NASA/TM—20205010985

Factors that Influenced Airplane State Awareness Accidents and Incidents
CAST SE-210 Output 2
Report 2 of 6

Randall J. Mumaw
San Jose State University Foundation

Dorrit Billman
San Jose State University Foundation

Michael S. Feary
NASA Ames Research Center

March 2019

NASA STI Program…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—20205010985

Factors that Influenced Airplane State Awareness Accidents and Incidents
CAST SE-210 Output 2
Report 2 of 6

Randall J. Mumaw
San Jose State University Foundation

Dorrit Billman
San Jose State University Foundation

Michael S. Feary
NASA Ames Research Center

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California

March 2019

Available from:

NASA STI Program
STI Support Services
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

This report is also available in electronic form at http://www.sti.nasa.gov
or http://ntrs.nasa.gov/

Table of Contents

Acronyms and Definitions

AC .... Advisory Circular
ADI .... attitude direction indicator
AoA .... angle of attack
ASA .... airplane state awareness
ASRS .... Aviation Safety Reporting System
ATC .... air traffic control
CAST .... Commercial Aviation Safety Team
CFR .... Code of Federal Regulations
CRM .... Crew Resource Management
CWS .... control wheel steering
ECAM .... Electronic Centralized Aircraft Monitor
EGPWS .... Enhanced Ground Proximity Warning System
EICAS .... Engine Indication and Crew Alerting System
FAA .... Federal Aviation Administration
FO .... First Officer
IMC .... Instrument Meteorological Conditions
JSAT .... Joint Safety Analysis Team
kts .... knots
LOC .... loss of control
LOC-I .... Loss of Control In Flight
MCP .... mode control panel
NASA .... National Aeronautics and Space Administration
NTSB .... National Transportation Safety Board
PF .... pilot flying
PFD .... primary flight display
PM .... pilot monitoring
SD .... spatial disorientation
SE-210 .... Safety Enhancement #210
SEs .... Safety Enhancements
SVS .... synthetic visual system
TAWS .... Terrain Awareness and Warning System
TL .... thrust lever
VS .... vertical speed

Factors that Influenced Airplane State Awareness Accidents and Incidents

CAST SE-210 Output 2
Report 2 of 6

Randall J. Mumaw, Dorrit Billman, and Michael S. Feary

Executive Summary

This report is part of a series of reports that address flight deck design and evaluation, written as a response to loss of control accidents. In particular, this activity is directed at failures in airplane state awareness in which the pilot loses awareness of the airplane's energy state or attitude and enters an upset condition. The Commercial Aviation Safety Team (CAST) created a team to analyze a set of incidents and accidents associated with the flight crew's loss of awareness of aircraft attitude or energy state. The CAST activity focused on a set of 18 loss of control (LOC) accidents and incidents. In those events, the pilot seemed to lose awareness of the state of the airplane, especially related to its energy state or its attitude. To understand the roots of that loss of awareness, we analyzed the events in relation to a set of factors that were present in many of them. We show how these factors contributed to lost awareness. Then, we use that understanding to identify potentially useful changes to the flight deck interface and how those flight deck changes could be evaluated.

SE-210 Project Overview

The Commercial Aviation Safety Team (CAST) created a team to analyze a set of incidents and accidents associated with the flight crew's loss of awareness of aircraft attitude or energy state. These events are referred to more broadly as a loss of Airplane State Awareness (ASA), and they are a substantial subset of loss of control (LOC) accidents. A subsequent CAST ASA team developed a set of mitigation strategies—referred to as Safety Enhancements (SEs)—to reduce the likelihood of ASA events occurring in the future. Six of the SEs (SE 200, 207 through 211) requested further research on mitigation strategies. Our work was specifically intended to address research identified in SE-210 Output 2 (see https://www.skybrary.aero/bookshelf/books/2540.pdf).

SE-210 Output 2 addresses the contributions from the flight deck interface in shaping pilot awareness. More specifically, the focus is on assessing or evaluating the flight deck interface to determine how well it supports ASA. We have produced a series of reports on this topic:

1. In a report titled "Overview of research approach and findings," we introduce our research approach and compile our key observations and findings. This provides a summary of how our research method developed and what we found.
2. Part of our work was a more-detailed analysis of the role of awareness in the ASA events. In this report (the current report), titled "Factors that influenced Airplane State Awareness accidents and incidents," we describe a number of factors that contributed to the apparent loss of awareness, or to the resulting loss of control. This analysis demonstrates that pilot attention and understanding of the system are important elements of awareness. This

report also offers proposals for modifications of the interface to mitigate those factors, and then, describes how you might evaluate the effectiveness of those proposed modifications.

3. In a related report, titled “The role of alerting system failures in loss of control accidents,” we analyze how alerting for LOC-related hazards, such as low airspeed, unreliable airspeed, and approach to stall, can fail to lead to an upset recovery. Alerting is the last line of defense against flight path management hazards; it is there to ensure awareness when pilot-driven attention and awareness fail. This report looks at why alerting does not always save the day.

Through our work, we had the opportunity to become more familiar with current evaluation and certification rules, guidance, and practices that define the process for the applicants (equipment manufacturers) and the Federal Aviation Administration (FAA). Evaluation and certification of flight deck interface elements consider a broad range of flight crew performance topics. We narrowed the focus of our work to flight crew awareness, attention, and understanding, and specifically examined these aspects of human performance in relation to relevant rules (e.g., 14 CFR 25.1302) and advisory material (e.g., AC 25.1302-1). This new material offers a more complete description of flight crew performance issues in the context of the flight deck interface; however, no consistent approach for application has been established.

4. In a report titled “Evaluation issues for a flight deck interface,” we attempt to describe the broader scope of flight crew performance issues to show how awareness and attention issues fit within the larger set. We also do an inventory of FAA certification rules to demonstrate that there are not rules that apply to every issue. AC 25.1302 has improved guidance for addressing evaluation of awareness, attention, and understanding, and we hope that our work can contribute to future updates of the guidance material.
5. A related report, titled “Identification of scenarios for system interface design evaluation,” focuses on the operational scenarios that can be used in the context of interface evaluation. It offers several perspectives on how to ensure that pilot or flight crew performance is evaluated in an important operational context. Because it is unlikely that evaluation can be performed for the full range of operational settings, this report offers a method for selecting appropriate scenarios.

Finally, the bulk of our work in this project was focused on methods for evaluating a flight deck interface for how well it supports awareness and its critical elements: attention and understanding.

6. A report titled “Best practices for evaluating flight deck interfaces for transport category aircraft with particulaar relevance to issues of attention, awareness, and understanding” focuses on evaluation techniques and metrics. It considers opportunities to evaluate the interface from early to late stages of development; it considers the various ways in which the interface can fail to support awareness, attention, and understanding; and it summarizes appropriate evaluation methods for different issues. This report draws on the characterization of issues and of scenario selection presented in other reports that are relevant to awareness.

1. Introduction

As stated above, the goal of our effort is to identify methods for evaluating the flight deck interface to determine if an interface element (e.g., a new display) can increase the likelihood that the flight crew will maintain awareness of airplane state; more specifically, will the flight crew develop and maintain attitude awareness or energy state awareness? To identify specific performance issues and then appropriate evaluation methods, we start by analyzing the:

- situations in which ASA accidents and incidents occurred to try to determine what led to the loss of awareness in those situations
- factors that were present in ASA accidents and incidents that may have contributed to the loss of awareness

Ideally, any proposed flight deck interface modifications or refinements will try to prevent these situations or remove these factors. Evaluation measures are then tied to the specific issue that is being addressed.

Note that the evaluation issues referenced in this report are introduced in a separate report ("Evaluation Issues for a Flight Deck Interface," Mumaw, Haworth, Billman, & Feary; 2019). There are 40 evaluation issues in that report that cover a wide range of human performance in the context of systems operation.

2. CAST ASA Contributing Factors

The primary source of information about situations in which the pilot lost ASA is the analysis performed by CAST. The CAST Airplane State Awareness (ASA) Joint Safety Analysis Team (JSAT) analyzed 18 safety events to better understand Loss of Control In flight (LOC-I) and, more specifically, loss of airplane state awareness (CAST, 2014). Figure 1 lists, on the left, the 18 events (a more-specific identifier for each can be found in Table 1). The events in the top half are related to attitude awareness, and those in the bottom half are related to energy-state awareness. Also, note that some of these events were accidents (bolded), and some were incidents (not bolded). The full list in Table 1 identifies other LOC-I events that were considered in this analysis.

The columns of this table provide a set of factors that contributed to one or more events; an "x" indicates that it was relevant for an event. For example, lack of external visual references indicates that the weather conditions were such that the flight crew likely could not see ground references (e.g., horizon). This factor was present in 17 of the 18 events. The right-most column shows the total number of factors in each event. There were at least six and as many as 11.

	Lack of External Visual References	Flight Crew Impairment	Training	Airplane Maintenance	Safety Culture	Invalid Source Data	Distraction	Systems Knowledge	Crew Resource Management	Automation Confusion / Awareness	Ineffective Alerting	Inappropriate Control Actions	Total
Formosa Airlines Saab 340	x	x			x		x	x	x		x		7
Korean Air 747-200F	x			x		x	x		x		x		6
Flash Airlines 737-300	x		x		x		x		x	x	x	x	8
Adam Air 737-400	x		x	x			x	x	x	x	x	x	9
Kenya Airways 737-800	x		x				x		x	x	x	x	7
Aeroflot-Nord 737-500	x	x	x	x	x		x	x	x	x	x	x	11
Gulf Air A320	x		x				x		x		x	x	6
Icelandair 757-200 (Oslo)	x						x		x	x	x	x	6
Armavia A320	x	x			x		x		x	x	x	x	8
Icelandiar 757-200 (Baltimore)	x				x	x	x	x	x	x	x	x	9
Midwest Express 717	x				x	x	x		x		x	x	7
Colgan Air DHC-8-Q400	x	x	x		x		x	x	x	x	x	x	10
Provincial Airlines DHC-8	x		x				x			x	x	x	6
Thomsonfly 737-800	x		x	x	x		x			x	x		7
West Caribbean MD-82	x	x			x		x	x	x	x	x	x	9
XL Airways A320		x	x	x	x	x	x	x	x	x	x		10
Turkish Airlines 737-800	x			x	x	x	x		x	x	x		8
Empire Air ATR-42	x	x			x		x		x	x	x		7
Overall	17	7	9	6	12	5	18	7	16	14	18	12	

Figure 1. Contributing factors identified by the CAST ASA JSAT (CAST, 2014).

While these factors do not have a simple causal relationship to the accidents, it is worth considering how some of these factors might be removed or mitigated by changes to the flight deck interface and might, therefore, improve ASA. More specifically, it might be possible to make changes to the flight deck interface in a way that removes or reduces the effect of some of these factors. Specifically, we consider the following subset of factors, selected because we believe they may lead to useful interventions:

- Automation Confusion/Awareness, which refers to the pilot's lack of understanding about the behavior of the autopilot or autothrottle.
- Invalid Source Data, which refers to a loss of basic airplane data, such as air data.
- Distraction, which refers to situations in which the flight crew was distracted by some other task and failed to focus sufficiently on flying the airplane.
- Inappropriate Control Actions, which refers to pilot actions that were counter to the actions that would have restored the airplane to safe and stable flight; e.g., the pilot rolled away from wings-level.
- Lack of External Visual Reference, which refers to flight in Instrument Meteorological Conditions (IMC) or night conditions where it is not possible to get orienting information from the outside world.
- Crew Resource Management (CRM), which refers to how well the flight crew works together to identify problems and take appropriate actions. In particular, there

were events in which the pilot monitoring (PM) knew that the pilot flying (PF) was making inappropriate control inputs but failed to intervene.

Table 1. Safety Events Considered in this Report

Low-energy or Low-airspeed Events	*Attitude Awareness Events*
Events Considered in the CAST ASA* Effort	Events Considered in the CAST ASA* Effort
Icelandair; 757; Oct. 19, 2002 Midwest Express; 717; May 12, 2005 Provincial Airlines; DHC-8; May 27, 2005 West Caribbean 708; MD-82; Aug. 16, 2005 Thomsonfly; 737-800; Sept. 23, 2007 XL Airways 888T; A320; Nov. 27, 2008 Colgan Air 3407; DHC-8-Q400; Feb.y 12, 2009 Turkish Airways 1951; 737-800; Feb.y 25, 2009 Empire Air 8284; ATR-42; Jan. 27, 2009	Formosa Airlines B-12255; Saab 340B; March 18, 1998 Korean Air 8509; 747-200F; Dec. 22, 1999 Gulf Air 072; A320; Aug. 23, 2000 Icelandair 315; 757-200; Jan. 22, 2002 Flash Airlines 604; 737-300; Jan. 3, 2004 Armavia 967; A320; May 3, 2006 Adam Air 574; 737-400; Jan. 1, 2007 Kenya Airways 507; 737-800; May 5, 2007 Aeroflot Nord 821; 737-500; Sept. 14, 2008
Other Low-energy or Low-airspeed Events	Other Loss of Attitude Awareness Events
Asiana 214; 777; July 6, 2013 Air France 447; A330; June 1, 2009 Aeroperu 603; 757; Oct. 2, 1996 Birgenair 301; 757; Feb. 6. 1996	Aerounion 302; A300-200; April 13, 2010 Afriqiyah 771; A330-200; May 12, 2010 British Airways 277; 767-300; Sept. 17, 2011 ANA; 737-700; Sept. 6, 2011 Scat Airlines; CRJ 200; Jan. 29, 2013

* Commercial Aviation Safety Team Airplane State Awareness; see http://www.cast-safety.org

Also, note that the "ineffective alerting" factor is addressed in-depth in a separate report, titled "The Role of Alerting System Failures in Loss of Control Accidents" (Mumaw, Haworth, & Feary, 2019).

3. CAST ASA Factors

3.1. Autoflight Confusion/(Loss of) Awareness

Figure 1 shows that *14* of the *18* ASA events involved some type of automation confusion or loss of awareness of the automation state. In most of these cases, this confusion/loss of awareness was tied directly to the loss of ASA.

3.1.1. Relevant Events: Energy State Awareness

In three of the CAST ASA accidents and in another more-recent event (Asiana 214), the pilot had a misunderstanding of what the autopilot or autothrottle would do regarding managing airspeed, which led to a low-energy/low-airspeed situation.

- In the Provincial Airlines incident, the pilot used a Vertical Speed mode (VS) to climb, not understanding (or not aware of the mode selected) that this mode for this airplane does *not* manage airspeed. Or, perhaps the crew just failed to monitor the mode's airspeed management. Airspeed bled off as the airplane trimmed nose up.
- In the Turkish Airways 1951 accident, the autopilot mode, due to a radio altitude failure, transitioned into an idle mode that failed to manage airspeed on the approach.

- In the Asiana 214 accident, the pilot's unusual autopilot inputs led to an autothrottle in HOLD mode, which does not manage airspeed. The airspeed bled off on approach.
- In the Thomsonfly incident, the autothrottle failed and the pilot was unaware of it. Again, airspeed bled off on the approach.

Also, in six of the CAST ASA cases—Turkish Airways, Provincial, Thomsonfly, XL Airways, Icelandair, and Colgan—the autopilot pushed the airplane into a nose-high attitude and an approach to stall condition. That is, after the airplane starts slowing, approach to stall occurs because the autopilot is trimming nose up to try to maintain a path (e.g., glideslope) or an altitude.

Comments on these events:

- While in some cases there were automation failures (notably, Thomsonfly), mode confusions typically occur when there is no failure (for example, Asiana). The automation mode is just not understood. In some cases, the confusion stems from the use of sub-modes that behave differently than pilots expect. In some cases, a primary mode is not understood; e.g., the VS mode is used for smooth altitude transitions and pilots may be unaware that it provides no speed protection.
- On approach, airspeed can be decreasing fairly rapidly; this is expected and desired. The problem occurs when it does not stop decreasing when it reaches the target approach speed. Unless the pilot is monitoring at this time, the failure to capture the airspeed will not be seen.
- In some cases, the first low-airspeed alert occurs at stick shaker; there is no other attention getter as airspeed decreases. In the case of Provincial, there was no airspeed alerting at all. In the case of Asiana 214, the alert occurred too low to the ground for any pilot response to be effective in avoiding a crash.
- It is notable that the autopilot has the authority to trim the airplane to such an extreme configuration. One might argue that the combination of airspeed below the mode control panel (MCP) target and the attitude going so far nose-up should lead to some airplane alert.
- This is a case in which the autopilot is focused on a single aspect of the path and is trimming into an unstable configuration. The autopilot should not be able to trim to that degree without some alerting. Another consideration in these nose-high situations is how much thrust and elevator trim will be required to overcome the nose-high attitude.

3.1.2. Relevant Events: Attitude Awareness

In two of the CAST ASA events, pilots failed to put the airplane into a stable autopilot mode, which led to an uncontrolled roll away from wings-level.

- In the Aeroflot Nord event, on approach the autopilot mode kept reverting to a control wheel steering (CWS) mode, which is not a mode that was useful during this phase of flight. The pilot, frustrated by the mode instability, disengaged the autopilot, which had been managing mis-calibrated thrust levers (the pilot was probably unaware of this), and was then unable to manage the unexpected yawing/rolling force on the airplane.
- In the Kenya Airways event, the pilot failed to engage the autopilot, and was unaware that it did not engage. The airplane, being mildly mis-trimmed, rolled away from wings-level, which was not recognized until it was at 35° of bank.

Comments on these events:

- In these attitude awareness events, the pilots got into a minor upset (bank angle in the 30–50° range) due to a misunderstanding of the autopilot state, and this minor upset was mis-handled into a major upset.
- Note that some airplane changes were made to address the issues uncovered. In particular, if the pilot attempts to engage the autopilot on a 737 (as was likely done in the Kenya Airways event) and it fails to engage, there will now be a Warning-level alert, which was not present during this accident. This should prevent the lack of awareness on autopilot state.

3.1.3. Possible Enhancements to the Interface/Information

One option for removing the automation confusion factor is to give pilots more knowledge about mode behavior, for example, through training. However, SE210 is focused on changes to the interface, and placing accurate information on the interface is a more reliable solution than relying on pilot knowledge. Thus, interface changes might be:

- A clear presentation of what the autopilot/autothrottle is doing to manage airspeed: something or nothing, and if something, what airspeed target is being managed.
- Shifting from automation to the consequences of losing automation awareness, there might also be some consideration of adding low-airspeed alerting or enhanced awareness of airspeed as it nears the low end of the airspeed envelope prior to the stick shaker (approach to stall). This issue was also raised by the National Transportation Safety Board (NTSB) report on the Asiana 214 crash.

Another airplane enhancement, which is not a change to the interface, is to use envelope limiting that prevents extreme nose-up pitch trim. This would need to be accompanied with an alerting scheme to indicate the airplane's inability to meet the path or altitude target (because it is prevented from pitching into a stall).

- The change to the interface could be some form of alerting. This alerting could be tied to the envelope limiting and the concerns about failing to meet the path or altitude target. Or, if there is no envelope limiting, the alerting could be tied to the status of pitch trim; specifically, that the airplane is pitching so far nose up that it is approaching a stall situation.

3.1.4. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in a companion report ("Evaluation Issues for a Flight Deck Interface," Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

The primary set of evaluation issues that are relevant here are those linked to *Automation Visibility and Intervention* (#29), which says that interface design should aid the user in being aware of current and impending actions from system automation (autopilot) or any autonomous agents. It also says that it should be clear to the user how to intervene (take control back from the automation/ autonomous agent). The more detailed set of issues say that the user should be able to:

- determine the status of automated or autonomous agents
- determine the actions and/or targets (objectives) of automated actions and whether they are currently engaged

- determine when the automation or autonomous agents has failed or is unable to carry out its actions or achieve its targets
- quickly determine how to intervene when the user wants to take over control from automation or some autonomous agent

The other important issue here is the development of an *Alerting Scheme* (#30), which focuses on aiding the user in identifying important changes to the system and aiding the user in seeing and organizing the full set of items that have been alerted. The more detailed set of issues say:

- When there is a failure or other system change that requires immediate operator attention/awareness, the alerting system uses a salient change to orient the operator to a message or cue, conveys the nature and urgency of the problem, and connects the problem to an action or set of actions for addressing the problem (when actions are needed).
- The alerts are either salient visually and located in the central visual field or attract attention through a salient cue presented through an auditory or tactile modality.
- The alert ensures that there is sufficient time for the flight crew to respond to the hazard.
- When there is more than a single alert, the alerting system will provide a method for prioritizing those that are the most important or urgent to address.

3.1.5. Potential Evaluation Scenarios

For operational tasks:

- Consider scenarios where airspeed is being managed by autopilot/autothrottle to ensure that the interface clearly communicates to the flight crew whether airspeed will be managed. This should include cases in which the autothrottle or autopilot fails; and should identify mode combinations that can lead to confusion about airspeed management.
    - For example, when autothrottle is engaged *but* it will *not* control airspeed to the target on the MCP (e.g., the Asiana HOLD situation, or a VS mode).
- Use a scenario that focuses the autopilot system on maintaining a vertical path or an altitude, it will use nose-up trim to achieve that target at the expense of angle of attack (AoA). Look at how the automation handles this in each scenario.
    - For example, when autopilot is engaged and the airplane is pitching up (due to the autopilot) beyond the point where airspeed drops below the target on the MCP.

For operational context:

- Consider scenarios in which there is a distraction. Introducing a distraction—either totally unrelated to operations or tightly linked to operations—allows the evaluation to focus on how well the interface supports managing attention.
- Consider scenarios that violate expectations. It can be difficult to create an unexpected event in an evaluation setting since, generally, in that setting, the participant expects certain types of events that may not occur frequently in actual operations (e.g., a system failure), and it is, therefore, difficult to simulate the onset of truly unexpected events. One approach for inserting unexpected events is to create strong expectations for other events; that is, tell the study participant that the scenario is about operational context and task A when it is actually about B. Another approach is to create surprises relevant to the interface element being evaluated. For example, if a new navigation and weather

display is being evaluated, useful scenarios might specify external environment changes in possible, but unlikely ways.

Also, note that there is a separate report on the selection of operational scenarios to support evaluation; the report is tilted "Identification of Scenarios for System Interface Design Evaluation." (Mumaw, Billman, & Feary; 2019).

3.1.6. Relevant Performance Measures

Performance measures for this issue center on the pilot's ability to:

- accurately report on the current automation state; specifically, show awareness of:
  - whether autopilot and autothrottle are engaged
  - what autopilot or autothrottle modes are engaged
  - where autopilot or autothrottle targets are coming from (MCP or FMS)
- anticipate airplane behavior based on automation state; specifically determine:
  - whether airspeed will be managed
  - which altitude will be captured
  - whether the airplane will meet waypoint constraints
- determine that a flight path target, presented on the interface, will not be captured by the autopilot or autothrottle; e.g., airspeed in Asiana 214
  - determine when it is necessary to intervene to ensure that flight path targets are met; e.g., if airplane is pitching up into a stall

Many of these questions can be answered through pilots actually interacting with the interface in an operational context. A part-task trainer (up to a full-flight simulator) may be sufficient to create enough of an operational context for evaluating how well a pilot maintains awareness and understands the implications.

3.2. Invalid Source Data/Loss of Air Data

Figure 1 shows that *5* of the *18* ASA events involved invalid source data.

3.2.1. Relevant Events: Energy State Awareness

Loss of air data, through frozen or blocked sensors (pitot tubes, AoA sensors, static ports), was a significant contributor to a loss of ASA in some safety events. The problem occurs when the pilot fails to understand that the airspeed (and/or altitude) indication is invalid and then chases it (or reacts to the related low- or high-airspeed alerts), which can lead into a true low-energy or approach-to-stall event. Various failure scenarios have led to major safety events. While newer airplanes (Boeing 777) attempt to identify and suppress bad data with voting schemes, those schemes don't always work—for example, the 2-out-of-3 voting selects the bad data. Examples of events that were triggered by air data problems are Midwest Express (from the CAST ASA set), AeroPeru, BirgenAir, and Air France 447.

A newer approach (787, A380, A350) is to derive airspeed from the traditional "pressure-based" approach, relying on pitot probes, and also from an AoA-based approach, relying on AoA sensors. By comparing these two independent systems, the air data computer is more likely to, at least, alert on a disagreement. And, in some cases, it can suppress the invalid data and replace it with a good airspeed indication.

Comments on these events:

- Primarily, this type of failure points to the fact that interface (display-based) approaches are limited in mitigating these safety events since it is also important to consider the air data that is feeding the display and the integrity of those data.
- It seems odd—although it is true—that pilots can consider erratic airspeed indications as valid and chase those indications (e.g., pitching down, pitching up). Ideally, when airspeed data are suspect (because of a disagreement), they should "look different" (e.g., coded in a different way, or a label on the display).
- Also, in the case of unreliable airspeed, alerting is often poor: lots of messages that do not seem related to airspeed or air data reliability (especially in older airplanes).

3.2.2. Possible Enhancements to the Interface/Information

It is probably impossible to prevent all sensor failures (due to ice, water, debris, unremoved protective covers, etc.). Therefore, the system needs to develop schemes that ensure that invalid air data are not presented as valid, and that if air data are suspect, they are labeled or coded to reveal that. Possible schemes are:

- Improved central alerting (e.g., Engine Indicating and Crew Alerting System [EICAS]) messages that remove seemingly unrelated messages and focus on or emphasize air data or unreliable airspeed.
- Coding of airspeed or altitude data to show that it is "suspect" or potentially erroneous; the airspeed data (for example) should "look different" so that the pilot does not start chasing airspeed without taking a closer look at the other indications.

3.2.3. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

The primary issue being raised here is *Data Validity* (#20), which says that the interface design should aid the user in knowing when displayed data are erroneous (not valid) or are uncertain (unknown validity). The more detailed set of issues say that the user should be able to easily identify when system data are:

- erroneous; that is, there is a difference in the presentation of the erroneous data vs the valid data
- suspect or uncertain; when there are disagreements from independent sensors or data processors, the data should change appearance or labeling to show that there is some uncertainty about their validity

3.2.4. Potential Evaluation Scenarios

For operational tasks:

- Consider complex scenarios that produce a range of failures in the air data system (could be between the different channels on a pressure-based system, or between different channels on an AoA-based system, or between the two types of systems) to determine how airspeed is presented; specifically, to ensure that invalid or suspect indications are marked as such, or are replaced by some other guidance (AoA, AoA-based airspeed, scale with AoA guidance, etc.).

- Consider also scenarios that produce multiple messages for unreliable airspeed. Ideally, the alert (EICAS/ECAM [Electronic Centralized Aircraft Monitor]) should lead the flight crew to the appropriate non-normal checklist.

For operational contexts:

- Consider the use of time pressure since airspeed indications can change rapidly.
- Consider increased levels of workload to ensure that decision making in this situation does not require significant attentional/processing resources.

3.2.5. Relevant Performance Measures

Performance in this case is initially tied to the display or interface element. A primary goal is to ensure that the display distinguishes between valid and invalid data. This evaluation can be a simple check to confirm that the display changes appropriately in all the various conditions.

Secondarily, operator (pilot) performance can be assessed to determine whether the pilot can reliably identify the invalid data and respond appropriately. Ideally, the pilot response is embedded in an operational context; that is, actually controlling. The setting can be as sophisticated as a full-flight simulator but also a simpler device could be used to generate stimuli.

3.3. Distraction/Attention Allocation

Figure 1 shows that *all 18* ASA events involved some form of distraction, which refers to situations in which the flight crew was engaged in some task and failed to focus sufficiently on flying the airplane. The ASA analysis split distraction out into two categories:

- Cases in which the pilot was focused exclusively on a very narrow set of events or indications and was unable to attend to other relevant information. In some cases, the report concluded that the pilot was spatially disoriented and was unable to recover an accurate orientation. Generally, this phenomenon is referred to as "channelized attention."
- Cases in which there was a more conscious decision to give attention to a task that is not flying or managing the airplane; e.g., deciding to complete paperwork or to troubleshoot a non-normal indication.

3.3.1. Relevant Events: Energy State Awareness

Part of being distracted away from flying the airplane is failing to monitor basic parameters, such as airspeed. When the pilot is flying manually, there may be no alerting on airspeed and it must be maintained through control inputs. For example, the Empire event was one in which the PF did a poor job managing airspeed while flying manually.

The NASA Aviation Safety Reporting System (ASRS) reports also revealed a number of these cases, often showing that the flight crew was distracted and stopped monitoring airspeed. In some cases, the pilot had used speedbrakes to descend or slow down and then later forgot that speedbrakes were deployed. In other examples, such as Colgan, the pilot simply mismanaged thrust. Not all airplanes have autothrottle (especially the smaller, regional aircraft), and airspeed needs to be managed by the pilot for those airplanes. If the pilot fails to monitor to detect errors and close the control loop, airspeed can move away from the desired value. Further, it is rare in these cases to get a "low airspeed" type of alert prior to getting the stick shaker.

Comments on these events:

- Monitoring from the flight crew will fail at some point due to distractions, high workload, etc. When airspeed is being managed through manual flight (pitch, thrust, drag), the system should have an alerting scheme that protects from this monitoring failure. Some recommendations have been made (e.g., NTSB Asiana 214 report) that the low airspeed alerting should take into account factors such as altitude (potential energy), current airspeed, the time required for engine spool-up, and the time for flight crew awareness and response.
- Having better predictability of energy can also be useful to support monitoring frequency.

3.3.2. Relevant Events: Attitude Awareness

A more extreme version of failing to monitor are the events in which the pilot was so focused or overwhelmed that she/he was unable to respond to an alert or an inappropriate maneuver. Sometimes the term "channelized attention" is used to describe this extreme form of a single focus. In the Flash Air event, the pilot seemed to become so confused about an unexpected automation change, that he stopped controlling the airplane and let it roll off 40°. In the Icelandair event (near Baltimore), both pilots were so engaged on the flight controls trying to stabilize the airplane that they were unaware they were each making inputs and fighting against each other.

More extreme are the cases in which a salient alert has been triggered but is insufficient to break a pilot out of his inappropriate flight control inputs. In at least three events (Gulf Air, Icelandair (Oslo), and Armavia), the pilot was pitched down flying toward the terrain. The terrain warning system (e.g., Enhanced Ground Proximity Warning System [EGPWS]) was loudly warning of terrain, but the pilot did not alter his control inputs significantly. Two of these events ended in crashes into the terrain; the other was saved by the co-pilot grabbing the controls away from the pilot.

Similarly, at least four events ended up with the pilot pulling the column aft (commanding a pitch up) while the stick shaker indicated the airplane was stalled. Remarkable here were West Caribbean and Icelandair (Baltimore), which had extended periods of time of alerting.

Comments on these events:

- Two elements are required for these events to become tragic: The PF executing flight path management poorly and the PM failing to intervene. Clearly, there are issues with CRM as well, which is discussed below.
- It is also interesting that a clearly salient (visual and aural) alert fails to jolt the pilot out of his flight control inputs. Little is being done to address this phenomenon (although see Dehais et al., 2013).

3.3.3. Possible Enhancements to the Interface/Information

For the cases in which the flight crew fails to maintain monitoring of critical parameters tied to energy state, it may be possible to provide better cues about where the energy state is headed. That is, there may be a way to provide an earlier indication of when energy state is trending toward an undesirable state.

When reliable monitoring cannot be ensured, it becomes important to shift to some type of alerting scheme. While alerting exists now on airspeed, the low airspeed alerting can occur too late to aid the pilot as mentioned above (e.g., Asiana 214). It may be possible to tie alerting more to airspeed targets than to the bounds of safe airspeed. Another important consideration is an alerting scheme that can overcome channelized attention.

3.3.4. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

A primary evaluation issue is *Monitoring* (#31), which addresses ensuring that the operator maintains a fairly complete and accurate understanding of the state of the system and the world. The more detailed guidance recommends the interface:

- aids the operator in gathering information about the current system state
- makes it easy for the operator to find any information being sought
- aids the operator in determining that the current set of indications are compatible with the current intention (or task)

From monitoring, the flight crew will develop an awareness and an understanding of both the current state of the system and of how that state is changing relative to the operational objectives (e.g., managing energy while attempting to slow down for final approach). Therefore, also relevant are evaluations tied to *System/State Awareness* (#32) and *Situation Assessment* (#33).

Evaluation for System/State Awareness is relevant to ensuring that the user can quickly and easily assess the current state of the system as it relates to its operation, and any impending threats to system safety. The more detailed issue says that the user always has available a view of the system that supports a quickly acquired understanding.

Evaluation for Situation Assessment is relevant to supporting the operator's higher-level, integrated assessment of the situation and of the evolving responses in that situation. The more detailed set of issues say the user should be able to:

- understand the status of system functions; e.g., the airplane can reach its planned destination and land, or airplane energy is being managed on approach
- determine how operator actions are affecting the achievement of operational goals, and if they are not, what actions are needed

The other important issue here is the development of an *Alerting Scheme* (#30), which focuses on aiding the user in identifying important changes to the system, and aiding the user in seeing and organizing the full set of items that have been alerted. The more detailed set of issues say:

- When there is a failure or other system change that requires immediate operator attention/awareness, the alerting system uses a salient change to orient the operator to a message or cue, conveys the nature and urgency of the problem, and connects the problem to an action or set of actions for addressing the problem (when actions are needed).
- The alerts are either salient visually and located in the central visual field or attract attention through a salient cue presented through an auditory or tactile modality.

- The alert ensures that there is sufficient time for the flight crew to respond to the hazard.
- When there is more than a single alert, the alerting system will provide a method for prioritizing those that are the most important or urgent to address.

The flight deck interface can play a role in helping the flight crew manage distractions. One evaluation issue that is relevant is *Task Management* (#35). The interface design should aid the user in attending to the appropriate system information at the appropriate time, and in understanding which tasks have the highest priority. The more detailed issues relevant here are:

- The user can see what tasks currently have the highest priority (or can determine the urgency for addressing specific tasks).
- Relative to interruption, the user can:
  - create a reminder tied to a task/action
  - create a reminder tied to passage of time
  - "book mark" a place in a procedure/task or there is a record of actions so you can recall which actions were completed and which were not

Also relevant to managing distraction is any role the flight deck interface can play in managing crew resources to ensure that some crew member remains engaged with flying the airplane, which is captured by *Coordinated Crew Actions* (#40). The interface design should aid the users in being aware of and coordinating with the actions of other users, including those users or agents that are not human. The more detailed issues say to:

- Communicate directly with other crew members in real time.
- Remain aware of the actions of other crew members, including automated or autonomous agents.
- Coordinate with others (other crew members or automated agents) to assign tasks or negotiate about task assignment (allocate tasks across crew members).

3.3.5. Potential Evaluation Scenarios

For operational tasks:

- Look first at scenarios that lead to low airspeed in various flight phases to determine when the alert occurs and how much time the flight crew has to respond to it.
- Look at when airspeed is *not* being managed by the automation (i.e., manual control), and the current airspeed has passed the target airspeed on the MCP by more than 4 or 5 kts (for example, but this will depend on flight phase).

For operational contexts:

- Distraction is the key element for these scenarios and there are a number of ways to introduce distraction to an operational setting.
  - Introduce an event unrelated to operations, such as a person interrupting with a minor task (e.g., reporting an unruly passenger) or an activity overtaking current efforts (e.g., spilling coffee on a laptop).
  - Introduce an event related to normal operations, such as an air traffic control (ATC) call or a traffic advisory.
  - Introduce a system failure or emergency that requires immediate attention.

- While this is difficult, if not impossible, to replicate in a simulator setting, there is value in creating scenarios that lead a pilot into channelized attention. To understand how to break someone out of that mindset, it is essential to genuinely create the phenomenon.

- The goal of the distraction is to create another task for the flight crew that needs to be addressed immediately because there is a demand from another person, or it has high importance.

3.3.6. Relevant Performance Measures

At the level of the individual pilot, the most relevant measure is the pilot's ability to maintain an awareness of critical flight path parameters. Even when distractions occur, the pilot should take action to ensure that he/she is staying on top of changes to these parameters. Monitoring may not occur at a consistent frequency. For example, there may be a need to sample more when airspeed is in a period of change. Eye tracking is one rough measure of the pilot's actions to monitor, but looking and awareness can be different (see the fuller discussion in the companion report).

This issue of distraction is most relevant to the behavior of the full crew. When problems arise, the flight crew needs to ensure that the PF continues to manage the flight path. It is generally fine if the other pilot is distracted by an important secondary task for a while. Thus, measurement in this case relates to the communication with the flight crew and their ability to manage tasks in the presence of the distraction

3.4. Inappropriate Control Actions

Figure 1 shows that *12* of the *18* ASA events involved the pilot making inappropriate control inputs, which are control inputs that make an upset condition worse. For example, inputs to increase pitch attitude (instead of decreasing pitch attitude) in response to a stick shaker. These actions may be indicative of a loss of ASA, or they may represent a poor understanding of the appropriate recovery maneuvers.

3.4.1. Relevant Events: Energy State Awareness

The Air France 447 and Colgan 3407 accidents brought significant attention to a pilot pulling back on the controller in response to a stall event, against training on responding to stall events. In the CAST ASA set, three other events showed the same pilot response. For Icelandair (Baltimore), Provincial, and West Caribbean, the pilot made a sustained input for nose-up pitch. West Caribbean was very similar to Air France in that the column was held aft as the airplane dropped more than 30,000 feet in a pitch-up attitude.

Comments on these events:

- The FAA now requires training that directly addresses the stall or approach to stall situation to ensure that pilots get accurate training on responding to these types of upsets.
- Ideally, a stall is prevented and there is no need to recover, but it is also worth considering how to support appropriate recovery actions when an upset occurs.

3.4.2. Relevant Events: Attitude Awareness

The CAST ASA work (based on a Boeing analysis) indicated that commercial airplanes can produce spatial disorientation (SD) in one of two ways: a sub-threshold roll or a somatogravic illusion

(Mumaw et al., 2015). The somatogravic illusion is a confusion between acceleration from behind the body and a sensation of pitching up. The sudden acceleration that is experienced by pilots in a go-around maneuver can be perceived as a sudden pitching up moment, especially if external visual information is degraded by IMC or darkness.

In the Gulf Air and Armavia accidents and the Icelandair (Oslo) incident, pilots were conducting a go-around with poor visibility. These were cases in which the approach was given up and a go-around initiated from a position different from what is typically trained. After a short period of climbing at a high rate, the pilot, in each case, pitched the airplane down to a nose-down attitude. They either continued that descent into the ground, or, in the Icelandair case, the co-pilot grabbed the controls and pulled hard for a climb. Other more-recent accidents have had similar patterns (e.g., the Scat Airlines CRJ-200 accident in Kazakhstan in January of 2013).

Three other events were tied to the sub-threshold roll form of spatial disorientation. Specifically, pilots in the Flash Airlines, Kenya Airways, and Aeroflot Nord events all made predominant control inputs away from wings-level, resulting in a roll off and crash.

Comments on these events:

- These illusions are powerful, and pilots are unable to break out of the illusion. In the pitch-down (somatogravic) illusions, pilots have continued to maintain nose-down inputs even when the terrain alerting system is saying, "pull up."
- In terms of trying to mitigate the roll-away-from-wings-level events, Boeing has developed an enhanced alerting scheme to present roll guidance whenever the airplane rolls past 45°. The existing bank angle alerting provides no guidance, but only alerts on the hazard: "bank angle."

3.4.3. Possible Enhancements to the Interface/Information

One potential enhancement is to find a way to make the Terrain Awareness and Warning System (TAWS) alerting effective. Influences on pilot attention may prevent them from breaking out of their focus on the pitch issue to be affected by the TAWS alert. Some work (e.g., Dehais et al., 2013) has tried to develop schemes to break pilots out of a channelized attention so that they are able to attend to the new alerts occurring.

Generally, the existence of these inappropriate control inputs suggests that the flight deck interface should provide guidance on control inputs. Some airplanes already have "stick pushers" that force the column or side stick forward when the airplane stalls. In some of the safety events (e.g., Colgan), the pilot took the wrong action by overcoming the additional stick pusher force. Thus, other types of cues should be explored for guiding the appropriate inputs.

3.4.4. Potential Evaluation Scenarios

For operational tasks:

- Only very specialized flight simulation devices can effectively replicate these types of vestibular illusions. It is difficult to imagine a scenario in a standard full-flight simulator that would allow an investigation into the attitude awareness events.
- For the stall events, the pilot should be placed in an unexpected stall to determine how well he/she can make appropriate control inputs.

For operational context:

- The upset events are always unexpected. Pilots gets surprised that they are at an attitude that was unexpected, and their inputs are sometimes confused. Thus, an element of surprise or unexpectedness should be maintained in the scenario.
- Spatial disorientation and confusion about attitude tends to occur when there are no external references for attitude. The scenario should be at night or in IMC to remove the horizon or other cues to orientation.

3.4.5. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

A major element of performance for these events is getting the pilot to make appropriate flight control inputs, which is an evaluation of *Task Performance* (#26). The interface design should support accurate, efficient, and complete performance of all anticipated system tasks, both normal and non-normal. The more detailed issues say:

- The user can perform each normal and non-normal task accurately, efficiently, and completely through the system interface (after some level of proficiency has been achieved through training).
- The task performance errors that are made during initial operator training and performance evaluation are errors that were anticipated by the interface design and are very unlikely to lead to undesirable outcomes.

For the issue concerning the failure to respond to alerts when there is a vestibular illusion, the focus should be on ensuring that alerts are salient and get the pilot's attention. Therefore, evaluation should focus on the *Alerting Scheme* (#30), which should aid the user in identifying important changes to the system, and it should aid the user in seeing and organizing the full set of items that have been alerted. The more detailed issues say:

- When there is a failure or other system change that requires immediate operator attention/awareness, the alerting system uses a salient change to orient the operator to a message or cue, conveys the nature and severity/urgency of the problem, and connects the problem to an action or set of actions for addressing the problem (when actions are needed).
- The alerts are either salient visually and located in the central visual field or attract attention through a salient cue presented through an auditory or tactile modality.

3.4.6. Relevant Performance Measures

Performance measures should focus on control inputs. How quickly do the pilot actions on the controls help to reduce the upset and return to a stable flight regime. In some cases, appropriate actions may initially not correct the situation (e.g., timing on adding thrust in a stall condition), but they should not make the upset worse. Other concerns might be on maintaining altitude and course, but these should be secondary to returning to a stable flight regime.

3.5. Lack of External Visual Reference

Figure 1 shows that *17* of the *18* ASA events were situations in which it is likely that the flight crew had no external visual reference (e.g., terrain or a horizon).

3.5.1. Relevant Events: Attitude Awareness

The loss of any external reference to the terrain means that there is no horizon that aids the pilot in judging roll and pitch attitude. The pilot becomes completely reliant on the airplane's instruments (and his/her vestibular system). While the attitude direction indicator (ADI) provides that information, studies have shown that the ADI can be confusing to pilots when the current attitude is unexpected and they can misinterpret the direction of bank roughly 4-8% of the time (Beringer et al., 1975). As we described above, three of the attitude state awareness events (Flash Air, Kenya Airways, and Aeroflot Nord) involved the pilot rolling away from wings-level. This response is unlikely when the pilot has an external view of the horizon that is equivalent to day-time VMC.

3.5.2. Possible Enhancements to the Interface/Information

The external view can largely be replaced by a synthetic visual system (SVS) that presents a representation of the terrain on the primary flight display (PFD) (instead of the standard brown lower half). Ellis et al. (2017) have been developing and evaluating these types of displays and trying to understand the extent to which a wide SVS display can provide the same cues for orientation as an external view.

Others have developed technologies that can help pilots maintain an awareness of attitude without looking at the ADI. One option is a "Malcolm Horizon" (Comstock et al., 2003), which projects a bright 0° pitch and roll line around the flight deck environment. This cue is much larger than any display-based horizon cue and takes advantage of the pilot's peripheral vision to detect changes to attitude. Another approach is to use an auditory cue (e.g., Brungart & Simpson, 2008) that changes as pitch or roll attitude changes.

3.5.3. Potential Evaluation Scenarios

For operational tasks:

- The scenario should present the pilot with the airplane in an unexpected attitude with the requirement to bring it back to wings-level. This can start from minor upsets (30–40°) or much larger upsets (90–120°). The initial airplane attitude should be unexpected.

For operational context:

- Surprise is a useful element of these scenarios. Ideally, it is possible to conduct at least one trial in which the pilot does not expect an upset or unusual attitude. However, this level of surprise cannot be sustained.

3.5.4. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

As in Section 3.4, the primary element of performance for these events is getting the pilot to make appropriate flight control inputs, which is an evaluation of *Task Performance* (#26). The interface design should support accurate, efficient, and complete performance of all anticipated system tasks, both normal and non-normal. The more detailed issues say:

- The user can perform each normal and non-normal task accurately, efficiently, and completely through the system interface (after some level of proficiency has been achieved through training).
- The task performance errors that are made during initial operator training and performance evaluation are errors that were anticipated by the interface design and are very unlikely to lead to undesirable outcomes.

3.5.5. Relevant Performance Measures

Appropriate performance measures, similar to those in Section 3.4, are focused on determining the correct flight control inputs. When pilots understand their current attitude, they can correct an upset and return the airplane to a stable flight regime. Initial flight control inputs and the time to return to wings-level are two relevant measures.

3.6. Crew Resource Management

Figure 1 shows that *16* of the *18* ASA events involved some type of failure in CRM.

3.6.1. Relevant Events: Attitude Awareness

There was a range of CRM issues identified in these events, but we focus on the subset tied most directly to loss of control. From this point of view, there were two important findings:

- Poorly coordinated use of controls; specifically, having both pilots on the controls at the same time.
- The failure of the PM to intervene when he/she is aware that the PF is not managing the airplane well.

In the Kenya Airways, Armavia, and Midwest events from the CAST ASA set, there were periods of time when both pilots were on the controls in an uncoordinated fashion. Typically, in response to an upset, the PM also took the controls and made inputs. In one case, Icelandair (Oslo), the PM's actions on the wheel and column saved the airplane. The First Officer (FO) was able to overpower the Captain's inputs to keep the airplane from continuing a steep dive into the terrain.

Regarding the second issue, in Flash Air, Gulf Air, and West Caribbean, the FO seemed to understand that the Captain was confused and making inappropriate control inputs, but they took no action to correct the situation.

Comments on these events:

- While many airlines use training scenarios that focus on "incapacitation," that concept is typically used to refer to more extreme forms of incapacitation, such as becoming unconscious. When the Captain is upright, on the controls, and talking, it is probably more difficult to see this behavior as incapacitation. This latter case is sometimes referred to as "subtle incapacitation." CRM training needs to progress to include these subtler forms of incapacitation where the PF is failing to understand the situation and is making inappropriate control inputs.
- The dual use of controls is probably a poor response to seeing the PF fail to manage the situation. However, if the PF is still on the controls, the inputs from the PM will

have limited effect. It would be better to truly intervene and have the PM take command of the airplane. In particular, Airbus controls work such that dual inputs are "summed," and it is, therefore, difficult for each pilot to know what effect he/she is having on the overall control input.

- For some airplanes (e.g., Boeing), the controls are linked and it is easier to determine that the other pilot is making inputs because you can feel those inputs. In other airplanes (e.g., Airbus), the controls are independent (not linked) and there is an alert to indicate that both pilots are applying force to the controls. Unfortunately, that alert can be suppressed when more important alerts, such as for stall, are active (which actually occurred in the Air France 447 accident).

3.6.2. Potential Evaluation Scenarios

For operational tasks:

- To evaluate situations in which both pilots are on the controls, the scenario could lead to a minor upset, followed by the PM (a confederate) making control inputs without announcing them. It is then up to the PF to recognize that there are additional inputs and take the appropriate actions to better coordinate control inputs.
- Regarding subtle incapacitation, there is value in creating situations in which pilots can begin to understand the necessary actions for intervening when the PF is confused and unable to recover the airplane from an upset. In the extreme, the "incapacitated" PF should not relent the controls easily, requiring the PM to practice methods for taking command.

For operational context:

- A common trait in these types of situations is that the flight crew is overwhelmed, all of their cognitive resources going into trying to understand what is happening with the airplane; why it is upset. The scenario can add cognitive workload in a number of ways. Most directly, by putting the airplane in an upset. There are also methods for just adding workload but these should be tied to flying/operating/managing the airplane. Artificial secondary tasks can increase workload but also take attention away from the airplane interface, which is where the new cues should be for recognizing the dual inputs.

3.6.3. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

A primary issue for evaluation concerns *Coordinated Crew Actions* (#40). The interface design should aid the users in being aware of and coordinating with the actions of other users, including those users or agents that are not human. Specifically, assess that the user can:

- communicate directly with other crew members in real time
- remain aware of the actions of other crew members, including automated or autonomous agents
- coordinate with others (other crew members or automated agents) to assign tasks or negotiate about task assignment (allocate tasks across crew members)

3.6.4. Relevant Performance Measures

There are two issues here and each points to performance measures. For the issue of control coordination, one aspect of performance is recognition/detection of the unexpected inputs. After that occurs, the PF also needs to find a way to re-establish a single source of input on the controls. The behavior is largely communication between the two pilots.

For intervening when one pilot is incapacitated, again appropriate behaviors need to include communications. It is unlikely that actions on the controls will be sufficient, unless there is a way to "lock out" the incapacitated pilot from the controls.

4. Accident Situations

In addition to exploring how the CAST ASA factors came together to create situations that could lead to loss of awareness, we also identified a few less common—but worth mentioning—situations that were tied to loss of awareness in the accident/incident set.

4.1. Mismanaged Lateral Force

4.1.1. Relevant Events: Attitude Awareness

In a number of accidents and incidents, the airplane was subject to a lateral force of some kind that the pilot needed to manage manually. The force can be from the airplane being mis-trimmed (not trimmed to maintain wings-level); from asymmetric forces, such as thrust levers not being aligned or being mis-calibrated or engine loss; from flight control surfaces such as a rudder that is inadvertently moved; or other causes of lateral force on the airplane. In some cases, the autopilot is managing these forces for a period of time and then the autopilot is disconnected or runs out of authority to manage the force. For example:

- In the Formosa accident, the airplane was compromised by system losses and was flying with asymmetric thrust. The pilot, flying manually due to loss of autopilot, was unable to manage the asymmetry and allowed the airplane to slowly roll away from wings-level. He became confused about what was happening and lost control of the airplane.
- In the Aeroflot Nord accident, the thrust levers (TLs) were mis-calibrated. When the autothrottle was engaged, it staggered the TLs to maintain equivalent thrust across the two engines. After the autothrottle was disengaged, the pilot aligned the TLs, which led to asymmetric thrust, which this was managed initially by the autopilot. Later, the autopilot was disengaged, and the pilot was unable to manage the asymmetric thrust, leading to a roll away from wings-level.
- In the ANA incident, the pilot inadvertently made large rudder trim inputs (intending to unlock the flight deck door). The autopilot was engaged and initially managed the lateral force but eventually the autopilot reached the limits of its authority and the airplane started to roll away from wings-level.
- In the Kenya Airways accident, the flight crew seemed to intend to engage the autopilot but somehow failed to engage it. The airplane was not perfectly trimmed, and without any pilot or autopilot inputs on the controls, it started to roll away slowly from wings-level.

- The Adam Air accident played out in a similar way: not trimmed perfectly and no pilot or autopilot control inputs, leading to rolling away slowly from wings-level.
- In the case of the British Airways 767 incident, the flight crew had actually shut down one engine at a point during the flight. At that point, they were managing the thrust asymmetry. However, later in the flight as they were descending for an approach, they forgot about the thrust asymmetry and stopped managing it. This led to a slow roll off that was caught fairly quickly by the PM.

Comments on these events:

- The slow roll rate that occurred in each event is relevant because the human vestibular system is unable to detect these slow rolls; it is sub-threshold. Therefore, the pilot can transition into a bank angle that is quite different from the one expected—e.g., being banked beyond 35° instead of being wings-level.
- Another element worth noting is that these events, as described here, started out with bank angles that would not necessarily lead to a loss of control; they were minor upsets that could have been easily managed. However, the initial upset was made worse by inappropriate pilot inputs. In each case, one pilot (and sometimes both pilots) rolled the airplane further away from wings-level, leading to the loss of control situation.
- The final element is that, in most cases, the PM or someone else in the flight deck understood that the control inputs were inappropriate but failed to intervene effectively. The person who did not suffer from spatial disorientation (who understood how to roll back to wings-level) failed to take the controls from the PF)

4.1.2. Possible Enhancements to the Interface/Iinformation

Boeing has already made changes to the 737 alerting to address some of these issues:

- In the case in which the autopilot fails to maintain the airplane in a wings-level configuration and the pilot needs to intervene, Boeing has developed an alerting scheme to make pilots aware that the autopilot can no longer manage the airplane.
- In the case in which the flight crew fails to engage the autopilot, there is now a salient alert on the 737 to let the flight crew know that they failed to engage autopilot.

An alternative to alerting is to provide guidance on the control input since, in these events, pilots were making control inputs in the wrong direction. Boeing has also recently developed a display element on the PFD that gives roll guidance to the pilot in the form of a roll arrow and a voice aural.

4.1.3. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

One goal here is to get the pilot to resolve a minor upset (airplane rolled away or rolling away from wings-level) by taking the appropriate actions on the controls. Therefore, evaluation of *Task Performance* (#26) is relevant. The interface design should support accurate, efficient, and complete performance of all anticipated system tasks, both normal and non-normal. The more detailed issues say:

- The user can perform each normal and non-normal task accurately, efficiently, and completely through the system interface (after some level of proficiency has been achieved through training).
- The task performance errors that are made during initial operator training and performance evaluation are errors that were anticipated by the interface design and are very unlikely to lead to undesirable outcomes.

4.1.4. Scenario Proposal to Evaluate an Interface Element

For operational tasks:

- Because these events involve a sub-threshold roll, it is possible to develop a scenario in a fixed-base simulator. If the pilot can be distracted away from monitoring the PFD (or other flight instruments), the airplane can be moved to a different roll attitude. Then the pilot will need to recover the airplane to wings-level without significantly worsening the loss of control situation. The PM would also have to be distracted from monitoring the flight path.

For operational context:

- Distraction is a key element for these scenarios and there are a number of ways to introduce distraction to an operational setting.
  - Introduce an event unrelated to operations, such as a person interrupting with a minor task (e.g., reporting an unruly passenger) or an activity overtaking current efforts (e.g., spilling coffee on a laptop).
  - Introduce an event related to normal operations, such as an ATC call or a traffic advisory.
  - Introduce a system failure or emergency that requires immediate attention.

  While this is difficult, if not impossible, to replicate in a simulator setting, there is value in creating scenarios that lead a pilot into channelized attention. To understand how to break someone out of that mindset, it is essential to genuinely create the phenomenon.

4.1.5. Relevant Performance Measures

The primary performance measure for these events is the recognition that there is an unintended lateral force on the airplane that needs to be removed or managed. When the initial upset occurs, or as it is developing, the pilot needs to see that it is occurring. That recognition should lead to both managing the airplane back into a stable flight regime and also identifying and removing the unintended lateral force.

4.2. Used Wrong Airspeed Target / Intentional Violations / Inadvertent Loss of Protections

4.2.1. Relevant Events

These are situations in which the flight crew sets up a low-energy situation. In some cases, the flight crew inputs an incorrect airspeed target to the autoflight system, which can lead to a stick shaker. Another path to a low airspeed or approach to stall are actions taken by the pilot, that is, the pilot creating a low-energy condition. For example, in West Caribbean, the pilot attempted to push airplane performance beyond what the airplane was capable of. In this case, the pilot held the column aft for 90 seconds despite having the stall warning sounding the entire time. There are other cases as well in which the pilots took actions that set them up for a real (XL Airways) or invalid stick shaker (Colgan) and led to loss of control scenarios.

Possible enhancements to the interface/information:

- The design goal here is to help flight crews realize that they have created an undesirable situation. Ideally, the interface aids them in understanding their situation, especially as it relates to energy management.
  - The interface can provide some indication of where energy is headed.

4.2.2. Flight Deck Interface Evaluation Issue(s)

A wide range of evaluation issues is identified in the companion report (Mumaw, Haworth, Billman, & Feary; 2019). The numbers here refer to the evaluation issue numbers in that report.

A primary evaluation issue is *Monitoring* (#31), which addresses ensuring that the operator maintains a fairly complete and accurate understanding of the state of the system and the world. The more detailed guidance recommends:

- The interface aids the operator in gathering information about the current system state.
- The interface makes it easy for the operator to find any information being sought.
- The interface aids the operator in determining that the current set of indications are compatible with the current intention (or task).

From monitoring, the flight crew will develop an awareness and an understanding of both the current state of the system and of how that state is changing relative to the operational objectives (e.g., managing energy while attempting to slow down for final approach). Therefore, also relevant are evaluations tied to *System/State Awareness* (#32) and *Situation Assessment* (#33).

Evaluation for System/State Awareness is relevant to ensuring that the user can quickly and easily assess the current state of the system as it relates to its operation, and any impending threats to system safety. The more detailed issue says that the user:

- always has available a view of the system that supports a quickly acquired understanding

Evaluation for Situation Assessment is relevant to supporting the operator's higher-level, integrated assessment of the situation and of the evolving responses in that situation. The more detailed set of issues say that the user should be able to:

- understand the status of system functions; e.g., the airplane can reach its planned destination and land, or airplane energy is being managed on approach
- determine how operator actions are affecting the achievement of operational goals, and if they are not, what actions are needed.

4.2.3. Scenario Proposal to Evaluate an Interface Element

For operational tasks:

- create undesirable low-energy/low-airspeed/high-AoA situations to see if the flight crew can recognize that they need to take some action

For operational context:

- Distraction is a key element for these scenarios and there are a number of ways to introduce distraction to an operational setting.
  - Introduce an event unrelated to operations, such as a person interrupting with a minor task (e.g., reporting an unruly passenger) or an activity overtaking current efforts (e.g., spilling coffee on a laptop).
  - Introduce an event related to normal operations, such as an ATC call or a traffic advisory.
  - Introduce a system failure or emergency that requires immediate attention.

  While this is difficult, if not impossible, to replicate in a simulator setting, there is value in creating scenarios that lead a pilot into channelized attention. To understand how to break someone out of that mindset, it is essential to genuinely create the phenomenon.

4.2.4.Relevant Performance Measures

The key element of performance is the recognition element. The pilot or flight crew needs to be able to recognize and point out (or call out) the inappropriate configuration.

5. Summary and Conclusions

In this report, we identified a number of flight situations or contextual factors that could lead to loss of airplane state awareness, which in turn can lead to loss of control. The goal for identifying and describing these situations is to consider:

- changes to the flight deck design that have potential for removing or mitigating these factors or situations
- the aspects of the flight deck interface that should be evaluated as it relates to the ways in which it supports flight crew performance
- considerations in developing evaluation scenarios
- aspects of human performance that are relevant for assessing the flight deck interface

We reviewed relevant accidents and incidents to identify and illustrate the types of factors and situations that can lead to loss of awareness. Each safety event is unique but the CAST ASA work identified factors that occurred in a number of these events.

References

Beringer, D.B., Williges, R.C., & Roscoe, S.N. (1975). The transition of experienced pilots to a frequency-separated aircraft attitude display. *Human Factors, 17*(4), 401–414.

Brungart, D.S., & Simpson, B.D. (2008). Design, validation and in-flight evaluation of an auditory attitude indicator based on pilot-selected music. *Proceedings of the 14th International Conference on Auditory Display*, Paris, France, June 24–27.

Commercial Aviation Safety Team (2014). Airplane State Awareness Joint Safety Analysis Team; Final report: Analysis and results. https://www.skybrary.aero/bookshelf/books/2999.pdf

Comstock, J.R., Jones, L.C., & Pope, A.T. (2003). The effectiveness of various attitude indicator display sizes on attitude maintenance in a part-task simulation. *Human Factors, 47*(1).

Dehais, F., Causse, M., Vachon, F., Regis, N., Menant, E., & Tremblay, S. (2013). Failure to detect critical auditory alerts in the cockpit: Evidence for inattentional deafness. *Human Factors, 56*(4): pp. 631–644.

Ellis, K., Prinzel, L.J., Arthur, J.J., Nicholas, S.N., Kiggins, D., Verstynen, H., Hubbs, C., & Wilkerson, J. (2017). Design considerations for attitude state awareness and prevention of entry into unusual attitudes. *Proceedings of the 19th International Symposium on Aviation Psychology*; 8–11 May 2017; Dayton, OH.

Mumaw, R.J., Billman, D., & Feary, M. (2019). *Identification of Scenarios for System Interface Design Evaluation.* NASA/TM-20205010988.

Mumaw, R.J., Groen, E., Fucke, L., Anderson, R., Bos, J, & Houben, M. (2015). A new tool for analyzing the potential influence of vestibular illusions. *Proceedings of the International Society of Air Safety Investigators*, Augsburg, Germany.

Mumaw, R.J., Haworth, L., Billman, D., & Feary, M. (2019). *Evaluation Issues for a Flight Deck Interface.* NASA/TM-20205010986.

Mumaw, R.J., Haworth, L., & Feary, M. (2019). The Role of Alerting System Failures in Loss of Control Accidents. NASA/TM-2019-220176.