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16. ABSTRACT

An air traffic control (ATC) facility is a dynamic, high-stress environment that requires that controllers rapidly detect problems and make time-critical decisions. Signals (alarms, alerts, and warnings) are essential for alerting controllers to potential collisions and other adverse events, but they can increase operators' response times and decrease their response rates (so-called alarm fatigue). To inform our project to create a handbook of design guidance for design and use of ATC signals, we have developed a signaling design philosophy that can enhance the effectiveness of signals in the ATC environment. We used reports from the Aviation Safety Reporting System (ASRS) over a 6-year interval from 2015 to 2020 and structured interviews to understand the complexity of the controller's tasks in the context of potentially high-consequence situations and events. (Ruskin et al., 2021) We found 370 relevant reports that we analyzed for hits, misses, false alarms, and correct rejections. We then conducted structured interviews with former controllers to further explore the role of signals in air traffic control. We are now using this information to develop strategies that can enhance signaling modalities (e.g., new auditory, visual, and tactile signals) and guide the ways that these signals are used. This signaling philosophy will be our roadmap for the next phase of the project, which is the development of a handbook for ATC signal design.

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ATC Signaling: The Role of Alarms, Alerts, and Warnings
Phase 2 Report: Signal Philosophy

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Executive Summary

An air traffic control (ATC) facility is a dynamic, high-stress environment that requires that controllers rapidly detect problems and make time-critical decisions. Signals (alarms, alerts, and warnings) are essential for alerting controllers to potential collisions and other adverse events, but they can increase operators' response times and decrease their response rates (so-called *alarm fatigue*). To inform our project to create a handbook of design guidance for design and use of ATC signals, we have developed a signaling design philosophy that can enhance the effectiveness of signals in the ATC environment. We used reports from the Aviation Safety Reporting System (ASRS) over a 6-year interval from 2015 to 2020 and structured interviews to understand the complexity of the controller's tasks in the context of potentially high-consequence situations and events. (Ruskin *et al*., 2021) We found 370 relevant reports that we analyzed for hits, misses, false alarms, and correct rejections. We then conducted structured interviews with former controllers to further explore the role of signals in air traffic control. We are now using this information to develop strategies that can enhance signaling modalities (*e.g.*, new auditory, visual, and tactile signals) and guide the ways that these signals are used. We determined that signals can be divided into four categories that require increasing levels of intervention by the controller:

- Priority 1: Immediate danger requiring urgent controller intervention. (*e.g,* Imminent near mid-air collision [NMAC], flight below MVA, AMASS)
- Priority 2: Risk of harm. Controller intervention will be required soon (*e.g.*, Predicted conflict, airspace alert)
- Priority 3: Informational. Intervention may be required (*e.g.*, Mode C intruder)
- Priority 4 or diagnostic (*e.g.*, Radar outage, localizer malfunction)

There are also opportunities to potentially improve controllers' trust in their automated ATC systems despite the many and varied signals they often produce. Trust in automation may be improved by incorporating information display strategies that include indicating the level of confidence that the automation has in particular situations, such as when notifying the controller of an impending loss of separation.

Our signaling philosophy addresses these four priorities for notifying the controller of important operational events, as well as considerations for varying operating environmental conditions, from the darkened radar room to the bright daytime illumination in the ATC tower cab environment. For example, we have noted that indicator lights and messages on screens may be less noticeable when displayed in a brightly illuminated control tower environment. In the tower cab, the increased use of auditory signals and display enclosures that enhance the visibility of screens and lights may be beneficial. Tactile displays (i.e., those using the sense of touch) can be used to draw a controller's attention to an urgent condition. Improving the localizability of auditory signals may help controllers diagnose a problem more quickly. The simultaneous use of signals for multiple sensory modalities might be valuable when controller response time is critical. Voice alerts for extremely high-priority alarms indicating potential loss of life has been shown to reduce response time in domains outside of aviation. New classes of auditory signals, including earcons and spearcons, may help controllers differentiate between different conditions and the urgency of a hazard. Making signals more acoustically rich and explicitly encoding intended urgency can improve alarm performance. This signaling philosophy will be our roadmap for the next phase of the project, which is the development of a handbook for ATC signal design.

Introduction

The United States Federal Aviation Administration's air traffic organization (ATO) encompasses a variety of Air Traffic Control (ATC) facilities that include towers, terminal radar approach control facilities (TRACONs), and air route traffic control centers (ARTCCs). ATC facilities are dynamic, high-stress environments that require rapid decision-making. Controllers routinely interact with pilots of varying skill levels, aircraft with different capabilities, and flights at dissimilar speeds, altitudes, and trajectories. Each of these factors add to the controller's task complexity. Additional complexity arises from the various automated warnings and alerts that are designed to gain the controller's attention and inform the controller of potentially high-consequence situations and events (*e.g.*, Conflict Alert, Minimum Safe Altitude Warning, inflight emergency, and lost communications (No Radio or NORDO alert). To develop our signaling philosophy, we first explored how operational events and automated ATC signaling systems affect controllers. We reviewed reports from the NASA Aviation Safety Reporting System and conducted semi-structured interviews with retired air traffic controllers to augment our review of near-miss reports. These reviews gave us a deeper understanding of how reliable and unreliable signals contribute to the complexity of their tasks. These insights will support the next phase of our project during which we plan to develop a handbook with recommended design guidance for improved signaling systems in ATC.

Signals

The term *signal* describes a sensory stimulus that serves the general function of notifying a human operator of a situation that might require their intervention (*i.e.*, an alarm, alert, or warning). Signals can convey a continuum of information that may range from alerting a controller to a situation that requires no action to an emergency in which the controller must act immediately in order to prevent harm or loss of life. To meet this requirement, effective signals are designed to be intrusive to attract the operator's attention and lead to an intervention. Bliss, Gilson, and Deaton (1995) have proposed a taxonomy of signals that is based upon the timing between a signal and its associated hazard. According to Bliss *et al*., an *alarm* is defined as a transient sensory signal (usually auditory or visual) that indicates the presence of an ongoing danger that requires immediate corrective action. An *alert* indicates that an adverse event may occur sometime soon, usually soon enough for the operator to remember the alert. While alarms and alerts are temporary dynamic signals triggered by a changing situation, a *warning* is usually a permanent visual indication of a static and unchanging hazard. Although this taxonomy has not been adopted for the signals currently used by air traffic controllers, the 2016 Human Factors Design Standard (HFDS), Section 5.5.1, offers recommendations for signals under the generic terms of *Alarms and Alerts*. For example, Bliss and Gilson would define the Minimum Safe Altitude Warning (MSAW) and the Conflict Alert (CA) as *alarm*.. The ERAM Conflict Probe (a steady visual indicator that may be activated up to 20 minutes for aircraft and 40 minutes for an airspace violation) would be defined as an *alert*. NOTAMs indicating a runway closure or restricted airspace would be defined as a *warning*. As part of this project, we may offer recommendations for a standardized signal taxonomy that could be incorporated into future versions of the HFDS.

Air traffic controllers rely upon accurate, timely, and reliable signals to maintain safety within the National Airspace System (NAS), but experience many nuisance signals. One study estimated that 62% of Conflict Alerts (CAs) and 91% of Minimum Safe Altitude Warnings (MSAWs) in the en route environment, and 44% of CAs and 61% of MSAWs in the terminal environment, did not require intervention by a controller (Friedman-Berg and Allendoerfer, 2008). In a study of the effects of imperfect automation on air traffic controllers, Rovira and Parasuraman (2010) found that both false alarms and misses had adverse effects on performance. Controller responses to signals may also vary based on the situation. Controllers may take action independently of a signal for some conditions or delay taking action until more information is available. For example, controllers tend to consider a MSAW more urgent than a CA and tend to respond to them more quickly (Allendoerfer, Pai, and Friedman-Berg, 2008).

Signals that operators perceive to be too unreliable are likely to provoke the so-called "cry-wolf effect," in which an operator either disables or deprioritizes the alarm (Breznitz, 1984). This effect can be especially problematic during periods of high workload when the operator does not have time to assess the aid's reliability and chooses instead to abandon it (Bliss and Dunn, 2000; Rice, 2009). The cry-wolf effect has been noted before and raises concerns about the effectiveness of alarms with poor reliability (Wickens, Rice, Keller, Hutchins, Hughes, and Clayton, 2009). A meta-analysis by Rein *et al* (2013) concluded that increased reliability was associated with improved performance, with greater than 67% reliability improving performance over baseline. This was a similar finding to a previous meta-analysis by Wickens and Dixon

(2007). The authors concluded with a caution that they could not determine a baseline level of reliability for all domains and that performance requirements should be determined by the specific task environment.

Operator experience and understanding related to signals can impact signal effectiveness. Operator behavior in response to signals can be divided into *reliance* (trust that silence means that no intervention is needed) and *compliance* (responding to a signal with a designated action) (Meyer, 2001). Signal errors can affect this interaction. Bliss (2001; 2004) initially found that excessive false alarms reduce compliance while excessive misses reduce reliance; however, Dixon and Wickens (2006), Dixon, Wickens and MacCarley (2007), and Rice (2009) showed that both type of errors affect both reliance and compliance. The alarm's actual function may not be the same as the user's perception of that function, which may also degrade trust. For example, if a smoke detector sounds an alarm because a toaster burns a piece of bread, it has functioned correctly, but the alarm may be perceived as a false alarm because there was no fire. A controller may perceive a correctly-operating CA to be a false alarm when two aircraft established on converging RNP approaches to parallel runways are approaching head-on but will continue to be safely separated as long as they remain on their respective published RNP approach flight paths. The operator must therefore understand a signal's intended function and thresholds in order for it to be effective.

According to Signal Detection Theory (Green and Swets, 1967), a signal can be a *hit* (true positive), a *correct rejection* (true negative), a *false alarm* (false positive), or a *miss* (false negative) (Stanislaw, 1999). In the ATC environment, false alarms can be further divided into a true *false alarm* (a signal is generated even though the threshold has not been exceeded) and a *nuisance alarm* (a signal is generated correctly based on exceedance of a threshold, but at a point where no response is needed). A controller may have already recognized the situation and planned an action to correct it but the alarm is activated because the automation has not yet detected the response (Wickens *et al*., 2009). ATC surveillance systems do not currently allow a controller to indicate that he or she has detected a potential problem and taken action to prevent it, causing the system to suppress the relevant signal while monitoring the situation in the background. For example, a Minimum Safe Altitude Warning (MSAW) may activate when an aircraft has a high descent rate, even if the pilot plans to level off at a safe altitude. Aircraft on curved approaches to parallel runways may fly routes that would eventually converge but are designed to ensure separation to the runway ends. This action may generate a conflict alert as the aircraft approach head-on because the automation predicts that a collision may occur if they continue their current trajectories, even though they will continue turning to their parallel inbound final approach paths.

Unreliable automation may lead to *trust failure*, in which the operator is reluctant to use the system. One practical effect of trust failure may be a decreased response to signals with a high false-positive rate (i.e., the system generates a signal when there it is not appropriate for the operator to take action). *Systemwide trust failure* is caused when a failure of one component of a system disrupts trust in the other parts of the same system (Geels-Blair, Rice, and Schwark, 2013; Keller and Rice, 2010; Rice and Geels, 2010). This series of studies revealed that when operators were exposed to automation errors (false alarms or misses) in one aid, they began to quickly lose trust in the other aids (up to 8 total aids), despite the reliability levels remaining perfect for those aids.

Automation, Workload, and Signals

Controllers do not passively wait for the signaling algorithms to alert them to an ongoing or future event; they work with conflict detection and other algorithms to maintain separation and provide safety alerts. Controller workload may be decreased when the automation is working as intended but can increase abruptly if the automation is degraded or fails. Situation awareness and an operator's ability to diagnose and manage a problem are also affected if the automation fails. This sudden increase in workload can reduce controller situation awareness and task performance. A person's manual skills may deteriorate as he or she becomes increasingly reliant on automation, making an accurate and timely response even more difficult during automation failures. The level of automation used in any system therefore represents a trade-off between improved routine performance, workload, situation awareness, and manual skills (Onnasch, 2014).

The environment in which controllers work may itself impact their performance. Interpreting degraded speech, for example, negatively affects cognition. In one study, young adults who listened to normal speech were better able to remember long strings of digits than those who listened to spectrally degraded speech. The same study also found that *extrinsic cognitive load* (adding a task that requires cognitive resources) impaired subjects' ability to recognize degraded speech. The effort used to listen to and interpret degraded speech impaired working memory and required the reallocation of limited cognitive resources (Hunter, 2018). Air traffic controllers are often required to decipher radio transmissions that are degraded due to propagation, multiple simultaneous (“stepped-on”) transmissions, or background noise. They are also required to interpret speech under the adverse listening conditions of a noisy environment.

Cognitive workload and background noise affect operators’ ability to respond to signals. Increasing workload has been shown to decrease a person field of view while also significantly altering its shape. (Williams, 1982; Rantanen, 1999) Although controllers use headsets for most communication tasks, there are often conversations occurring in the background, for example conversations between D- and R-side controllers or a controller using a loudspeaker for a landline conversation. Various signals may also be played over a loudspeaker. This background noise may also affect prospective memory (remembering to perform a specific task at a future time). Background noise in the ATC environment may arise from multiple alarms or speech originating from the radio or an adjacent controller. Even irrelevant sounds can disrupt attention, cognition, and prospective memory, and have been shown to impair tasks such as proofreading and language comprehension. The disruption caused by irrelevant sounds is enduring and does not decrease over repeated exposures. The disruptive effect of background noise may be primarily caused by the need for additional cognitive resources to determine which sounds can be disregarded (Banbury, 2001). One study of medical signals concluded that participants' ability to identify and localize simulated alarms was best during quiet conditions in which there was no secondary task. It was worse when the participant was given a secondary task (reading or mental arithmetic) while a recording of intensive care unit noise was played in the background (Edworthy, 2018).

Conversely, although background noise such as conversations between other people may be distracting, this “noise” may contain valuable information in a complex environment. Railroad operators routinely "listen in" to other conversations to learn of situations that may affect them at a later time (Roth, 2006). Air traffic controllers also build situation awareness by overhearing conversations between pilots and other controllers in adjacent sectors (Kontogiannis, 2013).

Signals in Current Use by ATC

Aircraft are controlled by a sequence of facilities, including air traffic control towers, Terminal Radar Approach Control facilities (TRACONs), and Air Route Traffic Control Centers (ARTCCs). TRACONs currently employ Standard Terminal Automation Replacement System (STARS) equipment to display traffic information to controllers. STARS uses six auditory signals with fundamental tones ranging from 800 Hz to 1600 Hz to alert controllers to an event that requires their attention (Table 1). These audio signals are used in conjunction with the visual displays such as a blinking data block. This auditory/visual signal pair is designed to minimize the time required for the controller to identify and correct a problem. The urgency of the condition is encoded by the frequency and duration of the signal. STARS signals include the Conflict Alert (CA), Minimum Safe Altitude Warning (MSAW), and Mode C Intruder (MCI) alarms.

The Special Transponder Emergency Codes (77xx) alarm is used to alert the controller to aircraft that are squawking specific transponder codes indicating hijack (7500), radio failure (7600), and emergency (7700). Transponder emergency codes are indicated by a 1400 Hz tone that is 600 ms on and 250 ms off (Newman and Allendoerfer, 2000). A default alarm is used to signal any condition that is not covered by these alarms. The current STARS CA uses a 1600 Hz tone with a rapid 60-ms on/60-ms off period. The MCI also uses 1600 Hz but with a longer 130-ms/130-ms period. The STARS MSAW alarm uses a two-tone “warble” signal that oscillates between 1600 and 2000 Hz, with a duration of 260 ms at 1600 Hz and 180 ms at 2000 Hz. This signal is used because it is unique and very easy to discriminate. The En Route Automation Modernization (ERAM) system used in ARTCCs relies only on visual displays and does not currently use auditory signals.

Table 1. Types of Air Traffic Control Facilities

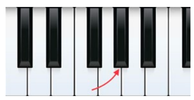
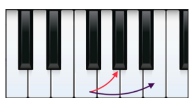
ATC facilities	**Phase of Flight**	**System(s) used**	**Alarms (selected)**	**Modality**
Tower*	**Takeoff and Landing**	Radar display, Airport Surface Detection Equipment, Model X (ASDE-X), Airport Movement Area Safety	Airport Surface Detection Equipment, Model X (ASDE-X), Airport Movement Area Safety System (AMASS), Conflict	**Visual and auditory**

		System (AMASS), Direct visualization	Alert (CA), Minimum Safe Altitude Warning (MSAW)	
TRACON*	**Approach and Departure**	Standard Terminal Automation Replacement System (STARS)	Conflict Alert (CA), Minimum Safe Altitude Warning (MSAW), Mode C Intruder (MCI), Special Transponder Emergency Codes (77xx. e.g. hijack: 7500, radio failure: 7600, and emergency: 7700), default alarm	**Visual and auditory**
ARTCC*	**En route**	En Route Automation Modernization (ERAM)	Conflict Alert (CA), Minimum Safe Altitude Warning (MSAW), Mode C Intruder (MCI), Special Transponder Emergency Codes	**Visual only (blinking)**

*Tower to TRACON to ARTCC is a common sequence of ATC facilities by a given flight. The exact airspace controlled by a given facility may vary by location. For example, airports with low traffic densities may not have a control tower. In areas without a TRACON, an airplane may be handed off from the control tower to an ARTCC.

Air traffic control towers also have a set of tools designed to assist controllers in separating traffic. Control towers in the United States can employ a radar display and Airport Surface Detection Equipment - Model X (ASDE-X), which is used to detect aircraft and vehicles' surface movement. Airport Movement Area Safety System (AMASS) is an add-on to ASDE-X that also receives information about airborne targets in the airport's immediate vicinity. Each of these systems can alert controllers to potentially hazardous conflicts. Signals in towers also include CA and MSAW signals; controllers in this environment generally assign a higher priority to AMASS and MSAW (Newman and Allendoerfer, 2000). AMASS is designed to provide both auditory and textual information to controllers if it detects a surface conflict or a potential conflict between an aircraft approaching a runway and a ground target.

Table 2. Control Tower and TRACON alarm features

Signal	**Auditory Frequency in Hz (Tone)**	**Length/Comments**
Conflict alert	**1600**  *	60-milliseconds on, 60-milliseconds off
Mode C Intruder [+] (airplane into airspace without notification)	**1600**  *	130-milliseconds on, 130-milliseconds off
Minimum Safe Altitude Warning	**Oscillating 1600-2000**  *	260-milliseconds at 1600 Hz then 180-milliseconds at 2000 Hz Two tone signal is unique and easy to discriminate

***Nearest tone(s) [+]TRACON only. Reference:** Newman and Allendoerfer, 2000

Aviation Safety Reporting System (ASRS) Analysis

On December 14, 1974, TWA Flight 514 collided with a mountain while flying an instrument approach into Dulles Airport, killing all aboard. The crew had misunderstood a clearance and descended below the minimum altitude of the approach segment. During the subsequent investigation, the National Transportation Safety Board (NTSB) discovered that many pilots at United Airlines had known about the problems with this approach. The fact that this critical information was not distributed outside of the airline was noted by the National Transportation Safety Board (1974) during its mishap analysis. In response to the NTSB's report, the Federal Aviation Administration (FAA) created the ASRS. To encourage the aviation community to trust the ASRS, the FAA entered into a Memorandum of Agreement with the National Aeronautics and Space Administration (NASA) to host the database (Billings, 1976).

Reports submitted to ASRS often describe an unsafe condition, a near miss, or an involuntary violation of a Federal Aviation Regulation that may be inadvertent or in response to an emergency. Reports are submitted voluntarily, either by mail or electronically by any aviation community member, including pilots, cabin crew, dispatchers, air traffic controllers, and maintenance technicians. Report submissions include descriptive information such as the reporter's role and experience, environmental conditions (if applicable), aircraft type and location, and a section for an open-ended description of the event. Reporters are encouraged to discuss the cause of the event and what they believe can prevent a recurrence. Although the information submitted to ASRS is voluntary and anecdotal, analysis of these reports provides insights into factors affecting the safety of the NAS (Bliss *et al*., 1999; Sarter and Alexander, 2000).

A qualitative description of adverse events related to signals may be helpful as part of a continuing effort to improve signal design and use. We hypothesized that unreliable automation could lead to near misses in air traffic control, as reported in the ASRS database, and reviewed six years of reports from the ASRS database for events that were related to alarms, alerts, and warnings in air traffic control. (Ruskin *et al*. In Press) After completing an analysis of the database, interviews were conducted with former air traffic controllers to gain deeper insights into some of the problems highlighted in the ASRS reports. Building on the theoretical framework that we have already developed (Ruskin *et al*, 2020; Ruskin and Hueske-Kraus, 2015; Wickens *et al.,* 2009), we can use this information to guide new design parameters for signals. These new parameters can hopefully increase signal reliability and improve controller awareness, timeliness, and accuracy.

Data Selection and Procedures

We searched for ASRS reports filed from January 1, 2015, through December 31, 2020, using the publicly accessible search engine (https://asrs.arc.nasa.gov/search/database.html). Reports were then individually reviewed and selected for inclusion if they were filed by air traffic controllers and contained at least one instance of the phrases *alarm, alert,* and/or *warning*. According to Signal Detection Theory, each report was then analyzed for a hit, miss, correct rejection, or false alarm on the part of the human operator and the automation. After analysis, representative narrative reports were selected for review if they provided additional information about alarm management. In many reports, controllers did not explicitly state whether they perceived or missed a signal in many of the reports, requiring that the human response to the signal be inferred from the context of the report. For example, we classified events as a human miss if a controller reported that the problem was first recognized after the automation produced a signal. Some reports do, however, mention that the controller was distracted or didn't notice a problem until the automated system activated a signal (*e.g.*, not noticing a loss of separation until the CA activated).

Structured Interviews

Information from the ASRS reports was used to develop structured interviews (Appendix A) by identifying the signals that were associated with the greatest number of reports. Interviews were conducted with a convenience sample of three former air traffic controllers who are now on the faculty of a large aerospace university in the southeastern United States. These interviews were used to develop a list of factors that affect controllers' ability to interact with and respond to signals. The structured interviews were exempted from review under the Embry-Riddle Aeronautical University IRB (Protocol 21-068).

ASRS Analysis

This search strategy returned 370 reports. 78 reports were filed by Tower personnel (ground and local controllers), 123 by TRACON controllers, and 169 by ARTCC (Center) controllers. The most commonly reported signals included MSAW, ASDE-X, and CA. Overall, the signals most commonly implicated in reports for alarm problems were MSAW (139), ASDE-X and ASSC (27), CA (195), and AMASS (4). Mentions of ASDE-X, ASSC, or AMASS appeared in 30 reports by ground or local controllers. TRACON controllers reported events involving MSAW 70 times and CA 51 times; these signals were also implicated by local controllers (22 and 25 times, respectively).

The most commonly mentioned alarm was the CA, which was cited a total of 195 times in the reports. Additional data are included in Tables 3A-C. Additional statistics are included in Tables 1-3. Logistic regression analysis revealed that errors associated with automated signals are more likely to include false alarms, while humans tend to experience more misses but also more correct rejections. The narrative reports revealed that controllers usually perceived and responded to a developing situation before a signal was activated.

	ASDE-X/ASSC	AMASS	MSAW	CA	Other
Tower	27	4	22	25	0
TRACON	1	0	70	51	1
Center	0	0	47	119	3

Table 3A. Alarms by Facility (From Ruskin *et al*., In Press)

	ASDE-X/ASSC	AMASS	MSAW	CA	Other
Hit	11	1	78	97	3
False Alarm	2	0	1	0	1
Miss	9	2	59	88	5
Correct Reject	5	1	1	9	2

Table 3B. Human Signal Detection (From Ruskin *et al*., In Press)
Signal detection performance categories are provided in the section entitled *Automation, Workload, and Signals*.

	ASDE-X/ASSC	AMASS	MSAW	CA	Other
Hit	17	3	17	13	4
False Alarm	5	4	3	4	1
Miss	4	5	11	11	5
Correct Reject	1	0	2	0	0

Table 3C. Automation Signal Detection (From Ruskin *et al*., In Press)

Individual narrative reports in our study revealed areas in which signals can be improved. Several reports indicated that too many false alarms may cause complacency. For example:

> *"Due to a lot of changing and "non-standard" MIA's and a large number of awkwardly shaped MIA's in our airspace, we get a lot of "non-event" MSAW warnings as aircraft often fly quite close to, or even through MIA's along their route. As a result, I believe there is some complacency with regard to the MSAW warning. A secondary indicator on the display would be helpful to identify aircraft that are definitely filed, or whose route line actually penetrates MIA's that are not safe for their altitude."*

“Aircraft X was an IFR from ZZZ to OTH. The D side gave him as filed to 060, his requested altitude. Aircraft X started flashing MSAW (Minimum Safe Altitude Warning) north of CEC, I didn't think anything of it because there were a couple areas in our airspace that the aircraft will flash MSAW because they are below the MIA but they are above the MEA and therefore at a safe altitude. For some reason, I thought the MEA on V27 between CEC and OTH was 060 so I though the MSAW alert was yet another erroneous alert. The MEA on V27 is 064, the MIA is 062.

Although retaining the knowledge of the MIAs and MEAs are my responsibility, the erroneous MSAW reports does desensitize us to those alerts. If the program or equipment was updated to fix this problem, aircraft flashing MSAW would elicit a faster response.”

Several reports indicated that education about alarm management may be beneficial. For example, one report described a runway incursion after a controller failed to issue a “Go-around” instruction for an ASDE-X alert:

“While giving instruction and demonstrating required activity for significant MORs to the CPC, I heard the ASDE-X alarm "Runway XR go-around" I immediately looked up and scanned Runway XR to assess the situation and determine what caused the alarm. I observed Aircraft Y, 1/2 mile final landing on Runway XR and a small GA aircraft on Taxiway [5] turning South on Taxiway [3]. I didn't observe any other targets or obstructions on the runway surface area. At that time Aircraft Y was already flaring out on the runway. I then asked the LC Controller why wasn't Aircraft Y sent around. The Controller responded, "The other aircraft cleared the runway." ... Remind controllers that the safety logic overrides same runway separation and that it's mandatory to comply with the safety logic instructions. I did have this conversation with my crew after the incident and was shocked to know they weren't aware of this and thought it was a discretionary decision.”

Examples of misses include:

“Aircraft X was upwind in the traffic pattern. Aircraft Y was in the pattern following Aircraft X. I was working Local Control. I anticipated Aircraft Y was turning in sooner than the typical pattern so I told Aircraft X to start his go around for Aircraft Y in trail of him. Aircraft X started his go around and was at approximately 80 feet on the upwind offset left of the runway when the Airport Surface Detection Equipment (ASDE-X) alarmed. The ASDE-X didn't alarm until Aircraft Y had already touched down. Also when the ASDE-X alarmed it said runway occupied instead of runway go around. I did not issue the Go around instructions to Aircraft Y because he had already landed and was following thru on his touch and go. The ASDE-X alarmed when Aircraft Y was between taxiways which was much too late for reasonable go around instructions to be issued. The ASDE-X is a constant problem and go around instructions should not be required due the inaccuracy of the system.”

“When Aircraft X said he could go direct to NENMY [a navigation fix], I cleared him and told him to cross NENMY at or above 3,000 feet. At the time and position I did not realize that track would take him over the 3,700 feet MVA (Minimum Vectoring Altitude) obstacle. The aircraft ended up passing over the MVA [minimum vectoring altitude] obstacle at 3,000 feet and already passed it when we realized it. The MSAW (Minimum Safe Altitude Warning) only flashed and there was no audible alarm heard.”

Reports also highlighted the benefits of listening to other conversations, and in some cases, offered suggestions for using those conversations to improve situation awareness:

“I strongly believe in the Tower team concept and felt very responsible for not alerting the Local Controller to the imminent situation. In the future I am going to make several changes to prevent this from occurring again. I am going to try and be closer to the front of the cab when training, so I can scan the runways better and fully hear what the Local Controller is saying. I am going to move my ear piece to the ear opposite of the other controller in the cab to hopefully pick up on their transmissions easier.”

Interview Analyses

We combined these structured interviews with ASRS data to identify factors that affect signal priority. We spoke to the controllers in all three areas of ATC (tower, TRACON, and en route). Two were former military personnel, and one had worked at several major airports in the United States. A summary of major themes from these interviews was as follows:

- Too many alarms
- Identical alarm sounds
- Overlapping data blocks
- Difficulty in localizing alarms (*i.e.*, which console is alarming?)
- Environmental alarms are too loud and annoying
- Turning off alarms
- No standards for whether to help other controllers with their alarms
- No control over environmental noise (*e.g.*, radios)
- No tactile alarms

Each controller mentioned the excessive number of alarms. This finding was true for the tower, en route, and TRACON. Most of these alarms were a result of conflict alerts or low altitude alerts. As one controller described:

> *"[You're] up in the tower and there were a number of different alerts and sounds. I mean some dealt with equipment outages if an ILS [Instrument Landing System] went out, there would be an alarm on that. But the thing that probably we heard the most was usually a conflict alert warning or a low altitude alert warning on an aircraft that was either inbound or outbound. I mean so those were things that went off 100 times a day. Those were the, actually the conflict alert and the low altitude were the main alerts that we would get. Like I said, we had equipment alerts and other things that were rare."*

In addition, many of these alarms had similar or identical sounds. This result was particularly true for conflict alerts and low altitude alerts.

> *"And there was no differentiation between a conflict alert or a low altitude alert. So they were the same, at least when I was there. Maybe they've changed/adjusted the sound. But they were the same beeping sound. So was it conflict alert or low altitude alert you know. Then you had to look at the display to say OK this is the*

same flashing LA [Minimum Safe Altitude Warning] so it's at low altitude or CA which is conflict alert."

Signals that are acoustically similar create extra cognitive steps because the controller must first identify the source of the sound and then determine what the signal indicates. Interviewees expressed concern that new controllers might have more difficulty in localizing the alarms and might become confused about which console the signal came from. The interviewees, who were more experienced controllers, mentioned that they did not have difficulty localizing alarms.

In many instances, the environmental alarms were considered too loud and annoying. This issue was handled in multiple ways. In some cases, controllers ignored the alarms once they determined that a hazard did not exist. In other instances, they turned off or attempted to mute the alarms to the best of their ability. In addition, there was little control over other environmental noises.

> *"Equipment and like building issues like something going off, probably maybe once every week or two. It wasn't very often. Maybe every couple of weeks. And the fire alarm that was [a] rare occasion. So that thankfully. So that wasn't too big of an issue, but like I said, when it went off it would it was like I said, scare the crap out of you. And same thing with some of the other alarms. There was often times that people would cover those up. But again, not to the point where you couldn't hear them, it just minimized where it was more of a background. I mean you could still. Cause some of these would go off, and you couldn't even hear airplanes calling you 'cause they were so loud. I mean it was actually extremely distracting. So that's and there was no volume control on these. It was like you got blasting or nothing."*

Limitations of the ASRS Review

We are using the comprehensive literature review written during the first phase of this project and our study of "near misses" in the ASRS database as the foundation of our signaling philosophy. There are several limitations related to our reliance upon ASRS reports and interviews with former controllers. Reports to ASRS are voluntary, anonymous, and anecdotal (Corrie, 1997). They may introduce biases that result from a greater tendency to report serious events than minor ones, from organizational and geographic influences, and from other factors such as a perceived violation of a Federal Aviation Regulation. Each submitted report is analyzed for the perceived benefit to the aviation community, and only a subset of received reports is analyzed and entered into the ASRS database. The events described in the reports are not independently verified and may represent only one side of the story (although the database will occasionally contain several independent reports of the same event from different reporters).

The anonymous, retrospective nature of ASRS reports introduces additional limitations. Reports that do not contain the keywords used in the search phrase would not have been found, and the number of reports obtained in our search of the ASRS database may not represent the total number of such incidents. These potential influences reduce the confidence that can be attached to statistical findings based on ASRS data. Despite these limitations, however, proportions of consistently reported incidents to ASRS, such as altitude deviations, have been remarkably stable over many years. It is reasonable to assume that incident reports drawn from a time interval of at least several years, such as our study that used reports over a 5-year period, will reflect patterns that are broadly representative of aviation safety incidents of a given type. Although this research can guide the conditions under which signals will be activated and how those signals are displayed to controllers, we do not yet have sufficient information to offer guidance on specific algorithms used by ATC. Any changes to signals should be sufficiently flexible to accommodate differences in the algorithms used to produce signals.

Potential Enhancements and Signaling Philosophy

Controllers work with many systems, including ground surveillance, airborne surveillance, and systems that monitor the status of the automation. An integrated approach that considers every system in the operational environment will help to minimize confusion about alarms across systems. Our review of the literature, analysis of ASRS reports, and controller interviews have identified specific problems and possible solutions that can enhance controllers' ability to maintain safe operations.

The signaling philosophy that we propose in this report includes new alarm sounds (Bennett, 2019), visual displays, and/or tactile feedback. Our findings may also be used to enhance the effectiveness of signals in the ATC environment by reducing repetitiveness, redundancy, unnecessary signals, and conflicting information. The overarching goal of a signal philosophy is to: 1) improve controller performance and safety; 2) improve controller trust in the system; and 3) reduce controller workload. In addition to the discussion below, Appendix B contains a list of enhancements that includes whether they are currently used in air traffic control, other domains within aviation, or outside industries.

Our prior literature review and ASRS study (Ruskin *et al*. In Press) suggest that there are opportunities for enhancement in the signaling system that is part of the human-automation interface used by air traffic control. Goel, Datta, and Mannen (2017) have suggested that the utility of a signal can be evaluated according to specific characteristics:

- **Uniqueness**: Each signal should indicate deviation from a unique parameter. Duplicate signals should be avoided.
- **Prioritization**: Each signal should be prioritized so that controller operator can identify the criticality of a given signal and respond accordingly.
- **Timeliness**: Signals must appear at the correct time. A signal that is activated too early or too late may prevent the controller from making the correct response and may decrease trust in the system.
- **Understandability**: A signal should have a suitable description that is easy to understand and will help the controller to identify the problem.
- **Relevance**: Each signal should be relevant and should also have operational value to the controller.
- **Required response**: A signal should require a definitive response from the controller.

Meeting these characteristics requires that controllers need to know the nature of the problem, the locations and altitudes of the involved aircraft or vehicles, and the urgency of the problem. We suggest that signals can be divided into four categories that require increasing levels of intervention by the controller:

- Priority 1: Immediate danger requiring urgent controller intervention. (*e.g,* Imminent NMAC, flight below MVA, AMASS)
- Priority 2: Risk of harm. Controller intervention will be required soon (*e.g.*, Predicted conflict, airspace alert)
- Priority 3: Informational. Intervention may be required (*e.g.*, Mode C intruder)
- Priority 4 or diagnostic (*e.g.*, Radar outage, localizer malfunction)

A variety of cues can be used to indicate alarm priority, including pitch, timbre, and verbal indicators. The ideal auditory signal is easy to localize, distinguishable from other alarms, not easily missed, resistant to masking by other sounds, does not interfere with communication, and easy to learn. Hansen *et al*. (2021) found that augmenting high-priority, emergency alarms with digitized human speech decreased response time. They also demonstrated that incorporating a slight delay before activating lower-priority automatically generated signals that are likely to be false-positives also improved operators' performance.

Signals should also be activated at the correct time so that they can aid controllers' prospective memory. When engaged in a surveillance task, operators often use a combination of proactive and reactive interventions to adapt to a demanding task environment. (Strickland *et al*., 2019) Controllers frequently identify a potential problem and proactively take steps to mitigate it before a signal is activated, but also rely upon prospective memory to accomplish this task. Boag *et al* (2019) found that controllers who perform a simulated conflict detection task share cognitive resources between ongoing safety-critical tasks and tasks that require prospective memory in proportion to their relative importance: They allocate most of their cognitive capacity to the task with the highest priority. In a study of prospective memory in air traffic controllers, aids that were set to flash when controllers were required to accept a target aircraft reduced prospective memory error and improved performance in simultaneous tasks that included aircraft acceptance and conflict detection. Memory aids that did not specifically alert the subjects when a target aircraft was present did not improve performance. (Loft, Smith, and Bhaskara, 2011)

Current STARS and ERAM systems allow controllers to suppress the conflict alert when the algorithm predicts a loss of separation. In this condition, the display continues to indicate that the algorithm has detected a potential loss of separation, but the data block stops flashing, and auditory signals are silenced. The controller is permitted to suppress this signal until the aircraft have violated the standard separation requirement. After the aircraft have violated the separation requirement, the signal can no longer be suppressed and the controller must intervene to separate the two aircraft. STARS and ERAM use different algorithms to activate their signals. STARS and ERAM CA use different algorithms both of which use surveillance data and dead reckoning to predict conflicts. The ERAM Conflict Probe uses advanced trajectory modeling, surveillance data, and route information to provide an alert up to 20 minutes before a potential conflict. The ERAM Conflict Probe does not, however, account for situations in which greater separation may be needed (*e.g.*, non-standard formations or very heavy aircraft such as the A380) or where reduced separation is permitted.

Both the structured interviews and ASRS reports have indicated that misses can arise from silencing or suspending alarms. This suggests that facility policy and operational guidance could be developed as to when and how signals can be permanently silenced or suspended in the tower, TRACON, and en route environments. This information may also help develop strategies that can improve trust in the automation, such as indicating the level of confidence that the automation has in predicting an impending loss of separation (Borst, 2017). If the controller is allowed to suppress an auditory signal, the data block should continue to show that the underlying situation is still present. Controllers should be provided with the ability to suppress a signal by informing the automation that a resolution has been implemented. For example, the controller might indicate that two aircraft have agreed to maintain visual separation or that formation flights will manage their own separation despite having discrete transponder codes. Subsequently, the auditory portion of the signal should automatically re-enable if the situation remains static or progresses, except in limited cases (*e.g.*, formation flight).

Environmental Limitations

The environment in which the controller is working affects the types of signals that can be used. For example, air traffic control towers have variable lighting, depending upon the time of day and the orientation of the tower. Visual signals may therefore not be as effective in attracting the controller's attention, especially during the day. Critical systems may be located in different areas of the tower cab, requiring the controller to move from one piece of equipment to another, especially when multiple signals are activated at once. Local and ground controllers in an air traffic control towers are also mobile, limiting the effectiveness of technologies such as tactile stimuli or highly directional audio. Some touch-screen displays may cause colors to be washed out or otherwise altered when observed from an oblique angle. To mitigate these effects, the priority of signals should be encoded with shapes as well as colors. For example, signals could be encoded as: Priority 1 [Red square], Priority 2 [Yellow triangle], Priority 3 [Orange nabla], Advisory [Cyan diamond] and Suppressed [Circle coded with color of alarm].

Both the structured interviews and the ASRS data suggest that environmental limitations might make some signaling modalities more effective in specific domains. For example, indicator lights and messages on screens may be less effective in a control tower because bright light makes them more difficult to see. This environment may therefore benefit from additional use of auditory signals while designing enclosures that enhance the visibility of screens and lights. Tactile displays (*i.e.*, those using the sense of touch) may be used instead to draw a controller's attention to an urgent condition, but the design of these devices must accommodate by controllers who move between stations. Improving the localizability of auditory signals may help controllers diagnose a problem more quickly. One relatively simple and cost-effective way to test these potential enhancements before further development would be to use a cognitive walkthrough study as described by Hah *et al*. (2017). For an impending situation that involves a high risk of harm, signals can offer suggested actions (*e.g*., ASDE-X “Go Around!” alarm). In addition, the simultaneous use of multiple modalities might be valuable when response time is critical and there are urgent and high-workload challenges (*e.g.*, aircraft in distress, multiple landline calls to coordinate) that may distract the controller. Using voice alerts for extremely high-priority alarms indicating potential loss of life has been shown to reduce response time in domains outside of aviation. (Hansen *et al*., 2021)

New Signal Strategies

Auditory Signals

The acoustic structure of signals affects their ability to effectively draw the operator’s attention to a hazard. The *cohort theory* of sound recognition suggests that an initial sound (or melody) activates a cohort of possible matches in a person’s mind. This list of possibilities is then narrowed as the sound progresses. A person identifies the specific word (or melody) after all other candidates have been eliminated. (Schulkind *et al*., 2003) The most basic delineation of auditory signals is between speech-based and non-speech-based sounds. Speech-based signals have the advantages of being easy to understand without the need to use abstract sounds (Leung, 1997), while signals that do not rely on speech are language-independent and recognizable in a cluttered acoustic environment. (Oleksy, 2018) Making signals more acoustically rich and explicitly encoding their urgency can improve their performance. Features of a signal’s melodic structure (*e.g.*, repeated notes, changes in amplitude, and easily recognizable intervals) can increase the likelihood that an operator will identify it correctly. (Gillard and Schütz, 2016) Rayo *et al*. (2019) also found that timbre can be used to encode alarm similarity and urgency, improving identifiability of different alarms. Heterogenous auditory signals are also easier to identify than using a single sound for multiple conditions (Edworthy, 2011). Potential methods of creating unique sounds include varying timbre, using chords (in a minor key), changing pulse length, or varying amplitude. Using acoustically rich signals sounds may therefore improve controllers' performance, particularly in a noisy environment or when multiple signals are being activated at once.

Improving the localizability of alarms can help controllers to determine where a given event is occurring. Binaural alarm systems that are designed to incorporate spatial cues may also help operators to identify a signal in an environment with high levels of background noise. (Uchiyama *et al*., 2007) Highly directional loudspeakers can help to reduce the overall noisiness of the environment by producing sounds that can be heard only in a narrow range (Shao *et al*., 2021). Humans are best at localizing sounds below approximately 2 kHz, and above 5 kHz, suggesting that signals should use frequencies in this range. (Grothe, Pecka, and McAlpine, 2010) Catchpole, McKeown, and Withington (2007) found that adding noise components to an auditory warning pulse can enhance information about the location of a signal, although there was a trade-off between the listener's ability to localize the signal and its perceived urgency.

New classes of auditory signals, including earcons and spearcons, may help controllers differentiate between different conditions and the urgency of a hazard. An *earcon* (or auditory icon) is a non-verbal auditory message that is used as part of a human-computer interface to provide information and feedback. The paper-crumpling sound many computers make when dragging a file to the trash is an example of an earcon (Blattner, 1989). Earcons are easy for operators to learn, especially when their sound correlates to a specific target event. (Keller and Stevens, 2004) In one study, non-physician participants quickly identified abnormal vital signs indicated by earcons while monitoring a series of simulated patients (Hickling, 2017). Graham (1999) found that earcons produced significantly faster reaction times than conventional warnings during simulated driving. However, earcons produced an increased number of inappropriate responses, in which drivers reacted by braking in response to a situation in which a collision was not imminent. The findings are explained relative to the perceived urgency and inherent meaning of each sound. A *spearcon* consists of artificially accelerated human speech and combines features of earcons and the spoken word (Walker, 2013). Spearcons can improve a user's ability to navigate menus and may be superior to other auditory cues. Although signals based on spearcons have not yet been evaluated in aviation, one study in medicine concluded that spearcons improved participants' ability to monitor multiple patients for abnormal conditions (Li, 2019).

Visual Signals

Modifications to visual signals can help controllers to identify and prioritize situations that require their attention. An easily accessible alarm summary window can provide a list of current situations requiring attention, especially when alarms have been suppressed. A visual indicator as to the potential risk and the speed at which a situation is developing may help controllers to prioritize multiple situations in parallel. For example, a bar underneath the data block of an aircraft about to enter an area with a higher MVA may appear to indicate the amount of time before a controller must either issue a climb instruction or vector it away from the obstruction. This "time to go" indicator can help the controller to manage the situation by providing the controller with an indication of how long he or she has before the problem becomes critical (*e.g.*, loss of separation). Such an indicator may consist of a progress bar or a circle, and its visual characteristics could be used to indicate the urgency of the problem. For example, stimuli that accelerate toward the end of their movement are perceived to be changing more rapidly than stimuli that are moving at a constant rate. (Matthews, 2011)

Tactile Signals

Tactile alerts have been shown to improve performance in an automated cockpit environment, producing a higher detection rate of, and faster responses to, potential failures. Operators' response to tactile alerts may be unaffected by concurrent visual tasks. (Sklar, 1999) Visual-tactile alerts seem to work best in a multitasking, high-workload environment. (Burke, 2006) Lane-departure warning systems in cars often use visual-tactile signals such as graphic warning displays on the dashboard paired with a vibration in the steering wheel to alert the driver when vehicle sensors detect that the car is deviating from the lane and starting to cross lane markings. These systems are only triggered when the turn signal has not been activated to indicate an intent to change lanes. Tactile signals using wireless, wrist-worn devices may be feasible even in users who require mobility (*e.g.*, tower controllers) (Lee and Starner, 2010). In general, users of these devices can discern temporal alert patterns but have more difficulty perceiving changes in intensity (Lee and Starner, 2010). Unanticipated tactile alerts can be startling, however, and maintaining vigilance for tactile alerts may also be stressful (Horberry et al, 2021), although Pratt *et al.* (2012) describe a method of indicating urgency without unnecessarily annoying an operator by varying the pulse rate of vibrotactile stimuli. This signaling modality therefore requires additional study in the ATC environment before implementation (DeLucia, 2020). Lastly, multiple signaling modalities may be used to indicate a particularly urgent condition that requires a rapid response. For example, both auditory and tactile stimuli might alert a controller to an aircraft in distress (*e.g.*, squawking 7700) or a runway incursion while another aircraft is attempting a takeoff or landing.

Trust

Operators must trust the systems that they use. An excessive number of false alarms may lead the operator to disregard the importance of a signal. Although Wickens *et al*. (2009) suggested that the "cry wolf" effect may not be as harmful as previously thought in the ATC environment, their study was limited to conflict alerts. One of the ASRS reports that we previously described suggests that the “cry wolf” effect may occur in the Tower environment with some misleading signals generated by AMASS. The ASRS narrative report that describes how false ASDE-X alarms may reduce the response rate to conflict alerts or MSAWs in a tower environment suggests that an excessive number of false or misleading signals may cause systemwide trust failure (Keller and Rice, 2010). Conversely, reports and structured interviews suggest that controllers usually respond to a developing situation before an alert is activated. This finding is consistent with a study by Allendoerfer *et al*. (2008).

Operators trust the system when automation performs as expected and the operator understands what the system is doing while maintaining vigilance for rare and potentially catastrophic failures. Signals should be transparent, providing an indication of why the signal is being presented, the likelihood of the condition, and the urgency of the condition. Improving the level of transparency helps to maintain operators’ trust in a system. This can be accomplished by indicating the automation’s level of confidence that the signal represents a situation that will require intervention on the part of the controller. For example, an ARTCC’s Conflict Probe alert for two targets that might converge in 30 minutes might indicate a lower likelihood than would a Conflict Alert for two converging targets that are less than six miles apart. The International Society of Automation standard ISA 18.2 defines *alarm flood* as “A condition during which the alarm rate is greater than the operator can effectively manage (e.g., more than 10 alarms per 10 minutes)." Alarm flood can be avoided by inhibiting multiple alarms that may arise from the same deviation.

Signal Implementation Process

Although the goals of this project are to develop a handbook for ATC signaling, the process by which these signals are developed can enhance their effectiveness. The HFDS documents a process for incorporating human factors into equipment design, while the ANSI/ISA-18.2 standard was developed to guide performance benchmarks for industrial alarm systems. (Wang, 2016) The ISA standard recommends 10 stages for an alarm management lifecycle:

- Development of a signal philosophy
- Identification of signal states
- Rationalization
- Detailed design
- Implementation
- Operation
- Maintenance
- Monitoring and assessment
- Management of change
- Audit

Our prior literature review, study of ASRS events, and development of this signal philosophy constitute the first two steps of this process, and the handbook that will be developed in the next phase of the project will fulfill the next two steps of the ISA standard. Managing signal changes within the ATO is beyond the scope of this project, but several change management systems are used within high-reliability organizations. Strategies include Total Safety Management (Kontogiannis, 2016) and Safety Change Management (Gerbec, 2016) which proactively address safety issues within an organization. These systems incorporate performance assessment, employee empowerment, risk analysis, and strategic continual improvement. These processes may improve the implementation phase as new signal strategies are developed and implemented.

Conclusions

ATC has been described as an integral part of the global "knowledge economy" (Owen, 2018) and shares similarities with other transportation industries (*e.g.*, rail and shipping), finance and medicine. As is also the case in these other domains, the NAS in which air traffic controllers work is a complex and demanding, multitasking environment. Effective design of signals is essential. ATC systems employ a high level of automation, using various algorithms to detect runway incursions, conflicts, and altitude deviations. Although the automation is designed to help controllers perform their job safely and effectively, imperfect automation with suboptimal signaling systems can degrade performance. Former controllers we interviewed cited false alarms and missed alarms as impediments to their jobs, and one narrative report from ASRS suggested that alarm fatigue impairs performance and impacts safety. Improving the signals that controllers rely upon can enhance the safety and efficiency of the NAS. The roadmap that we have developed in our signal philosophy will be used in the next phase of this project to develop a handbook for signal design. This handbook, which will include references to the HFDS, will provide equipment designers with guidance to help them develop signals that will help controllers to keep the National Airspace System the safest in the world.

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Appendix A

Structured Interview Questions

1. Where did you work before/currently?
2. What the is environment like?
3. How do you use signals?
4. Are there near misses?
5. Are you silencing alarms?
6. Are you allowed to turn them off?
7. When changes are made, how do you go into effect?
8. Do you have regularly scheduled changes when things are introduced?
9. How much time do you spend training on it?
10. How often do you record issues you have with alarms?
11. What types of problems do you have with alarms?
12. Voluntary versus required reporting?
13. How characteristic are the databases of actual reporting?
14. Do you accurately capture the real issues?
15. What are the most common distractions for them?
16. Are you more visual or auditory?
17. Do you have any tactile?
18. How many people hear the alarms?
19. Do you formally learn alarm behavior?
20. Process for multiple alarms?
21. How do the silence alarms?
22. What is the procedure for responding to alarms?
23. Do you have strict rules or unspoken rules or both?
24. How cluttered is their auditory environment?
25. What other sounds are there?
26. Do you get hearing tests?
27. Which sounds are localized versus hard to localize?
28. What colors are used?
29. What different frequencies are used?
30. How does loudness vary?
31. Which is easiest to hear and respond to?
32. Which is most annoying?

Appendix B: Potential Signal Enhancements

<u>Currently used in ATC</u>

- Pulsed auditory signals
- Verbal instructions (*e.g.*, ASDE-X “Go around!”)
- Visual signals, including color

<u>Currently used in aviation</u>

- Tactile signals (stick shaker)
- Increasing size of critical information
- Simplifying display to highlight critical information

<u>Used in industries other than aviation (*e.g.*, manufacturing)</u>

- Vibrotactile signals
- “Time to go” indicators (*e.g.*, moving bar)
- Color-coded and shape coded visual indicators
- Earcons

<u>Possible future applications: additional research required</u>

- Spearcons
- Sound characteristics to encode urgency
    - Timbre
    - Chords
    - Contour
- Directional signals
    - Incorporating noise into pure tones
    - Highly directional loudspeakers