Guidelines for NextGen Auditory Displays

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The Next-Generation Air Transportation System (NextGen) represents a major reconfiguration of the National Airspace System (NAS) within the United States by the Federal Aviation Administration (FAA) over the coming years. This document reviews auditory display design approaches and requirements for NextGen flight decks and air traffic control workstations. While some aspects of auditory alert design are well understood, the overall design of auditory displays must be considered from the perspective of the totality of auditory input to the listener, including speech, alerting signals, and noise. Recommendations for best practices and future research needs specific to NextGen auditory displays are given.

0 INTRODUCTION

The Next-Generation Air Transportation System (NextGen) represents a major reconfiguration of the National Airspace System (NAS) within the United States by the Federal Aviation Administration (FAA) over the coming years. The NextGen mid-term implementation goal of 2018 includes increased data communication between users, controllers, and systems for the goal of Integrated Air Traffic Management, which "leverages new technologies and collaboration with the users" to achieve efficiency goals "integrated across time and air traffic control domains" [1].

NextGen involves concepts of *free flight,* which places more responsibility on flight crews to maintain safe separation from other aircraft, and shifts aircraft separation responsibility from controllers to flight crews to create a *shared separation* authority environment. There is also an increased dependence on *automation* to improve safety through enhanced conflict detection and resolution capabilities, increased flexibility to manage flight operations, greater predictability within the NAS, and better decision-making tools for air traffic controllers and pilots. As a result, there will be a significant increase in the flow of critical information from automated systems to flight deck personnel and air traffic controllers. Innovations in auditory displays can meet the challenges of the increased flow of information in the NextGen environment, to maintain coordination, communication, situational awareness, and common understanding throughout the entire system.

For air traffic control centers, there is general agreement on a critical need for integrated displays of information to replace the current plethora of displays that have assimilated over time. In assessing current control towers, one FAA report states bluntly,

> No specific design guidance regarding the human factors characteristics of tower displays or the arrangement of displays within the tower cabs is readily available . . . [they] evolved as funding allowed for equipage and as traffic demand grew. As a result, most tower cabs have a piecemeal design that placed equipment where there was available space. This process has been further exacerbated as additional equipment and displays have been added to the tower cabs over time . . . there is not a clear understanding of tower controller information requirements [2].

These problems extend to terminal and area control centers as well. Interim solutions include the "Tower Flight Data Management" (TFDM) approach to integration. This uses a common display platform to integrate a diverse source of information streams, including ERAM (En Route Automation Modernization), FDM (Flight Data Management), ASDE (Surface traffic management), SWIM (System Wide information Management), and STBO (Surface Trajectory Based Operations).

The increased demands of NexGen requires a fresh evaluation of how to utilize auditory feedback that originate from automation for "normal" operations (e.g., successful initiation) in addition to a caution-warning system for off-nominal situations. Auditory alerts within the context of FAA operations have previously received considerable attention, particularly from the work of Ahlstrom [3, 4, 5, 6]. But in addition to alerts, the multiple layers of automation present in NextGen systems should subtly yet effectively make their users aware of automation status. It is obvious that addressing these needs via a completely visual-based system is unworkable due to the already dense amount of text and visual symbology. As the information rate and density of communications increase, the potential for multi-modal presentation technologies that can communicate via

Fig. 1. Weather information display and sound source

Fig. 2. Telephone handsets in the tower

visual, auditory, and even tactile-haptic sensation becomes more relevant.

From the standpoint of audio communications engineering, an integrated approach is advocated in consideration of the entirety of acoustic information that arrives at the ears of NextGen pilots and controllers. The control of this entire "acoustic scene" is via the design of an integrated *auditory display*—including radio communications, synthetic speech, caution and warning, and confirmatory audio feedback. As with the visual display strategies for future towers, successful design of an auditory display will depend on integration and consolidation of auditory alerts as well as all types of acoustic signals. It also requires careful assessment of concurrent undesired or uncontrolled sound, i.e., "noise," that arrives simultaneously at the ears. The success of an auditory display in conveying a message involves consideration of the influence of each stage in a 'source-medium-receiver' model of communication. In other words, information from the auditory display (the source) must be evaluated in terms of the medium (communication equipment within an acoustic environment: the control room) and the end user (perception and cognition).

1 CURRENT CONTROL TOWER AUDIO DISPLAYS

The following illustrates some common problems in current air traffic control rooms that would be mitigated via an integrated auditory display. Fig. 1 shows two photos of a weather information display. The display itself has a small loudspeaker that conveys an alert under certain conditions (arrow, left picture); note the hand microphone in close proximity. Located behind this display is an additional loudspeaker (right arrow) whose exact function was unknown to the interviewed controller. The location of this loudspeaker to the rear of the display, behind the console and in front of the reflective window is non-optimal for acoustical transmission. Furthermore, its signal would be co-located directionally with the weather display signal. Finally, the microphone's close proximity to the loudspeakers is non-optimal. Each system's alert comes from its specific hardware loudspeaker. This exemplifies the problem of multiple, diverse auditory alerts that are not designed in consideration of optimal or effective communication to the listener.

Fig. 2 represents the pervasive use of telephone handsets in the controller's working environment. The handsets on the right picture date from 1960s wall mounted designs; note the thumb-control volume wheel on the rightmost telephone (right arrow), presumably provided so that levels can be adjusted upward during a time of acoustic calamity (the design originally was intended for the hard-of-hearing). The handset on the left side, hooked over the top of the console as opposed to in a cradle, interfaces with the push-button interface, which also includes a loudspeaker (left arrows). A redundant handset interface is provided above, presumably for two persons to be listening simultaneously, over earpiece or loudspeaker, to two different channels. The ability for controllers to control levels, select channels, and communicate during specific scenarios is likely a function of the human adapting to the design, rather than from a careful consideration of human factors influencing the design. Such handsets are rapidly disappearing in everyday use in favor of hands-free headsets in the commercial world, including binaural "on-the-ear" headsets.

Significantly, controllers have individual volume adjustments available for alerts generated by different displays. Rather than the system determining the appropriate level of the alerts, and delivering the alert within a common framework, the user must tailor the levels for each type of display. One type of display has separate volume controls for "chime" and "speaker" with an indicator light to signal if alerts have been disabled ("tone removed"). The adjustments for another display allow the alarm and alerts to be separately switched on or off by means of the toggle switches and then their individual volume levels adjusted by the knobs.

The complexity of the interaction required by these systems to make an alert audible is representative of bad design, since it would be an easy matter to make alerts or alarms inaudible or too loud, and quite difficult to set to the correct level. Furthermore, multiple false alarms generated by a system will cause a user to attenuate or shut off the audio system. For example, the Minimum Safe Altitude Warning system (MSAW) can generate warning tones even when a controller intentionally infringed the altitude temporarily, and they offer no information to assist the problem solving process. "Currently, the separation loss audio alarms . . . are single condition alarms. That is, they offer no indication of the severity of the loss of separation. The alarm is the same if separation is 2 miles or 1/2 mile. If [air traffic control] issues instructions to an aircraft to correct the loss of separation but the problem continues or becomes worse, there is no specific indication of the increasing severity of the problem provided by the audio system" [7].

Air traffic controllers typically use "in-ear" single-channel headsets similar to those used in some aircraft; the origin of these headsets can be seen in U.S. Patent 3,184,556 "Miniature headset-microphone adapted for use with a mask," filed in 1961 by Wallace Larkin. One ear is "plugged" while the other ear is exposed to background noise or for spoken communication. The sound quality of these devices is influenced by the use of microphone and earpiece "tubes" that are tuned to compensate for the frequency response deficiencies of the miniaturized components. Using a single ear over the course of a career with such a headset may result in temporary or permanent unilateral threshold shifts since the level at the ear is dependent on the user control. Far preferable would be the use of a contemporary "on-the-ear" (supra-aural) headset covering either or both ears, with a flexible electret microphone boom. Such designs allow face-face communication to occur without the use of an intercom, while monitoring signals delivered to the headset, including binaural ("spatial") displays of auditory information. Modern headsets such as these can offer an extended frequency range, are more comfortable, and are adjustable over the course of the working day to the ears based on preference. The integrated auditory display concept of controlling signals that reach the ear by *design* are enabled by considering modern transducers such as these.

2 PRINCIPLES FOR AUDITORY DISPLAY DESIGN

The overall considerations for the design of an auditory display and the alerts it contains are consistent with general principles of good human factors engineering for high-stress human-machine interfaces (e.g., [6, 8, 9]) as well as principles of good user design in general.

Don Norman's influential book *The Design of Everyday Things* [10] highlighted the benefits of "user-centered design" as a first consideration over aesthetics or other factors. Norman's concept of *affordances* is introduced as an explicit, perceivable conceptual model for the basis of an understandable, coherent design, making "visible" the range and limits of its engendered activities. It is related to the well-known concept of forming a *mental model* of the world that influences behavior and aids in problem solving. In effect, an auditory display contains means of communicating the status of an outside world of machines and automation. A good auditory display design should allow understanding of this complexity via a mental model that is easily and consistently ascertainable among a group of users. Such a philosophy can be applied not only to the auditory display as a whole, but also to elements of the auditory display. These elements might include, as the result of an iterative design process, a specification of different voices so that different machine functions are associated with an easily recognized human-like "identity,"[1] or auditory alerts designed for ease of discrimination.

The industrial designer Dieter Rams is well known for articulating his "ten principles of good design" [11] of which four principles are most applicable to the design of auditory alerts: [2]

Good design makes a product useful.
Good design makes a product understandable.
Good design is unobtrusive.
Good design is as little design as possible.

These four principles are mirrored in several requirements and best practices for the design of auditory displays. Note that the "product" described in the first two principles is not the alert or other single element of the auditory display itself, but rather the complex world of the airspace operations represented by the NextGen automation system, for which the controller must create a mental model and access information in a prescribed manner. Most applicable to good alert design are the principles of "unobtrusive" and "as little design as possible." The opposite condition of unobtrusiveness is *nuisance,* which for alerts can create not only a disturbing but also unsafe condition when alerts are ignored, shut down, or regarded as false. Furthermore, the conventional wisdom for the design of auditory alerts converges toward using a *minimal* approach, where both the quantity and frequency of auditory alerts is minimized.

The acoustic environment of the controller's environment must be considered in its entirety, for both undesirable sounds (e.g., reverberation; acoustic intrusion from other persons) and the desired sounds that are communicated by the display. These desired sounds include radio communications, tones, and (perhaps) synthetic speech generated by the caution and warning system. Equally as important for consideration are so-called "innocuous sounds" that help communicate "normal operation": for example, a constant "purring" noise from a display that is recognized by experience as "normal" or expected, versus sounds that result from off-nominal conditions. These sounds can be useful, yet can also act to occlude, or mask, other layers of information.

For complex human-computer interaction, auditory display design may require audio feedback to a user that a specific operation has been successfully accomplished. This type of feedback is not properly an alert but still must be considered in the larger design of the auditory display. For instance, in a Route Assessment Tool (RAT) being developed for NextGen flight deck navigation displays, two separate manual operations yielded an "armed" and "triggered" condition [12]. It was found that separate confirmatory sounds enabled participants to more easily distinguish

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[1] One operations center uses the voices of cartoon characters for alerts (including Tweety Bird and Yosemite Sam) not only to draw attention, but also for discrimination between systems (personal communication, Greg Dyer).

[2] The other six principles articulated by Rams are: "Good design is innovative. Good design is aesthetic. Good design is honest. Good design is long-lasting. Good design is thorough down to the last detail. Good design is environmentally friendly."

between these two normal conditions than when the sounds were not present. Without this type of auditory feedback, pilots often forgot to check visually if the “armed” condition was satisfied, causing an execution error in the subsequent “triggering” operation. Another example is the use of auditory cues for touch display virtual switches, familiar in daily life from ATM machines and present in some PDAs and cellular telephones. The use of auditory information to confirm a finger action when visual attention is focused elsewhere is another example of a “subtle alert” that is inherently useful if designed correctly in accordance with the principles outlined in this document.

The flow of information from an auditory display can be considered as a *narrative* of causal events that a controller qualitatively evaluates as a gestalt; a set of events that are continually evaluated in terms of their “significance,” or *urgency* to a listener and then associated with a specific *action* in response. Examples: Does this set of sounds indicate that there is a possible emergency? Or does it indicate normal operation? Is this a random pattern of sounds that can be ignored? What must I do in response to this alert? When must I attend to it? These are questions that can be attended to quickly and subconsciously by a controller, via continuous analysis of the narrative flow of acoustic information within the overall auditory scene. In off-nominal situations that could potentially be catastrophic, the ability to integrate information from multiple (possibly multi-modal) sources of information and then analyze patterns in search of a solution can be critical. This involves an assessment of how listeners act upon multiple *auditory* s*treams* of information. An auditory stream is defined as a source of auditory information originating from a single source, used in the larger context of the cognitive segregation of multiple streams, known as *auditory scene analysis* [13].

3 CONTROL ROOM AURAL TAXONOMY

It is possible to develop a simple “aural taxonomy” of significant sounds received by a controller or pilot in terms of acoustic descriptors. For example, a listing might be as follows.

Noise Sources (within the acoustic environment):

- temporally constant, flat spectrum (air handling system; computer fans)
- temporally variable, flat spectrum (rain)
- tonal noise (obtrusive telephone ringing)
- impulsive or intermittent sounds (door slam)

Signal Sources (within the auditory display):

- mechanical feedback (switch sounds)
- radio communications (speech)
- intra-office “face-face” communications
- caution-warning system

The elements of this taxonomy might be viewed as a classic signal-to-noise ratio (SNR) calculation problem where the “signal intelligibility,” defined as a percentage of messages successfully communicated, is predicted from the SNR in a series of frequency bands. We can extend this to a concept of a *high-quality auditory display* by considering at each moment in time the number of signals to be heard; a pre-assigned relative importance to each signal; and its signal-to-noise ratio. Quality, Q, can be expressed as a summation of signal elements, x_i, each multiplied by a “coefficient of importance,” k_i, as follows:

$$Q = \frac{1}{n}\sum_{i=1}^{n} k_i\, x_i \tag{1}$$

where k_i depends on the criticality of detection of the particular signal at any moment. With increasing number of alerts, n, the competition for signal detection of any particular alert increases, thereby reducing quality as a function of $1/n$, assuming detection of all signals to be equally important. In practice, alerts are prioritized (a “fire warning” alert is more important than a “new data link message” alert).

To increase the accuracy with reference to the background noise environment, the temporal profile of each signal element’s spectral content must be weighted relative to the spectral content of the background noise. The weighting can be considered as an average within each of a series of time windows, where the length of the window is based on perceptual integration (e.g., $t = 125$ ms). For the ith signal, the ensemble average of the signal-to-noise ratio is

$$SNR_{average}(x_i) = \frac{1}{n}\sum_{t=1}^{n} SNR_t \tag{2}$$

where $SNR\ _t$ is defined as the ratio of the power P of the signal and noise, or as the square of the amplitude ratio within each time increment

$$SNR = \frac{Px_t}{Pn_t} = \left(\frac{A_{signal}}{A_{noise}}\right)^2 \tag{3}$$

The signal-to-noise ratio in decibels is

$$SNR_{\mathrm{dB}} = 10\log_{10}\left(\frac{Px_t}{Pn_t}\right) = Psignal_{dB} - Pnoise_{dB} \tag{4}$$

or

$$SNR_{\mathrm{dB}} = 10\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right)^2 = 20\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right) \tag{5}$$

with “optimal” quality defined as a decibel signal-to-noise ratio that ensures near to 100% intelligibility (e.g., +10 dB). These spectra can be further weighted in terms of audibility, e.g., in relation to an equal loudness contour or loudness model [14].

For each signal element, the noise can be considered to be the sum of background noise sources, n_i, and competing signals, x_i. The sum of all signals and noise, Y, is defined as:

$$\mathrm{Y} = \frac{1}{n}\sum_{i=1}^{n}(x_i + n_i)t \tag{6}$$

Taking the competing signals into consideration, the signal-to-noise ratio, *SNR′*, for a specific alert within an auditory display is the ratio of the signal of interest to the combination of competing signals and noise:

$$SNR' = \left|\frac{x_i}{Y - x_i}\right| \tag{7}$$

The concept of *SNR′* can be further elaborated by considering "extra-modal" noise or signals from visual displays, vibration, etc..

There is a fundamental weakness to such a model when applied to a complex auditory display having multiple messages that must be conveyed so that a listener successfully understands and acts with an appropriate response. The model reflects the fundamental essence of speech intelligibility testing in communication systems (e.g., [15]) but does not offer a holistic solution to the complex interaction of signals and their effect on human problem solving. Nor does it consider cognitive processing in terms of prioritization, familiarity, or other means by which a listener can effectively make sense of the acoustic display. Below, a human factors-based perceptual perspective is considered.

4 MEASURES OF AUDITORY DISPLAY QUALITY

The quality of an auditory display can be viewed in terms of how each of its signals or "messages" hierarchically satisfies four general principles: *detection; discrimination; intelligibility;* and *familiarity* [16]. *Detection* from the standpoint of signal detection theory refers to the statistical description of a human operator stating that a signal is present in the presence of noise. A *detection rate* is related to the probabilistic distribution of "hits" versus "misses" in a controlled laboratory experiment. Auditory signal detection is often described analytically for idealized conditions, such as for a subject wearing headphones in a soundproof booth performing a one-dimensional task (e.g., an audiogram evaluation of hearing level using tones). The discussion below, while focusing on auditory alerts, can apply to any message conveyed by an auditory display.

The influence of both the signal-to-noise ratio and bias is described by the so-called *receiver-operator curve* (ROC), which shows that (1) detection rates increase after a certain *threshold* is exceeded, and (2) the perceived cost of a missed detection influences the *criteria* used for stating a signal is present or not. Such a criteria shift can increase (or decrease) the number of *false alarms* made by an observer. We can therefore speak of not only the *detection rate* for a specific level of an alert; we can also refer to the *false alarm rate.* For unbiased criteria, the relationship is proportional as (*detection rate* = 100% – *false alarm rate*). As another example, a criterion shift (or *bias*) toward stating a signal is present can result in a greater number of detections but also an increase in the number of false alarms. For example, the black dot in the ROC plot of Fig. 3 shows an 80% detection rate and a 50% false alarm rate. A conservative criterion shift would result in fewer false alarms but also a lower detection rate. Note that the other possible scenarios, *misses* (no detection when there should have been) and *correct rejections* (no detection) are quantified respectively as (100% - *detection rate*) and (100% - *false alarm rate*).

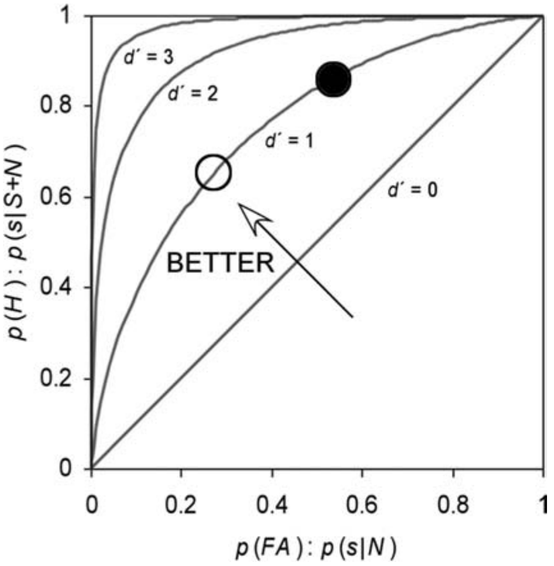

Fig. 3. ROC curves with d′ = 0, 1, 2, 3 (increasing sensitivity). The open circle indicates "neutral" criteria (unbiased). Criteria shift (filled circle) shows a greater number of false alarms along a given sensitivity curve.

It is possible to examine detection rates from a system perspective, a human perspective, or a combination of both. For example, we can refer to the ability of a system to detect a particular condition and then accurately or inaccurately provide an alarm signal, independent of the human. We can examine the human response to that alarm signal independent of the system, or in tandem. The discussion here is focused on human response to signals produced by an auditory display; nevertheless, the characteristics of the system will ultimately influence the criteria used by the human.

For example, a system that yields a great number or false alarms can cause humans to ignore its alerts. Alerts that are overly pervasive or that occur when they are not needed can lead to a user either ignoring or even deactivating the system, creating a potentially disastrous situation [17, 18]. A recent example is from the Deepwater Horizon oil rig explosion on April 20, 2010 that caused the loss of 11 workers and a historically massive spill in the Gulf of Mexico [19]. Testimony from the rig's electronic technician said that the general emergency alarm was set to 'inhibited' to avoid waking the crew: "They did not want people woke up at 3 a.m. from false alarms." The rig's owner stated that workers were allowed to inhibit the alarm to prevent it "from sounding unnecessarily when one of the hundreds of local alarms activates for what could be a minor issue or non-emergency."

For the design of alerts for auditory displays, the most relevant metric is the SNR that yields an equivalent detection rate. Specifically: for a given probability of detection, auditory alert, and background noise characteristic the metric indicates the signal *sound level* (measured in decibels as a sound pressure) relative to a specific noise sound level. The relevant metric for a false alarm rate can be expressed as a percentage relative to the desired detection rate.

The presence of an auditory alert usually presupposes a requirement for as close to a 100% "hit rate" as possible. Practically speaking, a 99.5% detection rate ($d' = 3$) is prescribed. Most auditory alert engineering guidelines err toward making the level higher than might be predicted by auditory masking experiments [20]. However, if the alert is too loud or too pervasive, negative effects on human performance can occur due to its *nuisance effect.* From the perspective of effective fault management, a startle effect requires time for physiological recovery [21]. Many alerts have a startling, excessively high level that is counter-productive from the perspective of human factors research; simultaneous alerts can exacerbate the problem.

The effectiveness of an alert is not only affected by its pervasiveness, but also its rarity. So called "black swans" are particularly rare off-nominal events (critical events that could potentially trigger an auditory alarm). Based on research in the areas of *change blindness* and *inattentional blindness*, the evidence shows that "people do a poor job noticing changes (events) when (a) these are unexpected, (b) they are not salient, and (c) they occur outside of foveal vision" [22].

Others have argued that the *Positive Predictive Value* (PPV) of the alert should be specified for the system detection, in addition to setting a detection rate and decision criteria [23, 24]. The PPV is related to the Bayesian statistic for the *posterior probability* of an event, which shows that the probability of "correctly" generating an alert is influenced by the *base rate* or *prior probability* of causal scenarios that trigger the alert. Even if an alarm system is designed to have a very high detection rate and low false alarm rate, a low posterior probability results if the quantity over time (rate) of actual alarms is low. This means that the *odds* that an alert is in fact triggered by a *true condition* becomes lower, and the greater number of apparent *false alarms* increases as the frequency of causal events becomes rarer.

The posterior probability can be expressed as the proportion of actual events S to the alerts given by the system R, and therefore indicates a measure of reliability of the alert representing a "true" event. This is calculated as the detection rate $P(R|S)$ divided by the detection rate plus the false alarm rate $P(R|N)$, adjusted by the base rate p:

$$P\,(S|R) = \frac{P(R|S)}{(P(R|S) + P(R|N)(1-p)/p)} \tag{8}$$

This is equivalent to the "classic" Bayes' formula:

$$P\,(H|E) = \frac{P(H) * P(E|H)}{P(H) * P(E|H) + (1 - P(H)) * P(FA|H)} \tag{9}$$

Eq. 9 shows the "support" for the hypothesis H based on evidence E (the posterior probability $P(H|E)$) as equal to the detection rate $P(E|H)$ (also termed *likelihood*) multiplied by the prior probability $P(H)$ in the numerator; divided by these same terms, but added to the false alarm rate $P(FA|H)$, whose probability is equivalent to (1 – probability of the detection rate). In other words, the probability of H conditional upon the evidence E is based on the rate of prior probabilities for detections and false alarms. Most importantly, Eqs. 8–9 show that the reliability of the alert representing a "true" event is not only affected by the hit rate and false alarm rate *but also by the base rate at which alerts occur*. Parasuraman [23] gives an example of a seemingly well-designed aircraft collision system with a detection rate of 99.23% and false alarm rate of 0.5%. In the case where the a priori probability of such an event is relatively rare ($p = .001$), only 1 in 6 alarms emitted by the system will be a true alarm. If the rarity of the event is equivalent to $p = .0001$, only 1 in 50 alarms is true.

Discrimination is the ability of humans to unambiguously identify an auditory alert from among a composite set of alerts, while *intelligibility* is concerned with recognition of the meaning of a specified auditory alert. Discrimination can be quantified in a manner similar to multiple-choice speech intelligibility testing for a word list: given n number of unique alternatives, what is the percentage of correct identifications from the set. Consideration of not only good design principles but also the environment's effects on an alert can help insure discrimination.[3]

Intelligibility refers to the correct identification of the meaning of a specific alert. It can be quantified in a manner similar to word list-based speech intelligibility testing, where subjects indicate the word spoken in the absence of any presented alternatives. The underlying basis for correct identification is partially due to a process of "gestalt recognition" based on an assimilation of a specific spectral and temporal acoustic pattern. Further cognitive reinforcement for recognition of an auditory alert as having a specific meaning is based on memory and association, or *familiarity.* Extending the gestalt concept of object recognition to sounds, a complex alert containing time-varying frequencies will more likely be grouped into a single unit if they are familiar or meaningful [25]. Research indicates that established alerts are preferred by listeners, precluding any design approach that would establish an entirely new "vocabulary" of alerts [6, 26].

5 SPECIFICS REGARDING AUDITORY ALERTS

Auditory alerts for caution and warning are perhaps of the most predominant components of many auditory displays; several publications give recommendations for level, frequency spectrum, repetition, and perceived urgency of specific alerts (e.g., [9] [27, 28, 29]). Of particular interest to the overall design of auditory displays are three primary

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[3] Some alerts can be perceptually if not completely acoustically transformed into another type of alert when their higher frequency components are absorbed at relatively long distances between source and receiver.

functions. First auditory alerts indicate that a specific condition exists that did not occur previously in time and that now requires attention. Second, they have a rudimentary function of stating, "*Look over here at this specific visual display*." This is a form of "directed attention shift" that is significant in the larger context of the cognitive challenge of fault management [30]. Third, their function is to relate the relative urgency of the alert through the semantic content contained in the alerts. The type of alert indicates: *Where in the hierarchy of possible auditory alerts does this new alert lie?* and *How quickly do I need to attend to this problem?* The degree to which the design of the auditory display can support these functions for each type of alert is an important measure of quality.

Survey data is of great value for making improved auditory displays because the "expert" knowledge enables a quantifiable and often straightforward relationship between subjective impression and objective communication engineering parameters. Responses from professionals in the field to general inquiries about the quality and perceived problems of auditory displays are based on extensive experience and are superior to a purely observational approach by a researcher. Survey data is also recommended as part of design requirements: "Auditory signals shall be tested and evaluated for usability, operational suitability, and user acceptance using representative users in as near to a realistic operational environment as possible before the signals are incorporated into a system" [4]. Common complaints include overly high levels [21]; high numbers of false alarms (e.g., [31]); lack of discriminability [7, 32]; and intrusiveness [17]. Here we consider four primary sources: commercial airline pilots [33], air traffic control [3], spacecraft [16], and nuclear power plant operators [34]. Overall, responses are highly similar between these different professions.

Peryer and colleagues obtained feedback from 50 commercial pilots regarding airliner flight deck alerts [29]. They examined subjective responses regarding loudness levels and the effective "cognitive impairment" caused by alarms, and obtained ratings for 10 currently used alarms. They report that "the most common complaint from auditory alerts is excessive volume." They go on to cite literature relating *auditory startle response* to loud alarms with abrupt, impulsive onsets and high sound pressure levels. The distracting natures of continuous, high-level alerts are also noted to be problematic for successful problem solving (see also [30]). In their survey they found:

- Levels are subjectively too loud (52% of responses);
- Auditory alerts impaired performance in a high-workload situation (46% of responses);
- Auditory alerts caused a startle effect in their experience (74% of responses);
- Auditory alerts having a combination of speech and non-speech elements were preferred over just having non-speech or speech alerts (64% of responses).

They include the following comment regarding the combination alerts: "Specificity when sounding an alarm reduces the discernment time for a pilot. When a non-speech alert is sounded, it takes time to scan the cockpit and recognize the source. Even familiar bells and chimes require absolute verification. This is not simply because the same alert may be used to designate different alarm conditions, flight regime depending . . . it's also because pilots who jump from airplane to airplane (as I have) may not have the desired familiarity or confidence in discerning the meaning of a particular chime or horn" [33].

Ahsltrom surveyed commonly cited problems associated with auditory alerts in the literature and then conducted an interview with 20 air traffic controllers [3]. The top five issues identified by users were as follows:

- Alerts are easily confused (because they sound alike);
- Alerts occur too frequently, especially false alarms;
- Alerts are annoying (due to startle effect, level, dissonance, and inability to terminate);
- Alerts are difficult to localize to their source;
- There are too many simultaneous alerts.

Begault et al. studied current and proposed alternatives for auditory alerts used on the NASA Space Shuttle [16]. The study involved having subjects categorize alerts as most appropriate for three different urgency levels, "emergency," "caution," and "warning." The post-experiment survey data indicated that familiarity with certain alerts, such as the traditional "wail" fire alarm to indicate a fire emergency, was important in the categorization, and that criteria for the decision was influenced by what alert was "most appropriate" for the given situation. Results were found to be similar between non-professionals and members of the flight crew.

Brown et al. conducted an assessment of the literature on alarm systems in nuclear power plants [34] and summarized as follows: "The auditory characteristics of alarms have often been found to be problematic, i.e., startling and distracting. More appropriate and acceptable methods of using tonal cues [sic] need to be identified. While the visual features of alarm systems are often overwhelming, the operator's ability to extract information from auditory cues has probably not been fully exploited." Regarding speech displays, they state that the presumed advantages are "attention capturing potential, reduction in demands on the visual information channel, ease of understanding the importance and meaning of the message, lack of training required, and public nature of the message." They found the applicability to the "acoustically crowded" control room to require further investigation.

Current guidelines for organizing and presenting a plurality of auditory alerts have for the most part responded to the issues raised by these survey data. One of the fundamental design considerations applicable to the visual-auditory display of alarms is the principle of *hierarchy.* In 1978, Veitengruber described the need for categorizing the hundreds of various alerts heard in flight decks of the time into urgency categories: warnings, cautions, and advisories [35]. Warnings are usually associated with red visual indicators and must be attended to immediately; cautions are usually associated with amber visual indicators and require immediate awareness, although not necessarily action. This parallels definitions cited in NASA standards for spacecraft caution-warning design [36]:

- EMERGENCY: Specifically identified life threatening warning event that requires immediate action.
- WARNING: Event that requires immediate action because it is or has the potential to become a life/mission threat.
- CAUTION: Event that needs attention, but not immediate action.

The use of a hierarchical system with "high-level groupings, or categories" is useful in helping controllers quickly understand the general nature of an alert [37]. A hierarchical system also enables *sequential* signal presentation from a plurality of activated alerts so that the auditory display facilitates recognition and consequent action. Tagging alerts in terms of a hierarchy provide a means to avoid the problem of *simultaneous* alerts. It is generally recognized that simultaneous alerts can affect intelligibility and discrimination, and likely raise stress levels not conducive to problem solving, due to the resulting cacophony of sounds. For example, an FAA standard practice document indicates that "Signals shall not be presented simultaneously; the highest priority alarm is to be presented first" [6]. NASA also specifies requirements for avoiding simultaneous alarms [36].

Another consideration is the concept of *appropriate usage.* Per the FAA standard practice document [6], "Audio signals should be provided (as necessary) to warn personnel of impending danger, to alert a user to a critical change in system or equipment status, to alert the user to the existence of a new alert, to remind a user of critical actions that must be taken or any other condition of which the user must be immediately aware." Furthermore, "auditory alerts shall be used "only when such signals contribute to understanding of an appropriate response to the operational and task environment"... it must also "provide the user with a greater probability of detecting the triggering condition than his or her normal observation would provide in absence of the system or signal" [6] (see also [9]). It also states that "The alert should prompt user action" and that "auditory alarm and alert signals should not be used to indicate normal conditions," i.e., only off-nominal conditions. This is in one sense contradictory to using audio alerts for situational awareness: e.g., the use of auditory signals for "sonification" of data related to the current operating status of a machine [38]. Another contrasting example is the use of "advisory" tones specified by NASA for Shuttle and Constellation that allow for determining out-of-limit conditions that *may or may not* require user intervention [36].

Limiting the number of alerts in a display is critical; the ability to learn and remember a set of abstract alerts is severely limited. In his landmark 1982 report, Patterson set a limit of four alerts for easy acquisition, stating that learning of up to three additional alerts is far more difficult [21]. The FAA standard practices document for limits the number of alerts to four "when absolute identification is required" [6]. For aircraft flight decks, Dorneich et al. recommends "a maximum of four individual warning sounds for immediate-action warnings, plus two attentions, one for the immediate-awareness warnings and one for the advisory alerts" [37]. It is possible to expand the "vocabulary" of alerts by separating them into two sections, a "prefix" and "suffix," in the manner of the current Ground Proximity Warning System used in commercial aircraft.

Most auditory displays include means for manual termination of alarms; some recommendations make a distinction for automatic termination. Dorneich et al. [37] recommends:

- Unique tones associated with time-critical warnings should be repeated and non-cancelable until the alerting condition no longer exists (e.g., restored separation), unless it interferes with the controller's ability to respond to the alerting condition. Unique tones associated with warnings should be repeated and non-cancelable if the controller needs continuous awareness that the condition still exists, to support the controller in taking corrective action.
- Unique tones associated with warnings should be repeated and cancelable if the controller does not need continuous aural indication that the condition still exists.
- For caution level alerts, the master aural and unique tone should continue through one presentation and cancel automatically.
- If there is any tone associated with an advisory, it should be presented once, and then cancelled automatically.

Designing how a user terminates a continuous auditory alert is nearly as important as how it is activated. The recommendations listed above should be considered in terms of the number of alert signals that may need to be heard sequentially within a given time window, and in terms of potential nuisance and if the continued presence of the alarm will accommodate problem solving. Consider the following hypothetical situation, where two off-nominal conditions separated by a period of time trigger a warning signal. If a user is able to cancel the auditory warning signal, but refer to a visual display while solving a problem related to the first condition, the resulting silence frees the auditory channel to detect a second warning signal for the second condition that occurs later. This is preferable to having a continuous warning alert that begins with the first off-nominal condition starts and ends when the last off-nominal condition is solved.

6 SPATIAL DISPLAYS TO FACILITATE AUDITORY STREAMING

The use of spatial auditory displays enables the auditory system to segregate sounds more effectively, aids in the intelligibility of multiple sources, and allows the spatial relationship between auditory events to map to events in the outside world [39, 40]. There are many sources that cite for spatial auditory displays a potential quantitative increase in informational transfer, compared to non-spatial auditory displays. For instance, Boyne et al. [41] refer to "auditory facilitation" as occurring "when the information about entities and spatial relations among them is coded redundantly, using the auditory modality to augment the visual. For instance, designing for auditory facilitation can be used to transmit more information to the commander and aid integration and coordination of disparate pieces of information."

The use of auditory displays capable of spatial auditory processing is recommended, particularly if the display includes one or more speech channels. The use of digital signal processing to create "virtual acoustic" locations for multiple radio communications was shown to provide an intelligibility advantage of up to 7 dB [40]. Besides the immediately apparent increase in intelligibility, an additional benefit was observed: individual volume controls for each channel needed to be manipulated less often compared to monotic or diotic playback. In a flight deck context, Ericson and McKinley [42] showed that spatializing four simultaneous speakers provided only a slight advantage over two-ear monaural (diotic) presentation, but found that initial call sign "capture" was facilitated. However, they attributed a greater advantage to a more realistic situation when speakers were not all talking simultaneously. Bronkhorst and Plomp [43] found a benefit from spatialization of up to seven simultaneous talkers with unsynchronized speech. Presumably, the segregation advantage given to speech would also apply to non-speech signals as well.

Spatial processing in the form of positional modulation can also be used to cause specific sounds to take precedence over static sounds within an auditory display. Begault [44] demonstrated an intelligibility advantage for spatially-modulated alerts for flight deck alarms, where the spatial position was modulated in a manner of an insect "buzzing" about the head.

7 FILTERING DATA TO THE AUDITORY DISPLAY

While the methodologies and types of sounds used for an auditory display frequently receive attention, principles for what and what not to display is a less developed area of research. In the context of the flight deck, Dorneich et al. [37] proposed an "information processing philosophy" designed to address the problem of overloading a user with an excessive number of alerts. The principles included:

- *Filter* information to reduce the overall amount of mental resources expended to process relevant information;
- *Integrate, categorize*, and *prioritize* information to enable information to be processed in a mentally economic way;
- *Embed* information in the alerting signal to allow preprocessing of signal to facilitate the efficient allocation of attention to the appropriate task.

Filtering data is prescribed as an initial step, where "only those messages that concern hazards or conditions that are predicted to affect the crew's mission should be brought to the pilot's attention." This is accomplished by having a system pre-process information and filter out irrelevant data that has no consequence on a stored flight plan. The next step is to integrate these data with other information and then to analytically categorize and prioritize it, in such a way that the most important alerts focus pilot attention. Regarding alerts that prescribe an action, they state that, "For all messages, the pilot remains the final authority for the appropriate response to take. In the most critical cases (e.g., wind shear detection) where an immediate response is necessary, the system indicates the hazard and the appropriate response, but it remains the crew's responsibility to initiate the evasive maneuver."

Dorneich et al. [37] address the final component of their information processing philosophy "to embed information in the alerting signal to allow preprocessing of the aural signal for strategic information. . . . This will facilitate the pilot in making the decision to continue with his current task or to switch his attention to the new alerted situation." This component reflects the strategy of "preattentive reference" [30]:

- Enable the operator to pick up the information in parallel with ongoing lines of reasoning (peripheral access). This allows the pilot to gather information about the source of the signal but does not require him or her to interrupt the current task.
- Include partial information about the condition in the signal. Limiting the information ensures that the resources required to process the signal are minimal.
- Provide ability to access in a mentally economical way (does not require focal attention). Again, a simple and clearly presented signal avoids engaging a substantial amount of the pilot's limited resources.

Preattentive reference requires that alerting signals contain sufficient information so that the pilot can decide whether or not to disengage their attention from a current task and attend to the message. "A careful balance needs to be obtained between providing an adequate amount information in the signal to make the decision, but not too much information that processing the alert would require conscious effort." Pre-attentive processing is efficient because it is a recognition-driven process as opposed to a "conscious decision" process, "thereby not requiring a significant amount of the observer's resources" [37]. Certain types of auditory feedback are more appropriate to preattentive processing. For example, sonification has been shown in surgical applications to allow anesthesiologists to maintain high situational awareness while performing other tasks more effectively, compared to visual-only displays [45].

Auditory displays can be designed to not only communicate information, but also to enable problem-solving strategies. Noyes et al. [46] recognized that centralized alerting systems in civil aircraft were improvements over earlier generation systems, but argued for inclusion of model-based reasoning techniques that would provide "high-level interpretation of the malfunction." McCann and Sprikovska [47] discuss the evolution of automated "systems health management" technologies that lead to fundamental questions regarding "how to display systems information in a way that maximally supports human situation awareness and decision-making capabilities, how to determine appropriate levels of human-automation function allocation, and how to develop human-machine interfaces that most effectively support human-machine collaboration." Such systems go beyond a simple alerting function since they provide means for solving the cause of the alert via "root cause analysis." Noyes et al. identified the following issues regarding current warning systems that could be addressed by automated reasoning techniques:

They have the ability to provide a large amount of data, but the presentation . . . could be improved to provide displays that are more task-oriented . . . this might involve integrating data from several sources into a single display that is determined by the current situation, e.g., current flight phase. . . . Few warning systems are designed to predict abnormal conditions before remedial action is needed. . . . There is limited advance indication of the consequences of crew actions [46].

The information encompassed by automated "collaborative problem solving" may present additional challenges for creating effective auditory displays, particularly if synthetic speech were used. Nevertheless, the concepts of task-oriented displays and source integration are relevant to the best practices described so far. Furthermore, the concept of a display that is "flexible" with regard to the current situation may be a means for eliminating nuisance alerts or orienting the priority of multiple alerts.

8 SUMMARY

The designer of auditory displays can successfully address the needs of the human operator by incorporating best practices for successful integration of sounds and for alert design. There is no single model, equation or solution that can be specified for a successful auditory display, particularly in the complex, legacy-rich system such as a commercial flight deck or ATC workstation, but the application of best practices will enable the designer to eventually accomplish this goal. These practices include:

- An "information processing philosophy" designed to address the problem of overloading the user with an excessive number of alerts is recommended:

– *Filter* information to reduce the overall amount of mental resources expended to process relevant information.
–*Integrate, categorize*, and *prioritize* information to enable mentally economic processing, using a hierarchical system with a limited number of categories.
–*Embed* information in alerting signal to allow preprocessing of signal to facilitate the efficient allocation of attention to the appropriate task.

- Auditory alerts should be used appropriately. They should be provided (as necessary) to warn personnel of impending danger, to alert a user to a critical change in system or equipment status, to alert the user to the existence of a new alert, to remind a user of critical actions that must be taken or any other condition of which the user must be immediately aware. Auditory alerts should be used only when such signals contribute to understanding of an appropriate response to the operational and task environment, and they must provide the user with a greater probability of detecting the triggering condition than his or her normal observation would provide in absence of the system or signal [6].
- Auditory displays might also include "subtle" sounds for improving situational awareness, including auditory feedback related to the completion of a task, synthetic speech messages, or status-monitoring messages that are noticed when a regular pattern of sound is interrupted. This may become increasingly important as new automation systems are introduced into the environment.
- Auditory alerts should be designed to enhance, not hinder, effective fault management by controlling level and other acoustical factors that can cause a "startle effect." In some situations, an auditory display can be purposely designed to enable problem-solving strategies by connection with root-cause fault analysis systems.
- Spatial displays enable the auditory system to segregate alerts, aid in the intelligibility of multiple sources, and allows the location of auditory events to map to the location of events in the outside world. Spatial modulation of an alert may help differentiation and can improve detection.

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