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Evaluation Issues for a Flight Deck Interface
CAST SE-210 Output 2
Report 4 of 6

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March 2019

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Acronyms and Definitions

AC............................Advisory Circular
AOC..........................Airlines Operations Center
ATC ....air traffic control
CAST ....Commercial Aviation Safety Team
CFR...........................Code of Federal Regulations
CIE............................International Commission on Illumination
COTS ....Commercial Off the Shelf
CVD..........................color vision deficiency
FAA ....Federal Aviation Administration
FMEA ....Failure Modes and Effects Analysis
FMS ....Flight Managment System
HFDS ....Human Factors Design Standard
HUD..........................head-up display
ICAO.........................International Civil Aviation Organization
LOC ....loss of control
NASA ....National Aeronautics and Space Administration
nm ....nautical miles
NPRM.......................Notice of Proposed Rule Making
PFD...........................primary flight display
RGB ....red-green-blue
SAE...........................Society of Automotive Engineers
SE..............................Safety Enhancement
TCAS ....traffic collision avoidance system
ToD ....top of descent
VNAV.......................vertical navigation

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Executive Summary

This report is part of a series of reports that addresses 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. Another report in this series of reports speaks directly to flight deck evaluation methods and metrics for the types of attention and awareness issues that were revealed from the airplane state awareness events.

In this report, we describe a wide range of flight deck evaluation issues tied to flight crew performance. The objectives are to establish a framework for thinking about how the flight deck interface should support the performance of the flight crew, and to aid the Federal Aviation Administration (FAA) in identifying relevant human performance issues during the evaluation/certification process. Issues are broken out into sections that cover physical ergonomics, design for usability, data integration and display content, attention and task management, flight crew problem solving, and flight crew teaming. For each issue, we recommend specific ways that the flight deck interface should support the flight crew. For each, we also identify existing 14 CFR Part 25 rules and guidance that are relevant to the issue. This allows the FAA to determine what current regulatory materials can support them in raising the issue with the applicant.

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 a 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 airplane systems (hardware and software) 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 Aerting 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 the current 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 Particular 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

A system interface—e.g., a flight deck interface—is a complex piece of technology. In the early airplanes that were designed decades ago, the interface was a place where a handful of sensor outputs, such as attitude and airspeed, were displayed for the flight crew. This sparse and unintegrated presentation placed the burden on the pilot to monitor and understand the state of the airplane and state of the world and to operate the airplane effectively. Over the years, much more information has been added to the interface, and our expectations for how it should support the flight crew have broadened. Further, a cognitive engineering perspective is shifting much of the burden for system management back on to the interface. Cognitive engineering acknowledges the limitations of human pilots and attempts to use technology to better support the flight crew in performing a difficult job; that is, the flight deck is now seen as a crew workstation and not as a place for two pilots to sit next to each other. Note that, in this document, we keep our focus on the flight deck interface and do not address the broader airplane design from a human-centered perspective, but we understand that effective design needs to start at that level.

The approach to interface evaluation needs to be modified accordingly. As interface requirements expand, some system developers have struggled to identify appropriate evaluation methods and measures. We believe that a critical element of developing evaluation methods is to articulate the appropriate role of the interface—that is, articulating how the interface should support the flight crew (or pilot) is a major driver for determining evaluation questions. For example, casting the flight deck interface as a crew workstation places requirements on the interface for supporting communication and collaboration between the two pilots.

This report proposes 40 human performance evaluation issues, each of which identifies specific expectations about how the interface will support the flight crew. Included in this large set of evaluation issues are a subset that addresses pilot attention and awareness, which are of particular interest for the current project. We also identify, for each issue, relevant 14 CFR Part 25 rules and guidance.

We believe that the value in describing these evaluation issues is that the existing Federal Aviation Administration (FAA) rules that govern evaluation in the context of certification are too narrow in scope relative to supporting flight crew performance. There are issues described here that have no rule backing them up. The relatively recent introduction of 14 CFR 25.1302 has moved in the appropriate direction, and the accompanying Advisory Circular (AC) describes flight crew performance pretty broadly. As we discuss the set of 40 human performance evaluation issues below, we attempt to show the ways in which 25.1302 allows for their evaluation.

2. The Scope of Interface Evaluation

The manufacturers for commercial jet transport interfaces (e.g., Honeywell, Airbus, Boeing, Gulfstream, Embraer) develop new flight deck interfaces and accompanying procedures, as well as occasional changes, refinements or upgrades to existing interfaces. It is incredibly rare that an entire system or system interface is changed. This document does not consider the option for a wholesale change; we consider changes to interface elements—indications, displays, controls, and system functions.

When a regulator evaluates a change to an avionics interface element, the typical types of changes they are assessing are the following:

- a new or modified system function that is on the interface; e.g., symbology that portrays the flight path vector
- new system information on the interface; e.g., the addition of angle of attack information, or a new alert
- a change to information in the form of its organization, its integration, or the way it is represented; e.g., an integration of flight path cues into an integrated primary flight display (PFD)
- new interface technology or a new "widget"; e.g., touch screen interaction on displays, voice-activated displays, display-based controls
- new operational procedures for flight crews

We use the term "interface element" throughout this report to refer to any new or modified part of the interface and its operational procedures. While we provide a broad set of considerations and recommendations, we understand that most evaluations will be focused on interface elements and not on the entire system interface.

3. Evaluation Issues (or Expectations of the System Interface Design)

As we stated above, to evaluate the system interface design, one must start with an understanding of how the interface should support the pilot, and then measure (in terms of human performance) how well it provides that support. Operating a complex, safety-critical system, such as a jet transport airplane, is an incredibly difficult task, and the interface design is a huge determinant of pilot performance. In this section, we identify the range of roles for the system interface. These evaluation issues are grouped to reflect the type of pilot or flight crew performance being addressed. We also, for each issue, identify the primary existing FAA Part 25 rules and guidance that are tied to the issue.[1]

[1] Note that the reference document Yeh, Swider, Jo, & Donovan (2016) was useful for identifying relevant rules.

The following list previews all of the evaluation issues that are described in more detail in this section.

- Physical Ergonomics
    1. Reach
    2. Strength
    3. Viewing angle
    4. Viewing across changing light conditions
    5. Viewing across visibility conditions
    6. Auditory perception
    7. Auditory persistence
    8. Motion and vibration
    9. Protective clothing
- Design for Usability
    10. Information coverage
    11. Color use
    12. Word, icon, and symbol use
    13. Interaction consistency/Learnability
    14. Feedback on control inputs
    15. Labelling, layout, and grouping
    16. Information recovery
    17. Control device characteristics
    18. Common user errors/Inadvertent control actions
    19. Mode behavior and transitions
    20. Data validity
    21. Interface state to system state mapping
    22. User input or action requirements
- Data Integration/Display Content
    23. Data integration/context
    24. Graphical formats
    25. Display space and coordination
    26. Fluent task performance
    27. Access to operational documents
    28. Identification of operational procedures
    29. Automation visibility and intervention
- Task Management/Interface Management/Attention
    30. Alerting scheme
    31. Monitoring
    32. System/state awareness
    33. Situation assessment
    34. Display management
    35. Task management
- Support of Pilot Problem Solving
    36. Decision making
    37. Knowledge-based performance

- Support of Crew/Team Performance
    38. Access to team resources
    39. Shared crew understanding
    40. Coordinated crew actions

To some extent the later issues depend on establishing a good design as determined by the earlier issues. Ensuring that the physical ergonomics are adequate—displays can be seen, controls reached, sounds heard—allows an evaluator to assess that the interface also supports activities such as monitoring or decision making.

Each of these issues is fleshed out in the following sub-sections.

3.1. Physical Ergonomics

There is a range of measures related to how well pilots are physically and physiologically compatible with the system interface and operational environment. The following specific issues should be assessed.

3.1.1. Reach

The interface design should make it possible for all pilots to reach and manipulate (appropriately) the controls/devices needed for system operation. Specifically, assess that pilots can:

- reach all parts of the interface that are interactive. This should apply to the full user population (i.e., allowable variation in stature), and it should consider user position during operations, especially if the user is sometimes restrained in a position.
- reach far enough to manipulate interactive devices adequately (e.g., turn knobs).

As a specific example, for U.S. commercial airline pilots, it should be demonstrated that pilots, throughout the full range of stature (5' 2" to 6' 3"), can reach the necessary flight deck controls from their seated, restrained position at the appropriate eye-height. The evaluation would fail in the case that a 5' 3" pilot is unable to reach a system control when he/she is seated and restrained.

Does evaluation require human participants?

No. Computer-based models, such as Jack, Catia, or Ramsis, make it possible to evaluate reach envelopes for a range of humans.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.771(c): If provision is made for a second pilot, the airplane must be controllable with equal safety from either pilot seat.

25.777(a): Each cockpit control must be located to provide convenient operation and to prevent confusion and inadvertent operation.

25.785(g): Each seat at a flight deck station must have a restraint system…that permits the flight deck occupant, when seated with the restraint system fastened, to perform all of the occupant's necessary flight deck functions.

25.1329(c): Each manually operated control for the system must be readily accessible to the pilots.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (5-8.d.2): The layout should take into account the flightcrew requirements in terms of: (a) Access and reach (to controls).

3.1.2. Strength

The interface design should make it possible for all pilots to move or position system controls and interaction devices as needed for system operation. Specifically, assess that the pilot can:

- execute actions on all controls/devices; specifically, there should be no limitations tied to strength. This should apply to the full pilot population (i.e., allowable variation in stature or strength), and it should consider pilot position, especially if the pilot is sometimes restrained in a position or has limited physical access to a control/device. Consider foot-controlled devices as well as hand-controlled devices.
- sustain a force on a control/device, when required; that is, the evaluation should not consider only the momentary forces.

As a specific example, for commercial airplane pilots, it should be demonstrated that pilots, throughout the full range of stature, can, from a seated position and using a finger and thumb, extract the quick-don oxygen mask in a timely way.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.143(b): It must be possible to make a smooth transition from one flight condition to any other flight condition without exceptional piloting skill, alertness, or strength, and without danger of exceeding the airplane limit-load factor under any probable operating conditions.

25.143(d): [a table of maximum control forces for pitch, roll, and yaw].

25.149: (d) [specification of maximum control forces] ***and*** (h)(2) The airplane may not exhibit hazardous flight characteristics or require exceptional piloting skill, alertness, or strength.

25.671(c): The airplane must be shown by analysis, tests, or both, to be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces (including trim, lift, drag, and feel systems), within the normal flight envelope, without requiring exceptional piloting skill or strength...

25.941(b): The dynamic effects of the operation of these (including consideration of probable malfunctions) upon the aerodynamic control of the airplane may not result in any condition that would require exceptional skill, alertness, or strength on the part of the pilot to avoid exceeding an operational or structural limitation of the airplane.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-6.b.1): To meet the general requirements of §25.1302, the applicant must show that functions of the proposed design are allocated so that: (a) the flightcrew can be expected to complete their allocated tasks successfully in both normal and non-normal operational conditions, within the bounds of acceptable workload and without requiring undue concentration, exceptional skill or strength, or causing undue fatigue. Flightcrew population demographics should be considered (for example age and gender) when determining exceptional strength.

3.1.3. Viewing Angle

The interface design should make it possible for all pilots to view and read the necessary displays, indications, controls, and relevant external inputs; this may include a need to view the other pilot's displays. Specifically, assess that the pilot can:

- view all required parts of the interface. This should apply to the full pilot population (allowable variation in stature), and it should consider pilot position, especially if the pilot is sometimes restrained.
- read all required parts of the interface (i.e., legibility is sufficient). This should apply to the full pilot population (allowable variation in visual acuity).

It is often not necessary for the pilot to be able to view the entire system interface from a single viewing point. The pilot may need to turn his/her head or body or change position to see some system interface elements (e.g., the overhead panel, which is above and behind each pilot). The evaluation should consider what elements of the interface are critical to be seen from a single viewing point (vs those that can be viewed through pilot movement), and what the primary viewing point will be for the pilot.

Design Trade-offs. Over the last few decades, changes to interface technology have reduced the relevance of this particular performance issue. In newer systems, the system interface may be provided by a workstation or set of displays directly in front of the operator. And, perhaps, the content of each physical display is under the control of the operator. In this design, typically all physical elements of the interface are easily viewed (although there is still value in assessing readability). However, this approach to design can create a burden on the operator to manage the content on each of the displays to ensure that the operator maintains an awareness of critical system information. The trade-off is between a smaller display space with flexibility in what system information can be viewed at any one time vs a much larger interface in which system information is always available and is dedicated to a spatial location. These related performance issues are discussed in more detail below, under the heading of Display Management (Section 3.4.5).

Does evaluation require human participants?
No. Computer-based models, such as Jack, Catia, or Ramsis, make it possible to evaluate viewability envelopes and the visual angle of text and symbols (readability) from a seated position.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.773(b.2.ii.d): Fixed markers or other guides must be installed at each pilot station to enable the pilots to position themselves in their seats for an optimum combination of outside visibility and instrument scan.

25.1321(a): Each flight, navigation, and powerplant instrument for use by any pilot must be plainly visible to him from his station with the minimum practicable deviation from his normal position and line of vision when he is looking forward along the flight path.

25.1381(a): The instrument lights must (1) Provide sufficient illumination to make each instrument, switch and other device necessary for safe operation easily readable unless sufficient illumination is available from another source.

25.1543(b): Each instrument marking must be clearly visible to the appropriate crewmember.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-4.d.1): Any control required for flight crewmember operation in the event of incapacitation of other flightcrew member(s), in both normal and non-normal conditions, must be shown to be viewable, reachable, and operable by flightcrew members with the stature specified in §25.777(c), from the seated position with shoulder restraints on.

3.1.4. Viewing Across Changing Light Conditions

The interface design should allow the pilot to maintain the ability to read displays, with no significant decrement in reading performance, in the full range of light conditions that can occur in the interface environment. Specifically, assess that the pilot can:

- adjust display brightness, contrast, back-lighting or position (or make adjustments to the light environment, such as blocking direct sunlight) to ensure the display can be read with no significant decrement in reading performance

Some system interfaces (e.g., airplanes, cars) will be subjected to a range of light conditions. Light levels may range from dark night to bright sunlight. The direction of the light source may also vary from directly on the display to being behind the display.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.773(a.2): Each pilot compartment must be free of glare and reflection that could interfere with the normal duties of the minimum flight crew. This must be shown in day and night flight tests under non-precipitation conditions.

25.1321(e): If a visual indicator is provided to indicate malfunction of an instrument, it must be effective under all probable cockpit lighting conditions.

25.1329(i): The flight guidance system functions, controls, indications, and alerts must be designed to minimize flightcrew errors and confusion concerning the behavior and operation of the flight guidance system. Means must be provided to indicate the current mode of operation, including any armed modes, transitions, and reversions. Selector switch position is not an acceptable means of indication. The controls and indications must be grouped and presented in a logical and consistent manner. The indications must be visible to each pilot under all expected lighting conditions.

25.1381(a): The instrument lights must (1) Provide sufficient illumination to make each instrument, switch and other device necessary for safe operation easily readable unless sufficient illumination is available from another source; and (2) Be installed so that (i) Their direct rays are shielded from the pilot's eyes; and (ii) No objectionable reflections are visible to the pilot.

25.1381(b): Unless undimmed instrument lights are satisfactory under each expected flight condition, there must be a means to control the intensity of illumination.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.11B: Various sections; too many to list.

25.1302-1 (5-4.c.2.a): ...Labels should be readable from the flightcrew's normally seated position in all lighting and environmental conditions, if intended for flightcrew use.

(5-5.b.2): Readability must be maintained in sunlight viewing conditions per §25.773(a) and under other adverse conditions such as vibration and turbulence.

3.1.5. Viewing Across Visibility Conditions

The interface design should allow the pilot to continue to use displays and controls even during unfavorable visibility conditions. Specifically, assess that the pilot can:

- take actions to preserve or recover the ability to view and read the interface or touch the interface accurately when the operating environment is affected by factors that can reduce visibility

Some systems operate in a setting that can be exposed to environmental conditions (e.g., smoke) that reduce visibility. In these conditions, it can become difficult to see and interact with the system interface. There may be different techniques for either clearing the environment around the interface (air movement devices) or blocking out the contaminated air.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-4.e.1.d): The applicant should show the controls required to regain airplane or system control and to continue operating the airplane in a safe manner are identifiable and usable in all environmental conditions, to include dense smoke in the flightdeck and severe vibrations. An example of the latter condition would be after a fan blade loss.

3.1.6. Auditory Perception

The interface design should ensure that the pilot can hear all operationally relevant system-generated and human-generated auditory information. Specifically, assess that the pilot can (with an operationally appropriate level of background noise:

- hear and understand all operationally relevant auditory information presented by the interface. This should apply to the full pilot population (allowable variation in hearing acuity and language skills)
- hear and understand all operationally relevant auditory information coming from other individuals involved with system management. This should apply to the full pilot population (allowable variation in hearing acuity and language skills)
- reliably distinguish the various elements of the auditory information being presented; that is, the pilot can distinguish between different tones or auditory signals that are intended to have different meanings

The flight deck can be a noisy environment and this environment can interfere with the pilot's ability to hear and comprehend auditory information presented by the system or communications from other individuals involved with system management. Similarly, the air traffic control (ATC) channel is passing information to multiple aircraft and creates auditory noise that adds to the difficulty of perceiving relevant information.

Even when the environment is not noisy, variation in language skills can affect comprehension, which presents an important consideration for selecting the evaluation participants. Specifically, when auditory information is presented in a single language, such as English, those who are not native-English-language speakers can have difficulty comprehending it. Accidents have occurred that resulted from this type of comprehension failure (e.g., China Northern flight 6901: flight crew failed to understand the English spoken by the warning system when it presented the auditory alert "pull up").

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1329(j): Following disengagement of the autopilot, a warning (visual and auditory) must be provided to each pilot and be timely and distinct from all other cockpit warnings.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-5.b.4.e): The applicant should show display text and auditory messages are distinct and meaningful for the information presented.

3.1.7. Auditory Persistence

The interface design should ensure that system-generated auditory information is also presented in a more enduring way. Specifically, assess that the pilot can:

- access auditorily presented information after its initial presentation through:
  - a continuation of auditory presentation until it is acknowledged or terminated by the pilot
  - a preservation in some more persistent form (e.g., a written message) after the auditory information is removed
  - or both

Auditory information can be very effective in getting a pilot's attention or presenting meaningful information through spoken language. However, if the pilot's auditory attention is focused on another source (e.g., a conversation with someone), the system's initial auditory presentation may be missed or not understood. This can be especially true if there are pilots who are not native speakers of the language of the interface.

Further, an auditory presentation may not persist long enough for all pilots to attend and understand it. Because it is quite difficult to present auditory information in parallel (like visual information), pilots want to clear away auditory signals quickly. The pilot, trying to restore a quiet baseline for other auditory cues or messages, may therefore quickly remove the auditory presentation.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-5.c.2.c): Because auditory information presentation is transient, designers should be careful to avoid the potential for competing auditory presentations that may conflict with each other and hinder interpretation. Prioritization and timing may be useful for avoiding this potential problem.

3.1.8. Motion and Vibration

The interface design should ensure that the pilot can manage or avoid system motion and vibration sufficiently to maintain the ability to read displays (with no significant reading performance decrement) and make system or control inputs (with no significant loss of accuracy or speed). Specifically, assess that the pilot can:

- maintain expected performance levels during periods of motion or vibration (at the upper end of what the system may experience), either through training or exposure, or by taking actions to reduce motion or vibration to restore the ability to perform his/her tasks

Some systems (e.g., airplane, space capsule) may be exposed to motions or vibrations that affect the interface, the user, or both. This motion or vibration can make it difficult for the user to read displays or to place hands, fingers, or feet on controls and maintain the required level of performance. In most cases, the pilot will have no ability to reduce or remove these forces and, to ensure continued performance at an expected level, there may need to be an alternative approach to interacting with the interface.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.771(e): Vibration and noise characteristics of cockpit equipment may not interfere with safe operation of the airplane.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (5-4.e.1.d): The applicant should show the controls required to regain airplane or system control and to continue operating the airplane in a safe manner are identifiable and usable in all environmental conditions, to include dense smoke in the flightdeck and severe vibrations. An example of the latter condition would be after a fan blade loss.

(5-5.b.2): Readability must be maintained in sunlight viewing conditions per §25.773(a) and under other adverse conditions such as vibration and turbulence.

(5-8.d.1): The system is subject to influences on the flightdeck such as turbulence, noise, ambient light, smoke, and vibrations (e.g., as may result from ice or fan blade loss). System design should recognize the effect of such influences on usability, workload, and flightcrew task performance. Turbulence and ambient light, for example, may affect readability of a display. Flightdeck noise may affect audibility of aural alerts. The applicant should also consider the impact of the flightdeck environment for non-normal situations, such as recovering from an unusual attitude or regaining control of the airplane or system.

3.1.9. Protective Clothing

The interface design should allow pilots with any job-related, protective clothing to perform their duties with no significant decrement in performance. Specifically, assess that the pilot can:

- perform their operational duties, with no significant decrement in performance, when wearing any job-related protective clothing (e.g., oxygen mask)

Some systems, under some conditions, may require system operators to wear protective clothing (e.g., oxygen mask, gloves) that can affect their ability to see or to make control or interface inputs. In some cases, this protective clothing is rarely worn (e.g., pilots wear a mask only when the airplane is depressurized or there is a concern with breathing the air in the cockpit), and pilots are unaccustomed to performing their jobs with a perhaps poorly fitting device on their body.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1447(c.2.i): [oxygen mask] can be placed on the face from its ready position, properly secured, sealed, and supplying oxygen upon demand, with one hand, within five seconds and without disturbing eyeglasses or causing delay in proceeding with emergency duties.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-4.e.1.b): If the use of gloves is anticipated, the design should account for the effect of their use on the size and precision of controls per §§ 25.1302(b)(2) and (c)(2).

3.2. Design for Usability

The previous section covered potential physical and perceptual barriers or incompatibilities between the interface design and the pilot population. Another large theme in interface evaluation is ease of use, which touches on human performance issues such as:

- locating the desired interface elements: indications, controls, displays
- understanding the information presented on the interface (each indication and display)
- understanding the relationships between user inputs and system changes
- ease of learning to use the interface
- improved transfer to novel interface tasks
- reducing or eliminating interaction errors

These issues focus on designing interface formats and interactions that are familiar, consistent, and transparent. Like the issues in the previous section, these evaluation issues ensure that basic interface requirements are met. While these issues do not, by themselves, ensure effective and safe system operation, they create a basic grammar for interactions between pilots and the system. The following specific issues should be assessed.

3.2.1. Information Coverage

The interface design should ensure that the full set of data and information is available to support all flight crew tasks. Specifically, assess that:

- all data and information are available on the interface to allow the flight crew to perform all anticipated normal and non-normal tasks

A minimum requirement of a system interface is that it provides the full set of data and information—which is "data in context," or processed data—the flight crew needs to perform all tasks. An important part of this assessment is an understanding of all of the tasks that the flight crew will need to perform. These tasks need to go beyond simple operational tasks tied to performing a routine flight to include tasks such as understanding airplane state, operational decision making, and managing non-normals.

Does evaluation require human participants?
No, an information analysis can be performed with pilot input.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (4-2.a): The applicant must show that these (installed systems and equipment for use by the flightcrew) systems, and that proposed equipment, individually and in combination with other such systems and equipment, are designed so that qualified flightcrew members can safely perform all of the tasks associated with the installed systems' and equipment's intended function.

(5-2.c.1.e): The requirement that equipment be designed so the flightcrew can safely perform all tasks associated with the equipment's intended function applies in both normal and non-normal conditions.

(5-5.c.1.a): The applicant should show the flightcrew can access and manage (configure) all necessary information on the dedicated and multifunction displays for the phase of flight. The applicant should show any information required for continued safe flight and landing is accessible in the relevant degraded display modes following failures, as defined by § 25.1309(d)(1), (2), (3), and (4).

3.2.2. Color Use

The interface design should use color coding effectively. Specifically, assess that:

- There is a well-defined (intentional) plan for color coding across the system interface.
- The pilot can reliably distinguish between the colors used on the interface, especially across all display dynamics and environmental conditions.
- The rules for color use are applied consistently across all system interface elements.
- The rules for color use are consistent with other color-use rules or practices within the industry and for the ways color is used in other technologies or within the society.

For the majority of pilots (with normal color vision), color coding is a salient trait and can be an effective means of adding information to the interface. However, a range of complications can occur in the application of color across a dynamic interface. Because there is a wide range of guidance on this topic, we have developed a more detailed discussion of these issues in Appendix A.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1322(e): Visual alert indications must: (1) Conform to the following color convention:
(i) Red for warning alert indications
(ii) Amber or yellow for caution alert indications
(iii) Any color except red or green for advisory alert indications

25.1322(f): Use of the colors red, amber, and yellow on the flight deck for functions other than flightcrew alerting must be limited and must not adversely affect flightcrew alerting.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

3.2.3. Word, Icon, and Symbol Use

The interface design should be consistent in the use of words, icons, and symbols. Specifically, assess that:

- The user understands the meaning of all of the words on the interface, and the words on the interface are consistent with their operational usage.
- Word use is applied consistently across all system interface elements.
- Word use is consistent with other word-use rules or practices within the industry.

- The user understands the meaning of all of the icons and symbols on the interface.
- Icons and symbols are applied consistently across all system interface elements.
- Icons and symbols are consistent with other uses or practices within the industry.

In support of operations and system use, words are used as labels on the interface and on displays (sometimes in an abbreviated form), are part of operational procedures, and are spoken by pilots. Ideally, the words used on the interface preserve their operational meaning so that pilots are not required to learn new meanings for familiar words.

Icons and symbols are also given meaning by the interface. Often, symbols and icons are borrowed from another medium (e.g., paper charts in an older system) but may be created because a new interface has created data formats that did not exist before. Further, the older media may have been less standardized, and may have produced variations of some symbols that have to become more standardized in the system interface (e.g., Yeh & Chandra, 2006).

A concern with words, icons, and symbols is that they can be found in the culture or in other technological applications with different meanings. This can be the most difficult area of the interface design to balance: usage within the system operations context and inappropriate associations from outside the operational context.

Does evaluation require human participants?
Yes for parts a) and d) only.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (5-4.c.2.d): When using icons instead of text labeling, the applicant should show the flightcrew requires only brief exposure to the icon to determine the function of a control and how it operates.

(5-4.e.2.e): Annunciations/labels on electronic displays should be identical to labels on related switches and buttons located elsewhere on the flightdeck. If display labels are not identical to related controls, the applicant should show flightcrew members can quickly, easily, and accurately identify associated controls so they can safely perform all the tasks associated with the systems' and equipment's' intended function.

(5-8.b.2): One way the applicant can achieve consistency within a given system, as well as within the overall flightdeck, is to adhere to a comprehensive flightdeck design philosophy. Another way is to standardize aspects of the design by using accepted, published industry standards such as the labels and abbreviations recommended in ICAO 8400/8.

3.2.4. Interaction Consistency/Learnability

The interface design should be consistent in the way it behaves and supports interaction so that pilots can easily learn the rules for interacting with the interface. Further, it should increase the ease of learning how to use the interface through a number of mechanisms, including interaction consistency, by creating relationships to what is already known. Specifically, assess that the pilot can:

- identify appropriate expectations about how an interface interaction will behave prior to the interaction
- determine how to perform "untrained" or novel tasks, based on how trained tasks are performed

An interface is composed of many "widgets:" menus, controls, display navigation buttons, data input fields, etc. Each of these widgets will have rules for its behavior. For example, for inputting data, you may have to click in the data field, enter values from a specific keyboard, with a specific format, and then use a keyboard return to complete the data input. Ideally, if you learn how to input data on one display, those same interaction rules apply to data inputs throughout the system interface. That is, consistency reduces what must be learned when the same representation form or action is reused across the device.

Another mechanism to increase learnability is the use of "general" widget rules in the interface. Virtually all pilots will have experience with commonly used technology (e.g., smart phones, iPads and other tablets), and those technologies carry a set of common interface interactions. While not all rules apply to every piece of technology, pilots will generally have some expectations about how an interaction will work (e.g., a small x in an upper corner of the display is likely to close the window). Maintaining consistency with those expectations will improve an interface's learnability. In some cases, pilots' expectations about interface interactions will come from older versions of the system or pieces of equipment that are associated with the system.

Yet another tactic is to make the interface transparent. Transparent displays make their function relative to pilot tasks clear and are easier to learn by someone already familiar with flying an airplane. It may be possible to find actions that are taken on real-world objects and translate them to a digital equivalent that quickly conveys the function; a familiar example is dragging a document into a folder.

Does evaluation require human participants?
Yes. Although checks on consistency can be done without pilot input, it is important to ensure that pilots also see the consistency.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(c): Operationally relevant behavior of the installed equipment must be (1) predictable and unambiguous; and (2) designed to enable the flightcrew to intervene in a manner appropriate to the task.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (5-2.c.10): Examples of designs or information that could cause errors are indications and controls that are complex and inconsistent with each other or other systems on the flightdeck. Another example is the presentation of a procedure inconsistent with equipment design. Errors caused by such designs or by confusing information are within the scope of this requirement and AC.

(5-4.e.2.a): To ensure that a control is unambiguous per § 25.1302(b)(1), the relationship and interaction between a control and its associated display or indications should be readily apparent, understandable, and logical. A control input is often required in response to information on a display or to change a parameter setting on a display. The applicant should specifically assess any input device or control that has no obvious "increase" or "decrease" function with regard to flightcrew expectations and its consistency with other controls on the flightdeck. The SAE International (SAE) publication ARP 4102, paragraph 5.3, is an acceptable means of compliance for controls used in flightdeck equipment.

(5-8.a.1): Many systems, such as the Flight Management System, (FMS), are integrated physically and functionally into the flightdeck and will interact with other flightdeck systems. It is important to consider a design not just in isolation, but in the context of the overall flightdeck. Integration issues include: where a display or control is installed, how it interacts with other systems, and whether there is internal consistency across functions within a multifunction display, as well as consistency with the rest of the flightdeck's equipment.

3.2.5. Feedback on Control Inputs

The interface design should ensure that feedback to the pilot on control actions is near to (or can be placed near to) the control device. Specifically, assess that the pilot can:

- get action feedback; that is, get immediate feedback that the control action was executed; i.e., a dial changes position, the commanded value changes, audible click, or something similar
- get system feedback; that is, get immediate feedback, from a source near the pilot input, on how a control action or interface action (e.g., data entry) is affecting the interface or the system; consider these issues as well:

– Feedback to the pilot should be immediate even if the effect on the system is delayed; in this case, the feedback would acknowledge the pilot input and reveal that the system response is not happening yet; it should also distinguish between a system inability to respond ("I can't do that") vs a delay ("I'm working on that but it will take a while").
– Feedback should be from a source that is in close proximity to the site of the action, or it should be in a central location that provides an overview or representation of system state.

When a control is being used, or there is a pilot input to the interface, it is important that the interface reveals that the action has indeed been executed and then allows the pilot to monitor the effects of his/her actions. This is also a reminder to build feedback regarding changes to system state into the interface.

Does evaluation require human participants?
Yes. Although some analysis can be done on system response.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (5-4.f):

(1) Feedback for control operation is necessary to let the flightcrew know the effects of their actions. Each control should provide feedback to the flight crewmember for menu selections, data entries, control actions, or other inputs if awareness is required for safe operation. If the flightcrew input is not accepted by the system, the input failure should be clearly and unambiguously indicated, § 25.1302(b)(1). Such feedback can be visual, auditory, or tactile.

(2) Section 25.1302(b)(3) requires that if feedback/awareness is required for safe operation, it should be provided to inform the flightcrew of the following conditions:

(a) a control has been activated (commanded state/value).

(b) the function is in process (given an extended processing time).

(c) the action associated with the control has been initiated (the actual state of operation or control value from the operation if it is different from the commanded state).

(d) The equipment should provide, within the time required for the relevant task, operationally significant feedback of the actuator's position within its range when a control is used to move an actuator through its range of travel. If awareness is required for safe operation, then feedback and awareness must be provided, § 25.1302(b)(3). Examples of information that could appear relative to an actuator's range of travel include trim system positions, and the state of various systems valves.

(3) The type, duration, and appropriateness of feedback will depend on the flightcrew's task and the specific information required for successful operation. As an example, switch position alone is insufficient feedback if the flightcrew must be aware, per § 25.1302(b)(3), of the actual system response or the state of the system as a result of an action that is required.

(4) Keypads should provide tactile feedback for any key depression. In cases when this is omitted, tactile feedback should be replaced with appropriate visual or other feedback that indicates that the system has received the inputs and is responding as expected.

(5) Equipment should provide appropriate visual feedback not only for knob, switch, and pushbutton position, but also for graphical control methods such as pull-down menus and pop-up windows. The user interacting with a graphical control should receive positive indication that a hierarchical menu item has been selected, a graphical button has been activated, or other input has been accepted.

(6) To meet the requirements of § 25.1302, the applicant should show that all forms of feedback are obvious and unambiguous to the flightcrew in their performance of all the tasks associated with the intended functions of the equipment.

3.2.6. Labelling, Layout, and Grouping

The interface design should present indications and controls, either on displays or on a physical interface, in a way to make it easy for pilots to locate and identify them. Specifically, assess that the pilot can:

- Accurately and efficiently locate and identify each indication or control, even when the indication or control is not on a display device that can currently be viewed (that is, menus and other display/interface navigation tools need to be considered). The following specific issues should be addressed:
  - Labeling should be sufficiently detailed and consistent with other labels/uses to aid the pilot in determining he/she has located the desired indication or control.
  - Labeling should reflect the tasks being performed. Ideally, the language that is used to present tasks to the pilot is reflected in the labeling of the system controls and functions. For example, if an anticipated task is to look

at a time history of certain system parameters, there should be a function somewhere in the interface to allow the pilot to select a parameter, the time period, etc. And, that function should be labeled in a way that ties it directly to the task (e.g., "time histories"), and that function should be found in a display space that reflects those types of analyses.

  – Ensure that the grouping of similar indications or controls in a small area uses ample labelling to allow the pilot to easily distinguish between all indications and controls.
  – Labelling should ensure that there is a consistent use of units (e.g., feet vs meters).

• Easily select/grab an interactive device or physical control without inadvertently engaging one nearby.

In some ways, the bigger issue is locating items that are not currently on the display being presented (it is on a display that is buried in the hierarchy). Having a well-organized, well-labelled navigation scheme, such as a menu, makes it possible to locate controls and indications that are not on the "surface."

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.777(g): Control knobs must be shaped in accordance with §25.781. In addition, the knobs must be of the same color, and this color must contrast with the color of control knobs for other purposes and the surrounding cockpit.

25.1301(b): Be labeled as to its identification, function, or operating limitations, or any applicable combination of these factors.

25.1329(i): The flight guidance system functions, controls, indications, and alerts must be designed to minimize flightcrew errors and confusion concerning the behavior and operation of the flight guidance system. Means must be provided to indicate the current mode of operation, including any armed modes, transitions, and reversions. Selector switch position is not an acceptable means of indication. The controls and indications must be grouped and presented in a logical and consistent manner. The indications must be visible to each pilot under all expected lighting conditions.

25.1357(d): If the ability to reset a circuit breaker or replace a fuse is essential to safety in flight, that circuit breaker or fuse must be located and identified so that it can be readily reset or replaced in flight.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.11B: Various sections; too many to list.

25.1302-1 (5-8.d.2): The layout should take into account the flightcrew requirements in terms of (a) access and reach (to controls); (b) visibility and readability of displays and labels; (c) an example of poor physical integration that affects visibility and readability is a required traffic avoidance system obscured by thrust levers in their normal operating position; and (d) task-oriented location and grouping of human-machine interaction elements.

3.2.7. Information Recovery

The interface design should preserve information in cases in which there could be value in recovering that information. When something is written down on paper, there is a record that can be retrieved and reviewed. With digital technology, information can scroll off a screen, be deleted, or be replaced with new information. In some cases, historical context helps the flight crew understand how a system has changed over time (e.g., fuel usage, alarm queues). When there is potential value in maintaining a record or preserving initial plans and decisions, make sure that the pilot can:

- access a trend over a previous period of time for important parameters
- recover earlier versions of outputs or plans (e.g., flight plans)
- see the full list of alerts that occurred according to onset time

It can be difficult to anticipate how transient data or information can be replaced or lost, and the functions for recovering these should be broad. There is also value in understanding how timely this recovery needs to be—within seconds or within hours or within days. Airplanes have systems that record airplane system data any time the airplane is operating but these data are not being collected for the flight crew.

Does evaluation require human participants?

No, except to get pilot input on information that may need to be recovered, and the timeliness of that recovery.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules were found.

Does part of 25.1302 apply?

25.1302(d): To the extent practicable, installed equipment must incorporate means to enable the flightcrew to manage errors resulting from the kinds of flightcrew interactions with the equipment that can be reasonably expected in service.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance was found.

3.2.8. Control Device Characteristics

The interface design should provide control and interaction devices that fit well with pilot expectations and needs. Specifically, assess that system control and input devices have the following characteristics:

- Are compatible with the pilot's expectations about how the controlled object will be affected by the input action (e.g., turning a wheel to the right makes the vehicle turn right).
- The range of motion of the control does not produce interference with other elements of the interface (e.g., motion of other controls, viewing angles or visual obstruction).
- Convey, through their appearance, the appropriate pilot action on the control device (e.g., turn it, push it, pull it).
- Convey when there are boundaries on a control action so that the pilot knows:
  - moving the control further will have no effect on the system; i.e., you are at the limit of the control's authority.
  - moving the control further means pushing through a boundary related to control behavior (e.g., after the boundary, the control will try to return to that boundary unless the pilot exerts sufficient force).

Ideally, controls should aid the pilot in taking appropriate actions on the system. A starting point for defining control actions are any cultural or industry standards that may exist regarding how controls are expected to work (e.g., pushing forward on an airplane control makes the airplane pitch down, or a handle on a door conveys the need to pull it). Violating existing expectations can significantly increase the difficulty in making appropriate control inputs.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.777(b): The direction of movement of cockpit controls must meet the requirements of §25.779. Wherever practicable, the sense of motion involved in the operation of other controls must correspond to the sense of the effect of the operation upon the airplane or upon the part operated. Controls of a variable nature using a rotary motion must move clockwise from the off position, through an increasing range, to the full on position.

25.777(c): The controls must be located and arranged, with respect to the pilots' seats, so that there is full and unrestricted movement of each control without interference from the cockpit structure or the clothing of the minimum flight crew (established under § 25.1523) when any member of this flight crew, from 5′2″ to 6′3″ in height, is seated with the seat belt and shoulder harness (if provided) fastened.

25.1329(e): Attitude controls must operate in the plane and sense of motion specified in 25.777(b) and 25.779(a) for cockpit controls. The direction of motion must be plainly indicated on, or adjacent to, each control.

25.1555(a): Each cockpit control, other than primary flight controls and controls whose function is obvious, must be plainly marked as to its function and method of operation.

Does part of 25.1302 apply?

25.1302(c): Operationally relevant behavior of the installed equipment must be (1) predictable and unambiguous and (2) designed to enable the flightcrew to intervene in a manner appropriate to the task.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.11B: Various sections; too many to list.

25.1302-1 (5-4.c.1.a): Each flight crewmember should be able to identify and select the current function of a control with the speed and accuracy appropriate to the task. The function of a control must be readily apparent so that little or no familiarization is required.

(5-4.c.1.b): The applicant should evaluate consequences of control activation to show that the consequences are predictable and obvious to each flight crewmember. Such an assessment would include evaluation of the control of multiple displays with a single device and evaluation of shared display areas that flightcrew members access with individual controls. The use of a single control should also be evaluated.

3.2.9. Common User Errors/Inadvertent Control Actions

The interface design should reduce, to the extent possible, the likelihood of pilot errors during system operation; a significant element of this is preventing or reducing the likelihood of inadvertent actions on a control, especially when those actions can lead to an undesired outcome. Specifically, assess that:

- The interface provides sufficient feedback so that common user error types (listed below) can be recognized and corrected by the pilot before they lead to an undesirable outcome.
- System controllers and input devices, for which an action can lead to an undesired outcome, are designed to prevent inadvertent actuation.
- (When it is not possible to lockout inadvertent actuation of a control) the pilot can identify and reverse unintended control actions before they lead to an undesired outcome.

Pilots, being humans, will make errors in the course of flight operations. This is inevitable. An objective of the interface design should be to reduce the likelihood of errors, when possible, and to ensure that errors are not likely to lead to some undesirable system outcome. Achieving the latter objective means making errors easily seen, recognized and corrected.

One common form of user error is an inadvertent (unintended) action on a control, whether a physical device or display-based, or on some other interface input. There are a number of possible reasons for this error, such as bumping into it or intending to engage a control next to it. In some cases, inadvertent actions can lead to an undesired outcome, and perhaps even a serious threat to safety. Ideally, the design puts barriers (e.g., switch guards) in place to prevent inadvertent actions or reduce the likelihood that those actions will lead to an undesired outcome.

There is a broader set of common user error types (see below). One approach to managing the full range of pilot errors is analyzing the interface with pilot tasks in mind to see which types of errors can occur and assess which types are likely to occur. Consider these types:

- *Substitution Error*. A correct action is taken but is taken on the wrong control. Look for similar controls placed near the correct control.
- *Capture Error.* A task may share actions with a more familiar task. The pilot, "captured" by the more familiar action pattern, performs the actions for the more familiar task instead of the intended task.
- *Transfer Error.* Because pilots can move from one airplane to another and there may be differences, in equipment or layout. It can be useful to consider transfer errors in which the correct action for one airplane interface is an inappropriate action in another interface. Look at the control actions to be taken on the existing airplane interface and determine if those actions would lead to an undesired outcome with the new airplane interface.
- *Wrong Control Setting* (for discrete control inputs). The error is making the wrong selection, such as on a toggle or two-state switch in the wrong position, rotary selector on the wrong setting, etc. Also, determine if a discrete selector can be "set" between selectable values (vs being forced into a selectable value). It should not be possible for this to occur.
- *Adjustment Error* (for continuous control inputs). This is an input made in the wrong direction or too much (overshoot) or too little (undershoot) in the correct direction.
- *Mode Error.* When there is a mode that can affect the outcome of a control action (continuous or discrete), the error is taking an action in the wrong mode. For example, there is an air-ground distinction in an airplane that can determine system behavior, and some actions are locked out in one mode but not the other (e.g., turning on pitot heat is prevented on the ground). If one takes an action that is appropriate in the air, but takes the action instead on the ground, this is a mode error.
- *Timing Error* (too early or too late in the task). When an action (discrete or continuous) is taken at the wrong time (typically before or after some other important event). Taking the action too late means the action was taken but not in a timely way (vs an omission, where the action was not taken at all and a next step is then taken).
- *Step Order Error*. Action steps are taken out of order. It could be a reversal in order for two steps, or a mixing of order of more than two steps.
- *Omission Error* (for a single action). A common error is skipping (omitting) a step. The error occurs when the pilot goes on to the next step or steps without completing the previous step. This error needs to be differentiated from the Step Order Error (above) in which the step is done after the next step.
- *Omission Error* (the entire task). In some cases, an entire task is omitted; it is not performed.

The following types of questions can be used to guide the interface evaluation:

- What are the potential consequences from each error? Consequences that are more significant should receive more attention to prevent and manage.
- What mechanisms have been designed into the interface to prevent each error type? Examples of mechanisms are:
  - designing the system so that incorrect actions cannot lead to an undesired outcome (e.g., your work on a document is saved no matter how you terminate the editing session).
  - locking out actions that are clearly errors (e.g., raising the landing gear while on the ground).
  - requiring a second, confirmatory action before the control input is executed.
- What type of interface feedback occurs when an error is made and how salient is that feedback?
- What mitigating actions are needed when the error is made and how difficult is it to take those actions? For example, some actions cannot be undone and will change the state of a system until the airplane goes to a maintenance technician; in other cases, simply undoing the action (e.g., turning the rotary selector back to the desired setting) will remove the undesired consequences.

Does evaluation require human participants?
Yes, although elements of this issue can be evaluated by analysis.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.677(a): Trim controls must be designed to prevent inadvertent or abrupt operation and to operate in the plane, and with the sense of motion, of the airplane.

25.697(b): Each lift and drag device control must be designed and located to make inadvertent operation improbable. Lift and drag devices intended for ground operation only must have means to prevent the inadvertent operation of their controls in flight if that operation could be hazardous.

25.777(a): Each cockpit control must be located to provide convenient operation and to prevent confusion and inadvertent operation.

25.1141(a): Each control must be located so that it cannot be inadvertently operated by persons entering, leaving, or moving normally in, the cockpit.

25.1322(d): The alert function must be designed to minimize the effects of false and nuisance alerts. In particular, it must be designed to:

(1) prevent the presentation of an alert that is inappropriate or unnecessary.

(2) provide a means to suppress an attention-getting component of an alert caused by a failure of the alerting function that interferes with the flightcrew’s ability to safely operate the airplane. This means must not be readily available to the flightcrew so that it could be operated inadvertently or by habitual reflexive action. When an alert is suppressed, there must be a clear and unmistakable annunciation to the flightcrew that the alert has been suppressed.

Does part of 25.1302 apply?

25.1302(d): To the extent practicable, installed equipment must incorporate means to enable the flightcrew to manage errors resulting from the kinds of flightcrew interactions with the equipment that can be reasonably expected in service.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.11B: Various sections; too many to list.

25.1302-1 (5-7.a.2): To comply with the § 25.1302(d) requirement that a design enables the flightcrew to "manage errors," to the extent practicable, the installed equipment design should meet the following criteria:

(a) Enable the flightcrew to detect, and/or recover from errors;

(b) Ensure effects of flightcrew errors on the airplane functions or capabilities are evident to the flightcrew and continued safe flight and landing is possible;

(c) Discourage flightcrew errors by using switch guards, interlocks, confirmation actions, or similar means, and

(d) Preclude the effects of errors through system logic and/or redundant, robust, or fault tolerant system design.

(5-7.b.1): Applicants should design equipment to provide information so the flightcrew can become aware of an error or a system/airplane state resulting from a system action. Applicants should show that this information is available to the flightcrew, is adequately detectable, and that it shows a clear relationship between flightcrew action and the error so recovery can be made in a timely manner, per § 25.1302(b)(2).

(5-7.d.2): Piloted evaluations in the airplane or in simulation may be relevant if flightcrew performance issues are in question for determining whether a state following an error permits continued safe flight and landing. Evaluations and/or analyses should be used to show that, following an error, the flightcrew has the information in an effective form and has the airplane control capability necessary to continue safe flight and landing.

(5-7.e.1): The design should provide a way to discourage irreversible errors that have potential safety implications. Acceptable ways to discourage errors include switch guards, interlocks, or multiple confirmation actions. As an example, generator drive controls on many airplanes have guards over the switches to discourage inadvertent actuation, because once the drives are disengaged, they cannot be re-engaged while in flight or with the engine running. An example of multiple confirmations would be the presentation of a temporary flight plan that the flightcrew can review before accepting.

(5-8.e.1): Systems should be designed and evaluated, both in isolation and in combination with other flightdeck systems, to ensure the flightcrew is able to detect, reverse, or recover from errors.

(And see all of 5-7): extensive discussion of managing errors.

3.2.10.Mode Behavior and Transitions

The interface design should make clear how the system mode will change the behavior of systems or control inputs. Specifically, assess that the pilot:

- can see how the current system mode will change the behavior of systems, control inputs, or interface actions; that is, the interface element clearly conveys, near the site for the action, what the outcome of the action will be
- is alerted (through an attention-getting mechanism) when there is an important mode change that was not initiated by the pilot

Many systems use different operating modes, and these modes can reveal, for example, how much automated control vs manual control is in effect, an operating regime (e.g., shut down, starting up, fully operational), or a larger system state (e.g., on the ground vs in the air, for an airplane). In many, if not all, cases, some system behavior is altered by a change in system mode (e.g., the specific VNAV [vertical navigation] mode determines whether or not the airplane will descend at the top of descent [ToD] point on its own), or the result of a system input or control action is changed by the mode (e.g., if you are in cruise and ***more*** than 50 nm from the ToD point, setting a lower altitude and pushing the altitude knob will initiate a cruise descent; if you are in cruise and ***less*** than 50 nm from the ToD point, setting a lower altitude and pushing the altitude knob will initiate an early descent, leaving cruise phase). Pilot awareness problems occur when these changes to system behavior are not revealed to pilots and an action taken to achieve one objective leads to a different outcome. This is called a mode error.

In some systems, the mode may be indicated in a place far from the system controllers, or not indicated at all (the pilot is supposed to know what mode the system is in). To improve usability, system controls should directly reveal what will happen in the current mode. That is, the human pilot should not have to figure out or remember how the mode will affect system behavior or user inputs.

Mode transitions can occur when the pilot selects or specifies a mode (or initiates a change in system operating regime), and they can occur without input from a pilot; for example:

- when a certain operating state is reached (e.g., reaching cruise altitude)
- when certain environmental conditions occur (e.g., temperature changes)
- when conditions cause the system to drop out of the current operating regime (e.g., loss of reliable air data causes a drop into a mode with reduced flight envelope protection)

When the mode transition occurs without pilot input, it is critical to make pilots aware that there is a new operating mode and to aid the pilot in understanding how system behaviors will change. If the range of system behaviors that are changed is very narrow (e.g., concern only one or a few control inputs), it may not be necessary to alert at the system level. It may be sufficient to highlight only the changes at the relevant control/input devices.

Does evaluation require human participants?
Yes, although many elements of this issue can be evaluated by analysis.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1329(j): Following disengagement of the autopilot, a warning (visual and auditory) must be provided to each pilot and be timely and distinct from all other cockpit warnings.

(k) Following disengagement of the autothrust function, a caution must be provided to each pilot.

Does part of 25.1302 apply?

25.1302(c): Operationally relevant behavior of the installed equipment must be (1) predictable and unambiguous; and (2) designed to enable the flightcrew to intervene in a manner appropriate to the task.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-6.c.2.b): Examples of system functional logic and system behavior issues that may be associated with errors and other difficulties for the flightcrew include the following: (b) Inadequate understanding and inaccurate expectations of system behavior by the flightcrew following mode selections and transitions.

(5-6.c.3.b): Mode annunciation should be clear and unambiguous. As an example, a mode engagement or arming selection by the flightcrew should result in annunciation, indication, or display feedback adequate to make the flightcrew aware of the effects of their action. Additionally, any change in the mode as a result of the aircraft's changing from one operational mode (for instance, on an approach) to another should be clearly and unambiguously annunciated and fed back to the flightcrew. Uncommanded mode changes and reversions should have sufficient annunciation, indication, or display information to provide awareness of uncommanded changes of the engaged or armed mode of a system.

25.1329-1C: Various sections; too many to list.

3.2.11. Data Validity

The interface design should aid the pilot in knowing when displayed data are erroneous (not valid) or are uncertain (unknown validity). Specifically, assess that the pilot can:

- easily identify when system data are erroneous; that is, there is a difference in the presentation of the erroneous data vs the valid data
- easily identify when system data are 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

It is essential for pilots to know that the system data they are seeing via the interface are valid indications of the system's (or the world's) current state. However, in current systems, system data may become invalid or erroneous, and it may be difficult to determine their validity. In older analog systems, an indicator would "peg" the data value to an extreme point on the indicator scale to show that there is no valid indication. However, this representation could also mean that the actual value is at the highest or lowest point on the indicator scale. The pilot cannot distinguish between the two.

Newer interface technologies, generally, have not maintained the potentially confusing “pegging” method but they may also not clearly show data validity. An example are the indications derived from air data (pitot pressure, static pressure), such as airspeed or altitude. These systems typically use a multi-channel comparison to select which source is most likely valid. Thus, if there are three sources of pitot pressure, and two of the three are in agreement, the third source is removed and airspeed (for example) is derived from the two that agree. In this case, the airspeed indication does not reveal that one source was not in agreement. And, there have been cases in which the two sources in agreement are invalid and the valid data were voted out.

Information about data validity needs to be communicated to the pilot so that he/she knows that there is a disagreement and, therefore, uncertainty about data validity. When the data may be suspect, as in the case of the disagreement, the indications should reveal the uncertainty.

Does evaluation require human participants?
Yes, although elements of this issue can be evaluated by analysis.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew’s use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-7.e.2): Another way of avoiding flightcrew error is to design systems to remove misleading or inaccurate information, which might result from sensor failures, or from inadequate displays. An example would be a system that removes flight director bars from a primary flight display or removes the “own-ship” position from an airport surface map display when the data driving the symbols is invalid.

3.2.12. Interface State to System State Mapping

The interface design should ensure that all operationally meaningful system states are uniquely represented in the system interface, and that all unique interface states represent an operationally meaningful system state. Specifically, assess that:

- The interface makes appropriate distinctions between operationally meaningful system states, such that:
  - each unique interface state (excluding changes within dynamic parameter indications) will represent an operationally meaningful system state.
  - each operationally meaningful system state will be represented through a unique interface state.
- The interface provides a unique representation of every operationally meaningful system state (this is a test of completeness).

The system interface offers a representation of the system state or condition—current sensor and parameter values, system modes, operating regime or phase, proximity to undesired states, etc.—and this is, typically, the only representation of system state that pilots have. The interface, therefore, needs to aid the pilot in having an accurate representation as it regards operating the system.

In some existing systems (see Feary, 2010), the interface provides the same representation for different system states, and the two system states have implications for system operation; that is, the interface fails to distinguish between two operationally different system states. Similarly, there are existing systems for which the interface presents distinct looks despite there being no difference in system state.

One difficulty in this type of evaluation is determining what differences between system states are operationally meaningful. For some situations, there may be no need to reveal the difference to the pilot through display differences. A judgment is required to determine which system states should be distinguished through a unique display (interface state).

Does evaluation require human participants?
No, this issue can be evaluated by analysis.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(c): Operationally relevant behavior of the installed equipment must be (1) predictable and unambiguous and (2) designed to enable the flightcrew to intervene in a manner appropriate to the task.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.2.13. User Input or Action Requirements

The interface design should aid the flight crew in understanding when pilot inputs or actions are required to perform a task. Specifically, assess that:

- The interface makes salient what inputs are required from the flight crew to perform a task, and when a task has been completed.
- The interface makes clear what actions are needed from the flight crew (vs what actions will be taken from an automated agent or from the system).

With current systems, there is likely to be automated or autonomous components that initiate tasks, manage tasks, or make control inputs. The display needs to aid the flight crew in identifying what data need to be input (or actions taken) by a pilot and what will be done by the system. In some cases, the system will be initiating or managing a task, and the required flight crew inputs may be distributed across several displays. The displays need to aid the flight crew in seeing and completing the full set of inputs. In other cases, task inputs will be shared or coordinated between the flight crew and the system, and the flight crew's role (and the limits of that role) needs to be clearly communicated.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(d): To the extent practicable, installed equipment must incorporate means to enable the flightcrew to manage errors resulting from the kinds of flightcrew interactions with the equipment that can be reasonably expected in service.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.3. Data Integration/Display Content

The ultimate objective of the system interface is to support pilots in performing tasks such as understanding the current system state, configuring the system, operating the system, making decisions about system goals, and responding to system failures.

In system designs from decades ago, there was an approach that can be referred to as "single-sensor, single-indicator," which was borne out of interface technology limitations at the time. In this scheme, each sensor in the system was linked to an indicator that was displayed to the system operator in a central location (control room, cockpit); there were individual indicators for measures such as temperature, pressure, flow, and speed. It was then the job of the operator to make sense of the full set of system indications, which included:

- allocating attention to the appropriate indicators at the right time since an operator cannot attend to all of them all of the time

- bringing operational context to each indication to understand what value it is expected to have and, if it doesn't have that value, why not
- determining if an indicator is near some threshold value and needs to be managed to prevent it from crossing the threshold
- identifying developing trends or problems in the system
- understanding the overall health or state of the system, and whether any of its capabilities have been lost or degraded
- determining if the system is achieving its objectives

Performing these types of tasks from single parameter indications places a huge burden on the system operators. They are working from a collection of sensor values to make sense of a large, complex, interconnected system.

Recent advances in interface technology (and a better understanding of cognitive engineering) allow us to move away from single-sensor, single-indicator approaches; new technology allows us to place sensor data in context, to integrate related indicators of system state, current sensor values, and system objectives or targets. Placing sensor data in context aids pilots in identifying trends or patterns in aircraft systems and forming an accurate representation of system state. There is now a burden placed on the system interface designer to create useful displays of data and graphical formats to support system operators.

The designer needs to strike a balance between narrow, task-specific formats that support elements of the operator's tasks effectively vs more general integrations of data that offer a representation of a larger piece of the system. Taking the former approach can lead to operators changing displays frequently as tasks change and losing the big picture view of the system. Taking the latter approach can fail to take advantage of the power of data integration to support real operator tasks.

This section addresses the organization of system data into displays and graphical formats to support operator tasks. The following specific issues should be assessed.

3.3.1. Data Integration/Context

The interface design should transform system data into "information" by placing it in context to support pilot tasks and decisions. Specifically, assess that:

- The interface supports task performance by placing the information relevant to each task on a single display, or within a relatively small area of the interface.
- The interface does not present sensor data (or derived parameters) without basic operational context, such as:
  - its commanded value (when there is one).
  - its expected value (when it can be determined).
  - any relevant thresholds (e.g., the upper bound of normal range, operational decision points) that may be near the current value or that represent an abnormal state.

Note that these statements (a and b) reflect an ideal state. The objective is to remove or minimize the need to move back and forth between displays to perform a task or make a decision (see also Section 3.3.3). It may not be possible to achieve this for all tasks, especially for less frequently performed tasks. The point of the evaluation is to determine how well the design manages this aspect of performance. The evaluation may uncover some data organization practices that can be modified to reduce the need for display shifting.

Further along the lines of creating information, there should be no need for pilots to do computations, conversions, or translations in their heads. The interface technology can perform tasks such as:

- determining a trend in parameter dynamics so that pilots can project how much a parameter value will change over a period of time, or how much fuel will remain upon reaching the destination
- modeling or computing projected system performance when there is a lag in system response so that pilots can see where the system state is likely going to end up given the control inputs made
- modeling a system to generate an expected value

By anticipating the types of decisions or actions the pilots will be expected to make, system designers can create the necessary information, ideally in an accessible format.

Does evaluation require human participants?
Yes, although elements of this issue can be evaluated by analysis.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1549: For each required powerplant and auxiliary power unit instrument, as appropriate to the type of instrument (a) Each maximum and, if applicable, minimum safe operating limit must be marked with a red radial or a red line; (b) Each normal operating range must be marked with a green arc or green line, not extending beyond the maximum and minimum safe limits; (c) Each takeoff and precautionary range must be marked with a yellow arc or a yellow line; and (d) Each engine, auxiliary power unit, or propeller speed range that is restricted because of excessive vibration stresses must be marked with red arcs or red lines.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.3.2. Graphical Formats

The interface design should provide graphical formats that support operational judgments (task actions) and decisions. Specifically, assess that the pilot can:

- quickly and easily access the information from a display needed to perform a task or make a decision

Examples of graphical formats are:

- digital or discrete displays, that show individual values
- tables and lists
- parameter meters
- multiple meters or bar charts
- trend plots or trend arrows
- parameter vs parameter plots
- maps or representations of physical space
- graphics that produce emergent graphical features (such as a polar graphic)
- system mimics (synoptics)

In many cases, the graphical format is the starting point for designing a display to support a task or make a decision. The graphical format identifies the types of data relationships that need to be presented. For example, if the task is about determining which of three systems is producing the greatest output, the graphical format should make it easy to compare (visually) those three outputs and select the one that is highest. More generally, good formats use perceptual distinctions to replace the need for cognitive effort on the part of the pilot.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.11B: Various sections; too many to list.

25.1302-1 (5-5.b.1.b): If the flightcrew's only way to determine non-normal values is by monitoring display values presented on the display, the equipment should offer qualitative display formats. Qualitative display formats convey rate and trend information better than quantitative (e.g. digital) presentations. If a qualitative display is not practical, the applicant should show the flightcrew can perform the tasks for which the information is used. Quantitative presentation of information is better for tasks requiring precise values.

(5-5.b.3.e): To meet the requirements in § 25.1302(b) applicants should show that layering information on a display does not add to confusion and clutter as a result of the color standards and symbols used. Avoid designs requiring flightcrew members to manually reduce the clutter of such displays.

25.1329-1C: Design of Controls, Indications, and Alerts. These features must be designed to minimize flightcrew errors and confusion. Indications and alerts should be presented in a manner compatible with the procedures and assigned tasks of the flightcrew and provide the necessary information to perform those tasks. The indications must be grouped and presented in a logical and consistent manner and must be visible from each pilot's station under all expected lighting conditions. The choice of colors, fonts, font size, location, orientation, movement, graphical layout, and other characteristics—such as steady or flashing—should all contribute to the effectiveness of the system. Controls, indications, and alerts should be implemented in a consistent manner.

3.3.3. Display Space and Coordination

The interface design should allow the pilot to perform all operational tasks with the existing display real estate, anticipating the potential for loss of display space. Specifically, assess that the pilot can:

- perform all common or anticipated operational tasks with the display real estate typically available
- perform all safety-critical or essential tasks with a reduced or minimum set of physical displays (in the case of display failures or losses)

Interface technology is generally headed in a direction in which pilots have a relatively small set of physical displays (or, more generally, display "real estate"), and they can decide which "system views" or displays will be placed on this real estate. Typically, they will have to select a small subset of the full set of system displays (e.g., there may be tens or hundreds of displays). In some cases, pilots will have limitations on which displays can be viewed or where certain displays can be placed. In other cases, pilots will have almost complete flexibility for placing system views onto their workspace. Further, if there are failures (losses) of physical displays, the pilots will have fewer options for what can be displayed.

While the ability to view any of the available displays provides flexibility, it forces pilots to choose what displays can be viewed at any point in time and to manage the display real estate. The pilot's role in configuring displays increases when they need to look at two or more displays at one time; that is, when single displays do not support a task action, a decision or system monitoring, there will be a need to coordinate multiple displays. For example, if there is limited display space available, the pilot may be required to view two or more displays in a single physical space, requiring them to switch back and forth between displays. Or, it may be that a display-based control is on one display and an indication to support using that control for a task is on a separate display. The evaluation should identify how much need there will be for using multiple displays to support common or anticipated operational tasks.

Does evaluation require human participants?
No.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: On some aircraft, one display system may be used to set the parameters for a number of systems on the flight deck. Consequently, too much task switching may be required; for example, even the simple task of changing communication frequencies could require the pilot to stop the current tasks in order to find and switch to the appropriate display page. Interruptions to ongoing tasks may lead pilots to lose their place, thereby introducing the potential for error. Information that must be monitored continuously may not be time-shared easily because the pilot would need to switch back and forth between the sources of information on the shared display, and this could be detrimental to performance on the monitoring task.

25.1302-1 (5-5.c.1.a): The applicant should show any information required for continued safe flight and landing is accessible in the relevant degraded display modes following failures, as defined by § 25.1309(d)(1), (2), (3), and (4).

3.3.4. Fluent Task Performance

The interface design should support accurate, efficient, and complete performance of all anticipated system and control tasks, both normal and non-normal. Specifically, assess that:

- The pilot 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). This includes controls, such as wheel and column, side stick, rudder.

- The task performance errors that are made during initial pilot training and performance evaluation are errors that were anticipated by the interface design and are very unlikely to lead to undesirable outcomes.

A primary role for the system interface is to support task performance. Tasks can be flight control tasks (e.g., pitch down, increase thrust) or system tasks. System tasks may require single inputs or simple monitoring of the interface but can also become much more complicated: multiple, varied steps; a lengthy process; or a complex procedure that involves logical branching or some other form of decision making during the task. Ideally, tasks are performed efficiently (not adding unnecessary steps or delays), effectively (achieving the system goal or state desired), completely, and within any time requirements the system may have.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.11B: Various sections; too many to list.

25.1302-1 (4-2.a): The applicant must show that these systems and installed equipment, individually and in combination with other such systems and equipment, are designed so that qualified flightcrew members trained in their use can safely perform all of the tasks associated with the systems' and equipment's intended functions.

(5-3.a): Section 25.1302 establishes requirements to ensure the design supports flightcrew members' ability to perform all tasks associated with a system's intended function.

(5-8.a.2): Section 25.1302 requires that "…installed equipment, individually and in combination with other such equipment, is designed so that qualified flightcrew members trained in its use can safely perform all tasks associated with the equipment's function.… To comply with this integration requirement, all flightdeck equipment must be usable by the flightcrew to perform all tasks associated with the intended functions, in any combination reasonably expected in service. Flightdeck equipment includes interfaces to airplane systems the flightcrew interacts with, such as controls, displays, indications, and annunciations.

3.3.5.Access to Operational Documents

The interface design should aid the pilot in locating and obtaining relevant sections of operational documents. Specifically, assess that the pilot can:

- locate and access relevant operational documents that may be used to supplement the set of operational displays

In older systems, a great deal of operational information was preserved in paper form. Examples are:

- performance tables and charts
- airport arrival plates
- checklists
- training materials
- decision aids

Newer interface technologies have made it possible to have operational information more integrated into displays that support relevant tasks and decisions and to remove (or reduce) the need for paper documents. Ideally, this operational information is integrated into task- or decision-oriented displays to reduce the burden on the flight crew in comparing information across displays or in performing mental calculations to make the information useful.

While, ideally, information is integrated to support pilot tasks, it can sometimes be hard to anticipate all of the ways in which information might be used by pilots. Therefore, there is value in making it possible to access certain types of information from a stand-alone document. The interface should provide an index for locating this information.

One potential downside to this additional, and perhaps less-well-integrated, information, is that it will require the use of display real estate. Therefore, the assessment of available display real estate should consider the potential for having operational documents available to the pilot.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(a): Flight deck controls must be installed to allow accomplishment of all the tasks required to safely perform the equipment's intended function, and information must be provided to the flightcrew that is necessary to accomplish the defined tasks.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-5.c.1.a): The flightcrew may, at certain times, need some information immediately. Other information may not be necessary during all phases of flight. The applicant should show the flightcrew can access and manage (configure) all necessary information on the dedicated and multifunction displays for the phase of flight.

3.3.6. Identification of Operational Procedures

The interface design should aid pilots in locating and accessing guidance for pilot actions when tasks are triggered by conditions in the system or in the world. Specifically, assess that the pilot can:

- know there is a task to be performed, identify the set of actions to take in response, and access those actions

In most situations, a pilot will initiate a task and access the displays or other operational information that are needed to perform the task. In some cases, tasks are generated in response to a condition in the system or in the environment; e.g., a system failure will generate the need to perform a non-normal checklist. In these cases, the system is detecting these conditions, and it then needs to provide guidance on accessing the appropriate pilot actions. The interface needs to provide a clear cue or link to the pilot guidance. In non-normal situations, there is typically an alert message (label) displayed that provides a link to pilot guidance that has the same label. Or, in other systems, pilot guidance is displayed as a response to the alert message.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1322(a.1): Flightcrew alerts must provide the flightcrew with the information needed to:
(i) identify non-normal operation or airplane system conditions, and
(ii) determine the appropriate actions, if any.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-6.a.3): If flightcrew intervention is part of the intended function, or part of non-normal procedures for the system, the flight crewmember may need to take some action, or change an input to the system. The system must be designed accordingly, per § 25.1302(c). The requirement for flightcrew intervention capabilities recognizes this reality.

3.3.7. Automation Visibility and Intervention

The interface design should aid the pilot in being aware of current and impending actions from system automation (autopilot) or any autonomous agents; it should also be clear to the pilot how to intervene (take control back from the automation/autonomous agent). Specifically, assess that pilots can:

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

When a system uses automation for elements of the operation (e.g., altitude hold or flight plan following for airplanes, maintaining a safe distance in cruise control for cars), it is important for the pilot to be aware of these automated actions and their goals or targets. This allows the pilot to stay in the loop in terms of how the system is being operated: aware of what the system is controlling to and how it will get there. One advantage of this knowledge is that the pilot can assess unexpected system behavior. There have been cases in which the system was failing but the pilot incorrectly believed the unexpected behavior could be attributed to system automation. Another advantage of this knowledge is that it leads to better coordination between human and automated agents. When the human pilot does not understand what the automation is doing or does not think the actions are appropriate, the human can intervene.

Yet another advantage of increased transparency is increased automation trust. The success of increasing capability with autoflight or other flight deck automation lies in the trust pilots have in the system, and transparency can be a significant contributor to increased pilot trust.

Finally, another element of this visibility is the pilot's ability to know ***how*** to intervene. The automation may be controlling to an incorrect target or taking an unexpected action, and the pilot needs to know how to take control away from the automation. In aviation, pilots are not always sure how to modify the automation's actions or goals.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1329(h): If the automatic pilot system can be coupled to airborne navigation equipment, means must be provided to indicate to the flight crew the current mode of operation. Selector switch position is not acceptable as a means of indication.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

25.1302(c): Operationally relevant behavior of the installed equipment must be (1) predictable and unambiguous and (2) designed to enable the flightcrew to intervene in a manner appropriate to the task.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-6.c.1): A system's behavior results from the interaction between the flightcrew and the automated system. The system's behavior should be determined by (a) the system's functions and the logic that governs its operation and (b) the user interface, which consists of the controls and information displays that communicate the flightcrew's inputs to the system and provide feedback on system behavior to the flightcrew.

(5-6.c.3.b): The following design considerations are applicable to operationally relevant system behavior and to the modes of operation of the systems:

1. The design should be simple.
2. Mode annunciation should be clear and unambiguous. As an example, a mode engagement or arming selection by the flightcrew should result in annunciation, indication, or display feedback adequate to make the flightcrew aware of the effects of their action. Additionally, any change in the mode as a result of the aircraft's changing from one operational mode (for instance, on an approach) to another should be clearly and unambiguously annunciated and fed back to the flightcrew.
3. Methods of mode arming, engagement and de-selection should be accessible and usable. For example, the flightcrew actions necessary to arm, engage, disarm, or disengage an autopilot mode should not be dependent on the mode the system is in. Requiring a different flightcrew action for each mode could contribute to errors. For specific guidance on flight guidance system modes, see AC 25.1329-1B, Approval of Flight Guidance Systems.
4. Uncommanded mode changes and reversions should have sufficient annunciation, indication, or display information to provide awareness of uncommanded changes of the engaged or armed mode of a system (§ 25.1302(b)(3)).
5. The current mode should remain identified and displayed at all times.

(5-6.c.4.a): Applicants should propose how they will show their design will allow the flightcrew to intervene in the operation of the system without compromising safety. The means of showing compliance should include descriptions of how the intervention of functions and conditions is possible.

(5-6.c.5.a): Automated systems can perform various tasks selected by and supervised by the flightcrew. Controls should be provided for managing functionalities of such a system or set of systems. The design of such "automation specific" controls per § 25.1302 should enable the flightcrew to do the following:

1 Activate the appropriate system function and clearly understand what is being controlled and what the flightcrew expects. For example, the flightcrew must clearly understand they can set either vertical speed or flight path angle when they operate a vertical speed indicator.

2. Manually intervene in any system function, as required by operational conditions, or revert to manual control. For example, manual

intervention might be necessary if a system loses functions, operates abnormally, or fails.

(5-6.c.6.a): Automated systems may perform various tasks with minimal flightcrew interventions, but under supervision of the flightcrew. To ensure effective supervision and maintain flightcrew awareness of system state and system "intention" for safe operation (future states), displays should, per § 25.1302(b)(3,), provide recognizable feedback on the following:

1. Entries made by the flightcrew into the system, so the flightcrew can detect and correct errors.
2. The present state of the automated system or mode of operation (i.e., "What is it doing?").
3. Actions taken by the system to achieve or maintain a desired state (i.e., "What is it trying to do?").
4. Future states scheduled by the automated system (i.e., "What is it going to do next?").
5. Transitions between system states.

3.4. Attention/Task/Interface Management

The systems being considered in this report are complex, highly interconnected, safety-critical systems. Operations can be highly dynamic and task priorities can shift quickly. While the ability to perform each and every operational task is a critical element of evaluating the system interface, equally important is supporting pilots in determining which tasks have the highest priority and what tasks should be performed. Determining this depends on understanding the current situation, which, in turn, depends on being aware of relevant variables and integrating this information into a useful Situation model, which is a mental representation of the current state of the system and its environment.

This set of evaluation issues is largely about the interface's role in managing attention and supporting pilots in directing attention to important tasks. We focus on six aspects as a way to organize the evaluation issues. In a separate report, titled "Best Practices for Evaluating Flight Deck Interfaces for Transport Category Aircraft with Particular Relevance to Issues of Attention, Awareness, and Understanding," we provide guidance on evaluation methods addressing five of these: alerting, monitoring, system/state awareness, situation assessment, and display management.

The six aspects are:

- *Alerting*. Alerting refers to the interface's generation of a salient cue to direct pilot attention to a specific situation or condition. Alerting is designed to initiate a prompted search; it is a salient, exogenous cue to direct pilot attention to specific information.
- *Pilot Monitoring*. Monitoring is a pilot-driven activity to seek information from the interface or from the world. In contrast to alerting, monitoring is directed by endogenous factors, such as the pilot's current goal. The role of the interface is to make it easy for pilots to locate the information they are seeking, and it should present that information in an appropriate context to give it meaning.

- *System/State Awareness*. Awareness is an end-state (or product) of pilot activity; that is, effective alerting and monitoring result in pilot awareness of relevant information. More specifically, the desired product is an awareness of the state of the system and of the world at a point in time. This awareness is never an exhaustive account; it is sufficient if it serves to guide appropriate actions and decision-making. Also, in the ideal world, the system interface itself should provide a description of the system that is accurate, is accessible, and includes all system information relevant to pilot decision making. The interface should support pilot awareness of situation-relevant states and variable values. State awareness is a primary constituent of situation assessment.
- *Situation Assessment*. Here, situation assessment refers to an integrated model for understanding the current operational situation. Accurate situation assessment depends heavily on system/state awareness, but includes more general knowledge from long-term memory, such as models of how a device works or expectations about how a type of situation will unfold. Linking the current situation with background knowledge is the primary way of generating expectations, so that dynamic events are recognized as normal or non-normal, expected or surprising. The interface should help the pilot a) integrate information about the current situation and b) coordinate this with expectations from long-term memory.
- *Display Management*. Display management is management of the information that is presented on the interface. The interface design should support efficient management of displays and controls.
- *Task Management*. Task management relies on the pilot's understanding of what tasks have the highest priority at any point in time so that task selection and performance can meet the needs of the system. Task priorities are determined largely from an integrated understanding of the situation; in rare cases, task priority is determined solely by an alert or from information detected in monitoring. Task management also includes an awareness of and consideration of what other human agents are doing in the system, and managing those activities. The interface should help the pilot effectively consider alternative possible tasks and prioritize the active task set.

To support these activities, the interface also needs to compensate for common limitations and vulnerabilities in human attention and reasoning, including the following:

- Attention is a limited resource. At the extreme, overwhelmed individuals can fail to see or hear even salient alerts.
- Attentional focus can be very narrow. When attending to one item, individuals can fail to see other items near it.
- The ability to monitor/track a large set of variables or indicators is limited. Performance of normal tasks and outside demands on the pilot (e.g., important communications) routinely pull a pilot away from an on-going, systematic updating of system state.
- Returning to interrupted tasks is difficult. Tasks are frequently interrupted when operating a dynamic system. The pilot must manage the interruption and return to

the task that was partially completed. Prospective memory—reminding oneself to return to these activities—can be fragile (Loukopoulos, Dismukes, & Barshi, 2009).

- Search is strongly biased toward finding an expected target, not an unexpected target. Individuals are effective at detecting changes or events they are looking for or expect; they are poor at detecting unexpected changes, particularly, changes in variables out of attention or not relevant to the primary current task.
- The ability to develop and sustain a Situation model of a complex, dynamic system is limited.

3.4.1. Alerting Scheme

The interface design should aid the pilot in identifying important changes to the system, and it should aid the pilot in seeing and organizing the full set of items that have been alerted. The interface should be assessed for the following:

- When there is a failure or other system change that requires immediate pilot awareness, the alerting system uses a salient change to orient the pilot to a message or cue; it conveys the nature, severity, and urgency of the problem; and it 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 less extreme forms of attention management (e.g., rate of change, central location) will, at some point, fail to get the pilot to allocate attention appropriately. Alerting is meant to be a final line of defense for getting pilot attention on important or urgent tasks. There are, however, potentially significant trade-offs in alerting system design. To be effective, alerting needs to present cues that are sufficiently salient to attract attention reliably. On the other hand, overuse of salient alerts can disrupt attention that should be directed elsewhere. Alerting should be sufficiently selective to avoid distracting pilot attention from other purposes.

As we said earlier, alerting is an important exogenous cue to initiate prompted search for information, which we refer to as prompted search. Prompted search refers to a broad class of externally cued information search; there is clear external guidance specifying, at some level, the information that is needed. Other examples: one pilot may ask a question that directs the attention of the other, or a pilot may be using a procedure or other operational documents that specify gathering specific information. How well the interface supports prompted search is discussed more fully under System/State Awareness (Section 3.4.3).

Because there is a wide range of guidance on this topic, we have developed a more detailed discussion of these issues in Appendix B.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

25.1322: [The entire rule is tied to alerting.]

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

3.4.2. Monitoring

Monitoring refers to intentional pilot activities to gather information from the system interface (or the world). It is driven, primarily, by a need to make sense of, or understand, the current state of the system and the operating environment; these are factors internal to the pilot (endogenous factors); the following are examples of the various objectives for monitoring:

- Gather specific information from the world or the interface to perform a task.
- Maintain awareness or update an understanding of the current system state.
- Confirm expectations about how the system is performing or what state it is in.
- Guide inputs on system controls or input devices.
- Pursue further information after observing something unexpected.
- Obtain system feedback after taking a system action.
- Assess how well operational goals are being achieved.
- Listen for expected noises/sounds tied to system operation.
- Listen to communications coming from other system users, such as a co-pilot or ATC.

There can also be specific exogenous factors to drive monitoring, such as:

- high-frequency changes (high information content) in a specific indication or display will lead to increased monitoring (Wickens, McCarley, & Thomas, 2003)
- a communication from a colleague to look at some indication
- orienting to a change in an indication—e.g., due to a visual cue

Monitoring is difficult because, typically, a large amount of possibly relevant information is available, more than a person can exhaustively notice or encode. Thus, effective monitoring in a rich operational context depends, in part, on appropriate selection of what is operationally relevant, which, again, is driven largely by a sense-making process.

The interface can aid the pilot in maintaining a fairly complete and accurate understanding of the state of the system and the world. That is, the objective is not just ensuring that the pilot can see all the system indications, but that the pilot's monitoring provides an accurate and sufficiently complete picture, relative to the pilot's current tasks or objectives. Evaluation objectives should include assessing whether the interface helps the pilot:

- gather information about the current system state.
- find any information being sought.
- determine whether or not the current set of indications are compatible with the current intention (or task), even when the pilot is not trying to assess compatibility. Thus, the objective is presenting data in a way so that any incompatibilities with the current intention are easily identified.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: Various sections; too many to list.

25.1302-1 (5-5.c.1.a): Information intended for the flightcrew must be accessible and useable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks, per § 25.1302(b)(2). The flightcrew may, at certain times, need some information immediately. Other information may not be necessary during all phases of flight. The applicant should show the flightcrew can access and manage (configure) all necessary information on the dedicated and multifunction displays for the phase of flight. The applicant should show any information required for continued safe flight and landing is accessible in the relevant degraded display modes following failures, as defined by § 25.1309(d)(1), (2), (3), and (4). The applicant must show, per § 25.1302(b), that supplemental information does not displace or otherwise interfere with required information.

3.4.3. System/State Awareness

An important objective for a pilot is to maintain an up-to-date understanding of the state of the system, the environment in which it is operating, and the operational crew. Awareness of the values of specific variables and the states of different components is a critical input to a broader, integrated understanding. Awareness of particular information is the result of attention, whether guided by endogenous (e.g., monitoring) or exogenous (e.g., alerting) factors.

The interface design should ensure that the pilot can quickly and easily assess the current state of the system as it relates to its operation, and any impending threats to system safety. Ultimately, awareness is critically important because system control requires conscious actions by the pilot, and the relevant actions cannot be initiated in response to the state if the pilot is unaware of it. For example, a pilot will not execute a go-round if they are unaware of the truck on the runway.

Specifically, assess that the pilot always has available a view of the system that supports a quickly-acquired understanding, including:

- an effective representation of system state, especially relative to system objectives or current operating objectives
- current state
- current set of interface elements that are not functioning (e.g., MEL; tag out)
- any trends that are developing; where they are headed
- a representation of which agents are currently controlling the system and how they are controlling it
- a way to show what are the expected or "normal" system values, which suggests that there is a need to capture system "state" or pilot intent
- deviations from expected or "normal," which needs to lead to efforts to make sense of those deviations
- context variables, such as those for weather, airspace, and airport status.

Evaluation methods and metrics for this topic are addressed in a separate report, titled "Best Practices for Evaluating Flight Deck Interfaces for Transport Category Aircraft with Particular Relevance to Issues of Attention, Awareness, and Understanding."

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.4.4. Situation Assessment

The primary focus in the previous section is on awareness of the distinct aspects of the current state of the system, of operations, or of the external environment. However, approached more broadly, the system interface needs to support the pilot's higher-level, integrated assessment of the situation and how that situation is evolving. This can also be described as building and maintaining an appropriate Situation model, including system dynamics (Durso & Gronlund, 1999; Fracker, 1988; Landman, Groen, van Paassen, Bronkhorst, & Mulder, 2017); it is related to levels 2 and 3 situation awareness (Endsley, 1995). Experienced pilots can "run" these models (mentally) to simulate situations to anticipate operational outcomes. Thus, situation assessment requires using long-term knowledge about how something works and adapting it within the context of the dynamics of the current circumstances.

An integrated interpretive framework for guiding expectations and understanding a situation has variously been called a Situation Model, frame, or schema. Maintaining and revising an appropriate frame—organizing both situation assessment and response planning (Roth, Mumaw, & Lewis 1994)—is important for operations, and can be viewed as "flying ahead of the plane." That is, updating expectations and actions to match the unfolding situation. Successful and fluent performance, sometimes called resilient performance (Hollnagel, 2014), draws on use of appropriate mental models both to guide perceptual attention and to guide action on the appropriate flow of tasks. Conversely, concerning performance problems, Landman et al. (2017) argue that "performance issues in unexpected situations can often be traced back to insufficient adaptation of one's frame to the situation."

Detection of a problem when system operation seems normal can be a difficult process, and is closely linked to identifying an appropriate frame (Klein, Pliske, Crandall, & Woods, 2005). It can be particularly difficult to understand anomalous events early in the flow of potentially dangerous events, at points where corrective actions may be most effective. Surprise has been explained in terms of mismatching frames, for normal events and aviation incidents (Rankin, Woltjer, & Field, 2016) and for accidents (Landman et al., 2017).

Development of a correct, higher-level understanding, in turn, supports performance in at least the following ways:

- assessing overall system state from a functional perspective; that is, in terms of how well system functions are being achieved
- anticipating potential threats to operations
- setting appropriate information-seeking goals, that is, the endogenous factors guiding perceptual attention and thus supporting System/State Awareness
- identifying relevant action goals, such as control and communication activities
- identifying and executing the relevant actions to accomplish these goals

All of these objectives can be addressed by helping the pilot select and adapt a relevant frame. In this setting, a frame (or Situation model) is used to refer to organized pilot knowledge developed from training, experience, and current observation, that includes:

- information and expectations about current and future states
- causal models about how things work
- relevant goals, tasks, and actions

Ideally, the system interface provides strong cues about the appropriate frame. Specifically, assess that the pilot can:

- quickly and easily recognize the current frame or type of situation and the relevant operational objectives
- find the information specifically relevant to the current situation
- identify when a different frame is more appropriate
- determine how pilot actions are affecting the achievement of operational goals, and if they are not, what actions are needed

While the value of providing technology support for this situation assessment has been noted, designing for it and evaluating an interface concerning these higher-level processes is less well understood.

As noted in previous sections, attention is heavily guided by expectations. Since frames guide expectations, maintaining a relevant frame is an important contributor to effective awareness, both in monitoring and in prompted search. And, helping the pilot match the current operational situation to a known, appropriate frame or Situation model provides an organized set of expectations and reduces the chance of "surprise." A surprise can result when a system event (or nonoccurrence of an event) does not match expectations, and may trigger a search for a new frame or for additional information that might explain the discrepancy with the current frame. These shifts can also occur for events that are considered to be expected (though not common) during normal operations, such as a shift from landing to go-round, when a new runway is specified, when weather conditions change substantially, or when aircraft behavior does not match expected autoflight guidance.

Evaluation of how well an interface supports finding and updating the appropriate frame can be assessed by measuring the pilot's knowledge and expectations about information linked to a relevant frame. Particularly useful is assessing knowledge or expectations that are unrelated to a contrasting, possible alternative frame; e.g., from failure to adapt in response to an ATC clearance, or reasoning based on an incorrect diagnosis of an off-nominal state. Evaluation of interface support of these variables particularly depends on good scenario design, to produce situations invoking the relevant frames and introducing the need for frame changes.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.4.5. Display Management

Display management is a type of task management that is very closely linked to interface design. As interfaces become complex, navigating among and configuring within individual displays can impose considerable burdens. The interface design should reduce the burden on the pilot to reconfigure the set of displays to change what can be viewed. Specifically, assess that the pilot can:

- view (at one time) all of the displays required for an operational task, which can include system monitoring
- maintain the appropriate set of system displays with the minimum number of display management actions (the idea is to minimize display management actions and to have frequently used functional displays quickly available)
- move from one display to any other display with a simple scheme and three or fewer actions

Display management takes time away from operational monitoring and execution of operational tasks. It also requires the pilot to have strong knowledge of the contents of each display and the organization of the set of displays within the system. Ideally, the pilot can select a basic set of displays for viewing that support most or many tasks and have quick, explicit links to other displays, as they are needed, to allow them to quickly configure displays suited to the operational context without losing track of where they are in the display hierarchy.

Methods for measuring navigation costs and many display management issues are well developed for static systems, such as web browsing, and may be usefully adapted for dynamic control.

Does evaluation require human participants?
Yes for some aspects, but number of actions required for navigation can be done without participants.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?

25.1302(b): Flight deck controls and information intended for the flightcrew's use must (1) be provided in a clear and unambiguous manner at a resolution and precision appropriate to the task; (2) be accessible and usable by the flightcrew in a manner consistent with the urgency, frequency, and duration of their tasks; and (3) enable flightcrew awareness, if awareness is required for safe operation, of the effects on the airplane or systems resulting from flightcrew actions.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25-11B: The number of sub-menus should be designed to assure timely access to the desired option without over-reliance on memorization of the menu structure. The presentation of items on the menu should allow clear distinction between items that select other menus and items that are the final selection.

25.1302-1 (5-5.c.1.a): The applicant should show any information required for continued safe flight and landing is accessible in the relevant degraded display modes following failures, as defined by § 25.1309(d)(1), (2), (3), and (4).

3.4.6. Task Management

The interface design should aid the pilot in attending to the appropriate system information at the appropriate time, and in understanding which tasks have the highest priority. Specifically, assess that:

- The pilot can see what tasks currently have the highest priority (or can determine the urgency for addressing specific tasks).
- The pilot can configure the interface to facilitate efficient and effective monitoring or to ensure that important but unexpected events are easily detected.
- Relative to interruption, the pilot 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

As stated above, pilot jobs can be dynamic, and task demands can shift quickly. Developing an interface design that allows the pilot to always be on top of which tasks should be performed is a tall order, and some of the burden needs to fall to the pilot to bring a more complete operational context for making those decisions.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-5.b.4.c): Applicants should give careful attention to symbol priority when displaying one symbol overlaying another symbol by editing out the secondary symbol, to ensure higher priority symbols remain viewable.

(5-5.c.2.d): Prioritize information according to task criticality. Lower priority information should not mask higher priority information. Higher priority information should be available, readily detectable, easily distinguishable, and usable per § 25.1302(b).

25.1322-1 (8.b.1): Aural alerts should be prioritized so that only one aural alert is presented at a time. If more than one aural alert needs to be presented at a time, each alert must be clearly distinguishable and intelligible to the flightcrew (§ 25.1322(a)(2)).

(10.d): If multiple checklists can be displayed (for example, multiple checklists associated with multiple alerts), the flightcrew should be able to readily and easily choose the appropriate checklist and action for each alert. For example, the flightcrew must be able to easily distinguish which checklist has priority regarding what the flightcrew needs to do first to determine the appropriate actions, if any (§ 25.1322(a)(1)(ii)).

(App 1, 2.b.5): A "collector message" can be used to resolve problems of insufficient display space, prioritization of multiple alert conditions, alert information overload, and display clutter. Use collector messages when the procedure or action is different for the multiple fault condition than the procedure or action for the individual messages being collected. For example, non-normal procedures for loss of a single hydraulic system are different than non-normal procedures for loss of two hydraulic systems.

3.5. Support of Pilot Problem Solving

Because systems are complex and the environment in which they operate can be somewhat harsh or unpredictable, it is inevitable that situations will arise that were unanticipated by the system designers. In these situations, the set of appropriate actions or pilot decisions will not have been considered in the system's operational documents. Therefore, pilots will need to pull together information, determine the appropriate operational objective or goal, and then develop a plan for achieving it, and the interface needs to support pilots in this type of "problem solving" activity.

In other cases, the interface designer can anticipate operational decisions that will need to be made, such as a diversion to a different airport. However, the interface can only aid the pilot in pulling together information relevant to that decision; the pilot will then often need to identify an appropriate decision from the information available. This can become even more complex if some of the information is uncertain or missing.

In very rare cases, there will be no framework for the pilot task; no specification of the information to pull together. A different form of problem solving occurs here in which the flight crew needs to identify relevant information, identify what they are trying to achieve, and determine what system actions might help them achieve it.

All of these potential situations will require pilots to step outside of written procedures to identify the appropriate decisions or actions. The system interface needs to anticipate these pilot activities and provide tools or support for them.

3.5.1. Decision Making

The interface design should provide a framework or structure for supporting the type of decision-making tasks where the decisions are expected (though perhaps not common) elements of system operations; e.g., selecting a diversion airport. Specifically, assess that:

- the interface presents, in an integrated fashion, data and information relevant to critical operational decisions.

There will, typically, be quite a few decision-making tasks that pilots may need to perform. These decision-making tasks are identified by pulling together current data and information to determine what action to take. Examples are to proceed to an airport where weather conditions may be marginal, select a diversion airport, or maybe deciding to divert for a medical emergency.

The interface can support the flight crew by making clear what information needs to be gathered, how that information should be weighted or prioritized, and what conditions may alter priorities. The pilot may need to add other information that cannot be obtained through the system (e.g., weather around them) or add other contextual information to make the optimal selection.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-2.c.3): Section 25.1302(b) contains requirements for flightdeck controls and information necessary and appropriate so the flightcrew can accomplish all of their tasks, as determined by compliance with § 25.1302(a). The intent of § 25.1302(b) is to ensure the design of control and information devices are usable by the flightcrew. This sub-paragraph seeks to reduce design-related flightcrew errors by imposing design requirements on flightdeck information presentation and controls. Sub-paragraphs (1) through (3) of the regulation specify these design requirements. Design requirements for information and controls are necessary to (a) properly support the flightcrew in planning and decision making for their tasks and (b) make available to the flightcrew appropriate, effective means to carry out planned actions and decision making.

3.5.2. Knowledge-Based Performance

The interface design should provide tools for pilots to solve operational problems that were not anticipated in the set of operational documents or that go beyond the level of complexity covered by the operational documents. Specifically, assess that:

- the interface offers tools/methods to solve system management problems that were not anticipated.

When performance is supported by a written procedure or a well-defined set of actions, it is referred to as rule-based performance (Rasmussen, 1983). When pilots need to perform a task without a written procedure—that is, when they need to invent the set of appropriate actions for a system task—it is referred to as knowledge-based performance. System designers plan for rule-based performance, but in a limited way. In the case of non-normal situations, system designers typically develop operational procedures for single system failures or for a small set of expected system failures (based on system history). While it is possible to develop procedures for more complicated situations (i.e., multiple concurrent failures), doing so would lead to an unmanageably large set of procedures.

Because there are limits on the development of procedures, the system interface should provide tools or methods to support those situations in which pilots are required to develop the set of appropriate actions. Pilots would benefit from methods that aid them in understanding the system state, the objectives of a response, and the general types of actions that can be used to achieve those objectives.

Does evaluation require human participants?
Yes.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.6. Support of Crew/Team Performance

In addition to supporting tasks performed by single pilots, flying also requires a team—the flight crew in the cockpit or the larger set of operational support staff that are in various locations and connected through communications technology. The interface design needs to find ways to support crew or team performance, which is quite different from supporting a single pilot. In particular, the focus here is on support for a shared understanding of the system and support for coordinating pilot actions.

3.6.1. Access Team Resources

For a number of systems (e.g., nuclear power plant, aviation), emergency response teams may be developed over time as the event is recognized and the more formal response is initiated. Team or crew members may be distributed initially when the operational event occurs; for example, ATC or Airline Operations Center (AOC) staff, or even the cabin crew in the airplane. The interface design should allow pilots to locate and connect to other team resources. Specifically, assess that:

- the interface provides a means to locate and communicate with team members that may be outside the immediate operational setting.

Also, think about the types of coordination and communication that will be needed between the different sets of operational support staff so that those forms of interaction can be supported by the technology.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

- No relevant guidance found.

3.6.2. Shared Crew Understanding

The interface design should aid the flight crew in establishing a shared understanding of the system state and the current operational objectives. Specifically, assess that:

- the interface provides a method or medium to ensure that all pilots (crew members) have the same information and understanding regarding:
  - – system state
  - – current objective or intention
  - – high priority tasks to perform

Note that "crew" refers to those who are part of day-to-day operations, as well as, any additional crew members that may become involved in emergency management from a remote location (dispatch, AOC, ATC).

The primary focus here is on the teams or crews that are operating the system routinely and thinking about how to ensure they maintain a coordinated understanding of system state and operations. However, in a number of systems, such as nuclear power plants or commercial airplanes, there are times when additional individuals will participate in emergency management or problem solving. These events are typically not planned but are in response to some unexpected event. The definition of the system interface needs to extend to the technology used by these individuals, as well. That distributed technology needs to be able to support coordination even when spoken communication is not possible.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-6.c.7.c): The applicant should consider the following aspects of automated system design: The automated system must, per § 25.1302(b)(3), support flightcrew coordination and cooperation by ensuring shared awareness of system status and flightcrew inputs to the system, if required for safe operation.

3.6.3. Coordinated Crew Actions

The interface design should aid pilots in being aware of and coordinating with the actions of other pilots, including those pilots or agents that are not human. Specifically, assess that the pilot 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)

Crew members for this discussion need to include automated or autonomous agents since one common failing of those technologies is a failure to coordinate sufficiently with the human pilots. Coordination starts with awareness of what the other pilots/agents are doing but also needs to address the ways in which pilots/agents communicate their intentions or operational targets.

Does evaluation require human participants?
Yes.

Relevant FAA Part 25 rules that are relevant (this set may not be complete):

- No relevant rules found.

Does part of 25.1302 apply?
No.

Relevant FAA Part 25 Advisory Circulars with relevant language (this set may not be complete):

25.1302-1 (5-4.c.3.a): If multiple controls for the flightcrew are provided for a function, § 25.1302(a) states the applicant should show sufficient information is available to the flightcrew to make them aware of which control is currently functioning. As an example, crewmembers need to know which flight crewmember's input has priority when two cursor control devices can access the same display. Designers should use caution when dual controls can affect the same parameter simultaneously.

4. Summary and Conclusions

Table 1 provides a summary of the 14 CFR Part 25 rules that were identified in the preceding sections. Along the left-hand side is a list of rules and across the top of the table are the 40 evaluation issues (identified only by number). The letter in each cell is the subpart of the rule (e.g., 771(c)) that was used; there are a few cells with an 'x' to indicate that the entire rule applies. The right-most column totals how often each rule was used.

This report listed a broad set of issues that can be applied to evaluating a flight deck interface. The set of issues represents the various aspects of flight crew performance, from ergonomic issues to crew performance issues. These 40 evaluation issues are written to express how the flight deck interface should support the pilot or the flight crew in operations, which, ideally, suggests a set of appropriate evaluation measures. Actual measures, and methods, are discussed for the attention/awareness-related issues in a separate report, titled "Best Practices for Evaluating Flight Deck Interfaces for Transport Category Aircraft with Particular Relevance to Issues of Attention, Awareness, and Understanding" (since attention and awareness were the focus of this research activity).

For each of the 40 issues, we also identified existing rules and guidance that may be relevant to that issue since it is often important to have an existing rule to call out an interface design issue during certification. In many cases, the recently developed 25.1302 rule (highlighted in Table 1) was a relevant rule, and the accompanying AC 25.1302-1 had the most relevant guidance. The 1302 rule was written to provide better coverage of human performance issues, and the table shows that it does touch on many of the human performance issues we identified. Note that it was easier to find multiple relevant rules for human performance issues in the physical ergonomics and usability areas. As you move to the right in Table 1, it becomes more difficult to locate existing rules that are relevant.

This report's objective is to aid the FAA in identifying a range of issues that may be useful when looking at a new flight deck interface element. Flight deck interface technology has been shifting in a number of ways—for example, using more integrated depictions of data, offering more flexibility in configuring displays, and having more task-oriented or decision-oriented displays that might be used infrequently. As technology shifts, the evaluation issues need to shift as well to ensure that potential human performance issues are identified early and evaluated appropriately.

In the past, the FAA has had to rely on general human performance rules, such as 25.771(a), which states "Each pilot compartment and its equipment must allow the minimum flight crew to perform their duties without unreasonable concentration or fatigue." This rule speaks generally to the overall workload or effort that may result from a poor interface design; it does not speak more specifically to the full range of design issues in this report. Our impression is that 771(a) has been used to justify calling out a more specific interface issue. Ideally, this report allows the FAA staff to better articulate human performance concerns and locate relevant guidance material.

Table 1. Summary of FAA Part 25 Rules and their Link to the 40 Evaluation Issues

	Phys Ergonomics									Usability													Integration/ Display Content							Attention						Prob Solv		Crew			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	
143		bd																																							1
149		dh																																							1
671		c																																							1
677																		a																							1
697																		b																							1
771	c							e																																	2
773			b	a																																					2
777	a														g		bc	a																							4
785	g																																								1
941		b																																							1
1141																		a																							1
1301															b																										1
1302	a	a	a			b	b	a	b	a	b	b	c	b	b	d	c	d	c	b	c	d	b	b	a	a	a		bc	b	b			b							29
1321			a	e																																					2
1322											ef							d										a		x											4
1329	c			i		j									i		e		jk										h												7
1357															d																										1
1381			a	ab																																					2
1447									c																																1
1543			b																																						1
1549																							x																		1
1555																	a																								1

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Appendix A. Existing Guidance on the Topic of Color Use

The interface design should use color coding effectively. Specifically, assess that:

- There is a well-defined (intentional) plan for color coding across the system interface
- The pilot can reliably distinguish between the colors used on the interface, especially across all display dynamics and environmental conditions
- The rules for color use are applied consistently across all system interface elements.
- The rules for color use are consistent with other color-use rules or practices within the industry and for the ways color is used in other technologies or within the society.

The following subsections provide a more-detailed discussion of each of these points and identifies a broad sample of existing guidelines, standards, and measurement techniques relevant to each.

A.1. Well-defined Use of Color Coding

Color can be used to give texture to or add a sense of realism to objects and images on a display or on the interface. But, more importantly, color can, among other functions, call attention to information, impose an organizational scheme on an array of displayed information, or assign a specific meaning to symbols or other interface elements. Color coding is a tool that can be exploited to add meaning efficiently to increasingly visually dense displays.

For many domains, there are existing regulatory and industry documents that establish how certain colors are to be used, and well-established rules on color use should not be tossed aside without very careful consideration. Those rules are in place to ensure that display information is communicated correctly. For example, some colors (typically, red and yellow) are associated with alerting (attention getting) for issues such as system failures/health or increased risk.

A more complete set of potentially effective uses for color includes:

- to differentiate qualities or characteristics of data, such as data source, degree of processing, validity, currency; the goal is to allow the user to locate the desired system data quickly
- to show items, such as controls, that are active or available vs those that are not currently active or available
- for organization or separation; to show grouping or functional relationships; to reveal categories or classes of information; to separate various levels of a class of data (e.g., terrain, weather)
- for salience; to attract attention to specific elements of the display that have more importance or urgency or priority; to have more dynamic information stand out from its context

Whatever color use design is developed needs to be documented in a color philosophy document, which is an element of a system design philosophy. The color philosophy should capture both color use driven by existing industry standards or regulatory requirements as well as novel color use. In some cases, there will be a need to accommodate legacy displays (e.g., such as a weather display from an older interface implementation) that may not fit with the recommended overall color philosophy. Legacy displays, when incorporated, often need to be looked at specifically to ensure that they do not create pilot confusion regarding color meaning when integrated with other pilot equipment and systems.

A.1.1. Limited Color Set

When colors are assigned specific meanings, it becomes important to ensure that users can reliably distinguish each color from the others on the display under all viewing conditions, and, thus, it becomes necessary to limit the number of colors used. Indeed, guidelines have been developed that recommend limiting the number of colors used for that reason (see below). Note that there is no clear agreement on the appropriate number of colors although these guidelines offer numbers in a small range.

> *Relevant Guidelines:*
>
> "If color is used for coding, it is considered good practice to use if six colors or less are used for coding parameters." (FAA AC 25-11B)
>
> "When the user must recognize categories of information (e.g., represent different variables on a graph, different types of information on a map) no more than seven colors shall be used to represent and distinguish between categorically different information." (MIL-STD-1472G 5.2.2.3.2)
>
> "If color coding is required, not more than five colors should be used. Only the following colors should be selected for control coding: Red, Green, Orange-yellow, White, Blue (only if an additional color is absolutely necessary)." (NASA Human Integration Handbook SP-2010-3407)

A.1.2. Redundant Information Coding

While color coding can be a powerful tool for adding information, there are several reasons why design guidance documents caution against using color as the only method for coding interface elements. An obvious reason is that some users may have color vision deficiencies, and may, therefore, be unable to perceive important color distinctions. Another important reason to not rely solely on color is that color perception can be adversely affected by ambient light. For example, changes in illumination levels or in the spectrum of environmental light (e.g., emergency lighting) can change color perception.

Examples of other information coding techniques that could be used to supplement color are shape, size, font characteristics (such as bolding or italicizing), location, text labels, motion, luminance, and texturing.

> *Relevant Guidelines:*
>
> "Color, when used for task essential information, should be in addition to other coding characteristics, such as texture or differences in luminance to present information." (FAA AC 25.1302 5b(3d)).
>
> "For critical information and critical tasks, when color is used to convey meaning, the system shall provide an additional cue. Rationale: Redundant coding is required to accommodate the variability in people's capability to see color under different lighting conditions and to increase the saliency of identification markings. Redundant cues can include labels, icons, and speech messages." (NASA-STD-3001 Vol 2A)

A.1.3. Special Case of Color Coding for Alerting

Alerting is often treated as a special case for color use. Through alerting, the system interface is signaling a significant safety threat or abnormal condition that needs to be identified, understood and addressed quickly. Saliency (through bright colors) is important, but also, color is often used to convey a level of urgency or level of threat. For example, in a commercial jet transport, a red-colored warning signals the need for an immediate pilot response, but a white color-coded advisory alert serves primarily to provide awareness of a non-normal situation (and may require a pilot response). When color-coding is used for conveying a level of urgency or importance in an alerting scheme, that color-coding scheme should be protected from other uses that can confuse the meanings used in alerting.

> *Relevant Guidelines:*
>
> "For visual alerts on multicolor displays, the colors red, amber, and yellow should be used consistently throughout the flight deck to maintain the effectiveness of an alert. The applicant must limit the use of red, yellow, and amber for functions other than flight crew alerting, so that misuse does not adversely affect flight crew alerting per §25.1322(f)."
>
> "Extensive use of red, yellow, and amber diminishes the attention-getting characteristics of warnings and cautions." (FAA AC 25.1302-1 5-5b.(3)(b))
>
> "In particular, consistent use and standardization for red and amber or yellow, in accordance with § 25.1322, is required to retain the effectiveness of flight crew alerts." (FAA AC 25-11B)
>
> "The most important or critical alerts are to be highly noticeable, and less important alerts are to be less noticeable. This is done so that, when there is an off-nominal event, the response of the crew is appropriate. The color red shall be used as a visual indicator for the highest alert level. Rationale: In situations where there is a need to communicate information about the highest level of alert, the color red is to be used for the text and/or graphics. The color yellow shall be used as a visual indicator for the second highest alert level. Rationale: In situations where there is a need to communicate information about the second highest level of alert, the color yellow is to be used for the text and/or graphics." (NASA-STD-3001, Vol 2, Rev A)

A.2. Ability to Distinguish between Colors

Color discrimination is the ability to reliably distinguish between colors under the full range of operational viewing conditions. Reliable discrimination can be especially important when color is used for alerting or to identify system limits in safety-critical systems.

Reliably distinguishing between two colors on an interface display (or other interface element) can be difficult for various reasons. One obvious factor is that there are differences among users in the ability to discriminate colors. A subset of humans—roughly 8% of men and 0.5% of women, according to the United States National Eye Institute (see nei.nih.gov)[2]—have some form of color

[2] Other references, including the recent New Zealand Defence Agency report, titled "Colour Vision Requirements for Aircrew" (DTA Report 405, NR 1687) and dated September 2015, provide the same percentages.

vision deficiency[3] (CVD). In addition, as humans age, there is typically a degradation in the ability to discriminate green from blue (Salvi et al., 2006). Methods have been developed for testing a user's color vision if there is a requirement for ensuring normal color vision (e.g., see the ICAO guidelines below).

Reduced reliability in color discrimination can also occur for reasons that are not tied to the users' perceptual limits. As mentioned above, the ambient light can change in some operational settings, which can degrade color perception. In other cases, system users are required to wear protective eyewear or visors (e.g., sunglasses) that can alter color perception. Also, certain head-mounted displays, such as night vision devices, may not be compatible with color displays and night lighting. These barriers can reduce a user's ability to discriminate between interface colors. Other factors are tied to the display medium, how it changes or degrades over time, and characteristics of the display elements. The following subsections offer more detail on these issues.

Relevant Guidelines:

The International Civil Aviation Organization (ICAO) medical provisions in Annex 1 (under Personnel licensing) provide the following guidance on licensing and color blindness: an applicant "shall be tested for the ability to correctly identify a series of pseudo-isochromatic plates." Such a test displays different numbers (or shapes or letters) that are made up of dots that are colored differently from background dots. Colors are chosen so that individuals with a color vision deficiency cannot reliably differentiate the number from the background. Individuals who fail to achieve an adequate score on this test can nevertheless be accepted for licensing if they can "readily distinguish the colors used in air navigation and correctly identify aviation colored lights." Depending on the country in which the application is made, this secondary test may take the form of a device (called a "lantern") that requires an applicant to identify different colored lights e.g. red, green and white and sometimes, depending on the exact lantern type, additional colors.

"Functional use of color. Where not in conflict with color codes specified herein, colors used for functional purposes (e.g., visual displays, controls, workspaces, equipment connections), shall accommodate users with color deficient vision." (MIL-STD-1472G)

Relevant Standards:

"The International Commission on Illumination (CIE) has established values that specify the perceptual distance between colors for color discrimination. (NASA-STD-3001 Vol 2A)"

The MIL-STD is more specific: "To maximize discriminability, colors having the dominant wavelengths listed Table A1 shall be used for color recognition as presented below" (MIL-STD-1472G).

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[3] Examples of color vision deficiencies (from MIL-STD-1472G) are deuteranopia and protanopia. In deuteranopia, the green retinal photoreceptors are absent, moderately affecting red-green hue discrimination, and thus making it difficult to distinguish between colors in the red-orange-yellow-green section of the spectrum. An individual who exhibits protanopia, has a severe type of color vision deficiency caused by the absence of the red retinal photoreceptors, affecting hue discrimination in the orange-yellow-green section of the spectrum. For these people, red appears dark.

"The FAA Human Factors Design Standard provides requirements and guidance regarding color characteristics for both color standardization and discrimination for displays. It addresses color temperature, color uniformity, off-axis color uniformity, RGB color settings, preventing color fringes, chromaticity desaturation, black level and color contrast." (FAA Human Factors Design Standard HF-STD-001B para 5.3.1.9)

Table A1. Wavelength Values for Color Discrimination

Color Name	*Nanometers (nm)*	*CIE value (x,y, Y)*
Red	700	0.6078, 0.3441, 31.05
Orange	600	
Yellow	570	0.4209, 0.5040, 111.4
Yellow-green	535	
Green	500	
Blue-green	493	
Blue	470	0.1566, 0.0808, 13.33

Evaluation Methods

A note on evaluation methods: While it may seem that it would make sense to evaluate whether system users can reliably distinguish between colors, the standard approach in certification is often two-pronged:

- Establish colors (as standards) that can be discriminated in the general population (e.g., see the Table A1 above).
- Ensure that the users have adequate color vision (or, use colors that even those with CVD can distinguish).

A recent report out of New Zealand (New Zealand DTA Report 405 NR 1686, "Colour Vision Requirements for Aircrew"), however, questions the effectiveness of traditional color vision screening in forecasting the ability of aircrews to safely operate transport airplanes. Specifically, it concludes that traditional color-vision screening methods have not been a good predictor of pilot success in using color displays in an operational setting. When people with CVD are aware of their deficiencies, they seem to find alternate methods to extract important information. Therefore, the best setting for determining whether people with CVD are capable of discriminating adequately may be an operational setting, not a clinical setting.

A.2.1. Dynamic Display Properties

As mentioned above, characteristics of the display and display medium can also affect discriminability. These include:

- The movement of a colored display element across the display medium can affect the ability to distinguish the color of the moving element due to smearing, luminance, and other background changes.
- The size of a colored display element. When a symbol becomes smaller, its color is harder to perceive. For example, font color becomes harder to determine when the font changes from a larger to smaller font.

- manner in which the display medium changes (degrades) over time and use, which means understanding how colors will be affected by those changes.
- The use of compacted formats and pop-up information should be examined for distinguishable use of color with changes between normal-sized formats to compacted (smaller) formats.

Relevant Guidelines:

"Ensure that display dynamic response time is sufficient for dynamic stability of colors such that the colors are identifiable under all foreseeable conditions, are not distracting and does not lead to misinterpretation of data. (FAA AC 25-11B)

MIL-STD 1472G provides this broader general guidance (beyond just color) on dynamic response time. "There shall be no discernible time lag between a change in a system condition being controlled or monitored and its indication on a display (see 5.1.2.1.4d). The time lag between system response to a control input and display presentation of that response shall be minimized, consistent with safe and effective system operation. (MIL-STD 1472G para 5.2.3."

"Ensure that the dynamic information in a display does not appreciably change color as it moves." (FAA AC 25-11B)

"Experience has shown that display quality may degrade with time and become difficult to use. Examples include lower brightness/contrast, distortion or discoloration of the screen (blooming effects), and areas of the screen that may not display information properly." (FAA AC 25-11B)

"Symbol size and color coding - the foreseeable change in symbol size ensures correct color interpretation. For example, the symbol needs to be sufficiently large so the pilot can interpret the correct color." (FAA AC 25-11B)

"The compacted display format should maintain the same display attributes to include correct color coding." (FAA AC 25-11B)

"Image failure, freezing, coasting, or color changes should not be misleading and should be considered during the safety analysis." (FAA AC 25-11B)

"If an automatic information pop-up condition is activated on the display and the system is in the wrong configuration or mode to display alerting information, and the system configuration cannot be automatically changed, then an annunciation should be displayed in the color associated with the nature of the alert." (FAA AC 25-11B)

A.2.2. Luminance of Individual Color Elements

Luminance refers to the intensity of individual display elements. Subjective (perceived) luminance of a single display element can be affected by the luminance of the elements that surround it. Thus, if the light from the surrounding display elements is so intense, the observer may not be able to easily distinguish the color of the individual element.

Relevant Guidelines:

"Displays or layers of displays with uniformly filled areas conveying information such as weather radar imagery should be independently adjustable in luminance from overlaid symbology. Specifically, the range of luminance control should allow detection of color differences between adjacent small filled areas no larger than 5 milliradians in principal dimension. While at this setting, overlying map symbology, if present, should be discernible." (FAA AC 25-11B)

A.2.3. Color Combinations

Perception of color for a single display element is affected by the colors that surround that element. On dynamic displays, the colors that are placed next to a display element (or provide a background) may vary as the display changes. It is critical to consider the combinations of colors that can occur on a display to ensure that distinguishing between colors is unaffected. This also applies to pop-up displays that overlay existing display medium. For example, the pop-up color should be made distinguishable against other colors in the display medium.

Relevant Guidelines:

"Color combinations that are similar in luminance should be avoided (for example, navy blue on black or yellow on white)." (FAA AC 25-11B)

"The following color pairs should be avoided: Saturated[4] red and green; Saturated red and blue; Saturated blue and green; Saturated yellow and green; Yellow on purple; Yellow on green; Yellow on white; Magenta on green; Magenta on black (although this may be acceptable for lower criticality items); Green on white; Blue on black; Red on black." (FAA Report No. DOT/FAA/CT03/05 HF-STD-001, Human Factors Design Standard [HFDS]: For Acquisition of Commercial Off-the-Shelf Subsystems, Non-Developmental Items, and Developmental Systems)

"Graphic depictions that use both color coding and color blending techniques to represent colors often used for background imagery should not interfere with the user interpretation of overlaid information parameters. Information elements such as labels, display-based controls, menus, symbols, and graphics should all remain identifiable and distinguishable." (FAA AC 25-11B)

A.3. Consistent Use across the System Interface

When color is used for coding (has meaning) it is important to consistently use the same color and its associated meaning across the system interface to ensure correct information transfer and to avoid confusion or an interpretation error.

Relevant Guidelines:

"Applicants should show the chosen color set is not susceptible to confusion or misinterpretation due to differences in color usage between displays. Improper color coding increases response times for display item recognition and selection, and increases likelihood of errors in situations where the speed of performing a task is more important than accuracy." (FAA AC 25.1302-1 5b(3c))

"Colors used for one purpose in one information set should not be used for an incompatible purpose that could create a misunderstanding within another information set. In particular, consistent use and standardization for red and amber or yellow, in accordance with §25.1322, is required to retain the effectiveness of flight crew alerts. A

[4] Saturation refers to the intensity of color in an image. When color is fully saturated, the color is considered in purest (truest) version.

common application is the progression from green to amber to red, representing increasing degrees of threat, potential hazard, safety criticality, or need for flight crew awareness or response." (FAA AC 25-11B)

"When inconsistencies are found, inconsistencies in the use of color should be evaluated to ensure that they are not susceptible to confusion or errors, and do not adversely impact the intended function of the system(s) involved." (FAA AC 25-11B)

A.4. Consistent Use with Industry and Cultural Norms

While the most important check on consistency is within the system interface itself, or within the larger operational setting, it is also important to assess consistency within the industry and, when possible, according to the ways color is used in other technologies or within society (e.g., the color green indicates a normal range).

Relevant Guidelines:

"Color-coding shall be used consistently within a display and across displays of other systems used by the same users." (MIL-STD-1472G 5.2.2.3.2)

"ANSI Z535.1 (Safety color code) establishes the standards, technical definitions, and tolerances for safety colors for sign, label and tag uniformity. These codes should be followed for consistency."

"Commercial Off the Shelf equipment (COTS) equipment should be closely examined when integrated within a system interface since the colors used in COTS equipment might not be consistent with colors already standardized for the system interface." (FAA HF-STD-001B December 30, 2016 provides guidance for COTS equipment)

References for Appendix A.

American National Standards Institute (2017). American National Standard for Safety Colors. ANSI Z535.1.

FAA (2014). Electronic flight displays. Advisory Circular 25-11B.

FAA (2013). Installed systems and equipment for use by the flightcrew. Advisory Circular 25.1302-1.

FAA (2016). Human factors design standard. FAA HF-STD-001B.

NASA (2010). Human integration design handbook. NASA SP-2010-3407

NASA (2015). NASA space flight human-system standard. NASA-STD-3001

Salvi, S.M., Akhtar, S., & Currie, Z. (2006). Ageing changes in the eye. Postgraduate Medical Journal, 82(971): 581-587.

U.S. Department of Defense (2012). Design criteria standard: Human Engineering. MIL-STD-1472G. DTIC.

Appendix B. Existing Guidance on the Topic of Alerting

The FAA, through The Federal Register Notice of Proposed Rule Making (NPRM) 14 CFR Part 25 (Docket No. FAA 2008–1292; Notice No. 09– 05) says "the purpose of alerting functions on airplanes is to get the attention of the flight crew, to inform them of specific airplane system conditions and certain operational events that require their awareness, and, in modern alerting systems, to make them aware of actions to address the condition."

Other documents provide more detail. A critical decision for managing alerts is to define an alerting philosophy. The need for a comprehensive alerting philosophy has dramatically increased as airplanes have become increasingly complicated. Airplane alerting in early airplanes started with limitations or thresholds marked on a round engine or airspeed gauge; these gauges later added simple alerting lights to call out an exceedance. More modern airplanes have become increasingly complex and integrated and have created many more alerted conditions. An alerting philosophy is needed to manage the various alerts (e.g., to set alerting priorities). The philosophy establishes what conditions or events will be alerted, how the alerts will be presented to the flight crew (visual, aural, tactile/haptic, or some combination of modalities), where the alerting information will be located, and, how to intelligently guide the flight crew (without error) to appropriate actions (if any).

Alerting Conditions. Designers must first determine what airplane system conditions should be alerted (e.g., low engine oil pressure). Further, the intended function of the alert should be described in sufficient detail that the alert can be evaluated, including its timeliness such that the flight crew has sufficient time to successfully recover the airplane from the alerting condition (e.g., sufficient time to prevent loss of control).

System Test. It is important to have a method for the flight crew to run a test to determine the performance of the alerting system.

> A single test switch shall be provided for testing all dedicated displays and, where possible, all subsystem circuitry within a given crew station. A test switch is not necessary if the function is automated within an integrated alert display. Blank signals, provided for a growth capability on the annunciator assembly shall also be included as part of the test circuitry. (MIL-STD-411F)
>
> 10.7.2.4 Visual and Auditory Annunciation Failures. The information management system shall test for a failure of the visual and auditory annunciators upon crew request. (NASA-STD-3001, Vol 2, Rev A)

Timely, Attention-getting Cues. Timely, attention-getting alert cues ensure that the flight crew is satisfactorily alerted and has adequate time to make any necessary actions (e.g., enough lead time to spool up the engines to recover from a low airspeed/energy condition). The most urgent alerts (Warnings and Cautions, see below) employ at least two different perceptual modalities (senses)—some combination of aural, visual, and tactile cues. Another element of the attention-getting is being able to acknowledge/silence an alert.

> Visual signals shall be presented and located to provide a perceptible luminance contrast to minimize the effects of excessive ambient light. At any location, the signals shall have a luminance and contrast that is fully readable and easily recognizable in a 10,000 foot-candle lighting environment. (MIL-STD-411F)

> Warning and caution alerts must provide timely attention-getting cues through at least two different senses by a combination of aural, visual, or tactile indications. (FAA §25.1322)
>
> 10.7.2.3 Audio Annunciation Silencing – The information management system shall provide a manual silencing feature for active audio annunciations. (NASA-STD-3001, Vol 2, Rev A)

Alerting Information. Designers must determine what alert information should be communicated to the pilot for a specific flight deck and operational context. This specification includes the alert message, its urgency, how it is prioritized among other alerts, and whether it should be inhibited in some operational situations.

Standardized Terminology/Definitions. Standardizing terminology and definitions for flight crew alerting supports consistent word meanings and applications of and compliance with the standard (e.g. defines the meaning of an alert and alerting levels).

Alert Presentation. Designers must determine how the alert is presented through the interface: its location, modality (aural, visual, tactile), and color standardization. Alerts should be readily and easily detectable and intelligible by the flight crew in all foreseeable operating conditions, including where multiple alerts are provided.

Color Standardization. Color use for alerting has been standardized (red for warnings; amber/ yellow for cautions) to visually indicate priority and importance. Using different colors to distinguish between different alert levels helps ensure that alerts are ‘‘readily and easily detectable and intelligible by the flight crew under all foreseeable operating conditions, including those where multiple alerts are provided” (§25.1322(a)(2)) and allows the flight crew to correctly recognize the ‘‘urgency of flight crew response’’ (§25.1322(b)).

> Conform to the following color convention: (i) Red for warning alert indications. (ii) Amber or yellow for caution alert indications. (iii) Any color except red or green for advisory alert indications. (FAA §25.1322)
>
> 10.7.2.5 The color red shall be used as a visual indicator for the highest alert level. (NASA-STD-3001, Vol 2, Rev A)

Presentation of Alerting on Monochromatic Displays. Certain flight deck displays, such as the head-up displays (HUD) located in the pilot’s primary field of view, are monochromatic and incapable of color-coding. Because there is an overall safety benefit in displaying alerts on the HUD, visual display coding techniques other than color need to be applied to those alerts so flight crews can easily and clearly distinguish between warning, caution, and advisory alert categories (§25.1322(e)(2)). For example, consistent display coding techniques such as location, shape, font style, size, boxing, texture, and other coding methods may be used to distinguish between alert categories.

> For monochromatic displays visual coding techniques, together with other alerting function elements on the flight deck, to distinguish between warning, caution, and advisory alert indications, if they are presented on monochromatic displays that are not capable of conforming to the color convention in paragraph (e)(1) of this section. (FAA §25.1322)

Alert Prioritization. A prioritization hierarchy communicates the urgency of each type of alert so the flight crew can address the most important conditions first. Alerts for airplanes are typically classified at levels or categories corresponding to Warnings, Cautions, and Advisories. Advisory Circular 25.1322-1 provides definitions and guidance regarding urgency and prioritization of flight crew alerts (see appendix 5 of the AC). The Federal Register for 14 CFR Part 25.1322 (Amdt. 25-131, 75 FR 67209, Nov. 2, 2010) provides the following examples:

1. Warning alerts require immediate flight crew awareness and an immediate flight crew response (e.g., to indicate an airplane is not configured for take-off).
2. Caution alerts require immediate flight crew awareness and a less urgent flight crew response (e.g., an auto throttle disconnect).
3. Advisory alerts are required for conditions that require flight crew awareness but may require subsequent flight crew response (e.g., the failure of a single fuel pump in a tank with redundant fuel pumps). Unlike warning and caution alerts, advisory alerts do not require immediate awareness and do not always require a subsequent flight crew response.

Minimizing Nuisance Alerts. A nuisance alert is an alert generated by a system that is functioning as designed, but is inappropriate or unnecessary for the particular condition; e.g., a traffic collision avoidance system (TCAS) alert that unnecessarily alerts the flight crew during takeoff to air traffic ahead of the aircraft at a considerable higher altitude. False alerts and nuisance alerts increase the flight crew's workload, reduce the flight crew's confidence in the alerting system, negatively affect their reaction to an actual alert, and may even lead the flight crew to take an inappropriate action. Nuisance alerts and their effects can be minimized by:

1. Preventing the presentation of inappropriate or unnecessary alerts that could cause a hazard if the flight crew was distracted by or responded to the alert.
2. Removing the presentation of a flight crew alert when the alert condition no longer exists to reduce unnecessary flight crew distractions, workload, and display clutter. (§25.1322)
3. Providing a means for suppressing an attention-getting component of an alert caused by a failure of the alerting system that interferes with the flight crew's ability to safely operate the airplane along with a clear and unmistakable indication that the alert has been suppressed. The means of suppressing the attention-getting component of an alert resulting from a failure of the alerting system must not be readily available to the flight crew such that it could be operated inadvertently or by habitual reflexive action. (§25.1322)

The alert function must be designed to minimize the effects of false and nuisance alerts. (FAA §25.1322)

References for Appendix B.

NASA (2015). NASA space flight human-system standard. NASA-STD-3001.

U.S. Department of Defense (1997). Aircrew station alerting systems. MIL-STD-411F. DTIC.