ECL**

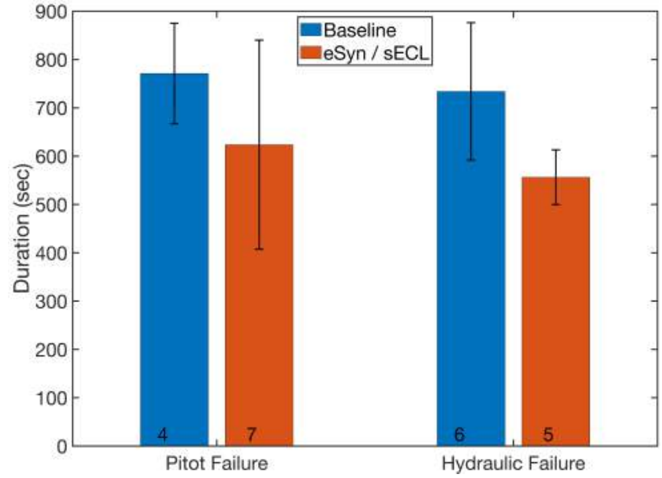

Figure 17: **Comparison of eSyn / sECL PM Mean Time in Task by Off-Nominal.**

spent by the PM in the Baseline and eSyn / sECL cases are compared in Figure 17. In the plot, the blue bars are the Baseline cases with the number of samples given at the bottom of each bar. Sample sizes are also given in the red eSyn / sECL bars. Finally, in the plot, the 1 σ variance values are plotted on each of the colored mean bars.

In Figure 17, note that the eSyn / sECL technology reduced the average amount of time for the PMs to work through the particular electronic checklist by about 2 - 4 minutes.

6. SUMMARY

Each of the display technologies that were evaluated in the RFD were designed to improve airplane state awareness, particularly in off-nominal or complex situations. A high-fidelity flight simulation study was conducted that included a variety of complex pilot-system interactions that occur in current flight decks. The study was comprised of various scenarios designed to induce low and high energy aircraft states coupled with other emulated causal factors in recent accidents. Three different display technologies were evaluated in this study. These technologies include an enhanced airspeed control indication of when the automation is no longer controlling airspeed, a stall recovery guidance algorithm and display concept, and enhanced synoptic diagrams with corresponding simplified electronic checklists. Selected results are presented here, primarily based on data recorded by an oculometer system.

In summary, this analysis is intended to provide insight into how pilots apply visual attention during complex and often off-nominal situations where loss of airplane state awareness can manifest. While oculometer data alone cannot tell the complete story, it can provide important and objective clues. Several of these are presented in this paper. Subsequent AIME studies are planned to build on the insights obtained here and through analyses of other data, to evaluate new systems that can mitigate potential vulnerabilities in an age of increasingly autonomous and complex systems.

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REFERENCES

[1] Airplane State Awareness Joint Safety Analysis Team, "Final Report Analysis and Results," Commercial Aviation Safety Team, Tech. Rep., 2014.

[2] L. J. Kramer, E. T. Evans, T. S. Daniels, S. D. Young, J. R. Barnes, Y. Santiago-Espada, E. T. Dangtran, R. M. Korovin, and C. M. Ferguson, "Evaluation of Technology Concepts for Energy and Automation Awareness in Commercial Airline Flight Decks," in *AIAA Science and Technology Forum and Exposition SciTech*, 2019.

[3] S. D. Young, M. Uijt De Haag, T. Daniels, E. Evans, K. H. Shish, S. Schuet, T. Etherington, and D. Kiggins, "Evaluating Technologies for Improved Airplane State Awareness and Prediction," in *AIAA Infotech Aerospace*. AIAA SciTech, 2016, no. AIAA 2016-2043, p. 2043.

[4] S. D. Young, "Airplane State Awareness and Prediction Technologies – Research Overview (2014-2018)," in *AIAA Science and Technology Forum and Exposition SciTech*, 2019.

[5] E. T. Dill and S. D. Young, "Analysis of Eye-Tracking Data with Regards to the Complexity of Flight Deck Information Automation and Management-Inattentional Blindness, System State Awareness, and EFB Usage," in *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015, p. 2901.

[6] E. T. Dill, S. D. Young, T. S. Daniels, and E. T. Evans, "Analysis of Eye-Tracking Data during Conditions Conducive to Loss of Airplane State Awareness," in *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017, p. 3277.

[7] L. Sherry and R. Mauro, "Design of Cockpit Displays to Explicitly Support Flight Crew Intervention Tasks," in *Digital Avionics Systems Conference (DASC), 2014 IEEE/AIAA 33rd*, 2014, pp. 2B5.1–2B5.13.

[8] T. Lombaerts, S. Schuet, J. Kaneshige, K. H. Shish, and V. Stepanyan, "Stall Recovery Guidance Using an Energy Based Algorithm," in *AIAA Guidance, Navigation, and Control Conference*, 2017, p. 1021.

[9] S. Schuet, T. Lombaerts, V. Stepanyan, J. Kaneshige, G. Hardy, K. Shish, P. Robinson, T. Etherington, L. J. Kramer, E. T. Evans, T. S. Daniels, and S. D. Young, "Piloted Simulation Study Findings on Stall Recovery Guidance," in *AIAA Science and Technology Forum and Exposition SciTech*, 2019.

[10] T. Lombaerts, S. Schuet, V. Stepanyan, J. Kaneshige, G. Hardy, K. Shish, P. Robinson, L. Kramer, T. Etherington, T. Daniels, E. Evans, and S. Young, "Design and Piloted Simulator Evaluation Results of Model Independent Stall Recovery Guidance," in *AIAA Science and Technology Forum and Exposition SciTech*, 2019.

[11] K. Latorella, K. K. Ellis, W. A. Lynn, D. Frasca, D. W. Burdette, C. T. Feigh, and A. L. Douglas, "Dual Oculometer System for Aviation Crew Assessment," in *54th Annual Meeting of the Human Factors and Ergonomics Society*, 2010.

[12] N. Kloosterman, T. Meindertsma, A. Loon, V. Lamme, Y. Bonneh, and T. Donner, "Pupil Size Tracks Perceptual Content and Surprise," *European Journal of Neuroscience*, vol. 41, 03 2015.

[13] A. Landman, E. L. Groen, M. M. R. van Paassen, A. W. Bronkhorst, and M. Mulder, "The Influence of Surprise on Upset Recovery Performance in Airline Pilots," *The International Journal of Aerospace Psychology*, vol. 27, no. 1-2, pp. 2–14, 04 2017. [Online]. Available: https://doi.org/10.1080/10508414.2017.1365610

[14] J. Rivera, A. B. Talone, C. T. Boesser, F. Jentsch, and M. Yeh, "Startle and Surprise on the Flight Deck: Similarities, Differences, and Prevalence," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 58, no. 1, pp. 1047–1051, 2014. [Online]. Available: http://journals.sagepub.com/doi/abs/10.1177/1541931214581219

[15] B. Hoeks and W. J. M. Levelt, "Pupillary Dilation as a Measure of Attention: A Quantitative System Analysis," *Behavior Research Methods, Instruments, & Computers*, vol. 25, no. 1, pp. 16–26, Mar 1993. [Online]. Available: https://doi.org/10.3758/BF03204445

BIOGRAPHY

***Taumi Daniels** received his B.S. degree in electrical engineering from NCSU in 1986, M.S. degree in electrical engineering from Georgia Institute of Technology in 1989 and a Ph.D. in atmospheric science from Hampton University in 2012. He is a research scientist at NASA Langley Research Center. His current research activities include flight simulator testing.*

***Cailin Ferguson** is a student at the University of Michigan pursuing a dual degree in electrical engineering and dance. She will complete her undergraduate studies in April 2020. She was an intern at NASA Langley in the Electromagnetics and Sensors Branch. She is interested in using and designing sensor technologies to measure human performance.*

Ellen Dangtran *is an electrical engineering major and computer science minor at Texas A&M University. She will obtain her bachelors degree in May of 2019. She has interned at CenterPoint Energy in the Power Distribution Protection group and at NASA in the Electromagnetics department. Her research interests include electromagnetics and power systems.*

Rebecca Korovin *is an engineering management, electrical specialization major at The College of New Jersey and will obtain her Bachelor's degree in May 2019. She has interned at Consolidated Edison, Inc. in New York City and at the NASA Langley Research Center in Hampton, VA. Her interests include power engineering with a focus on sustainability and green energy.*