Transportation Research Interdisciplinary Perspectives 22 (2023) 100965

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Validation of a new method for designing air traffic control alarms

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ARTICLE INFO

Keywords:
Alarms
Alerts
Warnings
Signals
Automation
Air traffic control

ABSTRACT

Alarms, alerts, and warnings are critical to maintaining safety in the National Airspace System and should be designed to support aircraft separation as well as supplementary tasks such as weather avoidance. The purpose of this study is to validate a novel alarm design framework by asking air traffic controllers to evaluate an existing alarm.

Methods: We invited four air traffic controllers to participate in a structured interview that is part of a novel Signal Design Framework. Controllers were asked a series of scripted questions about 15 specific alarm properties. They were then asked to choose the three properties most important to the design of the conflict alert. Lastly, controllers were asked a series of questions about the overall quality of the taxonomy and its potential for impacting aviation safety.

Results: All participants agreed that the taxonomy captured all the important characteristics of an alarm and that no gaps or failures existed in the alarm framework. They also agreed that the framework was easy to understand, that the structured interview was easy to understand, and that applying the framework to alarm design and revision would improve alarm ease of use, reduce confusion, and improve overall safety.

Conclusions: The structured interview encouraged controllers to think about the Conflict Alert and helped them to develop novel solutions that could potentially improve this alarm in the Air Traffic Control environment.

Introduction

Alarms, alerts, and warnings (collectively called *signals*) (Bliss et al., 1995) are critical to maintaining safety in high-risk industries such as air traffic control. The signals that air traffic controllers use should be designed to support the controllers' ability to maintain aircraft separation, provide low altitude alerts, and accomplish secondary tasks such as assisting flight crews with weather avoidance. Signals should therefore support the early recognition and mitigation of hazards such as traffic conflicts. Conversely, false alarms, signals that are difficult to interpret, and nuisance signals can impose additional workload, potentially leading to errors. (Ruskin et al., 2020).

As part of a project funded by the Federal Aviation Administration to improve alarms, alerts, and warnings for the Air Traffic Organization, our group has developed a new method to guide the design and evaluation of signals in air traffic control. (Ruskin, Rice, and Ruskin, 2022) The framework consists of 15 properties that comprehensively describe a signal. End-users' responses to a structured interview (Appendix 1) describe how a signal can be best suited to alert a person to a discrete hazard in the environment in which the signal will be used. This 'Signal Design Framework' facilitates collaboration and provides a common language between human factors experts, subject matter experts, and equipment designers.

The Signal Design Framework can be used to create a new signal by asking subject matter experts (air traffic controllers) to first think about a new signal and the specific characteristics that would make it function well in their environment. Next, subject matter experts (i.e., air traffic controllers) are asked to answer a series of questions about each of 15 characteristics. The interview process can also be used to evaluate the effectiveness of an existing signal and determine which if any changes would enhance its effectiveness. Finally, for each characteristic, the subject matter expert is asked to provide a Likert score to quantitively indicate its relevance.

In this paper, we describe a preliminary study to validate the framework by asking air traffic controllers to evaluate an existing alarm. This study is the first step in assessing the utility of the framework to guide alarm design and validate its use for a wide range of applications within the transportation industry as well as other domains.

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https://doi.org/10.1016/j.trip.2023.100965
Received 30 May 2023; Received in revised form 9 September 2023; Accepted 3 November 2023
Available online 20 November 2023

Literature review

Federal Aviation Administration (FAA) air traffic controllers rely on signals including the Conflict Alert (CA), Mode-C Intruder (MCI) alert, and Minimum Safe Altitude Warning (MSAW) to warn them of potentially hazardous conditions. (Newman and Allendoerfer, 2021; Ruskin et al., 2020). Some controllers also receive alarms for conditions such as wind shear, microbursts, and runway incursions. These signals are presented visually, often on the controller's radar display or a nearby device, and there may be a corresponding audible alarm in air traffic control towers and Terminal Radar Approach Control Facilities (TRACONs). *Human factors engineering* applies the current understanding of human capabilities and limitations to equipment design to ensure that tasks and the work environment are compatible with the sensory, perceptual, cognitive, and physical attributes of the personnel who are responsible for its safe operation. Signal design that is based on the principles of human factors can help to ensure that new and existing signals help controllers to maintain the safety of the National Airspace System.

According to Signal Detection Theory (Green and Swets, 1966), a signal can be characterized as a *hit* (true positive), a *correct rejection* (true negative), a *false alarm* (false positive), or a *miss* (false negative). 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 that correctly indicates that a threshold has been exceeded but does not require a response). A nuisance alarm may occur when a controller has already recognized a hazard and planned an action to correct it, but the alarm is activated because the automation has not yet detected the controller's response (Wickens et al., 2009). ATC surveillance systems do not currently allow controllers to suppress some of their signals, and controllers are actively discouraged from suppressing signals until the associated hazard has been resolved. As a result, a signal may be activated even if the controller has detected the underlying problem and taken action to prevent it. One example involves a non-precision approach procedure, which is an instrument-based approach to landing that does not have a specified glideslope for the aircraft to follow. A Minimum Safe Altitude Warning (MSAW) may activate when an aircraft has a high descent rate on such a non-precision approach, even if the pilot intends to level off at the altitude specified in the procedure.

Current ATC signals and their sources

Signals currently used by the STARS (Standard Terminal Automation Replacement System) workstation in TRACONs and towers include the Conflict Alert (CA), the Minimum Safe Altitude Warning (MSAW), and Mode C Intruder (MCI) alarms. Each of these signals includes an auditory and visual component. ASDE-X (Airport Surface Detection System, Model X) is used in towers at larger airports, and incorporates information from sources including surface movement radar, ADS-B, and multilateration sensors to alert controllers to potential runway incursions or wrong surface events. Signals that indicate low-level windshear and microbursts are displayed on an Information Display System (IDS) in some towers and TRACONs. The special transponder codes (77xx) also activate an alarm to draw a controller's attention to an aircraft whose transponder is set to indicate a hijack (7500), radio failure (7600), or emergency (7700) (Ruskin et al., 2020). En Route Automation Modernization (ERAM) systems in air route traffic control centers monitor aircraft for possible loss of separation with both a Conflict Alert and a Conflict Probe. The Conflict Probe uses a combination of dead-reckoning and trajectory analysis to predict loss of separation up to 40 min before it may occur. ERAM systems use only visual signals; there is no auditory component.

A controller's response to a given signal may vary based on the specific circumstances of the hazard. Controllers may act independently of a signal for some conditions or delay acting on other conditions until more information is available. For example, controllers often consider a MSAW to be more urgent than a CA and may therefore respond to an MSAW more quickly (Allendoerfer, Pai, and Friedman-Berg, 2008).

Table 1
Signal Design Framework.

	Factor
HOW	**Modality**
	(Visual, auditory, tactile, olfactory)
	Priority
	Saliency/Noticeability
	(Contrast, color, size, shape, luminance, amplitude and frequency, texture, speed/pattern)
	Disruptiveness
WHAT	**Distinguishability**
	Exclusivity
	Familiarity
	Recognizability
	Consistency
	Informativeness
WHERE	**Location**
	Recipient
WHEN	**Temporality**
	Suppressibility
WHY	**Accuracy**
	Reliability

Unreliable signals

Air traffic controllers rely upon accurate, timely, and reliable signals to maintain safety within the National Airspace System (NAS). Rovira and Parasuraman, 2010 found that false alarms and misses had adverse effects on performance. Signals that are perceived to be overly unreliable can 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 Jul). 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). Moreover, a controller may require additional time to gather his or her thoughts and resume a previous task after being interrupted by a signal (Altmann & Trafton, 2002 Jan), which may also impair performance.

False alarms, nuisance alarms, and misses occur frequently in air traffic control operations. One study estimated that 62% of Conflict Alerts (CAs) and 91% of Minimum Safe Altitude Warnings (MSAWs) displayed for en route aircraft, and 44% of CAs and 61% of MSAWs in the terminal environment, did not require intervention by a controller (Friedman-Berg et al., 2008). Signal performance may also depend on the specific installation at some facilities. For example, in one TRACON, the signal is paired with a specific information display system that is used only in a few airports (*e.g.*, the NAS Information Display System). At this facility, the auditory windshear/microburst alarm uses the same sound as that of the runway lights mismatch alarm, which is activated frequently. (Personal communication) At this facility, a windshear/microburst alarm also displays a table depicting the current winds at the relevant airport, while the runway light mismatch alarm flashes the light settings by the Runway Visual Range (RVR) display.

Improving the signals used by air traffic controllers may promote safe operations. A *meta*-analysis by Rein et al (2013) concluded that increased reliability was associated with improved performance. The authors found a consistent relationship between automation reliability (i.e., overall percent correct) and performance, with values greater than 67% associated with performance gains. This finding agrees with those of a prior *meta*-analysis by Wickens and Dixon (2007). A study of French air traffic controllers concluded that attentional blindness and decreased attention were significant safety concerns, and inattentional deafness affected controllers' ability to cooperate with each other. (Migliorini, Imbert, et al., 2022) Moreover, auditory attention has been associated with visual inattentional blindness (Pizzighello and Bressan, 2008). These studies further highlight the need to design signals that quickly draw controllers' attention to potential hazards without being unnecessarily distracting. Multiple signals occurring in close temporal proximity can produce a masking effect that could also impair a controller's ability to detect and identify an alarm. (Wan and Sarter, 2022) This suggests that improving the reliability of signals may therefore enhance a controller's ability to respond to a hazard.

Signal design framework

The Signal Design Framework that we developed consists of 15 alarm properties in five categories (How, What, Where, When, and Why) and is intended to comprehensively characterize an alarm in any environment. (Table 1) (Ruskin, Rice, and Ruskin, 2022) It includes quantitative and qualitative components, each of which is then incorporated into a written record that provides comprehensive, permanent documentation of the rationale for each design feature. The framework is designed to provide controllers, human factors experts, and equipment manufacturers with a common language to describe, classify, and objectively evaluate and design signals that will be used in an air traffic control facility. The framework and its associated structured interview allow air traffic controllers (or subject matter experts in other domains), human factors professionals, and system designers to objectively score a new or existing signal. Although specialized alarm taxonomies have been developed for research purposes (Bliss et al., 2014; O'Hara and Fleger, 2022), this Signal Design Framework is the first to link end-user needs to alarm design.

The framework is designed to be user-centric: A controller can describe how a particular alarm or alert should be designed, or which features work well in a previous design. To use the framework, the personnel who use equipment that generates a signal (i.e., the subject matter experts) participate in a structured interview that asks them to describe and rate each property's importance in relation to a given alarm. This information can then be used to develop a prototype for expert evaluation using the same structured interview. This process is then repeated until the alarm meets the subject matter expert's goals. The resultant prototype alarm is then tested, first in simulation then in limited real-world situations before implementation. The information generated during this process creates a permanent record that can later be referenced to understand the original intentions of the subject matter expert and the designer when a signal must be modified to account for changes to the equipment or environment.

Methods

Development of the framework

A full description of the Signal Design Framework has been published in the United States Department of Transportation's ROSA-P National Transportation Library as part of a handbook for signal design in air traffic control (Ruskin, Rice, and Ruskin, 2022). This description also includes the rationale for each of the properties and a script for a structured interview.

Study procedures

After University of Chicago IRB Designation as exempt (IRB22-1647, Nov 2022), all air traffic controllers participated in a structured interview and answered demographic questions (Appendix A) via videoconference (Zoom, San Jose, CA, USA). All interviews were transcribed to preserve anonymity of the participants. Participants first received a detailed description of an alarm that occurs commonly in the Air Traffic Control Tower and TRACON settings, the Conflict Alert. For each of the 15 taxonomy properties, participants were first given a detailed description of that property (Appendix A), then asked if they thought that was a good definition for that property. Participants were then asked to answer a series of specific structured interview questions and then to rate the importance of the property for the conflict alert alarm on a Likert scale of 1–5 (1 = not important through 5 = very important). This sequence of questions was repeated for each of the 15 properties. At the end of the structured interview, participants were asked to choose and then rank which three out of the 15 properties were most important to the design of the conflict alert. They were then asked if this 15-item framework completely characterized the alarm's properties. At the end of the structured interview, participants were asked a series of questions about the overall quality of the taxonomy and its potential for impacting aviation safety.

Table 2
Do the Framework Factors Matter for Air Traffic Control Alarms? Likert score (1 = not at all important and 5 = very important).

	Factor	Importance for the Conflict Alert (mean (SD))	Importance Overall for Air Traffic Control Alarms(mean (SD))
HOW	**Modality (Visual, auditory, tactile, olfactory)**	5 (0)	4.5 (1)
	Priority	4.75 (0.5)	4.55 (0.58)
	Saliency/Noticeability (Contrast, color, size, shape, luminance, amplitude and frequency, texture, speed/pattern)	4.55 (0.58)	4.25 (0.96)
	Disruptiveness	3.75 (0.96)	4.25 (1.5)
WHAT	**Distinguishability**	4.5 (1)	3.75 (0.96)
	Exclusivity	4.5 (1)	4.25 (0.5)
	Familiarity	4.55 (0.58)	4.75 (0.5)
	Recognizability		
	Consistency	4.75 (0.5)	3.5 (1)
	Informativeness	4.25 (0.5)	3.75 (1.89)
WHERE	**Location**	3.5 (1.91)	3.75 (0.96)
	Recipient	4.25 (0.96)	3.75 (0.96)
WHEN	**Temporality**	4.25 (0.96)	4.25 (0.96)
	Suppressibility	3 (1.41)	3 (1.41)
WHY	**Accuracy**	4.55 (0.58)	4.5 (1)
	Reliability	4.75 (0.5)	4.25 (0.96)
Overall		Fair agreement on these ratings between subjects ($\kappa = 0.266, Z = 8.028, p < 0.05$)	Fair agreement on these ratings between subjects ($\kappa = 0.243, Z = 7.785, p < 0.05$)

Statistics

Microsoft ® Excel for Mac, version 16.67 (Redmond, WA, USA) was used for statistical analysis. Fleiss' Kappa (Fleiss, 1971) was used to evaluate interrater reliability (the level of agreement among multiple observers who observe the same phenomenon).

Thematic analysis

We used the process outlined in Kiger and Varpio (2020) to perform a thematic analysis of the structured interview responses. In brief, we first familiarized ourselves with the responses, developed initial codes corresponding to specific ideas, searched for broader themes, and reviewed these themes. Data was then organized into tables with themes and subthemes where appropriate. Each table contained one theme or subtheme. We organized the data so that, within each table, each row contained a relevant action item, the corresponding taxonomy parameters, and the reasoning and examples behind the item, often using

Table 3
What to keep – Conflict Alert (CA) Alarm.

Item	Related Taxonomy Parameters	Reasoning/Example
Auditory Component [Tower and TRACON only]	**Modality Disruptiveness**	• The current auditory alarm (a pulsed tone) is helpful because it will redirect the controller's visual scan path, alert the controller to look back at the radar display, draw the attention of the supervisor and adjacent controllers, and interrupt less urgent activities.
Visual component	**Modality**	• The current visual blinking red 'CA' designation draws attention.
Volume and tone	**Saliency Disruptiveness**	• The current CA alarm tone, and beeping frequency strike a good balance to get your attention, to disrupt what you are doing but are not so distracting that you can't think. The visual alarm on the radar display is small enough that you can still see the primary targets.
Adjacent controllers seeing visual alarm	**Saliency Location**	• The field of view on the radar display is appropriate so that the controller can see adjacent airspace that is depicted on their display, including the data block (representing 1 aircraft) and the red 'CA' alarm, when indicated.
Color coded	**Saliency Consistency**	• The visual CA alarm is always red, controllers are taught that red indicates a problem.
User settings	**Consistency Saliency**	• The controller can set their own magnification, brightness, map preference, font size, and volume at their individual workstation as a 'preference set.' Always seeing these familiar display features may contribute to situation awareness and improve safety.
Position of visual alerts	**Location**	• All of the systems (the STARS display, IDS, ASDE-X, and the paper flight progress strips) that controllers need are usually within their field of view. [Tower environment]
Different alarms for different events	**Distinguishability**	• Controllers are intuitively familiar with alarm sounds. "For the CA there is already a built-in reflex that I know what the tone means even if it is not loud – I already have an elevated sense of alertness to it in my brain 'this is bad'. When you hear the low altitude alert, you perk up but not nearly to the extent you would with a CA."Ground radar alarms (ASDE-X) and CA alarms are from separate systems, which increases safety because different actions are needed for each alarm. [Tower environment]
Timing	**Temporality**	• The CA sounds immediately when the hazard is detected (set for a certain number of miles) and continues until the hazard is resolved or the controller silences the alarm when a loss of separation is predicted. (If separation has been lost, the CA cannot be suppressed.)
Reliability	**Reliability**	• The current CA alarm is very reliable and is configured to ensure that the number of missed alerts is at the absolute minimum. "Can't afford for it to not go off. Having a miss would be the worst thing."

Legend: CA = Conflict Alert.
TRACON = Terminal Radar Approach Control Facilities.
STARS = Standard Terminal Automation Replacement System (workstation in TRACONs and towers). IDS = Information Display System. ASDE-X = Airport Surface Detection System, Model X.

quoted or paraphrased responses from the structured interview itself.

Results

All four Air Traffic Controllers (all men) who were invited agreed to participate, average years as a Controller was 21.1 (SD 7.4). One worked in the tower setting, 1 in the TRACON and 2 in combined tower/TRACON settings. Two controllers also had experience with alarms and automated systems as general aviation pilots. During the structured interview, all controllers agreed that the definition of each individual property was an accurate definition ($\kappa = 1$). Participants also agreed on a Likert scale (1 = not at all important and 5 = very important) that having an alarm for a Conflict Alert in the ATC environment was important, (5 (0)) (mean (SD)). The Likert scores were analyzed for the importance of each individual property for the Conflict Alert in the air traffic control setting and for air traffic control overall (Table 2).

At the end of the structured interview, each participant was asked to choose the three most important properties for the conflict alert alarm out of the 15 taxonomy properties (Table 1). This generated a list of twelve properties from the four participants. 'Reliability' was chosen by three participants, 'Accuracy' was chosen by two participants, 'Consistency' was chosen by two participants, 'Distinguishability' was chosen by two participants, and 'Modality,' 'Priority,' 'Saliency,' and 'Informativeness' were each chosen once.

All participants agreed that the taxonomy captured all of the important characteristics of an alarm ($\kappa = 1$) and that no gaps or failures existed in the alarm framework ($\kappa = 1$). They also agreed on a Likert scale (1 = not at all; 5 = to a great extent) that the framework was easy to understand (4.5 (0.58)), that the structured interview was easy to understand (4.5 (0.58)), and that applying the framework to alarm design and revision would improve alarm ease of use (5 (0)), reduce confusion (4.5 (1)), and improve overall safety (4.75 (0.5)) (mean (SD)).

The structured interview elicited opinions about the conflict alert in the Air Traffic Control environment. Our thematic analysis revealed the broad themes of 'What to Keep (Table 3),' 'What to Consider Changing (Table 4),' What to Avoid (Table 5),' and 'What Was Controversial' (Table 6). Table 4 was further divided into the subthemes of 'Possible with Current Technology' (Table 4a) 'Environment/Systems Issues' (Table 4b), 'Education and Customization' (Table 4c) and 'Requires New Technology or Equipment' (Table 4d).

Discussion

In this study, we have validated a novel structured framework for signal design by asking air traffic controllers to describe characteristics of the Conflict Alert. The structured interviews identified characteristics which were then classified using a thematic analysis into four categories: 'What to Keep,' 'What to Consider Changing,' What to Avoid,' and 'What

Table 4a
What to consider changing: possible with current technology – Conflict Alert (CA) Alarm Characteristics.

Item	Taxonomy Parameters	Reasoning/Example
Add additional modalities or features for more important alarms	**Modality** **Priority** **Saliency**	Currently the visual indicator is a red 'CA' that flashes on top of the data block for an individual aircraft. Could add:White circles around the aircraft at risk (or other indicators such as a box around the call sign which turns red when the aircraft are about to lose separation) .Automatic appearance of R lines and "bats," graphics that show an aircraft's projected direction.An indicator of the specific distance or time remaining before the aircraft lose separation. An indicator of if the alert is for a projected trajectory collision versus close proximity of two aircraft. This suggests that controllers might benefit from knowing the specific algorithm that triggered the CA.An indicator of ways to resolve the CA, corresponding to the directions that the flight crew already receive from TCAS. For example, a down arrow next to the data block for the aircraft that is being told to descend.
Volume of alarm should be based on its importance	**Saliency** **Priority** **Disruptiveness**	• Currently, the CA and MSAW [low altitude] alerts are similar. A CA requires faster action and requires more steps of higher complexity; therefore the CA alarm should be a higher priority signal than the MSAW. Restrict that volume could not be lowered beyond a certain point – want disruptiveness to still be there.
Alarm should change as hazard becomes more urgent	**Modality** **Temporality** **Informativeness**	• The CA alarm should be "graduated to get your attention more as it becomes more urgent." For example, if the targets were several minutes apart on a conflict course, there would an initial alert, when closer the alert would increase in salience, and when very close the alert would further increase in disruptiveness. [Note: this is currently implemented in ARTCC for en route environments as a conflict probe, which gives up to 40 min' warning for airspace violations and 20 min of warning for aircraft-to-aircraft conflicts. The en route conflict probe is displayed on a separate monitor and is differentiated as green/yellow/red.]
Want distinct signals for specific events	**Exclusivity** **Informativeness**	• The CA alarm should be "completely different [from other alarms]. The CA is currently acoustically similar to the low altitude (MSAW) alarm. If the CA is a high pitch, could have the low altitude alarm in the bass scale, also vary speed." It is difficult to differentiate what is alarming if multiple conflict alerts occur simultaneously, or if multiple other alarms are occurring at the same time. Alarms that are more distinct would help with this problem.

Legend: CA = Conflict Alert.
TCAS = Terminal collision avoidance system, currently used on aircraft.
MSAW = Minimum Safe Altitude Warning.
ARTCC = Air Route Traffic Control Center.

Table 4b
What to consider changing: possible with current technology – Environment/Systems Issues.

Item	Related Taxonomy Parameters	Reasoning/Example
Extensive re-training would be needed for a new alarm	**Familiarity**	• The meaning of the current alarm and the actions required become ingrained over time. A new alarm would take time and effort to learn.
Differentiate alarms	**Distinguishability**	• Signals should be very easy to recognize and to discriminate from one another. "If there is any kind of confusion about what the alarm is you have lost the meaning of the alarm."
Add alarms	**All parameters**	• Would help to add a ground collision alarm (especially for blind corners).
Keep controller engaged	**Saliency**	• Signals should help the controller to regain situation awareness quickly when a loss of separation is imminent. "The majority of operational errors happen during low workload periods. The controller is less engaged, could be having a sidebar conversation. During a busy arrival period, there are fewer errors."

Was Controversial' (Tables 3-5). We also calculated interrater reliability, which was 'fair' for the Likert scores given for the importance of each of the 15 properties. Participants stated that signals should enhance situation awareness when a loss of separation is imminent, and offered several suggestions that would accomplish that goal. Overall, controllers stated that they need their signals to immediately communicate a hazard without causing confusion. All participants noted that the CA has similar acoustics to other signals, which could lead to confusion.

Participants suggested that the Conflict Alert could be "graduated" to become more salient as it becomes more urgent. The structured interviews about the CA also revealed that the controllers wanted an indicator of the time and distance available to resolve the potential conflict but wanted that indicator to fit into their existing workflow. Participants agreed that a new "time-to-go" bar would be too distracting. They suggested using the Terminal Proximity Alert (a wedge-shaped graphic that shows the minimum allowable separation between two aircraft) to indicate time and distance for aircraft that trigger a Conflict Alert. These tools are already used to facilitate separation of aircraft on the STARS workstation.

Signals are designed to attract the controllers' attention, causing

Table 4c
What to consider changing: possible with current technology – Education and Customization.

Item	Related Taxonomy Parameters	Reasoning/Example
Changes to alarms must be incremental and related to what is familiar from the current system to avoid confusion	**Familiarity**	• Controllers instantly recognize current alarms. "Controller base has a wide variety of people – some can adapt quickly, and some do need more time to adjust to changes."
Training on distraction management Modification to allow the system to increase the volume of signals as the ambient noise level increases	**Saliency** **Disruptiveness**	• "The tower can be a noisy environment, with conversations between co-workers or other sounds in tower such as cleaners vacuuming the carpet during the midnight shift. If you are by yourself and dealing with an emergency aircraft and drawn in, that takes away from hearing the CA going off." "Once you become experienced, it is easy to think you can carry on a conversation and watch the scope. But [everything] is in the details – even missing a small detail could result in loss of life."

Legend: CA = Conflict Alert.

them to interrupt their current task and focus their attention on the aircraft that triggered the alarm. An excessive number of false alarms can, however, cause alarm fatigue. (Breznitz, 1984; Ruskin and Hueske-Kraus, 2015 Dec; Ruskin et al., 2021) This may lead to a controller ignoring or delaying a response to a signal that indicates a safety–critical situation. (Ruskin et al., 2021) Frequent disruptions increase controller workload and may decrease overall performance and impair prospective memory. (Boag et al., 2019; Strickland et al., 2019 Dec) Nuisance alerts can also reduce controller trust in automation. The framework validated in this paper allows controllers to specify the level of disruptiveness that a signal is designed to produce and the level of perceived accuracy and reliability that will help them to safely separate aircraft. During the structured interviews, all controllers stated that they would be willing to accept a high rate of false alarms to avoid a potential miss. Although the precise rate of false alarms that controllers are willing to accept is unknown, Wickens et al (2009) found that a false alarm rate of 45% did not affect controllers' responses to conflict alerts. Future studies should seek to quantify the rate of false alarms that would be acceptable for a given hazard.

The structured interview format used by the framework encouraged controllers to think about alarms systematically, allowing them to develop innovative solutions to the problems that they identified. Many of the design changes suggested by the controllers are consistent with findings in other studies of signal design, such as making auditory signals easily distinguishable by varying pitch, duty cycle, or other features (Edworthy et al., 2011). Participants independently remarked that they had not thought about other ideas, such as automatically displaying the distance between the aircraft triggering the CA, until participating in the structured interview. This suggests that using the signal design framework may facilitate the design of more effective signals that better meet the needs of the people who rely on them.

Table 4d
What to consider changing: will need the development of new technology or addition of new equipment.

Item	Related Taxonomy Parameters	Reasoning/Example
Increase accuracy to avoid alarm fatigue Provide controllers with a way to indicate that visual separation is applied. The system could then assume that visual separation is applied and suppress the CA for that aircraft pair	**Accuracy** **Reliability**	• The current auditory alarm is good – but the problem is that when a controller hears the alarm, they then must take the extra step to decide whether a hazard really exists. False alarms draw a controller's attention from something that may be more urgent.Formation flights will signal a CA if more than one aircraft has their transponder on. For example, helicopters that are working in a particular area, (e.g., crime scene, news scene) know about each other. The CA will still be activated even though everyone knows they are circling each other over the scene."When [the alarm] goes off all the time, it is easy to gloss over it (e.g., if it goes off more than once in a 5-minute period) ."
Directional speakers	**Saliency**	• A signal can be distracting to a controller who is working at the station next to the one generating the CA. "You could be hearing an alarm that sounds like it is yours." A directional speaker might focus the alarm "right down on the controller who is impacted."
Notifications should be situational	**Accuracy** **Reliability**	• During conditions of low visibility at night, notifications about malfunctioning center line lighting are essential. During unlimited visibility during daytime operations, this notification is unneeded.Increase alerts at 2 AM when alertness is down (should be user-selected option) .
Additional modalities	**Modality**	• Tactile alerts for an "extreme situation like a midnight shift – like a wristband that would increase pressure if I fell asleep – would have to be very dependent on a specific modality needed for a specific circumstance."
Modify alarm for environmental factors	**Distinguishability** **Saliency**	• Alarm volume can increase as the ambient noise level increases. (e.g., if cleaners vacuuming during midnight shift.)
Additional display	**Modality**	• In an air traffic control tower, a "heads up display on the glass around the work area [would allow a

(continued on next page)

Table 4d (*continued*)

Item	Related Taxonomy Parameters	Reasoning/Example
		controller] to look out the window and at information projected on the glass. The CA could display in red on the glass in the corner. To tie into the ASDE-X situation could put a red line on the glass outlining where on the runway where a potential problem is occurring – a virtual presentation – if you are looking out the window, says that something bad is happening." [tower]
Add TCAS features	**Informativeness**	• "Right now, [the display is] pretty simple. It puts a CA in the data blocks of the 2 aircraft in conflict. The controller has to evaluate the raw data, [including] aircraft speed and how to take action to address the conflict. If there were TCAS type features within a CA (for example, the computer might recommend to 'climb this airplane, descend this airplane), I don't know if helpful or not. TCAS might be helpful if it was built into our system and gives a recommendation on how to fix the conflict."

Legend: CA = Conflict Alert. TCAS = Terminal collision avoidance system, currently used on aircraft. ASDE-X = (Airport Surface Detection System, Model X)

Table 5
What to avoid – Conflict Alert Alarm.

Item	Related Taxonomy Parameters	Reasoning/Example
Over-alerting	**Disruptiveness** **Saliency** **Modality**	• "Too many modalities would be distracting." Controllers do not want a signal that is going to demand their full attention and distract them from other responsibilities. Too much flashing is distracting.

Limitations

This study has several limitations. Firstly, the number of participants was small because participants were limited to air traffic controllers who already participate in human factors studies as part of their job responsibilities. We report a mean and standard deviation as part of our results, but the interpretation of these values is limited because of the sample size. Although a larger study population would have been desirable, we were able to achieve statistical significance and fair inter-rater reliability with the controllers that we were able to recruit. We also observed some overlap between controller responses in the thematic analysis, further suggesting that our sample size was sufficient to produce reliable data. Secondly, the controllers that were interviewed worked in both the TRACON and air traffic control towers. The differences in how signals are used in these two environments may have decreased the level of inter-rater reliability. The Conflict Alert is used in both environments, however, and the diversity of opinions between the two groups of controllers led to some creative ideas for improving the signal. The variation in results that we observed in this study may increase when a larger group is studied. This highlights the need to carefully consider the rate of similar responses to each question using a thematic analysis. It is possible, however, that the range of responses could lead to a result that does not work well for some end-users. This emphasizes the need for multiple rounds of iterative design and testing, which is one of the design features built into the framework. Lastly, we tested the framework with only one type of alarm that that was already familiar to the participants. Additional studies are necessary to validate this framework for other types of signals.

Future Research

The innovative solutions developed by the controllers themselves highlight the utility of the Signal Design Framework. Although this study has validated the Signal Design Framework for evaluating an existing signal, additional studies could validate the use of the Framework for designing a new signal. Controllers could be interviewed about a signal that is not currently in use or that needs to be modified. After a prototype signal is designed, the participants would then be asked to evaluate it either in an informal conference room setting or in an air traffic control simulator.

As part of this project, researchers visited several ATC facilities, including a TRACON, an Air Route Traffic Control Center (ARTCC), and an air traffic control tower for a busy Class Bravo airport, where controllers' interactions with signals were observed during live operations. Air traffic controllers and managers were also interviewed about their experiences with signals. One interesting finding was that some controllers found it hard to describe the sound of a specific signal (*e.g.*, MSAW) in a conference room while they were away from their equipment, but they immediately identified it when it occurred during live operations. Additional studies could explore how this finding might affect the design of auditory signals in the TRACON or tower

Table 6
What was controversial – some wanted to keep/add, some wanted to change/avoid: Conflict Alert (CA) alarm.

Item	Related Taxonomy Parameters	Pro Reasoning/Example	Con Reasoning/Example
Verbal component	**Modality**	• A voice that said 'conflict alert' could be beneficial.	• "You could also argue that [a vocal alarm] could be too much."
Tactile Component	**Modality**	• Tactile signals could help when multiple other alarms are activated, or conversely, during low workload periods.	• Tactile signals could be unnecessarily distracting. "If something starts buzzing, it would draw your attention away from what is going on and increase your stress in a highly stressful situation. It would also be startling."
Multiple keystrokes to suppress (CA+, slew, click on the aircraft)	**Suppressibility**	• Difficult/unlikely that would be suppressed accidentally.	• Cumbersome to suppress. Suppressing the CA has the advantage of getting "rid of that high level distraction after you have resolved that issue."

Legend: CA = Conflict Alert.

environment.

Signals designed by the end users may be more likely to be accepted by the community, although this remains a topic for further study. Future research studies may also determine whether signal characteristics that have been described by air traffic controllers are effective in other domains, such as the terminal collision avoidance system (TCAS) alert used on aircraft.

Conclusions

This study is the first validation of a signal design framework for air traffic control. The framework includes quantitative and qualitative components, each of which is incorporated into a written record that provides comprehensive, permanent documentation of the rationale for each design feature. Objective answers to structured interview questions achieved fair inter-rater reliability, suggesting that the framework provides consistent results. The structured interview encouraged controllers to think about their signals in an organized fashion and helped them to develop novel solutions that could potentially improve the conflict alert in the Air Traffic Control environment.

Contributions: KJR and ACR designed the study, analyzed the data, and wrote and edited the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank the members of the Federal Aviation Administration's Air Traffic Terminal Computer Human Interface Team for their assistance with the research and thoughtful review of the manuscript. The authors also wish to thank Ben Willems, Human Factors Lead of the FAA's Planning and Analysis Team for his review of the manuscript and guidance throughout this project. The authors also thank Karl Kaufmann of the FAA's NextGen Human Factors Division for his review of the manuscript and assistance with this project.

This work was funded by a Federal Aviation Administration Cooperative Research Agreement.

Funding: Keith J Ruskin is funded by Federal Aviation Administration Cooperative Research Agreement 692 M151940006

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2023.100965.

References

Allendoerfer, K.R., Pai, S., Friedman-Berg, F.J., 2008. The Complexity of Signal Detection in Air Traffic Control Alert Situations. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 52 (1), 54–58. https://doi.org/10.1177/154193120805200113.

Altmann, E.M., Trafton, J.G., 2002 Jan. Memory for goals: An activation-based model. Cognitive science. 26 (1), 39–83.

Bliss, J.P., Dunn, M.C., 2000. Behavioural implications of alarm mistrust as a function of task workload. Journal of Ergonomics 43 (9), 1283–1300. https://doi.org/10.1080/001401300421743.

Bliss, J.P., Gilson, R.D., Deaton, J.E., 1995. Human probability matching behaviour in response to alarms of varying reliability. Ergonomics 38 (11), 2300–2312. https://doi.org/10.1080/00140139508925269.

Bliss, J.P., Rice, S., Hunt, G., Blair, K., 2014. What are close calls? A proposed taxonomy to inform risk communication research. Safety Science. 61, 21–28. https://doi.org/10.1016/j.ssci.2013.07.010.

Boag, R.J., Strickland, L., Loft, S., Heathcote, A., 2019 Oct. Strategic attention and decision control support prospective memory in a complex dual-task environment. Cognition. 191, 103974 https://doi.org/10.1016/j.cognition.2019.05.011. Epub 2019 Jun 21.

Breznitz, S., 1984. *Cry wolf: The psychology of false alarms*. Psychology Press. Lawrence Erlbaum Associates, Hillsdale, NJ.

Edworthy, J., Hellier, E., Titchener, K., Naweed, A., Roels, R., 2011 Mar 1. Heterogeneity in auditory alarm sets makes them easier to learn. International Journal of Industrial Ergonomics. 41 (2), 136–146. https://doi.org/10.1016/j.ergon.2010.12.004.

Fleiss, J.L., 1971 Nov. Measuring nominal scale agreement among many raters. Psychological bulletin. 76 (5), 378.

Friedman-Berg F, Allendoerfer K, Pai S. Nuisance Alerts in Operational ATC Environments: Classification and Frequencies. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 2008;52(1):104-108. 10.1177/154193120805200123.

Green, D.M., Swets, J.A., 1966. Signal detection theory and psychophysics. John Wiley.

Kiger ME, Varpio L. Thematic analysis of qualitative data: AMEE Guide No. 131. Medical Teacher. 2020;42(8):846-54.

Migliorini, Y., Imbert, J.P., Roy, R.N., Lafont, A., Dehais, F., 2022 Mar 8. Degraded states of engagement in air traffic control. Safety. 8 (1), 19. https://doi.org/10.3390/safety8010019.

Newman RA, Allendoerfer, K. Assessment of current and proposed audio alarms in terminal air traffic control. (DOT/FAA/CT-TN00/21) URL: https://rosap.ntl.bts.gov/view/dot/16679 (Accessed 10 March 2021).

O'Hara JM, Fleger, S. Human-System Interface Design Review Guidelines. United States Nuclear Regulatory Commission. NUREG-0700. Revision 3. Accessed From: https://www.nrc.gov/docs/ML2016/ML20162A214.pdf Accessed On: 30 June 2022.

Pizzighello, S., Bressan, P., 2008. Auditory attention causes visual inattentional blindness. Perception. 37 (6), 859–866. https://doi.org/10.1068/p5723.

Rein, J.R., Masalonis, A.J., Messina, J., Willems, B., 2013. Meta-analysis of the Effect of Imperfect Alert Automation on System Performance. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 57 (1), 280–284. https://doi.org/10.1177/1541931213571062.

Rice, S., 2009 Jul. Examining single- and multiple-process theories of trust in automation. J Gen Psychol. 136 (3), 303–319. https://doi.org/10.3200/GENP.136.3.303-322.

Rovira, E., Parasuraman, R., 2010 Jun. Transitioning to future air traffic management: effects of imperfect automation on controller attention and performance. Hum Factors. 52 (3), 411–425. https://doi.org/10.1177/0018720810375692.

Ruskin, K.J., Hueske-Kraus, D., 2015 Dec. Alarm fatigue: impacts on patient safety. Curr Opin Anaesthesiol. 28 (6), 685–690. https://doi.org/10.1097/ACO.0000000000000260.

Ruskin, K.J., Corvin, C., Rice, S.C., Winter, S.R., 2020 Sep. Autopilots in the Operating Room: Safe Use of Automated Medical Technology. Anesthesiology. 133 (3), 653–665. https://doi.org/10.1097/ALN.0000000000003385.

Ruskin, K.J., Corvin, C., Rice, S., Richards, G., Winter, S.R., Ruskin, A.C., 2021. Alarms, alerts, and warnings in air traffic control: An analysis of reports from the Aviation Safety Reporting System. Transportation Research Interdisciplinary Perspectives. 12, 100502 https://doi.org/10.1016/j.trip.2021.100502.

Ruskin KJ, Rice SC, Ruskin A. (2022) A Handbook for Signal Design: Alarms, Alerts, and Warnings in Air Traffic Control. URL : https://rosap.ntl.bts.gov/view/dot/65620. (Accessed 30 April 2023).

Strickland, L., Elliott, D., Wilson, M.D., Loft, S., Neal, A., Heathcote, A., 2019 Dec. Prospective memory in the red zone: Cognitive control and capacity sharing in a complex, multi-stimulus task. Journal of Experimental Psychology: Applied 25 (4), 695–715. https://doi.org/10.1037/xap0000224.

Wan Y, Sarter N. Attention Limitations in the Detection and Identification of Alarms in Close Temporal Proximity. *Human Factors*. 2022 Jan 10:187208211063991. 10.1177/00187208211063991.

Wickens, C.D., Dixon, S.R., 2007. The benefits of imperfect diagnostic automation: A synthesis of the literature. Theoretical Issues in Ergonomics Science 8 (3), 201–212.

Wickens, C.D., Rice, S., Keller, D., Hutchins, S., Hughes, J., Clayton, K., 2009 Aug. False alerts in air traffic control conflict alerting system: is there a "cry wolf" effect? Hum Factors. 51 (4), 446–462. https://doi.org/10.1177/0018720809344720.