ALERTS ON THE NEXTGEN FLIGHT DECK

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The future generation of cockpit may substantially change the nature of displays, automation, and their implications for alerting systems. Flight deck automation and information systems imposed by NextGen will create system states that may need to be alerted. New concepts of providing continuous flight information can benefit pilot awareness. Ecological interface displays keep the operator aware of the system status and constraints, informing the pilot of emerging concerns before an alert is triggered. Continuous auditory and tactile displays support pilot awareness without requiring focused operator attention. Both approaches improve awareness of system state, but suffer poor operator acceptance. Automation can support pilots through carefully considered degrees of automation, through transparent automation design, and through adaptive automation that identifies when pilots fail to respond to alerts, and increases the salience of alerts or assumes control to implement the necessary actions. This paper summarizes a report that reviewed empirical research regarding these approaches.

Since the early days of aviation, there has been a need to improve alerts on the flight deck. Initially, the need was simply to provide alerts that would draw the pilots' attention to important status information (e.g., fuel level low). As experiences were gained and technologies improved, the alerting systems became increasingly sophisticated, warning pilots about proximity to ground or the nearby presence of other aircraft, or predicting the collision potential of surrounding traffic based on their trajectories. Aviation personnel have done a commendable job tracking incidents and accidents, and systematically evaluating them to identify lessons learned that enable continual improvements in alerting systems. Despite these efforts, challenges remain, and are likely to become even trickier in NextGen operations. The implementation and integration of new technologies will result in even more information on the flight deck (FAA, 2016), and additional automated systems may further increase complexity.

Some challenges with current-day systems include keeping the pilot aware of the status of the aircraft and automated systems, and appropriately applying alert suppression. For example, flight mode advisories (FMAs) inform the pilot of the current autoflight status and mode that result in changes in throttle or pitch control. The pilot uses this information to react to changes and correctly employ the automation. The FMAs are located at the top of the primary flight display and require directed visual focus and attention. During visual approaches, takeoffs, and other high workload situations, the pilot flying is primarily looking outside. Important changes on the FMA may easily be missed, possibly leading to lack of mode awareness. Improved salience or repositioning of the indicators appear to be needed.

Alerting systems on current flight decks attempt to support pilot performance by inhibiting nuisance information during critical phases of flight. For example, on many modern airplanes, caution alerts are inhibited above 80 knots during takeoff, with the intent of minimizing unnecessary information and helping the pilot make a go / reject decision. However, if a malfunction occurs, a message may still appear on the engine indicating and crew alerting system (EICAS). This message is presented without a caution light or sound, and the pilot is left to decide if the message warrants a rejected takeoff. Other information may also be presented, such as "high engine temperature" or "low oil pressure," displayed in red font on the EICAS. The result is that takeoffs are sometimes rejected when an actual takeoff would have been less risky. While the intent of inhibiting nuisance information makes sense, the current implementation seems to be clumsy and in need of improvement.

Dynamic situations, uncertain contexts, and fallible operators all contribute to challenges in the design of robust, appropriate and informative alerting systems. But there are also numerous opportunities for improved displays and intelligent automation to support performance. This paper, integrating many of the findings from a longer report (Wickens, Sebok et al., 2016) discusses potential future directions in flight deck alerting systems regarding ecological, predictive and multi-modal displays, and of automation; its more aggressive forms, its transparency and its adaptivity.

Alerts can fail to perform their intended function for several reasons. They may not be noticed, because of deficiencies in pre-failure monitoring, fatigue, cognitive tunneling, or insufficient alert salience or being located too far out of the normal field of view (Wickens, Sebok, McDermott & Walters, 2016). Alerts may be noticed, but not interpreted correctly. There may be too many alerts, confusing or misleading the pilot (Martensson & Singer, 1998).

Displays to Support Intuitive Monitoring

Displays can be designed to provide the operator with better awareness of the system and improved ability to predict undesirable future states than is provided by current-day displays and alerts. Such improvements should mitigate surprise and possible startle caused by the alert. Several techniques have been found to assist both the detection and subsequent diagnosis, above and beyond the alerts themselves. These displays provide a contextual background to support operator anticipation of an alert (improving detection) and diagnosis (understanding and prediction). Such displays depend upon **pre-attentive reference** (Woods, 1995), in which a perceptual cue (a sound or visual indication) provides information to the operator regarding the current state of the system. This can occur naturally, as part of the system operation, or it can be artificially added. Examples include the hum of an engine that changes in frequency as the throttle is applied or decreased. Changes to the cue, such as an engine that begins emitting a “knocking” noise and vibrating, can rapidly draw the operator’s attention to a potential concern, without invoking the startle characteristics of an auditory alert (Rivera et al., 2014). These features support perception and understanding in a way that does not require effortful processing to realize that something is wrong or even perhaps to identify what is wrong (Woods, 1995). This approach to supporting pilot detection of non-normal events and hence supporting alert management has been investigated from several perspectives, including ecological interface design (EID), predictive displays, sonification, and tactification.

Visual Displays: Ecological, Configural and Predictive Displays

The goal of EID displays is to integrate data into intuitive graphics that present important information to the operator or pilot. This requires identifying the most important factors and parameters for performing the tasks, and putting that information together in a meaningful, readily understood graphical representation (Bennett & Flach, 2013; Muller, Manzey et al., 2015). These displays show not just the status of individual sensors, but current and predicted states. One example in aviation is related to energy management (Muller et al., 2015). Pilots think of flying tasks in terms of energy management, yet current displays do not directly support that concept. The following figure shows one example of an aviation EID energy management display.

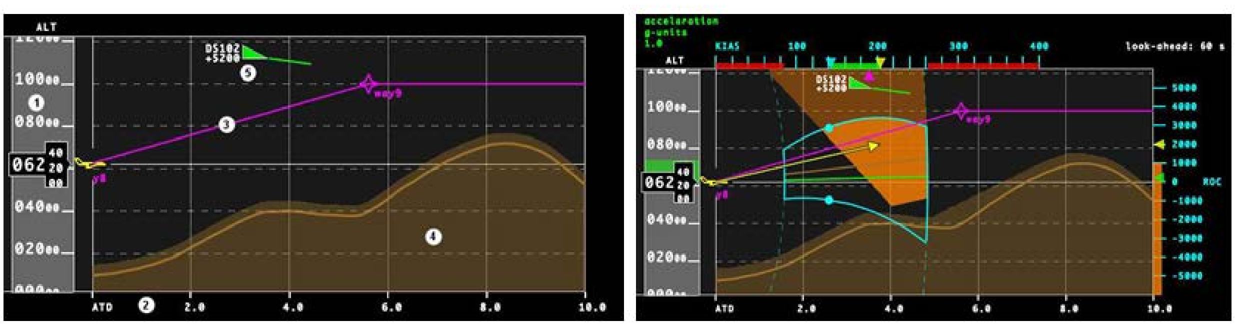

Figure 1: Vertical Situation Displays (from Borst et al., 2011). The left figure is a current-day display, and the right figure includes energy management information. Both show the ownship, a yellow aircraft at the left of the displays. The cyan outlined area in the right figure shows the potential future locations of the aircraft, given the minimum and maximum speed and climbing characteristics. The orange area above the brown “terrain” line shows the space in which the pilot can safely fly to avoid colliding with the other aircraft (green triangle) and the terrain.

The EID display allows the operator to monitor those key parameters with relatively low workload, and determine their proximity to danger boundaries that would trigger discrete alerts. Thus the EID provides operators with information regarding relationships in the system data and system constraints that are not normally presented on more conventional displays, or are presented in a less integrated fashion. In aviation, such a constraint might be the combinations of angle of attack, power and pitch that cause a stall (Wickens & Andre, 1990), or the combination of potential energy, sink rate, altitude and available thrust that creates unstable flight (Muller et al., 2016; Lambergts et al., 2008). By explicitly and graphically depicting the proximity of the current state of the system to these constraint boundaries, an EID can prepare the operator to detect a failure when the boundaries are crossed, to prevent that boundary crossing through proactive control, and to better diagnose the reasons why they are violated so that corrective actions can be applied appropriately. Thus by providing additional information, the EID should support operator monitoring, maintaining situation awareness (SA), detecting, diagnosis, decision making and fault management. Another benefit of EID displays is that, by integrating important system status information into a single display, the pilot can maintain awareness without needing to more widely distribute visual attention. However, the pilot will still need to seek information that is not included on the EID.

Two important components within many EID displays, used to help present the constraints and constraint boundaries, are configural object displays and predictive displays**.** A configural display presents multiple parameters graphically, so that their combined values form a shape or object. This object changes shape depending on the relative values of the parameters. Thus, the object can easily depict a departure from a normal state and its shape indicates the nature of the abnormal state. Successful examples include an octagon display indicating non normal conditions with a distortion of symmetry by the change in the location of one of the eight points (Beringer & Chrisman,1991); a rectangle display whose departure from the perfect symmetry of the square depicted the approach to stall, with deviations of appropriate airspeed and angle of attack (Wickens and Andre,1990), or the adjacent depiction of indicators of angle of attack and total energy angle, to signal the preservation, or departure from, minimum energy capabilities in vertical maneuvering (Muller et al., 2016).

Wickens, Sebok, Walters, et al. (2016) examined studies that compared performance with ecological displays against performance with conventional displays on the four aspects (monitoring, detection, diagnosis, fault management) of human processing of the non-normal events that trigger alerts. In many of these studies, the EID display condition presented more information than the traditional displays with which they are compared. Four aviation studies (Comans et al., 2014; Ellerbroek et al., 2013; Borst et al., 2011; and Rijneveld et al., 2010) examined non-normal events of the sort that might be alerted. All of these concerned traffic conflicts. Two of these studies (Ellerbroek et al., 2013; Comans et al., 2014) suggested a significant advantage of the EID concept, while the other two (Borst et al., 2011; Rijneveld et al., 2010) showed neither an advantage nor disadvantage. Of 11 aviation studies that were examined, 8 revealed superior performance in the EID conditions versus conventional conditions in some aspect of performance relevant to alert processing. The remaining 3 studies found no difference between conditions. These findings suggest the potential for EID displays to support more effective performance.

Predictive displays have long been known to increase control performance by inferring the future dynamic state, and hence allowing proactive control (Jensen, 1981). The advantages of predictive displays in flight path control are well documented (Wickens, 2003). These predictive displays include the “noodle” on the navigational display, or the predictive aircraft and 3D tunnel on synthetic vision system displays (Prinzel & Wickens, 2009). If aircraft state is trending toward a hazardous boundary (e.g., loss of separation, loss of sufficient potential energy or excessive temperature), the predictive algorithm can trigger the alert before the boundary is crossed. Yet often, as in the case of the traffic collision avoidance system (TCAS) alert, the only information displayed to the pilot is the discrete onset. There appears to be an advantage to also presenting the continuous predictive trend toward the boundary, so that a maneuver or control adjustment can be implemented prior to the time the alert would have occurred (to forestall the alert), or can be implemented more effectively after the alert, avoiding surprise. The benefits of such a continuous predictor have been validated for collision avoidance in cockpit displays (Alexander et al., 2005; Wickens, Gempler & Morphew, 2000) or engine parameters (Trujillo et al., 2008). Thus, much like ecological displays, a predictive display presents a broader context, which supports the pilot in predicting the future state of the aircraft. This, in turn, supports more expedient responses to the discrete alerts if they do occur, or more proactive control that will prevent the occurrence of an alert altogether.

Multi-modal Displays

The concept of multi-modal displays and alerts for the flight deck has received some recent attention (Lu et al., 2013). One approach has been to deliver alert indications in non-visual modalities, e.g., in auditory, tactile, or a redundant combination, typically redundant with a visual indication. Another approach is through the display of continuously changing parameters, such as the bearing of a potential traffic conflict, or the engine power through the tactile or auditory modality. These continuous displays are referred to as tactification and sonification respectively. Such an approach has the clear advantage of capitalizing on different perceptual resources than the visual channel which is predominately involved in flying, and thus allowing some degree of parallel processing (Wickens, 2008). A continuously changing auditory or tactile signal might also provide the same sort of pre-attentive reference and predictive information that was seen above to offer an advantage to proactive response to out of tolerance parameters. However there is one key limitation. While changing pitch or tactile intensity are effective for displaying the rate of change in a parameter (routine control), they are not as effective as vision for depicting the **absolute value** of the parameter, which is how alert boundaries or thresholds are characterized. In general, studies that investigate the use of sonification indicate that it is most effective when used in combination with a visual indication (Wickens, Sebok, Walters et al., 2016). Tactification approaches have also shown promise in terms of supporting situation awareness and early response to developing problems, particularly when used in combination with visual information presentation.

Both sonification and tactification however currently suffer poor operator acceptance (as reviewed in Wickens, Sebok, Walters et al., 2016). This can be due, in part, to a novelty effect, but it is also related to the inappropriateness for the particular environment. For example, sonification has been evaluated in simulated medical environments, where there are typically many patient monitoring systems that present auditory alerts, as well as verbal communications among the surgical team members. This noisy environment is a problem for effective sonification. Similarly, the flight deck currently has discrete auditory and voice alerts, and interpersonal communication. Sonification, in today's environment, simply adds another auditory signal to an already noisy operational context. It appears more likely that sonification and tactification would be used in remotely piloted aircraft, where there is a good deal more control over the pilot's environmental conditions.

Implications of Automation for Alerting Systems

Future forms of automation in NextGen and beyond have three direct implications for alerting systems. These are discussed in much greater detail in Wickens, Sebok, Walters et al., (2016) and summarized below.

Degree of Automation

The degree of automation (DOA) characterizes how aggressively and authoritatively automation assists the pilot's task (Parasuraman et al., 2000; Ferris et al., 2010; Sebok & Wickens, 2016). With respect to alerting systems, a low degree of automation may simply **inform** the pilot of the likely state, e.g., a low fuel alert, or the cause of the non-normal condition, such as the TCAS traffic alert. The alerting automation may more aggressively *recommend an action* (the TCAS resolution advisory), or even **implement** the action (the "pull up" function of the automatic ground collision avoidance system (Auto-GCAS) in the military F-16), representing the highest DOA. Empirical research is needed to establish the appropriateness of high degrees of automation because existing research has indicated that automated action advice or implementation, when based on uncertain inferences, may be quite problematic on the infrequent occasions when the inferences upon which the recommendations are made are incorrect (Sarter & Schroeder, 2001; Onnasch et al., 2014, Sebok & Wickens, 2016). Empirical research indicates that automation wrong is more problematic than automation gone failures, particularly when the automation provides a wrong (but plausible) diagnosis or recommends an incorrect course of action (Wickens, Clegg et al., 2015; Sauer, Chavaillaz & Wastell, 2015). As Onnasch et al., 2014 found, automation **can** potentially support operator performance during a failure, **if** the displays provide information needed to support SA.

Transparency of Automation

One technique for mitigating the costs of automation errors at higher DOA is to provide **transparency** (Sebok & Wickens, 2016) or **observability** (Ferris et al., 2010), sometimes in the form of a display to indicate what automation is doing (and why). This directly supports pilot SA. On the flight deck, such transparency can support mode awareness (Ferris et al., 2010), and the transparency offered by the traffic display of TCAS renders it easier to follow the advice of the resolution advisory. In air traffic control, Trapsilawati et al. (2017) have found that the transparency offered by a vertical situation display can offset imperfections of a conflict resolution aid. A number of studies investigating different approaches to enhancing transparency were found to provide better operator performance, both in routine and off-nominal conditions (Wickens, Sebok, Walters et al., 2016). The only potential drawback identified in these studies was that sometimes the more transparent automation drew the operator's attention and placed additional workload on the operator. Generally, though, these costs were mitigated by better performance in the case of automation failures or situations that were outside the realm of typical operations.

Adaptive Automation

It has been argued that automation should not necessarily always be present, but only be invoked in circumstances when it is needed because of high pilot workload (Dorneich, 2016; Kaber, 2013). This is considered **adaptive automation**. While adaptive automation has shown some promise in aviation systems, it has spawned another class of mode change alerting systems in the cockpit, namely alerting the pilot, as to when automation has taken control of the relevant aviation system (given that workload is assumed to be high), or when automation has returned control to the pilot. Failure of the pilot to be aware of the second of these mode changes can be particularly problematic. Another concern with adaptive automation is the logic and criteria used to determine when the pilot is overloaded and needs assistance. Techniques such as eyetracking, physiological parameters (heart rate, respiration), or time required to respond to requests for information are all used to predict when the operator needs assistance. If the automation incorrectly interprets that the pilot needs help, and offers assistance when it is not needed, that can be annoying to the pilot. Perhaps even worse is the condition where the pilot does need assistance, yet the automation does not detect or offer it. These problems can be addressed through the use of adaptable systems, or hybrid adaptive / adaptable systems that give the pilot control over when the automation is invoked.

Summary of Alerting Systems on the NextGen Flight Deck

A variety of display techniques can be, and have been (at least in experimental settings) used to support operator monitoring of a system, maintaining system awareness and responding to non-normal events. Some empirical evidence indicates that ecological displays and configural displays support rapid, accurate operator detection of non-normal conditions and accurate responses to these conditions. Predictive displays support operators in anticipating the future state, and avoiding alerts. In other modalities, empirical results are less conclusive than for visual displays, yet sonification and tactification can potentially provide techniques for supporting continual awareness of system state. Automation is expected to be more pervasive in the future flight deck, and can contribute to the detection of and response to alerts. Transparent automation systems can help pilots in assessing the appropriateness of diagnoses or recommended courses of action. Adaptive automation can assist pilots by increasing the salience of not-noticed yet critical alerts, or by deferring a low-priority alert that occurs during a high-workload situation. In summary, advanced, integrated visual displays or predictive displays; auditory and tactile alerts that provide continual system state information; and intelligent, transparent, and adaptive automation are potential techniques for supporting pilot performance on the NextGen flight deck.

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