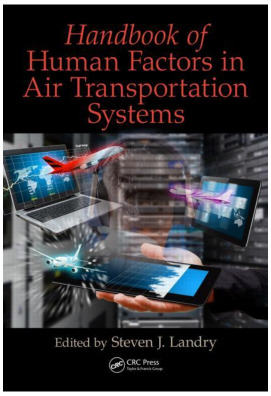

Handbook of Human Factors in Air Transportation Systems

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Flight Deck Human Factors

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12 Flight Deck Human Factors

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CONTENTS

INTRODUCTION

Human factors research into new and current flight deck technologies and operations enables a data-driven approach to identifying and resolving potential safety issues. Human factors is generally estimated to contribute to approximately 70% of commercial accidents and incidents (e.g., National Research Council, 1998; Shappell, 2006; U.S. Congress, 1988). Human factors is not just one thing but rather a combination of design, training, decision-making, flightcrew interaction, and automation, to name a few.

Advances in technology are intended to improve the safety of operations, but while it may solve some problems, it introduces others. Implementation of new avionics functions or systems must be considered with respect to the flightcrew member to avoid potential vulnerabilities. The purpose of this chapter is to identify and discuss some key human factors considerations in flight deck design and evaluation. This chapter does not intend to provide a comprehensive list of human factors considerations; rather, we focus on those topics that are frequently seen or reported in the approval of flight deck systems or procedures.

The current chapter is organized using a sociotechnical model of the flight deck environment. The sociotechnical model was first proposed in Moray and Huey (1998) and applied to the nuclear regulatory and rail domains (Moray, 2006). We apply the model here to capture flightcrew interaction through a systems perspective. The sociotechnical model consists of four subsystems, shown in Figure 12.1: the technical/engineering system, the personnel subsystem, the organizational/management infrastructure, and the environmental context. The four elements in the sociotechnical framework interact such that a change in one layer will exert influence on the other layers. For each layer, we have identified a corresponding aspect of flight deck human factors. By considering each layer and the interaction among these layers, flight deck human factors can be viewed as an integrated systems approach intended to ensure safe operations.

At the center of the model is the *technical/engineering system*. This layer defines the physical system—the flight deck, and the boundary between this layer and the next, the personnel subsystem, represents the human–machine interface. As defined here, this layer consists of the flight deck avionics systems that are used by the pilot/flightcrew and the design and evaluation of those systems. Much of this chapter is devoted to human factors aspects related to the technical/engineering system. In the model set forth here, this layer includes aspects of user interface design, for example, a *design philosophy* to guide system development and in particular, the introduction and use of automation on the flight deck. This layer also addresses the *location* of the avionics display. Finally, we address some recurring flight deck human factors issues in the design and use of *alerts, symbols*, *color*, and *labels and controls*.

Factors that influence how the pilot processes the information are represented by the second layer, the *personnel subsystem*. Pilot behavior on the flight deck is influenced by factors other than the design of displays and controls. This layer addresses factors that affect the cognitive ability of the pilot to respond appropriately, such as *fatigue* and *workload*. We also consider the role of *human error* and how to improve error prevention, detection, and recovery.

Flightcrew behavior will also be influenced by the *organizational/management infrastructure*, which define pilot performance standards. This layer addresses teamwork and group behavior, for example, pilot's interaction with other flightcrew members as well as interaction with dispatchers, mechanics, flight attendants, and airport personnel. This chapter focuses specifically on pilot training and the different approaches and perspectives for training.

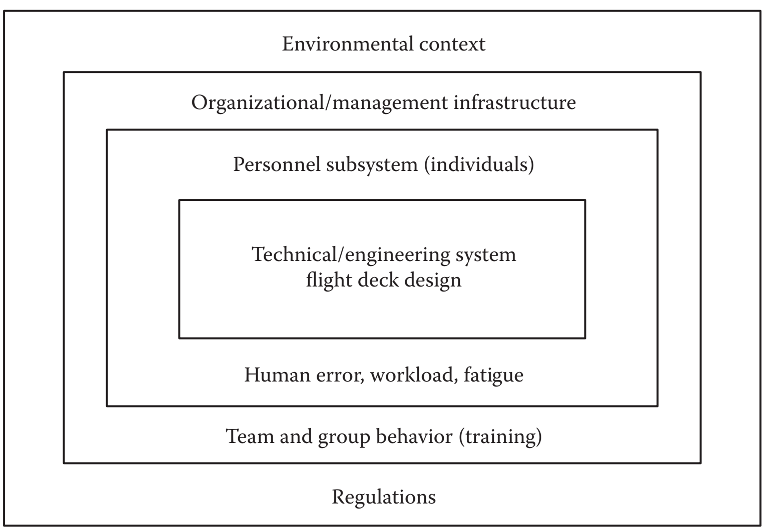

FIGURE 12.1 Sociotechnical model of the flight deck environment.

All these layers function within a political, cultural, and social environment, as highlighted by the outermost layer of the model, the *environmental context*. Regulatory oversight and public support or opposition to specific policies and actions also influences safety. Regulatory influences are addressed in more detail in Chapter 9, but we provide one example of how the layers interact with respect to pilot fatigue to influence flight, duty, and rest regulations.

Note that the sociotechnical framework applied here is only one way to describe flightcrew behavior and interactions. In addition, the sociotechnical system can be described in various ways and at many levels. Several models have been proposed to describe human capabilities and limitations, for example, SHEL (Hawkins, 1987) and the "Swiss Cheese model" (Reason, 1990), and can serve as valuable frameworks in other contexts.

TECHNICAL ENGINEERING SYSTEM

This *technical/engineering system* addresses considerations in the design of the avionics interface and the interaction between the flightcrew and the avionics. This section will begin with a discussion of the importance of a *design philosophy*. The technical/engineering system also includes technology considerations with focus here on lessons learned in the implementation and use of *automation*. We also consider how the *display location* influences the effectiveness of and attention given to an avionics display. Finally, we identify some recurring human factors issues related to flight deck design.

Design Philosophy

The process for designing a flight deck is complex and varies from one manufacturer to another. Over the years, the design of flight decks has shifted from the simple replacement of units (with newer displays and controls) to redesign with consideration of human perception and performance. A design philosophy outlines the assumptions for the flight deck and defines guiding principles that can improve consistency and compatibility across flight deck systems. A flight deck design philosophy describes how information should be presented, how color is used and applied on the displays, how information is managed, how the pilot/flightcrew will interact with the displays, and how failures are accommodated or mitigated. A flight deck design philosophy may also describe assumptions about roles and responsibilities, for example, the allocation of functions between the flightcrew and the automation.

Establishing a design philosophy for the flight deck provides an overarching "style guide", which can change the focus from technological implementation only to considerations of user interface and flightcrew interaction. This is especially important when systems made by different avionics vendors with potentially different underlying design philosophies are integrated onto one flight deck. Federal Aviation Administration (FAA) Advisory Circular (AC) 25-11B, *Electronic Flight Displays*, recommends that the design philosophy addresses five aspects of the user interface (FAA, 2014):

1. Information presentation, for example, "quiet dark" flight deck.
2. Color of electronic displays: What is the meaning and intended interpretation of the different colors?
3. Information management, for example, when should the pilot take action to retrieve information, should the information be brought up automatically?
4. Interactivity, for example, when is feedback provided?
5. Redundancy management: How are failures accommodated (e.g., single and multiple display failures, power supply failures, etc.)?

Each airplane manufacturer specifies a design philosophy, and the design philosophy may differ from one to another. Airbus and Boeing are known for having different design philosophies, particularly when it comes to the implementation of automation, although both philosophies recognize that the pilot is ultimately responsible for safe flight.

Airbus has described its automation philosophy as follows (FAA, 2005a):

- Automation must not reduce overall aircraft reliability; it should enhance aircraft and systems safety, efficiency, and economy.
- Automation must not lead the aircraft out of the safe flight envelope, and it should maintain the aircraft within the normal flight envelope.
- Automation should allow the operator to use the safe flight envelope to its full extent, should this be necessary due to extraordinary circumstances.
- Within the normal flight envelope, the automation must not work against operator inputs, except when absolutely necessary for safety.

Boeing's automation philosophy addresses the following (FAA, 2005a):

- The pilot is the final authority for operation of the plane.
- Both crewmembers are ultimately responsible for the safe conduct of the flight.
- Flight crew tasks, in order of priority, are safety, passenger comfort, and efficiency.
- Design for crew operations based on pilot's past training and operational experience.
- Design systems to be error tolerant.
- The hierarchy of design alternatives is simplicity, redundancy, and automation.
- Apply automation as a tool to aid, not replace the pilot.
- Address fundamental human strengths, limitations, and individual differences—for both normal and non-normal operations.
- Use new technologies and functional capabilities only when they result in clear and distinct operational or efficiency advantages and there is no adverse effect to the human–machine interface.

Based on their automation design philosophy, Airbus' approach has tended toward greater flight management system (FMS) authority and enforcement of "hard" limits, in which the aircraft does not exceed the flight envelope regardless of the pilot's control inputs. On the other hand, Boeing's automation philosophy has been to implement automation as a support tool rather than replacement for the flightcrew. Other manufacturers may have different philosophies from Boeing and Airbus. Regardless, the design philosophy should be documented, so the pilot can understand the design philosophy for the aircraft being flown and the level of authority being granted.

Automation

The job of the pilot has changed as automation in the flight deck has increased. The term *automation* is used generally to describe different types of automated systems, including control automation, information automation, and management automation. *Control automation* is automation that is intended to aid or replace a pilot in controlling the aircraft. *Information automation* describes the integration, filtering, and transformation of data and includes avionics displays for communication, navigation, and surveillance. Finally, *management automation* refers to automation that helps pilot manage the mission strategically versus tactically (Billings, 1997). In this chapter, we use the term *automation* generally when it applies to all three types of automation.

Control, information, and management automation provide alternatives for accomplishing tasks, but at the same time, these forms of automation changes the nature of the tasks to be performed and methods of operation. Automation is often introduced to reduce workload, but it may actually have the opposite effect as it simply shifts flightcrew tasks from physical actions to cognitive ones by creating new tasks related to controlling or monitoring automated functions. That is, the pilot takes on a supervisory role with respect to the automation and is expected to manage the systems' operation (FAA, 2005a; Wickens, Hollands, Banbury, & Parasuraman, 2013; Wood, 2004).

As noted in the previous section, the pilot should understand the rules and design philosophy governing the automation's behavior for the aircraft being flown. However, the internal processes may only be partially revealed to the pilot. Previous research has identified vulnerabilities related to how flightcrews manage the automation, specifically whether pilots understand and can anticipate the automation's behavior as well as when it is appropriate to use the automation and the appropriate level of automation in unusual/non-normal situations (FAA, 2013b).

Vulnerabilities may result from a miscalibration of trust in the automation. In some cases, the pilot may think the automation is more reliable than it is and *overtrust* the automation. Overtrust tends to lead to *overreliance*, which can cause the pilot to accept the advice of the automation without confirmation. Overreliance on flight deck technology and failure to understand the changes in the levels of automation is one of the biggest potential threats to airliner safety. The PARC (Performance-based operations Aviation Rulemaking Committee)/CAST (Commercial Aviation Safety Team) Flight Deck Automation Working Group conducted an analysis to identify potential vulnerabilities in the operational use of flight deck systems for flight-path management (FAA, 2013b). As part of that analysis, the Working Group reviewed 734 relevant incident reports in the aviation safety reporting system (ASRS) incident database from 2002 to 2007, 46 accidents and major incidents, as well as Line Operations Safety Audit (LOSA) aggregated data for over 9,000 flights from 2001 to 2009. The Working Group concluded that pilots overrelied on automation and delegated authority to those systems, sometimes deviating from the desired flight path. In approximately 25% of the accidents, the Working Group analyzed, participants were overconfident in the automation and were sometimes hesitant to intervene. Furthermore, in 50% of the accidents identified by the Working Group, pilots were out of the control loop and were not prepared to assume control of the aircraft. The PARC/CAST Working Group noted that the perceived high system reliability resulted in insufficient cross-check of the data, a failure to recognize when the autopilot or autothrottle had disengaged, or a failure to maintain speed, heading, or altitude.

On the other hand, the pilot may think that the system is not reliable and *undertrust* it, failing to use the system when it is appropriate to do so. Undertrust can lead to underreliance on automation such that the pilot turns off the automation or ignores it when it may help. This may happen if the automation produces too many false alarms and becomes a distraction (Billings, 1997; FAA, 2010; Parasuraman & Riley, 1997). This was particularly a problem for early traffic collision and avoidance systems (TCAS) and ground proximity warning systems (GPWS).

Another potential vulnerability with respect to flightcrew awareness of automation behavior has been ensuring that the pilot understand what mode the automated system is in (FAA, 2013b). A loss of mode awareness can lead to a mode error, that is, an incorrect action for the current system state that would have been appropriate had the automation been in the assumed state. The PARC/CAST Flight Deck Automation Working Group noted autoflight mode selection, awareness, and understanding as a continued vulnerability, and that pilots' lack of knowledge about the automation led them to misuse automation in certain circumstances (FAA, 2013b). For example, the flightcrew of Pinnacle Airlines Flight 3701 that crashed on October 14, 2004, outside Jefferson City, Missouri, inappropriately used the vertical speed mode under autopilot control while climbing from 37,000 to 41,000 feet rather than the autopilot airspeed mode that could have prevented the loss of airspeed. Consequently, the aircraft was in a low-energy state when it reached 41,000 feet. The National Transportation Safety Board (NTSB) concluded that the use of vertical speed during the climb was a misuse of automation and this was compounded by the fact that the pilots did not understand how airspeed affected aircraft performance (NTSB, 2007).

Loss of mode awareness may result from an incomplete or inaccurate mental model of the automation behavior, inadequate feedback from the automated system, or complexity in the design of the automated system. In their analysis, the Working Group identified 27% of the accidents related to *mode selection errors*. The analysis also attributed 12% of ASRS reports and 50% of major accidents and incidents to *pilots were out of the loop*, indicating that pilots were not aware of the airplane state or situation (FAA, 2013b). Prior to the Working Group's analysis, there were also numerous reports of autopilot systems that changed modes without sufficient indication to the flightcrew, particularly in high workload situations; for example, an annunciator light alone that indicated the current mode was not always salient (FAA, 1996, 2006a).

The interaction between flightcrews and aircraft has changed as more functions are delegated to or shared with automated systems. The vulnerabilities may be mitigated though system design. For example, providing feedback on automation states and behavior may help the pilot's mode awareness. In addition, making the automation behavior more "transparent" or providing reliability information could help the pilot better calibrate trust in the system (Mumaw, Sarter, & Wickens, 2001; Wickens, Hollands, Banbury, & Parasuraman, 2013). The issues discussed here are common across the different types of automation (control, information, or management), but the importance of the issue and the appropriate mitigation may differ from one type of automation to another.

Display Location

The location of the display can significantly affect the attention paid to the information on the display as well as the readability of the display. As new avionics and functions are introduced, limited space on the flight deck had led to compromises when integrating and installing new systems. In particular, the use of portable electronic technologies has broadened the flight deck visual field, sometimes increasing the pilot's normal viewing area. The FAA requires that "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" (14 CFR 25.1321(a)). Furthermore, displays should be placed in such a way that they can be monitored by minimal head and eye movement. The field-of-view is measured by establishing the design eye position, which is the point at which the midpoint of the pilot's eyes would be located when properly seated at the normal position (FAA, 2011a, 2014c). The visual field for each eye is approximately 135 degrees vertically and 160 degrees horizontally (FAA, 2002c). However, it is only in the fovea, an area approximately 22 degrees in visual angle in the center of the visual field, where fine detail can be resolved (Wickens, Lee, Liu, & Gordon-Becker, 2004).

The literature defines two specific regions in the visual field: the *primary field-of-view* and the *secondary field-of-view*. The primary field-of-view (sometimes referred to as the optimum field-of-view) is generally defined as a region with a 15 degrees radius extending from the normal line of sight, established 15 degrees below a line extending horizontally from the eye (Cardosi & Huntley, 1993; Department of Defense, 2012; FAA, 2013a, 2014c). This region is shown in Figure 12.2. The primary field-of-view is the area of the visual field with the highest acuity. From the center of the eye, the density of receptor cells decreases toward the periphery.

FAA regulatory and guidance material requires primary flight instruments and alerts, specifically warnings and cautions that require flightcrew awareness and response, to be presented in the primary field-of-view (e.g., see FAA, 2010, 2011b, 2014c). In older Part 23 aircraft, powerplant information was sometimes located on the right side of the flight deck, and these displays created not only head and eye movement but were also difficult to read. The FAA guidance is supported by

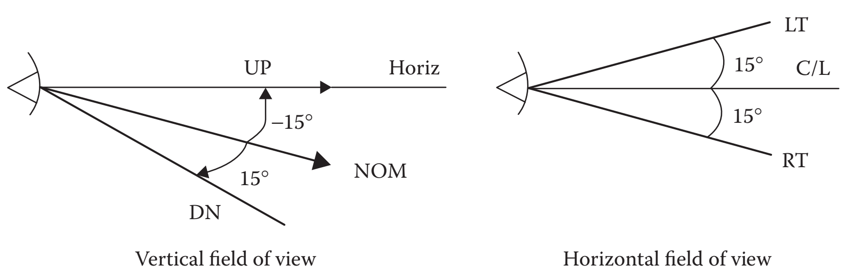

FIGURE 12.2 Primary field-of-view.

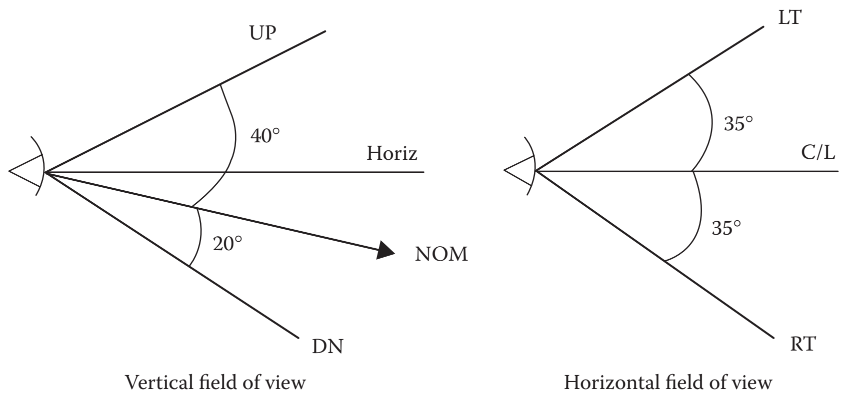

FIGURE 12.3 Secondary field-of-view.

the research literature; in general, the closer information is to the primary field-of-view, the more likely it is that the information will be scanned, detected, or noticed compared with information that is further away (Cardosi & Huntley, 1993; Wickens et al., 2016). In fact, a meta-analysis of research examining detection rate as a function of alert location indicated that the miss rate was unchanged from 0 to 15 eccentricity (i.e., the degrees of visual angle away from a central point), but increased as the alerting stimulus was presented farther outside the primary field-of-view (Wickens et al., 2016).

The secondary field-of-view (also referred to as the maximum field-of-view) is a region around the primary field-of-view that extends vertically +40 degrees up and −20 degrees down and horizontally +35 degrees, as shown in Figure 12.3. There is less guidance as to what information should be in the secondary field-of-view, compared with the primary field-of-view.

The location of avionics displays on the flight deck must be balanced so that the information is visually accessible, as appropriate. To determine how visually accessible information is, one can measure the angle with which the avionics display is offset from the pilot's centerline of vision (FAA, 2002d). It is important to consider that detectability of information may be influenced by the expectancy of that information, salience, and workload. That is, recommendations for presenting alerts in the primary field-of-view support detection of a salient, "expected" event under modest workload, but if the event is surprising, if the alert is not salient, or if workload is high, alerting information may need to be presented closer to the center of the visual field (Wickens et al., 2016). We discuss the presentation of alerts further in the next section.

Alerts

The number of alerts and annunciations on the flight deck has proliferated as more complex avionics are introduced. In the past, annunciator panels contained all the systems' alert information in one place, and discrete lights would illuminate to indicate non-normal conditions. The pilot could see immediately which system experienced a problem. As avionics systems have become more integrated, the alerting function has been incorporated within the display, creating operational complexity (FAA, 2002a; Veitengruber, Boucek, & Smith, 1977).

The term *alert* is used in different ways in literature and in regulatory and guidance material. It can be used generally to refer to a wide range of annunciations, some of which may be *normal* conditions, or it can also be used more specifically and refer only to indications of more serious or *non-normal* events that require some type of pilot action or awareness. This chapter uses the term *alerts* in the most generic sense; it is the activation of any visual or aural indication, annunciation, or alarm that is intended to make the pilot aware of an event that requires his/her awareness and possibly provide advice as to potential actions to take.

The purpose of an alert is to draw the pilot's attention to a specific condition and report the nature of the condition (FAA, 2010). An alert may take many forms (e.g., switches, lights, flags, prompts, or messages), be presented in several modalities (visual, auditory, and haptic), and vary in their criticality. The effectiveness of an alert will depend on the design of the complete alerting function, including the condition(s) required to trigger the alert, the urgency and priority assigned to the alert, the presentation of the alert, and whether the presentation is consistent with the urgency. Critical alerts should be easily distinguishable from noncritical alerts; alerts should not be generated for conditions that do not require pilot's awareness (FAA, 2010; McAnulty, 1995). An alerting philosophy can help integrate the various alerts across flight deck systems to reduce the number of alerts and annunciations presented and ensure that the pilot is not given contradictory information. Alerts should be prioritized so that the most urgent alert is presented first (Boucek, Erickson, Berson, Hanson, & Leffler, 1980; FAA, 2010).

The FAA classifies alerts in three categories—warnings, cautions, and advisories (see 14 CFR 25.1322):

- Warning: for conditions that require immediate flightcrew awareness and immediate flightcrew response
- Caution: for conditions that require immediate flightcrew awareness and subsequent flightcrew response
- Advisory: for conditions that require flightcrew awareness and may require subsequent flightcrew response

Alerts must be prioritized in two ways: first by grouping into categories of warning, caution, or advisory, and second by evaluating the importance of the alert within the category. There is little empirical work on how alerts can be prioritized by flight phase. Consideration during prioritization should be given to the urgency of flightcrew awareness, urgency of flightcrew response, the speed of the response required, and the potential consequences of failing to detect the alerting condition (Cardosi & Huntley, 1993; Cardosi & Murphy, 1995; FAA, 2010; Palmer et al., 1995). Failure to prioritize or standardize the presentation of alerts on the flight deck can result in confusion and recognition errors.

Furthermore, warnings must be presented in red and cautions in amber/yellow (14 CFR 25.1322 (e)(1)), based on results of previous research that showed red lights were typically detected as fast or faster than other lights (Boucek et al., 1980). Use of the colors red and amber/yellow (or colors confusable with red or amber/yellow) for means other than alerting has been hypothesized to desensitize pilots to the urgency of the alerts and diminish the effectiveness of those colors (Boucek, Veitengruber, & Smith, 1977; Gabree, Chase, & Cardosi, 2014; Veitengruber, Boucek, & Smith, 1977; Widdel & Post, 1992).

It may not always be clear when a situation should be classified as a warning or a caution, however. The distinction between warnings and cautions is subtle, although the consequences are quite different. In addition, the increase in the number of aircraft systems has also caused an increase in the number of warnings, cautions, and advisories, making it more difficult for pilots to identify which system generated the alert. Careful consideration should be paid to which situations are warnings and which are cautions and how to make it apparent as to which event(s) generated the warning or caution (FAA, 2002a).

The detectability of an alert depends on where, when, and how it is presented. Evaluation may be needed to ensure that alerts are detected in a manner timely to the information provided. Warning and caution alerts must be indicated through two different senses using a combination of visual, aural, or tactile indication (14 CFR 25.1322(c)(2)). The FAA requires visual indications of warnings and cautions to be placed in the pilot's primary field of view to maximize the likelihood they will be detected (14 CFR 25.1322). Boucek et al. (1980) further recommend that high priority signals be placed within 15 degrees of the pilot's centerline of vision, and lower priority signals be presented within 30 degrees. Consequently, space limitations on the flight deck may result in other alerts placed in less desirable locations where they may not be easily noticed. Several visual coding methods can be used in combination with location to attract attention, including blinking or flashing, reverse video, size coding, and color. The effectiveness of these coding methods will vary depending on the context. For example, blinking or flashing lights are generally detected faster than steady lights, but the detection time for a blinking or flashing light increased if the background contained other blinking or flashing lights (Boucek et al., 1980). In general, each of these coding methods must be applied carefully, however, as these coding methods are by their nature intended to be distracting, and overuse of a coding method or combining too many methods can minimize the effectiveness of any one method. In particular, blinking or flashing must be applied carefully as indiscriminate use can reduce legibility and lead to visual fatigue. Blinking or flashing is recommended only for the most urgent warnings (Cardosi & Murphy, 1995; GAMA, 2000; Garner & Assenmacher, 1997; McAnulty, 1995).

Aural alerts have the advantage over visual alerts of being omnidirectional; that is, the signal can be perceived regardless of head or eye orientation (Wickens, Lee, Liu, & Gordon-Becker, 2004). However, because aural alerts are transient, they are more effective in drawing attention to information on a display rather than being the sole source of information (FAA, 2010). The volume of aural alerts is an important design consideration; the volume should be able to be heard above the ambient noise but not be so intense that it is above the danger level for hearing or that it will distract or cause discomfort (Mitman, Neumeier, Reynolds, & Rehmann, 1994; Wickens, Lee, Liu, & Gordon-Becker, 2004). A review of aural alert-related incidents and feedback from pilots regarding aural alert presentation highlighted the following issues (Cardosi & Murphy, 1995; McAnulty, 1995, Mitman et al., 1994; Patterson, 1982; Peryer et al., 2005):

- Aural alerts were too loud and interrupted flightcrew's performance of an ongoing task, masked other important aural information, or startled the flightcrew.
- The onset and offset of aural alerts were too abrupt, with the potential to startle the flightcrew and disrupt ongoing tasks.
- The temporal patterns used for warnings were not distinctive and were confusable. Similarity will make it more difficult for the pilot to identify which system generated the alert and increase workload in diagnosing the alert.
- The length of the aural alert was too long, unnecessarily adding to the noise level on the flight deck.
- The spectral characteristics (tones) of the alerts were such that lower priority warnings were perceived as being more urgent than higher priority alerts.

Recommendations have been provided to address these concerns in the design of aural alerts. First, the volume of an aural alert should range from 20 to 30 dB greater than the ambient noise level (FAA, 2010; McAnulty, 1995; Wickens, Lee, Liu, & Gordon-Becker, 2004). Second, the rise in tone, which characterizes a non-normal event, should be approximately 20–30 milliseconds for the portion of the tone in which the sound level is above the threshold noise level (Patterson, 1982). Third, aural alerts may be designed to be unique from other sounds from the flight deck by varying one or more of four dimensions: the pitch or frequency, the envelope (e.g., is the tone rising or constant), rhythm, and location (Cardosi & Huntley, 1993). Recommendations for how long a tone should be are less clear; the detection of a tone may take up to 50 milliseconds, and presenting a signal beyond 300 milliseconds does not provide much benefit (Patterson, 1982). The minimum duration should be 50 milliseconds, but beyond that the signal duration may vary depending on the urgency level and the type of response required (FAA, 2010; McAnulty, 1995).

Voice alerts may be used to indicate conditions demanding immediate flightcrew awareness, because the alerts provide the information directly. However, voice messages have some limitations. First, voice alarms are likely to be more confusable with other voice communications (e.g., flightcrew communications, air traffic control [ATC]) than other aural alerts. The artificiality of computer synthesized speech may help one distinguish the message from other voice communications but may also make the message difficult to understand. Second, too many different voices can be a nuisance and a distraction, similar to having too many aural alerts. Finally, depending on the length of the message, understanding a voice message may take more time than reading a visual message (Cardosi & Murphy, 1995; McAnulty, 1995; Wickens, Lee, Liu, & Gordon-Becker, 2004).

As alerts may be distracting, it may be helpful to sometimes inhibit alerts that are inappropriate or unnecessary for a particular phase of operations to minimize distractions to the flightcrew from what may be perceived as a nuisance alert. For example, warnings, annunciations, and messages that are not critical to the safety of instrument approaches or missed approaches may be suppressed during those phases (RTCA, 2006). In fact, surveys of pilots have indicated that it is a potential for the presentation of too many noncritical alerts during critical phases of flights, when the alerts would be perceived to be a distraction, and agree with the need to inhibit noncritical alerts during these critical phases of flight (Boucek et al., 1980). Whether to allow the flightcrew to inhibit, cancel, or defer alerts must be considered carefully, however, because this action essentially defeats the presentation of the alert in the first place (Boucek et al., 1980). The ability to inhibit alerts is used on all air transport aircraft to minimize nuisance alerts. Alerts should not suppress or inhibit other displays or alerts requiring immediate flightcrew attention (FAA, 2010).

Finally, the integrity and reliability of the alerting system should be evaluated, as perceived trust and credibility will decrease as the number of false alarms increase. Alerts are one form of automation, and consequently, the system will sometimes make mistakes and signal that there may be a problem when one does not exist. A high number of false alerts or alerts that provide inaccurate information may increase workload and slow response time in the case of a real alert. As noted in the Automation section earlier, pilots have suppressed or ignored alerts because the number of false alarms was too high (see also Parasuraman & Riley, 1997; Wickens & Dixon, 2005). Thus, care should be taken when setting the alerting threshold to prevent the likelihood of false or nuisance alerts. In addition, training to the user to help explain the tradeoff between misses and false alarms may help pilots understand the inevitability of false alarms rather than view them as a system failure (Wickens, Hollands, Banbury, & Parasuraman, 2013).

Symbols

The design of symbols is complex due to the wide range of display technology and functionality on which they may be shown. A consistent symbol design across manufacturers and chart providers will facilitate recognition of symbols. Historically, however, the symbols used by manufacturers and chart providers differ slightly. Although there is no standard set of symbology for navigation information, there are common properties in the symbols used by manufacturers and chart providers (e.g., in terms of shape or fill). Symbols currently in use by various avionics and chart manufacturers for navigation aids and airports as well as line and linear patterns are documented in a Volpe Center report, *Survey of Symbology for Aeronautical Charts and Electronic Displays: Navigation Aids, Airports, Lines, and Linear Patterns* (DOT/FAA/AR-07/66; DOT-VNTSC-FAA-08-01). Industry recommendations and guidelines for symbology are provided in the following:

1. SAE ARP4102/7, *Electronic Displays*, Appendices A through C (for primary flight, navigation, and powerplant displays)
2. SAE ARP5289A, *Electronic Aeronautical Symbols*, (for depiction of navigation symbology)
3. SAE ARP5288, *Transport Category Airplane Head Up Display Systems*, (for Head Up Display symbology)

To promote consistency, displays should use symbols similar to those shown on published charts and sectionals or with commonly accepted aviation practices, when possible. New symbols, a new design, or a new symbol for a function historically associated with another symbol, should be tested for flightcrew comprehension, retention, and ability to distinguish from other symbols. In particular, considerations for new symbol design should include the *legibility*, the *distinctiveness*, and *interpretability* of that design.

Legibility: The legibility of information on an electronic display is influenced by several factors including the viewing angle, pixel density, and contrast ratio (Nelson et al., 2014; Yeh & Chandra, 2005). Some symbols may have fine details that are difficult to see when viewed off-angle or under degraded display conditions. The *viewing angle* refers to the angle at which a symbol subtends the eye, measured in degrees of arc, and captures the relationship between symbol size and viewing distance. That is, a small symbol viewed at a close distance could have the same visual angle as a larger symbol viewed from farther away. The *pixel density* describes the number of pixels per inch of a display. Five pixels are needed to draw a letter on a display, but six pixels are needed for the letter to be "fully recognizable" (Nelson et al., 2014). Finally, *contrast ratio* describes the difference in luminance between the symbol and the background. Contrast ratio varies depending on the display hardware, the information being shown, and the amount of light on the flight deck.

Nelson et al. (2014) incorporated these factors into two tools to objectively evaluate the legibility of electronic charts on portable electronic devices. One addresses legibility with respect to visual angle and specifies whether the electronic chart is legible to a person with 20/40 vision by measuring the smallest text on the chart and considering it with respect to the viewing distance. The other tool examines whether the pixel density is sufficient to display the information clearly.

Distinctiveness: A symbol is distinctive if it can be easily discriminated from other symbols. Symbols should have a basic shape or characteristic that can be recognized with and without context. If a symbol is identifiable *only* with context, then the pilot may be relying on context cues, and the meaning may not be intuitive. Distinctiveness should be considered within and across symbol sets to ensure *consistency* in the use of a symbol, regardless of the manufacturer or chart provider, and to prevent *confusability* of a symbol with other symbols (Yeh & Chandra, 2004). Pilots must be able to identify and understand information conveyed by symbols for flight planning, position awareness, and navigation.

There have been instances in which a symbol shape used by one manufacturer is confusable with a symbol shape used by another. The Figure 12.4 provides an example of using the same symbol shape for two different meanings.

In 1999, the FAA identified the potential for confusion because the U.S. representation for a fly-by waypoint looks similar to the International Civil Aviation Organization (ICAO) representation for a fly-over waypoint. The meanings are quite different, however. A *fly-by* waypoint allows the pilot to anticipate a turn to avoid overshooting the next flight segment. A *fly-over* waypoint is used when the aircraft must fly over the point prior to initiating a turn. If these symbols were misinterpreted, the resulting flight path deviation could have safety consequences (Yeh & Chandra, 2008).

The Volpe Center conducted an exploratory paper-based study to evaluate the saliency of the U.S. and ICAO fly-over and fly-by waypoint symbols, shown in Figure 12.4. Pilots were asked to find fly-over and fly-by symbols in cluttered paper charts; saliency was measured as the accuracy with which the symbols were detected. The results showed that the ICAO *fly-by* waypoint symbol was detected *more* accurately than the USA symbol for a *fly-by* waypoint, but the ICAO *fly-over* waypoint symbol was detected *less* accurately than the USA *fly-over* symbol. However, the lower

	USA symbols	Previous ICAO symbols
Fly-by waypoint		
Fly-over waypoint		

FIGURE 12.4 Fly-by and fly-over symbols.

accuracy for finding the ICAO fly-over waypoint symbol was due primarily to detection performance when that symbol was drawn at the runway and the size of the symbol was reduced so that the runway could remain visible. In 2000, this discrepancy and potential safety risk was resolved when ICAO added a circle to their recommended fly-over waypoint symbol (Yeh & Chandra, 2004).

Yeh and Chandra (2005) examined the role of representativeness in symbol design by identifying key defining features for eight navigation aid symbols (DME, fix, NDB, TACAN, VOR, VORDME, VORTAC, and waypoint). Pilots were presented with symbol shapes currently in use by aviation display manufacturers and chart providers and asked if they considered whether a symbol shape was representative of a specific symbol type. Symbol recognition was evaluated on the basis of the frequency with which a test symbol shape was considered to be representative of a symbol type. The results of the study are shown in Table 12.1. Pilots identified a representative symbol shape for seven of the eight symbols; no representative shape was identified for the DME, likely because DMEs are typically drawn in conjunction with another symbol (e.g., the VORDME). Closer examination of the data showed that symbol shape was the key factor for classifying symbols, despite variations in size, color, and orientation.

Interpretability: Symbols may be designed so that one symbol contains multiple features that convey information. Using the example in Figure 12.4, a single symbol shape (the four-pointed star) is used to convey what the symbol represents (a waypoint), but the fill of the symbol also conveys information (i.e., whether it is fly-by or fly-over). Variations in fill, color, and border (e.g., a circle surrounding the symbol) have been proposed to convey information. (Note, however, that color alone should not be used to convey meaning. This is an issue that will be discussed further in the next section.) The amount of instruction that pilots are given about how the rules are applied may influence how easily they learn the rules. In addition, key features of the symbol (e.g., fill or color) should be applied clearly and not be confusable with other features. This is a particular issue for Cockpit Display of Traffic Information (CDTI) displays, which may use the color brown/tan to represent aircraft on the ground, and in some cases (e.g., lighting conditions, viewing angle, etc.), the brown/tan color is confused with yellow/amber that represents a warning or caution (Gabree, Chase, & Cardosi, 2014).

One consideration is ensuring symbology on new avionics systems is consistent with symbology on older, more familiar systems. For example, symbology for new CDTI may or may not be based on

TABLE 12.1
Representative Navigation Aid Symbol Shapes

Symbol Type	Representative Shape
DME	None identified
Fix	
NDB	
TACAN	
VOR	
VORDME	
VORTAC	
Waypoint	

traffic symbology used for TCAS, an air-to-air surveillance system, but because of previous pilot experience with TCAS, it is desirable to consider aspects of how TCAS symbology is designed and coded in the design of CDTI symbols (Zuschlag, Chandra, & Grayhem, 2013). Thus, when expanding the definitions of current symbols, integrating symbols, or remapping symbol shapes, the design of the symbol needs to be evaluated to determine whether the meaning conveyed by the combined features is clear.

Color

Display technology allows the presentation of a myriad of colors with good fidelity, allowing manufacturers to use a large number of different colors on their systems. Color is often applied with the intention of differentiating among the information elements displayed, and it can be an effective method for coding and enhancing the understanding of information, when applied appropriately. However, excessive or inappropriate use of color can decrease the effectiveness of a display, add more complexity, increase visual search time, and increase the potential for misinterpretation.

A common issue that has been observed in avionics submitted for approval is the inappropriate use of color, particularly in the use of red for elements that may *not* require an immediate response, or the use of amber/yellow for elements that may *not* need corrective action (FAA, 2002a). The consistent use of color within an application and across all flight deck displays is encouraged. The FAA reserves the use of red and amber/yellow for warnings and cautions, specifically (see 14 CFR 25.1322; FAA, 2010).

There are also special considerations with the use of the color blue. The human eye has the least number of blue-light sensitive cells, and those cells are located in the periphery of the eye rather than the fovea, so it takes more time to bring that color into focus. Consequently, the color blue should not be used for small, detailed symbols. In addition, blue is at the far end of the visual spectrum, so the eye may have difficulty focusing on blue at the same time as other colors. In particular, red and blue should not be used together because the two colors are at opposite ends of the visual spectrum; so when one color is in focus, the other will be slightly out of focus (Gabree, Chase, & Cardosi, 2014).

Another consideration related to color is the perception of color, which varies considerably from one individual to another. The *2010 Aeromedical Certification Statistical Handbook* (Table 22) estimates that there were 4,438 active airmen (male and female) with color vision deficiencies as of December 31, 2010, with 1,553 of these holding firstclass medicals, 991 holding secondclass medicals, and 1,894 holding thirdclass medicals (Skaggs, Norris, & Johnson, 2012). In addition, aging of the eye causes the lens to yellow and reduces the ability to distinguish between colors (Salvi, Akhtar, & Currie, 2006). To accommodate the proportion of pilots that are colorblind or color deficient, color should be applied redundantly, for example, with shape, location, or fill. Use of two or more coding techniques will also improve recognition, identification, and interpretation.

In general, no more than six colors should be used if information is color coded to avoid errors in judgment. Research shows that although we can discriminate among colors when they are placed side by side, it is harder to identify a specific color alone. In other words, the human observer may not be able to accurately judge the level of a color with precision if there are more than six levels (Wickens, Hollands, Banbury, & Parasuraman, 2013; FAA, 2014c). In addition, colors that are assigned meaning should be identifiable when presented alone and with respect to all backgrounds and in all viewing conditions (Gabree, Chase, & Cardosi, 2014). Color coding is most effective if the intended meaning of the coding is immediately understood, for example, when color is a natural representation of the information or conforms to pilot stereotypes.

Colors should be selected so that they are easily discriminable to reduce the potential for misinterpretation. Color is defined by hue, saturation, and brightness. The term hue is generally synonymous with color; it describes the degree of "red"-ness or "blue"-ness. Saturation is the purity of the color, and brightness is how light or dark a color is. The Commissions Internationale de L'Eclairage developed a model defining color by its u', v' coordinates, as shown by the Commissions Internationale

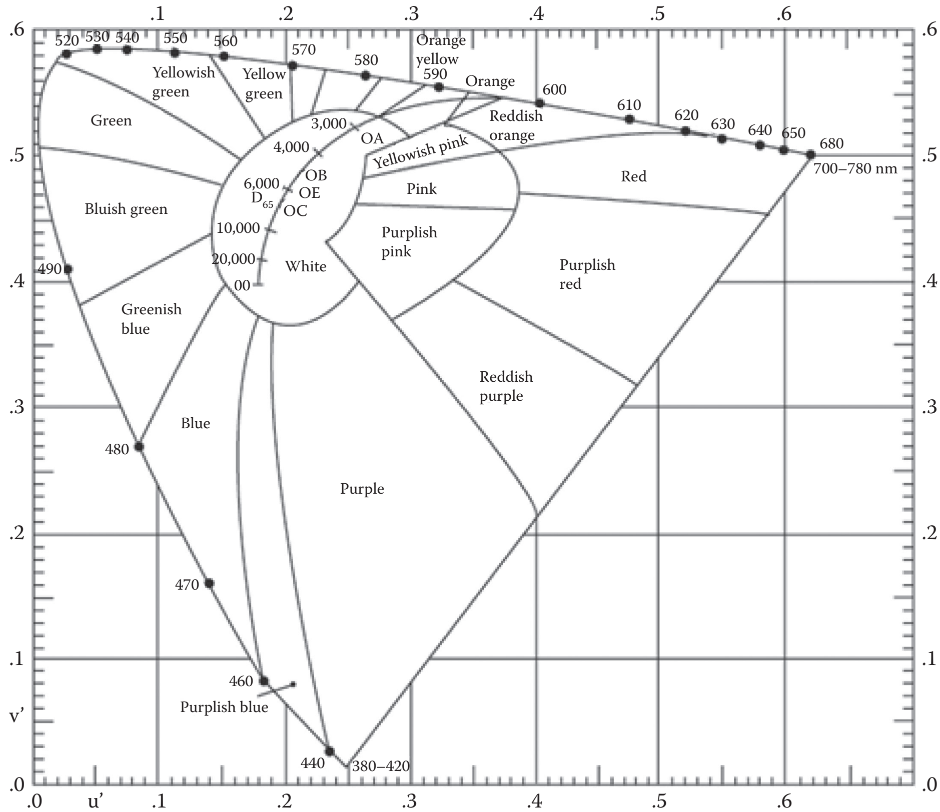

FIGURE 12.5 Commissions Internationale de L'Eclairage chromaticity diagram.

de L'Eclairage chromaticity diagram in Figure 12.5. The distance between two colors in the figure is a direct reflection of the perceptual difference between those two colors. Colors that are widely spaced apart in the figure will appear more different from one another.

The topics so far have focused on the information display. We now turn to control devices and the methods for interacting with the information.

Control Devices

Control devices are the primary means for inputting information. The term *control* in this chapter refers to input devices rather than flight controls, such as a yoke or rudder pedals. A modern flight deck may have more than 200 control devices, such as buttons, knobs, keyboards, switches, cursor-control devices (e.g., mouse, touchpad, trackball, and joystick), or touch screens. Each control device has unique characteristics that will influence its effectiveness for an application or avionics system. Previous experience and expectations affect usability of controls, so control design that is consistent within a system and across the flight deck can reduce the chance of confusion. A design philosophy for controls will help promote this consistency.

The usability of a control is influenced by its function, operation, and arrangement with respect to the operating environment. Each of these factors will be considered in turn. An application of these principles to touch screens is also included to address some of its unique characteristics.

Function: The function of a control device should be identified quickly and accurately, as appropriate for the task. Control labels are the most common means for identifying and describing control functions so that the pilot can easily identify what each control does. The labels should be readable and legible from the pilot's normal operating position and in all lighting conditions (see FAA, 2014c). As the number of separate controls has increased, creative approaches have been used to communicate a control's function. In many cases, the length of the labels introduced new abbreviations and acronyms, and some times, the labels did not sufficiently describe the function performed.

One solution to the labeling problem is to use icons, but most functions do not have a universally accepted icon (FAA, 2011a). Another solution was to reduce the number of controls by using multifunction controls, in which one device controls several functions or systems. However, a disadvantage for multifunction controls is that it may not be obvious what is being controlled, increasing the potential that the pilot may inadvertently activate the wrong function or provide input to the wrong system. Thus, proper labeling is quite important to indicate the active function (FAA, 2011a). Multifunction controls with hidden functions should be avoided as they increase the potential for error and workload (European Aviation Safety Agency, 2007).

Operation: The interaction between a control device and the system or display being controlled should be apparent and understandable. That is, the movement required to operate a control and the resulting movement or action on the system or display should be obvious. The conventional relationships between a control function and the expected direction of movement are provided in Table 12.1. The control should be installed in an orientation such that the direction of the control movement is consistent with what is being controlled.

Control operation must also consider response gain, that is, the sensitivity with which the movement of a control or the force applied to a control is transformed to produce an output. A control that has a high gain requires only a small movement of the control to produce a large change in the display output, which allows more rapid inputs but can lead to overshooting the target. Low-gain controls require more input or force than high-gain controls but provide for precision. The response time and accuracy with which the task must be performed need to be traded off. Some controls provide variable gain to support high-gain task when the control is moved quickly and low-gain tasks when the control is moved slowly (Table 12.2).

Controls should also provide feedback about the results of the actions. Feedback provides information to the pilot about whether a control has been activated and confirms whether the input has been accepted or not. Response time for feedback is important in terms of system acceptability. There is an expectation that system response time will be faster for tasks that are considered to

TABLE 12.2
Conventional Relationships between Control Function and Direction of Movement

Function	Direction of Movement
Increase	Up, right, forward, clockwise, push
Decrease	Down, left, rearward, counterclockwise, pull
On	Up, right, forward, pull, depress, rotate clockwise
Off	Down, left, rearward, push, release, rotate counterclockwise
Right	Right, clockwise
Left	Left, counterclockwise
Up	Up, forward
Down	Down, rearward
Retract	Rearward, pull, counterclockwise, up
Extend	Forward, push, clockwise, down

Source: Federal Aviation Administration (FAA), *Controls for flight deck systems* (Advisory Circular 20–175), Washington, DC, 2011a, Retrieved from: http://www.faa.gov/documentlibrary/media/advisory_circular/AC%2020–175.pdf.

be simple than those that require more complex calculations. However, long or variable response times can lead to a negative perception for usability (Nielsen, 1994). The response time and appropriateness of feedback varies depending on the task being performed and the specific information required for successful operation (FAA, 2011a).

Arrangement: Limited space on the flight deck may lead to controls that are placed in less-than-ideal locations. Controls should be arranged as a function of the tasks that need to be performed and the sequence with which those tasks are performed. 14 CFR 25.777 requires that "each cockpit control must be located to provide convenient operation and to prevent confusion and inadvertent operation." To comply with this rule, the position of the control must fall within the reach envelope of the intended pilot population. Anthropometric data may provide a means for accounting for differences in human size, including reach, hand, and finger size. Dedicated controls should be as close to the display being controlled as possible. Controls should be placed so that the function being controlled and related elements (e.g., indications and labels) can be seen when manipulating the controls. Controls placed below the display or to one side could minimize visual obstruction when operating the control.

Inadvertent activation of controls should be prevented to the extent possible, although controls will be operated inadvertently at some point. For example, the pilot may accidentally bump a control or activate one control while activating another. Common means for preventing inadvertent activation include spacing buttons of an ¼ inch (6.25 millimeter) apart, providing physical protection for hard control devices, and logical protection for software-based controls (FAA, 2011b). The designer must consider the tradeoff between preventing inadvertent activation and the control's operation as methods to prevent inadvertent activation may make controls more difficult to operate (Cardosi and Murphy, 1995; FAA, 2002a, 2002d).

Operating Environment: The usability of control devices must be considered with respect to the operating environment. Some considerations are (FAA, 2011a) as follows:

- The target population or end user, such as body size, previous experience with a specific control, and training
- Use in lighting conditions from bright sunlight to darkness
- Use of gloves while operating the control, which influence factors such as button size and spacing, and use of capacitive touch screens
- Effect of turbulence or other vibrations
- Potential interruptions while performing a task
- Objects that could interfere with control movement, such as interference from pilot clothing or flight deck equipment
- Pilot incapacitation for aircraft designed for multicrew operation, specifically whether controls are viewable, reachable, and operable by both flightcrew members
- Use of nondominant hand and
- Excessive noise

It will not be possible to consider *all* environmental and use cases, but a representative set should be considered that addresses the environment in which the controls are expected to be used, including normal and non-normal conditions.

Touch Screens: As technology has evolved, traditional controls (such as knobs, push buttons, and switches) are being replaced with touch screens. A touch screen provides a direct relationship between input and output and is helpful when space is limited. The use of touch screens for installed systems on the flight deck emerged with the advent of touch screen portable electronic devices, such as the Apple iPad and the Microsoft Surface, which host applications such as electronic charts, electronic documents, and airport moving maps.

There are several touch screen technologies that vary in how they sense and respond to touch: resistive, capacitive, and infrared. A touch screen device may be developed from one or a combination of these technologies. *Resistive* touch screens are the most common of the three. It is composed of several layers of electrically conductive material. A "touch" applies pressure so that the layers come into contact with each other, and this action completes a circuit and is processed as input. The pressure required to produce a response varies from one resistive touch screen to another. A *capacitive* touch screen is coated with conductive material. A *touch*, usually skin contact, creates a change in capacitance, which is processed as input. Consequently, use of gloves or use of a stylus that is not specifically designed for the touch screen will not create a measurable change in capacitance. Finally, an *infrared* touch screen has infrared beams across the surface of the touch screen, and a *touch* is registered when the beams are disrupted (e.g., by a finger). In this case, touching the screen is *not* necessary, because the beams of light are slightly above the screen.

Touch screens are not appropriate for all tasks and operating environments, however. They have unique considerations from traditional controls related to readability in various lighting conditions, surface contamination (e.g., smudges and scratches), inadvertent touch, and feedback. Specifically, fingerprint smudges may create glare in some lighting conditions, reducing display readability. In addition, touch inaccuracy may be higher relative to traditional controls, thereby increasing the potential for error. With respect to feedback, touch screens generally do not provide tactile feedback, so the pilot may not know whether his/her input was accepted without looking directly at the display (Dodd et al., 2014).

It is important to consider factors such as how quickly a response is needed, the force needed, feedback, and inadvertent activation. Dodd et al. (2014) conducted a series of studies to examine the effects of touch screen location (overhead, to the left of the pilot—"outboard", forward panel, center panel), touch screen size (8″ or 15″), touch target size (0.25″ or 0.50″), and touch screen technology (projected-capacitive or resistive) on pilot usability with and without moderate turbulence. Pilots flew a simulated path while performing data entry, panning, and menu navigation tasks on a touch screen display. So that the study simulated a traditional flight, the primary task required maintaining a straight and level path, and interacting with the touch screen display was secondary.

Not surprisingly, the time needed for data entry and the number of data entry errors increased in turbulence than without turbulence. However, touch target size moderated these effects, such that pilots using large touch targets in moderate turbulence made fewer errors than pilots using small touch targets in no turbulence. In addition, pilots completed the tasks quickly and more accurately with the resistive touch screen than the projected-capacitive touch screen.

With respect to display location, touch displays on the center panel and overhead locations led to higher subjective ratings of fatigue relative to the forward panel. There was no difference with the outboard location relative to the other locations. More importantly, observation of the pilots during the study showed the need for hand rests; Figure 12.6 shows photos taken during the study of how pilots stabilized their hands based on display size and location. As the figure shows, pilots tended to use the edges of the touch screen to stabilize their hand, regardless of display location. The data collected showed that this stabilization improved input accuracy and minimized fatigue.

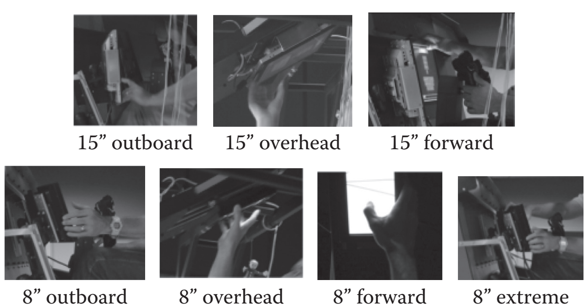

FIGURE 12.6 Method for hand stabilization (Courtesy of Dodd).

The discussion so far has focused on flight deck design and the information presentation—that is, the technical system itself. Flight deck design cannot be considered in isolation, however, and any design must consider the knowledge and skills of the pilots who will be operating the aircraft. Any assumptions about what the pilot is expected to do should be explicitly identified, and individual characteristics inherent to the end users must be considered. This is a topic that is addressed by the second layer of the sociotechnical model, the personnel subsystem.

PERSONNEL SUBSYSTEM

The second layer of the sociotechnical system addresses the people—*personnel system*. Although there are several types of people involved in flight deck interactions (the air traffic controller, maintenance personnel, dispatch, etc.), we focus here on the pilot; the maintainer was addressed in Chapter 5, and the air traffic controller is addressed in the next chapter. Specifically, we address three factors that influence the pilot's ability to apply knowledge, skills, and abilities to respond and perform a given task: workload, potential for error, and fatigue.

Workload

Workload describes the mental and physical demand imposed by pilot duties, work, and the number of tasks to be accomplished given the time constraints within which those duties, work, and tasks must be completed. Workload may be used as an indication of how busy the pilot is as well as the complexity of the task as it reflects the mental and physical resources needed by the task relative to the amount of resources available. Each task performed imposes some amount of workload, but the level of workload experienced will vary depending on the pilot's experience with the task, training, and skill. In addition, the workload experienced for one task may vary at different times depending on what other tasks are being performed concurrently. Each system on the flight deck should be evaluated in isolation as well as in combination with other systems to understand its impact on pilot workload in both normal and non-normal situations.

14 CFR 25.1523 addresses flightcrew workload, requiring that:

The minimum flight crew must be established so that it is sufficient for safe operation, considering

(a) The workload on individual crewmembers;
(b) The accessibility and ease of operation of necessary controls by the appropriate crewmember; and
(c) The kind of operation authorized under § 25.1525.

Demonstrating compliance to 14 CFR 25.1323 requires evaluating the predicted overall flightcrew workload as well as measuring the workload for each individual crewmember. There are several ways to measure workload using objective measures, subjective measures, or a combination of the two. Objective measures include collecting data on primary task performance, secondary task performance, or physiological data. The *primary task* is typically flight performance, that is, how well is the pilot maintaining the predefined flight path. Measures such as deviations from the flight path or control activity (the amount of displacement on the flight controls) are indicators of workload. A *secondary task* may also be imposed; a secondary task is one that is not the focus of the study but rather is introduced to measure the "spare" mental or physical resources. Decrements in task performance on the secondary task (e.g., response time and response accuracy) are assumed to be indications of higher workload, because as workload increases, pilots will focus on the highest priority task (the primary one). Physiological measures, such as changes in heart rate, heart-rate variability, or evoked brain potential, have also been proposed; increases in workload would be reflected to a higher heart rate, more variability, or increased brain activity.

Workload is also assessed using subjective measures, in which participants provide an estimate of their workload on different tasks. Common scales for subjective workload measures are the Bedford workload scale (Roscoe & Ellis, 1990), NASA-TLX (National Aeronautics and Space Administration-task load index) (Hart & Staveland, 1988) and the subjective workload assessment technique (SWAT; Reid & Nygren, 1988). These scales differ in their dimensionality. The Bedford workload scale is unidimensional and provides “one number” that describes the workload experienced based on a series of questions: Was it possible to complete the task? Was workload tolerable for the task? Was workload satisfactory? On the other hand, the NASA-TLX and SWAT are multidimensional, assuming that several dimensions contribute to workload. The NASA-TLX measures mental demand, physical demand, temporal demand, performance, effort, and frustration. The SWAT gathers feedback on the time demand imposed by the task, the mental demand, and the stress imposed.

The problem with subjective workload measures, however, is the potential for response bias. Every pilot is different, and the individual perception of workload can vary considerably. In addition, subjective workload measures may not always agree with performance measures (Wickens, 1993). Therefore, we generally recommend that subjective data be used in conjunction with objective data to increase the reliability of the results.

The issue of workload is often mentioned with respect to the introduction and use of automation; it is generally believed that one way to reduce flightcrew workload is to introduce automation. Although there are in fact periods of time in which automation does decrease workload, there are also periods when task demand is high in which use of the automation adds *more* complexity and workload to the tasks being performed (Parasuraman & Riley, 1997; Wiener, 1988). In particular, programing of the automation has shifted workload from takeoff and approach and landing to the time periods prior to these phases of flight, but this is also the time period when ATC may notify the pilot of a route or approach change. Consequently, the flightcrew may need to reprogram the automation at a time when they also need to be managing the aircraft and lead to aircraft mishandling errors (FAA, 2009).

Furthermore, the PARC/CAST Working Group noted that workload management is an important consideration for flight-path management. Although workload and distractions are discussed in flightcrew training courses, the Working Group was concerned that flightcrews are not adequately prepared to manage tasks on the flight deck when workload is high. In particular, task prioritization for aviating, navigating, and communicating is harder to operationalize when there are many tasks to be performed in each category, and the tasks overlap, or are queued (FAA, 2013b). For example, on July 6, 2013, Asiana Airlines Flight 214 struck a seawall at San Francisco International Airport when the flightcrew mismanaged the aircraft’s vertical profile during the approach, relied on automated flight controls without a full understanding of the system, and did not notice their speed was too slow. Although there were many contributing factors to the accident (including pilot fatigue), NTSB investigators found a period of increased flightcrew workload due to the complexity of the flight control computers, so none of the pilots noticed that the automatic airspeed control had deactivated (NTSB, 2014b).

This section has focused on those cases in which workload was too high, but workload that is too low—*underload*—must also be considered. Underload refers to long periods of relative inactivity, for example, as on transoceanic flights where the pilot does not have much to do apart from monitoring displays. The focus on the flight deck has generally been on reducing workload, but maintaining vigilance in low workload situations may be fatiguing as well (Hancock & Warm, 1989). Low workload is generally more difficult to detect than high workload, but the consequences are similar to those observed in high-workload conditions such that pilots are less efficient and do not perform the task at a commensurate level of effort (Hancock & Verwey, 1997). As the level of cognitive activity dedicated to a task is influenced by the task demands, as demands change, so too does the effort invested in a task to maintain “level” performance. Complacency and boredom reduce vigilance and may hinder pilots from effectively responding to surprises and non-normal events on the flight deck. In fact, Young and Stanton (2002) have proposed that attentional resources are reduced in low-workload situations and may not return to the maximum attentional capacity that would be normally available, even when task demand increases. In addition, pilots who are sleep deprived do not perform as well as pilots who are well rested under low-workload conditions (Wickens, 1993).

There are fewer studies examining the effects of low workload, and measuring low workload is not as clear as measuring high workload. Research is needed to evaluate the effect of designs for susceptibility to underload situations. In particular, the Working Group reported hearing concerns from pilots about low workload and attempts to engage the flightcrew, particularly when pilots are further out of the control loop.

Human Error

On October 31, 2014, Virgin Galactic's SpaceShipTwo crashed in the Mojave Desert due to the premature unlocking of the spaceship's feather system. The NTSB attributed the crash to a failure to consider and protect against human error. Specifically, the NTSB noted that the design of the system had created a single-point human error, and that the hazard analysis did not account for the possibility that the feather could be unlocked prematurely, consequently extending in conditions that could lead to a catastrophic failure of the vehicle. In addition, the manuals and procedures did not provide information about the consequences about unlocking the feather early (NTSB, 2015).

Human performance is often the largest contributor to system variability, and human error is the most common accident theme, occurring in one form or another in nearly all investigated accidents (Abbott, 2001; FAA, 2015a; U.S. Congress, 1988). Accidents generally result not from one error but rather from a combination of factors, only some of which are human errors. The potential for error is influenced by system design, previous experience, and training. Preventing *all* human error is not possible. The most qualified and well-trained flightcrews will commit errors even if the flight deck is well designed. Fortunately, most errors are detected and mitigated and will not result in a safety event (FAA, 2013a). Rather, an understanding of the issues created by the intersections between and systems and end users is needed and is critical to preventing the risk of errors mitigating the ones that do occur.

Human error is an action or omission of an action that was not intended, expected, or desired. Human error is often classified by examining behavior in terms of skills, rules, and knowledge (Rasmussen, 1983; Reason, 1990). These three categories generally refer to the amount of conscious control required to perform a task. Skill-based tasks are "automatic", highly practiced, and generally not under conscious monitoring once the intention to act has been formed. Rule-based tasks are characterized by the application of a rule or procedures (e.g., instructions, checklists) used to determine a course of action. Knowledge-based tasks are generally novel and unexpected and require conscious thought (Wickens, 1993).

Errors in skill-based tasks are generally errors of execution; that is, a plan of action has been identified and the intention is correct, but the plan is executed incorrectly. There are two types of errors: slips and lapses. A slip is a correct action that is carried out inappropriately, such as activating the wrong control. Slips may result because there is a slight deviation from an expected sequence of behavior, because the intended action is similar to the conditions of a more frequent action, or because the action is so "automatic" that attention was directed elsewhere. A lapse is a memory failure that results in an action that is not taken, for example, a missed step in a checklist.

A mistake is the result of an incorrect intention that is executed. A mistake may be rule based, in which the pilot applies a "rule" to the wrong situation or applies the wrong *rule* (reference). Mistakes may also be knowledge based, in which the diagnosis of the situation is incorrect so the plan (execution) is inappropriate. Planning errors may be due to decision-making biases, in which pilots on only a subset of available information that is consistent with the original diagnosis (a confirmation bias) or gather data from what is available rather than what is most reliable and relevant (availability). Mistakes may have more serious consequences than slips and lapses because the operator committing the mistake believes that s/he is taking a correct action, regardless of other signs that may tell otherwise. Note that a mistake is different from a *violation*, which is an action that is deliberate and known to violate rules or procedures (Reason, 1990).

Reason's framework is only one approach to looking at human error. There are several other models for predicting human error that can be applied early in the design process. THERP (Technique for Human Error Rate Prediction) is a human reliability assessment technique that assumes human error is a result of omission, commission, selection, sequence, timing, and quantity and requires examination of "performance shaping factors" that influence the probability of human error (Swain & Guttman, 1983). Systematic Human Error Reduction and Prediction Approach is another predictive method that attempts to link methods to reduce error to the underlying cause of the error. Systematic human error reduction and prediction approach combines hierarchical task analyses methods with error taxonomies (e.g., the skill, rules, and knowledge framework defined by Rasmussen) to identify credible errors (Harris, Stanton, Marshall, Demagalski, & Salmon, 2005). The purpose of this chapter is not to provide a comprehensive discussion of the many models for classifying human error but to generally recognize their contributions for managing and mitigating errors.

Error Management refers to how the system design facilitates error prevention, detection, and recovery. To effectively manage errors, the system designer must understand what types of human error have occurred on the basis of previous accidents and incidents, and how to compensate. *Error Prevention* is intended to avoiding errors and is generally accomplished through system design, for example, by switch guards, confirmation actions, or interlocks, or by reducing the occurrence of cognitive factors that contribute to error (e.g., distraction, workload). *Error Detection* is intended to ensure that errors can be detected quickly, enabling recovery. Feedback is particularly important for error detection; immediate feedback can provide information to the flightcrew about the correctness of their actions, for example, with alerts to a specific error or system condition, annunciations of aircraft state information during normal operations, or indications of external hazards. Finally, *ERROR RECOVERY* addresses how easy it is to recover or return to a safe state after the error (Human Factors Harmonization Working Group Final Report, 2004). Procedures and checklists that remind the pilot of the sequence of tasks that need to be completed can support error recovery.

In a complex system like the flight deck, there are multiple defenses to mitigate known errors. *Error Mitigations* may be in the form of changes in equipment design or establishing new operations and procedures. Mitigations have also been proposed in the form of "error tolerant" and "error resistant" systems. "Error tolerant" systems help to mitigate the errors that are committed. This approach to human error assumes that errors are unpredictable and inevitable. It gives the pilot flexibility in maintaining safe and level flight, and although that flexibility sometimes may lead to a wrong action, in general, that flexibility is advantageous, and the system should respond in a way that tolerates and forgives the errors that do occur. The automation monitors the system and informs the pilot of errors, if they occur. As an example, the Boeing 757/767 aircraft shows its error tolerance by presenting an alert when a pilot enters a destination into the flight management computer (FMC) that is not compatible with the fuel load (Wickens, 1993; Weiner & Nagel, 1988).

On the other hand, "error resistant" systems attempts go one step beyond error tolerant system and may control and correct for pilot inputs that are considered to be erroneous. For example, automation on the Airbus A-320 prevents the pilot from exceeding the aircraft's operating envelope, regardless of the control stick input. However, by seizing control, these systems become potential sources of error (U.S. Congress, 1988).

Finally, training is often proposed as a mitigator for human error, but training can only reduce errors, not eliminate them. Training influences the knowledge, skills, and abilities of pilots, but the method by which this occurs is influenced by the airlines and evaluated by the FAA or appropriate regulatory authority. This topic is addressed by the organizational/management infrastructure.

Fatigue

Fatigue is a topic of interest for human factors professionals directing or advising any workforce regarding hours of operation and work schedules, and particularly for industries that must cover 24/7 operations. Fatigue effects on performance and safety have been recognized and are well documented (Bonnet, 2000; Carskadon & Dement, 1987; Dinges & Kribbs, 1991; Dinges, 1992; Horne & Reyner, 1985; Naitoh, 1975). We find that the length of one's work period plays a role in increasing fatigue, as does the timing of the shift as it occurs within each 24-hour period. Personnel who are required to work in a 24/7 operations setting are particularly vulnerable to working during hours of the day when they would ordinarily be sleeping. Most people know how difficult it is to remain alert between the hours of midnight and 6 a.m. We see that when changing or rotating from one shift schedule start time to another, one might experience what is called shift lag that is not unlike the experience of flightcrew who have traversed multiple time zones and experience the desynchronous effects of jet lag (Caldwell, 1997; Commercial Transportation Operator Fatigue Management Reference, 2003). Over the last decade or so, we have seen significant advancements in the science of fatigue including sleep, circadian rhythms, and chronobiology (Kecklund, Di Milia, Axelsson, Lowden, & Akerstedt, 2012). We have also seen that the integration of this knowledge into the operational aviation environment has remained difficult and challenging.

Definitions: There are about as many definitions of fatigue as the number of individuals questioned. You may have developed your own personal definition from experiences with your work and life activities. Even the research literature espouses definitions with slight variations. With regard to aviation, the FAA defines fatigue as a "physiological state of reduced mental or physical performance capability resulting from a lack of sleep or increased physical activity that can reduce a flightcrew member's alertness and ability to safely operate an aircraft or perform safety-related duties" (FAA, 2012). The ICAO expands the definition a bit by stating that fatigue is also the result of "sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety related duties" (ICAO, 2012).

So, respectively, it is clear that fatigue is not based on a single dimension, but rather the result of a combination of several factors related to an individual's physiological sleep needs, internal biological rhythms, and the kind of work in which one is actively involved. Significantly, even though fatigue is relatively complex and difficult to define, the operational causes and consequences are surprisingly very consistent across different aviation operations and personnel (Battelle Report, 1998; Miller, 2006).

Research results illustrate how operator performance is negatively affected by factors associated with fatigue, such as lengthy duty times, times of the day that the work period is scheduled (e.g., working at night), acute sleep loss from getting less than a normal amount of sleep in a single night, and an accumulated sleep debt that occurs over several days/nights of restricted sleep (Eriksen and Akerstedt, 2006; Powell, Spencer, Holland, Broadbent, & Petrie, 2007; Samel, Wegmann, & Vejvoda, 2005). In addition, we find that time on task and workload issues contribute to fatigue, though presently it is not clear how to quantify these effects. For the crewmember, Caldwell et al. (2009) state, "… both long- and short-haul pilots commonly associate their fatigue with night flights, jet lag, early wakeups, time pressure, multiple flight legs, and consecutive duty periods without sufficient recovery breaks." Goode (2003) and Powell, Spencer, Holland, and Petrie (2008) discuss elevated risks associated with lengthy flight and duty time, and the need for limiting these flight duty periods (FDP) and flight times. So, it is clear that within the aviation industry, running 24/7 combined operations contributes to fatigue at the onset, and that science can certainly share the responsibility with industry to develop mitigation and management strategies to minimize the effects of fatigue to improve flightcrew alertness and performance, and maintain safety.

The following paragraphs provide brief descriptions of a few key elements in the study and understanding of fatigue:

Sleep: Humans are normally active during the daylight hours (diurnal) and sleep during the night. The optimal length of our sleep period is generally around eight hours, though some people appear to need less or more sleep than others. We typically cycle through different stages of sleep during the sleeping period. Generally, we fall asleep during stages 1 and 2 and cycle into progressively deeper sleep stages 3 and 4 before returning to lighter sleep and Rapid Eye Movement (REM) sleep in around 90–120 minutes. This cycle repeats itself four to five times throughout the night. We experience more non-REM sleep stages (i.e., stages 1–4) during the first half of the night with more REM sleep occurring in the latter half of the sleep period. As we age (40–45 years +), we experience less deep or slow-wave sleep and tend to spend more time in the lighter sleep stages, from which we are more easily awakened (Carskadon & Dement, 2011).

During non-REM or deep, slow-wave sleep, biological reconstruction and physical maintenance occurs through nocturnal increases in protein synthesis and cell division (Van Cauter & Tasali, 2011). Moreover, during non-REM and REM sleep, the restoration of higher cognitive elements, emotional balance, and mood occurs along with what we believe is a process for the consolidation of declarative and spatial memories (non-REM) and nondeclarative memories (REM) (Peigneau & Smith, 2011). We need to cycle through both types of sleep staging (i.e., REM and non-REM) to feel fully rested. Studies show that we respond best to a single, consecutive period of sleep, though some work has suggested that if part of a split-sleep schedule is *anchored* to our normal nighttime and the remaining sleep occurs at another time and adds up to a total of 8 hours within that 24-hour period, our performance is not significantly degraded. The results of the Mollicone et al. (2008) study suggest that split sleep schedules are feasible and can be used to enhance the flexibility of sleep/work schedules for operations that might involve restricted nighttime sleep due to work period and task scheduling. But this remains somewhat controversial and not without what appears to be sleep restriction costs over several days and nights.

Circadian rhythms: Circadian rhythms refer to the changes in physiology, alertness, and performance that are regulated by our internal (biological) pacemaker or body clock (i.e., suprachiasmatic nucleus of the hypothalamus). The neuronal and hormonal activities that the suprachiasmatic nucleus generates regulate many different body functions in a 24-hour cycle. Fatigue-related performance effects are also found to fluctuate across the daily cycle and include changes in subjective alertness and sleepiness, performance of mental and physical work, and our sleep and wake cycle (Akerstedt, 1995). Briefly mentioned before, the risk of significant impairment in performance has been shown to be greatest for individuals working at night when normally sleeping. Elevated risk also occurs during the morning hours prior to an early show time (Battelle Report, 1998; Dinges, 1992). Going to bed earlier in preparation for early morning work is difficult because you are trying to begin sleep during the "evening wake maintenance zone," identified in the few hours before your usual bedtime and associated with high alertness and an elevated core body temperature (Gander, Myhre, Graeber, Andersen, & Lauber, 1989). Moreover, greater risks of impaired performance are associated with the repeated effects of consecutive night time schedules in which an accumulation of sleep debt typically occurs because we do not fully adapt to sleeping during the daytime and working at night (Naitoh, 1975).

Desynchrony: So, our circadian rhythms are normally entrained by external time cues (i.e., Zeitgebers) and specifically by the light and darkness cycle. Jet lag among flightcrew is commonly described as the feelings of malaise and fatigue that accompany a time zone change. This primarily occurs during that period of resynchronization of your circadian rhythms to the *new* external time cues in the new location (i.e., again, to light and darkness). For other aviation workers like those in ATC or technical operations, shift lag is described as the feelings of malaise and fatigue that accompany changes in shift schedules, for example, from daytime work to nighttime work, and vice versa. Shift lag occurs during the period of *forced* resynchronization of circadian rhythms to the new external time cues due to the work schedule. Compared with jet lag, however, the attempt to resynchronize to a nighttime work and a daytime sleep schedule occurs more slowly and is much less successful because the main time cues (i.e., daylight and darkness) tend to inhibit the resynchronization process (Miller, 2006).

Aviation relevance: Alertness and performance degradation occur when individuals are scheduled for work during times that encroach on their normal sleep times, either by extending and completing a flight duty period beyond midnight or by beginning a flight duty period very early in the morning (Gander, van den Berg, Mulrine, Signal, & Mangie, 2013). These times when the body clock is expecting sleep, for example, when flight duty periods and flight time encroach on the *back side of the clock*, we experience significantly degraded performance during that period of maximum sleepiness, identified as our window of circadian low (between 0200–0600) and during the resynchronization period following time zone changes (Gander, Graeber, Foushee, Lauber, & Connell, 1994).

Degraded performance can also occur with early morning *show times*, for example, before 6 a.m., because this schedule essentially restricts your sleep time by trying to sleep earlier than normal during the wake maintenance zone. Lastly, if flightcrew are required to sleep during the daytime when they are normally awake, sleep is found to be qualitatively less restful, and quantitatively less likely to occur consecutively for up to eight hours. Sleep would be difficult during the morning hours when our alertness is normally rising or outside of the secondary window of circadian low (i.e., 1400–1700). Repeating any of these restricted sleep scenarios over the few days and/or nights of a trip sequence would certainly produce a cumulative effect that would trigger the need for *recovery sleep* before another trip sequence could begin (Battelle Report, 1998; Bonnet, 2000; Hursh & Van Dongen, 2010; Dinges, 1989).

Ultralong Range (ULR) Flight/Safety implications: Flight crewmembers are particularly vulnerable to schedules that place their work and wakefulness at odds with their circadian rhythm. Previous 14 CFR Part 121 flight crewmember duty and rest regulations had not originally considered much of what is now known about our internal body clock and scheduled flight operations that occur during hours of reduced alertness and performance.

With modern technology and manufacturing developments, commercial aircraft became capable of flying longer segments without the requirement to refuel. Hence, long-haul and ULR flight operations became possible. Fatigue and human alertness limitations then became more imposing to the FAA and the international aviation community. In 1993, Air New Zealand was interested in a progressive and innovative data-driven approach for developing crew scheduling, particularly for long-haul flight operations. Most every route they flew was a long-haul trip. They teamed with British, New Zealand, and NASA scientists to develop this new approach. They also formed an internal multidisciplinary team to implement the approach and established an external oversight panel. These activities contributed to the aviation industry to *think outside of the box*, that is, beyond the prescriptive limitations of regulations, to manage fatigue.

In 1998, an International ULR Crew Alertness Steering Committee was formed at around the same time that Singapore Airlines requested approval from the Civil Aviation Authority of Singapore to fly ULR flights from Singapore to Los Angeles. This city pair route required flight times of 16 hours and flight duty periods of 18–22 hours (Flight Safety Digest, 2005). This had never before been done. Three ULR Crew Alertness Workshops were held from 2001 to 2003 with the objectives to identify common fatigue mitigation approaches, develop a technical basis for operational and regulatory guidance to maintain crewmember alertness, and seek global multistakeholder consensus. The workshops attracted as many as 90 participants, including many prominent scientists and flight safety personnel from 14 countries. Eventually, Singapore Airlines was granted a *safety of flight operation* status based on the carefully directed efforts of the International Crew Alertness Steering Committee, and they began ULR flights to both Los Angeles and New York City in 2004. The important operational experience, data collection and analysis, and scientific knowledge from the steering committee's work, and the work of Australian scientists, established a basis for a new operational model and an approach to monitor and mitigate flightcrew fatigue. The procedure is now known as fatigue risk-management systems (FRMS). This nonprescriptive approach has become an exemplary basis for the U.S. FAA's authorization of the ULR Operation Specification

A-332, first issued to Delta Air Lines in the development of its New York City to Mumbai city pair route in 2006. We discuss FRMS in more detail later in this chapter in the context of flight, duty, and rest regulations.

Summary: The definition of fatigue is found to be varied and complex for many reasons, and it seems that the more that is understood about fatigue, the more difficult it becomes to manage. The operational definition used by the FAA touches on important aspects of fatigue to include that it is a “physiological state of reduced mental or physical performance capability resulting from a lack of sleep or increased physical activity that can reduce a flightcrew member’s alertness and ability to safely operate an aircraft or perform safety-related duties.” Expanding this definition a bit, ICAO includes the influence and impact of extended wakefulness, circadian rhythms, and workload. It is also important to recognize that there are both work and nonwork related components and many other factors that interact with each individual’s tolerance to fatigue.

The discussion with respect to the personnel subsystem has focused on individual behavior, but operating an aircraft is not a task conducted in isolation but rather as part of a system that requires coordination with other pilots, airline operators, dispatchers, and air traffic controllers, to name a few. This coordination is addressed in the third layer of the sociotechnical model, the organizational/management infrastructure.

ORGANIZATIONAL/MANAGEMENT INFRASTRUCTURE

The organization/management infrastructure layer of the sociotechnical model acknowledges the role of teamwork and group behavior. In this chapter, we focus specifically on pilot training and the development of pilot performance standards for air transport operations. In addition, we examine the means for understanding human errors when they occur and identifying areas where additional training may be needed.

Requirements for pilot training appear in 14 Code of Federal Regulations (CFR) Part 61 and are administered by the FAA. They differ by categories of operations, resulting in different certificates (airline transport, commercial, private, recreational, sport, and student pilots), ratings (airplane, rotocraft, glider, lighter than air, etc.), and classes (single-engine, multiengine, land, and sea), some with training supplements in their own parts of the CFR, including 121 and 135 for commercial airlines. Training regulations are written to ensure pilots acquire individual technical skills necessary to their intended certificate, rating, and class. At a fundamental level—definition of certificates, ratings, authorizations, endorsements, and so on—these requirements have been fairly stable since the dawn of the jet age and establishment of the Federal Aviation Agency in 1958. But the science and practice of human factors engineering and psychology have impacted training in a number of key ways:

- Training has evolved from a solely individual skill and maneuver focus to incorporate skills necessary to perform in a multicrew cockpit within a realistic operational environment.
- This has further expanded to consider the interfaces with other front-line employee groups within airline operations, including dispatchers, mechanics, flight attendants, and airport personnel.
- Hazard and task analyses and instructional system design (ISD) have influenced the design of operating procedures and the focus of training, especially with increasing levels of cockpit automation and recognition of unique skills for pilot flying and monitoring roles.
- Systems of feedback on operational performance have become a driver of training emphasis.
- Specific issues identified through feedback systems and accidents have required significant additional training modules and programs.
- Controversies remain and evolution of training is ongoing.

Multicrew Operations

Although solo private pilots may transport friends and family and solo commercial pilots may move small numbers of passengers and quantities of cargo for hire, most passenger transport is accomplished in multipilot aircraft—at a minimum, a pilot in command or Captain, and a copilot or first officer. The crew may be larger on older aircraft requiring a flight engineer or for longer duration, typically international flights requiring relief crewmembers. Foushee (1984) argued that air transport crews share capabilities and are susceptible to errors typical of small work groups, meaning much of social psychological research should be considered to apply. A series of accidents in the 1970s and 1980s resulted in classroom and simulator training focusing on crew resource management (Cooper, White, & Lauber, 1980). Prior to this point, training and performance evaluation were very much individually focused and maneuver based. The practical test standards for air transport pilots (FAA, 2008) require that an applicant for a certificate be able to perform each maneuver deemed necessary to safely operate an aircraft and focuses minimally on the coordination with other pilots or the context in which non-normal maneuvers might be required. So for example, a pilot will demonstrate the ability to perform a nonprecision approach to a runway by these criteria:

1. Exhibits adequate knowledge of nonprecision approach procedures representative of those the applicant is likely to use
2. Accomplishes the nonprecision instrument approaches selected by the examiner
3. Establishes two-way communications with ATC as appropriate to the phase of flight or approach segment and uses proper communications phraseology and techniques
4. Complies with all clearances issued by ATC
5. Advises ATC or the examiner any time the applicant is unable to comply with a clearance
6. Establishes the appropriate airplane configuration and airspeed, and completes all applicable checklist items or coordinates with crew to ensure completion of checklist items in a timely manner and as recommended by the manufacturer
7. Maintains, prior to beginning the final approach segment, the desired altitude ±100 feet, the desired airspeed ±10 knots, the desired heading ±5; and accurately tracks radials, courses, and bearings
8. Selects, tunes, identifies, and monitors the operational status of ground and airplane navigation equipment used for the approach
9. Applies the necessary adjustments to the published minimum descent altitude (MDA) and visibility criteria for the airplane approach category when required, such as
   a. Notices to airmen (NOTAM), including Flight Data Center Procedural NOTAMs
   b. Inoperative airplane and ground navigation equipment
   c. Inoperative visual aids associated with the landing environment
   d. National Weather Service reporting factors and criteria
10. Establishes a rate of descent that will ensure arrival at the MDA (at, or prior to reaching, the visual descent point , if published) with the airplane in a position from which a descent from MDA to a landing on the intended runway can be made at a normal rate using normal maneuvering
11. Allows, while on the final approach segment, not more than quarter-scale deflection of the course deviation indicator or (five inches the case of the Radio Magnetic Indicator [RMI] or bearing pointer and maintains airspeed within) 5 knots of that desired
12. Maintains the MDA, when reached, within −0, +50 feet to the missed approach point
13. Executes the missed approach at the missed approach point if the required visual references for the intended runway are not unmistakably visible and identifiable at the missed approach point
14. Executes a normal landing from a straight-in or circling approach when instructed by the examiner (pp. 58–59)

Performance standards for emergencies precipitated by other than, say, an engine failure at a critical altitude are more vaguely specified. At best, pilots are presented with a sampling of possible failures over the course of their career, most likely within the vicinity of an airport at relatively low altitude. These standards are now supplemented by training requirements and advisory circulars on crew resource management (FAA, 2004a) and line operational simulation (FAA, 2015b). This guidance emphasizes how to train and test skills necessary to perform as a crewmember and within the context of flight.

The 2009 Air France accident over the southern Atlantic Ocean illustrates some of the challenges (Bureau d'Enquêtes et d'Analyses, 2012). After an uneventful takeoff and ascent to a cruise altitude of 35,000 feet, the captain turned over the controls to his copilot and relief officer and left the cockpit for planned crew rest. Shortly thereafter, the aircraft entered some turbulence associated with a strong weather system common to the area during summer months, and airspeed indications became inconsistent due to ice accumulation in the pitot probes (used to measure airspeed), not perceived by the crew. On account of the airspeed inconsistency, the following occurred: the autopilot and autothrust control systems disengaged, several messages alerting failure of systems that use airspeed data were displayed to the crew, and the flight controls exited *normal law* and entered *alternate law* (discussed next). The copilot-flying made several pitch and roll changes. Roll inputs were most likely intended to maintain wings level; initial pitch inputs were most likely intended to correct a slight pitch down and decrease in indicated altitude when airspeed indications were lost and the autopilot disconnected. The copilot-flying also increased engine power to takeoff/go-around thrust. Aircraft pitch attitude slowly increased beyond 10 degrees nose-up, and airspeed decreased from 275 to 60 knots. Persistence of the nose-up input could not be explained by the investigators, though they presented multiple hypotheses. The aircraft climbed until it entered an aerodynamic stall, and then descended rapidly until impact with the ocean four minutes later. Although aerodynamic stall is precluded on modern Airbus aircraft operating under *normal law*, in which the flight controls mitigate pitch commands that exceed critical angle of attack, this function is not possible in *alternate law*. The crew apparently never gained a full understanding of the stall and did not lower the nose of the aircraft sufficiently to recover lift. Potentially contributing to the crew's confusion, stall warnings are inhibited when angle of attack is so extreme as to be considered an invalid indication. In this case, this produced a paradoxical result: When pitch was reduced sufficiently to produce an angle of attack considered valid, stall warnings resumed, giving the appearance that an appropriate corrective action was making the situation worse. The investigation examined information displayed and warnings announced to the crew, functionality of the aircraft in these conditions, how crewmembers were trained, industry expectation of crew actions in that context, and the actions of crews that had previously encountered loss of airspeed information. The investigation said of crew actions during the accident sequence:

> The occurrence of the failure in the context of flight in cruise completely surprised the pilots of flight AF 447. The apparent difficulties with aeroplane handling at high altitude in turbulence led to excessive handling inputs in roll and a sharp nose-up input by the PF (copilot flying). The destabilization that resulted from the climbing flight path and the evolution in the pitch attitude and vertical speed added to the erroneous airspeed indications and ECAM (Electronic Centralized Aircraft Monitoring) messages, which did not help with the diagnosis. The crew, progressively becoming de-structured, likely never understood that it was faced with a *simple* loss of three sources of airspeed information. (p. 199)

To prevent such an accident, one must focus on ensuring each pilot understands the aircraft systems and how such a failure might be diagnosed, the procedures for recovering from both the failure and a resulting extreme aircraft attitude or upset, and aircraft performance at high altitudes. Portions of each would be present in ground school and simulator-based training and are reflected in approach to stall, stall recovery, and unusual attitude recovery, as required by the practical test standards. However, none of this ensures training in the specific or generic events in the context of this situation—stall recovery is typically trained at low altitudes because aircraft operate at low speed when departing or arriving at an airport, making departure and approach stalls more likely than high-altitude stalls. But perhaps, more importantly from a human factors perspective, the availability of more than one crewmember should make detection, diagnosis, and recovery easier. A threat to safe flight or an error by one crewmember should be detected and corrected by the other(s) (Helmreich, 1998). This did not occur, even when the Captain returned to the cockpit.

Methods for ensuring each crewmember's functions not just as a technically competent individual, but as a contributor to a work team, complementing each other's capabilities and limitations are key human factors contributions to flight deck safety and are now reflected in FAA ACs. Key knowledge, skill, and abilities described in AC are communication processes and decision behavior, team building and maintenance, and workload management and situation awareness**.** Their antecedent research bases are documented in Wiener, Kanki, and Helmreich (1993), and Orlady and Orlady (1999). Continued evolution of these concepts in research is illustrated by Dismukes, Berman, and Loukopoulos (2007). Research and industry collaboration and guidance culminated in advanced qualification training (SFAR 58; GPO, 2003), wherein aircraft and crew position specific task analyses by phase of flight lead to definition of training proficiency objectives that must be demonstrated in maneuver validation and line-oriented evaluation.

Workforce Interfaces

Any human interface with the cockpit crew introduces both capabilities and limitations and can become a source of error if not managed effectively. Consider the role of the flight dispatcher. Were air transport pilots to self-dispatch, they would require an hour or more before each flight to consider weather conditions, choose an optimal route, determine the passenger, baggage, and freight load for the flight, determine how much fuel to carry, and identify any limitations of aircraft or ground equipment impacting their flight plan. Instead, 14 CFR Part 65 provides for aircraft dispatchers who exercise responsibility with the pilot in command in the operational control of the flight—planning, monitoring, advising of changing circumstances, and terminating the flight at destination or an alternate airport. The dispatcher provides information to the pilots and monitors their progress. This represents a relief of workload, a profoundly valuable source of advisory information, a coordination challenge, *and* a potential source of error in information exchange. Training has expanded to accommodate this and other interfaces—flight attendant, mechanic, ground crew, and so on. This is reflected in FAA ACs on dispatch (FAA, 2005b) and maintenance (FAA, 2000) resource management.

Key Inputs to Training

If pilot qualifications are defined in terms of maneuvers, the training design task for introducing a new aircraft type may be defined as tailoring the footprint of ground instruction and simulator or aircraft training developed for previous generations of aircraft. This has often been successful. Airlines have developed and gained approval for training footprints describing a certain number of days of ground school and simulator sessions and then generalized this to new fleets. A notable exception was the introduction of FMC aircraft, which integrate area-navigation functions with aircraft performance management, allowing computer entries to guide or control the aircraft in four dimensions and integrate warning and alerting systems for mechanical problems. Models include Boeing's 757, 767, 777, 787, and recent generations of the 737; Airbus's A-300-600, 310, 320, 330, and 340; Fokker's F-100; and McDonnell-Douglas's MD-88 and MD-11. They incorporate increasing levels of flight guidance, flight control, and system automation, requiring accommodation in training. Chidester (1999) argued that these aircraft produced a two-decade accommodation in policy, procedure, and training. Two FAA human factors Working Groups (FAA, 1996, 2013b) documented a range of issues encountered in the operation of FMC aircraft.

But the broader lessons for training were found in task analysis and ISD, typically implemented under the advanced qualification program. Training must become an end result of a comprehensive application of human factors to the aircraft, its procedures, and its intended interface with the airspace system. Hazard analyses, task analyses, and procedures for normal and abnormal operations are antecedents of training design. If reconfiguring aircraft controls (flaps, slats, gear, etc.) or systems (pressurization, hydraulics, etc.), or coordinating with ATC is required during flight, what are the designed means of configuration or coordination? What are the impacts of not doing so in a timely or correct fashion? What safeguards may be put into place to prevent or correct error? Where safeguards cannot be engineered, procedures and training are required.

Pilot flying and monitoring roles have become a special emphasis of procedures and training, perhaps in part due to the effect of increasing automation. Having more than one pilot in the cockpit accommodates workload, requires some division of labor, and enables detection and correction of error. Typically, one pilot serves as a flying pilot (PF), the other as a monitoring pilot (PM). This is independent of the pilot-in-command concept; the Captain and First Officer may serve in either PF or PM role, but the Captain always retains pilot-in-command authority and responsibility. The PF controls the flight path of the aircraft by direct inputs to the control wheel, yoke, and pedals by entering targets into a flight guidance panel, or by making changes to the control-display unit of the FMC, the latter two coupled to the autopilot. The PM crosschecks data entry, monitors, and calls out key events or deviations from target values, manages configuration changes and checklists, and communicates with ATC. Monitoring skills are complex, challenging to apply, and historically underemphasized to the point of accident involvement (Sumwalt, Thomas, & Dismukes, 2003). When flying an approach to landing in instrument conditions, for example, the PF must shift gaze and attention between the instrument panel and the windscreen. Looking out, the PF searches for the runway environment. Looking at the instrument panel, the PF must ensure the flight path and speed remain appropriate until a safe transition to visual maneuvering to landing can be accomplished. What should the PM look at? Should they watch to ensure the runway environment is acquired, that approach constraints are honored and called out, that the aircraft is appropriately configured, that checklists are complete before landing, that landing clearance has been received, and that weather conditions remain as expected? The accident literature abounds with failures in each of these tasks. The Flight Safety Foundation (2014) offered a comprehensive set of recommendations to improve pilot monitoring, including, among others:

- Brief flight path–related plans and announce any deviations from the prebriefed plans
- Manage workload to prioritize flight path monitoring
- Be particularly attentive to the flight guidance automation
- Clearly define the monitoring role of each pilot, recognizing this may change when autoflight systems are engaged
- Emphasize predictable areas during flight where risk of flight path deviation increases, heightening the importance of task and workload management
- Implement policies and practices that protect flight-path management from distractions and interruptions
- Train pilots about why they are vulnerable to errors and monitoring lapses

Perhaps, most importantly, an airline must provide guidance and training that addresses the focus of the flying and PM by phase of flight. Otherwise, a simple deviation from a constraint can cascade to an accident. Consider these excerpts from the NTSB (2014a) accident sequence narrative of a United Parcel Service A-310 at Birmingham, Alabama:

> On August 14, 2013, about 0447 central daylight time (CDT), UPS flight 1354, an Airbus A300–600, N155UP, crashed short of runway 18 during a localizer nonprecision approach to runway 18 at Birmingham-Shuttlesworth International Airport (BHM), Birmingham, Alabama.

> The captain was the pilot flying, and the first officer was the pilot monitoring. Before descent, while on the direct-to-KBHM leg of the flight, the captain briefed the localizer runway 18 nonprecision profile approach, and the first officer entered the approach into the airplane's flight management computer (FMC).
>
> However, although the flight plan for the approach had already been entered in the FMC, the captain did not request and the first officer did not verify that the flight plan reflected only the approach fixes; therefore, the direct-to-KBHM leg that had been set up during the flight from Louisville remained in the FMC. This caused a flight plan discontinuity message to remain in the FMC, which rendered the glideslope generated for the profile approach meaningless.
>
> Had the FMC been properly sequenced and the profile approach selected, the autopilot would have engaged the profile approach and the airplane would have begun a descent on the glidepath to the runway. However, this did not occur.
>
> When the autopilot did not engage in profile mode, the captain changed the autopilot mode to the vertical speed mode, yet he did not brief the first officer of the autopilot mode change.
>
> About seven seconds after the first officer completed the Before Landing checklist, the first officer noted that the captain had switched the autopilot to vertical speed mode; shortly thereafter, the captain increased the vertical descent rate to 1,500 feet per minute. The first officer made the required 1,000-feet above-airport-elevation callout, and the captain noted that the decision altitude was 1,200 feet msl. but maintained the 1,500 feet per minute descent rate. Once the airplane descended below 1,000 feet at a descent rate greater than 1,000 feet per minute, the approach would have violated the stabilized approach criteria defined in the UPS flight operations manual and would have required a go-around. As the airplane descended to the minimum descent altitude, the first officer did not make the required callouts regarding approaching and reaching the minimum descent altitude, and the captain did not arrest the descent at the minimum descent altitude.
>
> The airplane continued to descend, and at 1,000 feet msl. (about 250 feet above ground level), an enhanced ground proximity warning system (EGPWS) *sink rate* caution alert was triggered. The captain began to adjust the vertical speed in accordance with UPS's trained procedure, and he reported the runway in sight about 3.5 seconds after the *sink rate* caution alert. The airplane continued to descend at a rate of about 1,000 feet per minute. The first officer then confirmed that she also had the runway in sight. About two seconds after reporting the runway in sight, the captain further reduced the commanded vertical speed, but the airplane was still descending rapidly on a trajectory that was about one nautical mile short of the runway. Neither pilot appeared to be aware of the airplane's altitude after the first officer's 1,000-feet callout. The cockpit voice recorder then recorded the sound of the airplane contacting trees followed by an EGPWS *too low terrain* caution alert (pp. 10–12).

The sequence involves multiple errors by both the PF and PM, but the monitoring function—to call out the MDA and deviations from the stabilized approach requirements—was intended as a final layer of safety protection by the crew, backed up by the GPWS. Error, failure to catch and correct error, and last minute terrain warnings are typical of controlled flight into terrain accidents; emphasizing and directing monitoring is one key solution (Flight Safety Foundation, 2014). In a sense, this might be construed as merely a more substantial definition of crew resource management. More broadly, developing procedures for function within operating constraints and emphasizing required coordination inside and outside the cockpit have been emphasized by Degani and Wiener (1993) and Barshi, Dismukes, and Loukopoulos (2012).

Operational Feedback

In the 1990s, airlines began routine collection and analyses of safety reports and recorded flight data. Aviation Safety Action Programs (ASAP; FAA, 2002b) allow certificated airmen to report any safety concern they encounter, even if they inadvertently caused the concern. Pilots, dispatchers, mechanics, and others report events, deviations, or observations during line operations, and these are investigated collaboratively by airline, FAA, and employee representatives. Flight Operational Quality Assurance programs (FOQA; FAA, 2004b) routinely collect and analyze digital flight data downloaded from aircraft after flight. They enable airlines and the FAA to identify locations and contributing factors to exceedances of the desired flight envelope, such as unstable approaches. Line operations safety audits (LOSA; FAA, 2006b) provide a cadre of observers trained to evaluation standards, who review and provide feedback on flight deck, maintenance, and ground operations.

All of these programs attempt to discover developing issues in an airline's operations that may be precursors of incidents or accidents. Antecedents of these programs can be found in the ASRS managed by NASA on behalf of the FAA since 1975, and NTSB use of flight data in accident investigation since the 1960s. ASAP, FOQA, and LOSA have both become a driver of training issues and provided a compelling method of presentation for training. A good example is the emphasis on stabilized approaches. Most airlines require that before descending below 500 feet above the runway in visual, or 1,000 feet in instrument meteorological conditions, the aircraft be on the correct flight path, at target airspeed, configured for landing, descending at target rate, and with engines powered to target thrust value (Flight Safety Foundation, 2000). Many approach and landing accidents have been preceded by an unstable approach. FOQA programs have identified airports and runways where unstable approaches are more likely, and ASAP reports have often explained why they occurred. Airlines have dedicated a great deal of training emphasis as a result of feedback, and recreations revealing precipitating factors, progress of the approach, and outcomes in difficult landings, or execution of missed approaches have come from FOQA data and ASAP reports.

Responding to Discovered Hazards

A broader phenomenon of training as a key method of responding to discovered hazards can be observed in accident investigation and recommendations by the NTSB. When Delta Air Lines Flight 191 crashed during a thunderstorm at Dallas-Ft. Worth airport in 1985, the airline industry gained an understanding of microburst and wind shear hazards (NTSB, 1986). The legacy is escape maneuvers trained in initial and recurrent aircraft training incorporated into the practical test standards for air transport pilots. When Air Florida flight 90 crashed into the Potomac river shortly after takeoff from Washington National Airport in 1982 (NTSB, 1982) and USAir Flight 405 crashed on takeoff from New York LaGuardia airport, the airline industry gained an understanding of the impact of ice accumulation on wings and engine nacelles during ground operations (NTSB, 1993).The legacy is strong deicing procedures, holdover times allowed between deicing and takeoff, and emphasis in airline classroom and simulator training. A similar pattern has followed loss of control accidents, such as Colgan Air flight 3407 (NTSB, 2010), which resulted in a statutory requirement to implement a formal rule requiring stall and upset prevention and recovery training (Federal Register, 2014a).

Responsive training interventions will continue, possibly accelerate, through collaborative review of shared safety data using the aviation safety information analysis and sharing (see http://www.asias.faa.gov/pls/apex/f?p=100:1:) program, led by the CAST (see http://www.cast-safety.org/). Their methodology focuses on risks identified through incident and report review and will likely impact training requirements and emphasis. Interventions have already been accomplished as a result of GPWS and TCAS events observed in data.

Controversies

Training and human factors contributions to training are not without unresolved controversy. Here are three. First, consensus defining optimal approaches to training for aircraft with advanced automated systems appears to have been destabilized by continuing advances. Chidester (1999) describes airline consensus around uses of levels of automation, as documented by an Air Transport Association Human Factors Subcommittee:

> When immediate, decisive, and correct control of aircraft path is required, the lowest level of automation – hand flying without flight director guidance – may be necessary. Such instances would include escape or avoidance maneuvers (excepting aircraft with flight director wind shear guidance)

> and recovery from upset or unusual attitudes. With the exception of visual approaches and deliberate decisions to maintain flying proficiency, this is essentially a non-normal operation for flight guidance or FMS-generation aircraft. Is should be considered a transitory mode used when the pilot perceives the aircraft is not responding to urgent aircraft demands. The pilot can establish a higher level of automation as soon as conditions permit.
>
> When used with flight director guidance, hand flying is the primary takeoff and departure mode. It is also the primary mode for landings, except autolands.
>
> Where short-range tactical planning is needed (i.e., radar vectors for separation or course intercept, short-range speed or climb rate control, etc.), Mode Control or Flight Guidance inputs may be most effective. This level should be used predominantly in the terminal environment when responding to clearance changes and restrictions, including in-close approach/runway changes.
>
> Autoflight coupled to the FMS/GPS is the primary mode for nonterminal operations and should be established as soon as *resume own navigation* or similar clearance is received. This level exploits programming accomplished preflight. Where the longer-range strategic plan is changed (i.e., initial approach and runway assignment, direct clearances, etc.), Flight Management inputs remain appropriate. However, when significant modifications to route are issued by ATC, the pilot should revert, at least temporarily, to lower levels of automation (p. 180).

The Flight Deck Automation Working Group (FAA, 2013b) suggested that the issues have expanded, making this consensus less clear. While recognizing the extent to which pilots mitigate operational risk, the Working Group reported concerns including maintenance of manual flying skills, managing malfunctions, use of automated systems, communication within the cockpit and with ATC, usability of standard procedures, data entry and verification, operating policies, workload management, flight path knowledge and skills, training time and content, and equipment design and standardization. Pilots must be provided opportunities to practice manual and flight path monitoring skills. Mode awareness is challenging, even when choices among levels of flight path automation are deliberate. Much automation progress has involved information rather than flight control; little guidance is available for optimizing use of electronic flight bags, map displays, and electronic checklists. This requires a new round of hazard and task analysis and development of new guidance. The Working Group made 18 recommendations involving design and certification, procedures and training, interfaces with air traffic services, and regulatory oversight. The issues are broader than training, and existing training accommodations are not comprehensive.

Second, it is not clear when and how much maneuver-based versus line-oriented training is needed. Maneuver-based training is efficient. By having a pilot fly in the vicinity of the airport, conducting many takeoffs, approaches, and landings, an instructor can accomplish a great deal of training, and an evaluator can observe many events in a typically four-hour block of simulation. From the pilot's perspective, this can be like batting practice—having many problems thrown at them in succession and honing their responses. But this form of training offers little context. Every real flight presents some unique challenges and each requires only a single takeoff and landing. Line oriented simulation allows practice and evaluation in context. Industry consensus reflected under advance qualification programs appears to embrace both, culminating in a maneuvers validation and a line-oriented evaluation in both initial/qualification and recurrent/continuing qualification training. But examination across airlines would reveal different numbers of maneuver and line-oriented events preceding validation, suggesting an optimal balance has yet to be found.

Third, some industry challenges butt up against the limits of simulation, especially training for recovery from extreme upsets or unusual attitudes. The performance characteristics of air transport aircraft have been measured and modeled for known flight envelopes defined in pitch, roll, yaw, acceleration, and speed. When an aircraft is upset beyond those limits, its performance is not quantified and modeled in a way that can be incorporated into simulation. So, the simulator must extrapolate from nearby known values and might perform differently than the aircraft, leading the pilot to dysfunctional recovery strategies. Further, forces exerted on the aircraft and its occupants in extreme upset cannot be recreated in simulators. As a result, the pilot may be surprised, startled, or misled in interpreting forces encountered in an actual event. Industry collaboration resulting in the Airplane Upset Recovery Training Aid (Upset Recovery Industry Team, 2008) offers a set of maneuvers that can be practiced within current simulation envelopes. FAA (2013b) will require extended envelope training, including upset recovery and recovery from full stalls and stick pusher activation. This necessitates a revision to requirements for flight simulation training devices; a notice of proposed rulemaking (NPRM) for 14 CFR Part 60 has been published in the Federal Register (2014b).

Summary

Requirements for flight training are both well established and evolving in response to systems of feedback. Human factors science and practice has improved training by expanding its focus from individual and maneuvers-based events to line-oriented training and evaluation, strengthening the ability to perform as a crewmember in context. Hazard and task analyses and ISD have influenced the design of operating procedures and the focus of training, especially with increasing levels of cockpit automation and recognition of unique skills for pilot flying and monitoring roles. FOQA, ASAP, and LOSA have become a driver of training emphasis. Specific issues identified through feedback systems and accidents have required significant additional training modules and programs. Controversies remain, but human factors researchers and practitioners are closely involved in developing solutions.

ENVIRONMENTAL CONTEXT

The outermost layer of the sociotechnical model is the environmental layer that encompasses the regulatory, social, and cultural influences in aviation safety. Chapter 9 describes regulatory aspects in detail. In this chapter, we take one example—pilot fatigue—and explore the interaction of these factors in the development of 14 CFR 117, *Flight and Duty Limitations and Rest Requirements: Flightcrew Members.*

Flight, Duty, and Rest Regulations

Experience and research results gathered over the years have established that pilot fatigue interacts with essentially all aspects of flight operations, and as mentioned earlier, its impact depends on the scheduled flight time, how long the pilot has been awake, how much sleep was attained in a 24-hour period, and if sleep had been reduced multiple times over a trip sequence before recovery rest opportunities were received (Dinges, Graeber, Rosekind, Samel, & Wegmann, 1996; Mallis, Banks, & Dinges, 2010). But the U.S. regulations for flight, duty, and rest remained complex and unchanged until an effort had been initiated in the early 1990s.

The FAA considered revisions to Title 14 CFR part 121 flight, duty, and rest regulations in June 1992. They chartered an Aviation Rulemaking Advisory Committee to determine a path for changing the regulations to improve the mitigation of fatigue and maintain alertness and flight safety. Convened over a rather long period, the Aviation Rulemaking Advisory Committee members could not agree on recommendations or the path forward. Nevertheless, the FAA issued a NPRM in 1995 and received more than 2,000 comments from industry associations, pilot union groups, and the flying public. Although the commenters, including the NTSB, NASA, Air Line Pilots Association, and Allied Pilots Association, agreed that the proposal would enhance safety, many industry associations opposed the 1995 NPRM, stating the FAA lacked safety data to justify the rulemaking and that compliance would impose significant costs to the industry. The FAA never finalized the 1995 rulemaking and eventually withdrew it because it was outdated and raised many significant issues that needed to be reconsidered before proceeding with a final rule.

Accident Prompting Rulemaking Change

A national debate was triggered on the effects of fatigue and flight safety in 2009 following the investigation of the crash of Colgan Air Flight 3407. At that time, the NTSB had listed fatigue as one of the top 10 safety issues since the early 1990s. The NTSB database contained 23 accidents (with a total of 349 fatalities) since 1991, as having causal or contributing fatigue-related factors.

The accident statistics combined with the knowledge that sleep, circadian rhythm, and fatigue sciences were never considered in the original flight, duty, and rest regulations, prompted the FAA to charter an aviation rulemaking committee on June 24, 2009. This committee, comprised of members from industry and labor, met with the FAA and science representatives weekly between July and August. The aviation rulemaking committee provided its recommendations to the FAA on September 9, 2009. Transcribing the recommendations into rulemaking language took nearly a year, and as a result, the FAA published an NPRM on September 14, 2010, in the Federal Register. Even with a brief period for public review and comment, the FAA received more than 8,000 comments in response to the NPRM. During resolution of all those comments, the FAA made a number of functional changes to the regulatory provisions proposed in the NPRM. The final rule was published in the Federal Register January 4, 2012, and Title 14 CFR Parts 117, 119, and 121 flightcrew member duty and rest requirements was fully implemented two years later on January 4, 2014. Part 117 now governs flight and duty limitations and rest requirements for all certificate holders and flightcrew members conducting passenger operations under Part 121.

It should be mentioned that during the rulemaking timeframe, the President signed into Public Law111-216, the Airline Safety and Federal Aviation Administration Extension Act of 2010. This mandate was published in FAA Order 8900.1 CHG 301, Section 1, review and acceptance of fatigue risk-management plans (FRMP). In Section 212(b), the mandate required each air carrier conducting operations under 14 CFR part 121 to develop, implement, and maintain an FRMP, which, effectively, is an air carrier's fatigue management plan for reducing the potential effects of flightcrew member's fatigue and improving flightcrew member alertness on a day-to-day basis within the structure of the flight, duty, and rest regulation.

Several ACs were also developed during this timeframe and released as supporting guidance and information relevant to fatigue mitigation and training, including these documents:

- AC 120–100, Basics of Aviation Fatigue
- AC 117–1, Flightcrew Member Rest Facilities
- AC 117–2, Fatigue Education and Awareness Training Program
- AC 117–3, Fitness for Duty
- Clarification of the Flight, Duty, and Rest Requirements of Part 117 (Docket No. FAA-2012-0358)

Fatigue Risk-Management System

In addition to the new rule and the mandate for FRMP, Section 117.7, FRMS of the rule contains an optional provision that permits air carriers the flexibility for conducting operations that might exceed the rule's limitations. An FRMS can be proposed to the FAA with enhanced fatigue management approaches that provides an *alternative method of compliance* (AMOC) to the rule. Guidance for the authorization process is found in the FAA AC 120-103A—FRMSs for aviation safety. This AC provides certificate holders with detailed guidance and step-by-step procedures required for the development of an FRMS proposal and the approval process. The FAA's five-step FRMS authorization process requires a systematic and progressive approach, including scientific review and evaluation of the proposed alternative methods.

So, an FRMS employs multilayered defensive strategies to manage fatigue-related risks regardless of their source. For the FAA, the FRMS is an AMOC based on specific numerical standards, for example, the maximum allowable time of the flight duty period and/or the amount of rest required before and after specific types of operations. The AMOC must target the specific limitation(s) from which the carrier seeks relief and justify its request for exceeding those limits. In addition, the AMOC must provide a demonstration of an equivalent level of safety. This is accomplished through a required data collection phase of the authorization process that is specific to the proposed AMOC. Each flight exemption must be examined prior to data collection, and the resultant data analyses are *validated* by the FAA before the air carrier is granted an FRMS authorization in the form of Operation Specification A318.

In essence, the air carriers seeking an FRMS authorization must collect data to verify that the sleep and performance results are equivalent or better than found for the targeted limitation(s). Essentially, the carrier must demonstrate that its proposed AMOC with enhanced fatigue mitigations produces the same outcomes as a safety standard operation, which is defined as a flight operation having comparable features, such as departure/arrival times, direction of flight, (approximate) flight time, and operating within the limitations of Part 117.

In addition to reviewing all of the FRMS documentation submitted by the carrier, the FAA must review the empirical sleep and performance data and its analysis to validate the AMOC. Throughout the latter stages of the FRMS process, the carrier is responsible for submitting those data to the FAA at various intervals, which range from monthly, during the initial data collection and validation steps; quarterly, once an authorization is issued; then semiannually; and then yearly. The data collection requirements continue until the carrier no longer requires the FRMS authorization or the rule changes.

ICAO and Fatigue Management

In parallel with the United States developments of improved fatigue management, the international aviation community has been addressing similar issues and making its own regulatory revisions and recommendations for Member States to incorporate nonprescriptive approaches, such as FRMS, to manage flightcrew fatigue. In 2011, ICAO released two guidance documents titled "FRMS Implementation Guide for Operators" and the "FRMS Manual for Regulators" following a major international task force effort chaired by Dr. Curt Graeber.

Very similar to the FAA approach, the resultant ICAO standards and recommended practices relating to the management of fatigue experienced by flight and cabin crew provide a high-level regulatory framework for both prescriptive flight and duty limitations and FRMS as methods for managing fatigue risk. Both the United States and the International methods share two important basic features:

1. They are required to take into consideration the dynamics of transient and cumulative sleep loss and recovery, the circadian biological clock, and the impact of workload on fatigue along with operational requirements.
2. As fatigue is affected by all waking activities and not only work demands, regulations for both are necessarily predicated on the need for shared responsibility between the operator and individual crewmembers for its management. So, whether complying with prescriptive flight and duty limitations or using an FRMS, operators are responsible for providing schedules that allow crewmembers to perform at adequate levels of alertness, and crewmembers are responsible for using that time to start work well-rested (IATA, ICAO, IFALPA, 2011).

After a few years of experience by some member states to develop and implement functional FRMS programs, it became clear that countries varied significantly in their approaches, with some facing greater challenges than others. ICAO is now building on its experiences and is developing new detailed guidance documents that provide more instructions on the *how to* develop and implement an FRMS to complement its recommendations of fatigue-smart regulations. These taskforce efforts were led by ICAO's Dr. Michelle Millar and released in April 2016.

SUMMARY

A great deal of progress has been made in recent history toward the recognition and establishment of sound, science-based fatigue risk-management practices. First, the U.S. FAA implemented the FRMP mandate for air carriers to manage fatigue on a day-by-day basis. Second, the FAA fully implemented a new flight time, duty, and rest regulation with its internal interacting components of fatigue mitigation. And third, the *optional* FRMS procedures are available for air carriers to propose enhanced fatigue mitigation strategies with required data collection for those special instances in which flight operations exceed the limitations of the rule.

The FAA finds that a comprehensive program for the management of fatigue risk in aviation requires an integrated, multifaceted, and shared approach. Based on the successes of many organizations within the aviation industry, it is clear that with genuine effort, the risks associated with fatigue can be managed in ways that can benefit all. But it does require a commitment from all parties, including the regulators, the air carriers, and the flight crewmembers. First and foremost, science and operationally based regulations and flight scheduling practices go a long way toward managing fatigue. Moreover, contributing to success is the air carrier's leadership and its demonstration of commitment to the management of fatigue by providing proper resources including a disciplined, risk-based approach (e.g., FRMP) that is carried out with appropriate data reporting and communications with all relevant stakeholders. And finally, success comes from the professionalism of the flightcrew, its operational understanding of fatigue, and the importance of exercising personal fatigue risk-management principles and good sleep hygiene. All combined, the aviation industry now has the essential tools to improve the management of fatigue and to maintain safety within the National Airspace System and beyond its borders.

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