CONSIDERATIONS ARISING FROM THE DEVELOPMENT OF AUDITORY ALERTS FOR AIR TRAFFIC CONTROL CONSOLES

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ABSTRACT

Previously, the authors reported in detail on the development of a set of auditory alerts for the air traffic control consoles now used throughout Australia [1]. The present paper briefly describes these alerts again, but focuses on the issues raised and lessons learnt in the development and evaluation process. It also presents preliminary results from a review, conducted seven months after implementation. The alerts are to be presented for discussion in the poster session.

1. INTRODUCTION

The job of an air traffic controller involves receiving, analyzing and acting upon complex information in a timely manner. Since this information and action can affect many lives, it is vital that the operations environment is optimized such that the situational awareness and communication effectiveness of controllers and their supervisors are maximal [2, 3]. In Australia, an air traffic control console conveys information through multiple screens, a communication headset and a small under-desk loudspeaker for auditory alerts. In this paper we outline issues around a set of auditory alerts designed for this system, and implemented in July 2005.

Figure 1. *The visual display and computer interface used for air traffic control consoles in Australia.*

Airservices Australia is a government agency responsible for many aspects of air transport support, including air traffic control. Its area of responsibility extends beyond the Australian continent, accounting for 11% of the world's airspace and 47 million passengers per year. Two major operations centers are in use, in Brisbane and Melbourne, controlling upper level airspace of about half of Australia each. Smaller control centers exist in other Australian cities, especially for control in relation to airport traffic (using the same console configuration).

2. PREVIOUS AUDITORY ALERT SCHEME

One of the most interesting aspects of this project, from an auditory display perspective, is the auditory alert scheme that preceded the current implementation. This scheme used a 1.7 kHz pure tone as an alert for every event. Some events were represented by a short tone, and others by a long tone, but in practice operators were unable to distinguish these. With many consoles in a large operations room, a general 1.7 kHz hum could build up at busy times. The sound was considered to be unpleasant and annoying. In general, pure tones are difficult to localize, and the frequency of this tone made it especially difficult because it is in the range between effective inter-aural level difference and effective inter-aural time difference cues [4]. The under-desk loudspeaker position imposes a further limitation on localization. The practical effect of this was that an operator might be unable to discern aurally whether an alert is coming from their console, or another console.

The previous auditory display did serve a purpose, which was to alert operators and supervisors to events. However, it was relatively ineffective in conveying information, and it had detrimental side-effects. This serves as a reminder that auditory display is not always unequivocally good, and an appropriate design is needed for an effective display.

3. DESCRIPTION OF AUDITORY ALERTS

The current alert scheme consists of four 'priority' alerts, which represent four levels of urgency, as well as some supplementary alerts for information, communication and feedback.

3.1. Priority alerts

Studies of urgency encoding in auditory alert design have identified parameters in pulsed sequences of sound that convey urgency [5-12]. These include pulse rate, number of pulses in a group, fundamental frequency, inharmonicity, and others. Psychophysical scales for urgency encoding have been determined especially for simple pulsed signal sequences, so that a display designer can select a set of alert signals to convey appropriate relative urgency levels.

Rather than determining the scale value of urgency for the various events, and then synthesizing stimuli to match these based on urgency models, the alerts for these consoles were designed directly – i.e. air traffic control specialists listened to many candidate alerts, and selected and tweaked the alerts to match their impression of the urgency of the event category. In the end, a large range of urgency encoding was established, although it is not possible to quantify this fully based on data of previous studies. These alerts are organized as a series of pulses in a group, which repeats after a period of time. The timbres are harmonic, and include a percussive attack with an approximately exponential decay for each pulse. The key characteristics of the alerts that convey urgency are given in Table 1.

Priority	**P1**	**P2**	**P3**	**P4**
Number of pulses in group	14	5	2	1
Pulse rate	6.3 Hz	1.9 Hz	1.3 Hz	-
Group repetition period	3.3 s	4.6 s	5.5 s	21.6 s*
Fundamental frequency	740 Hz	520 Hz	385 Hz	268 Hz
Sound level (vol. = 3)	70 dBA	63 dBA	57 dBA	58 dBA

Table 1: Key characteristics of the priority alerts P1-4. *The P4 alert has a delay of 60 s prior to sounding for some events.

P1 is the highest priority level of alert, and is for system-detected critical events. This includes warnings for aircraft approaching too close to each other, too close to the ground, or entering restricted (e.g. military) airspace. P2 alerts are for aircraft onboard emergencies. P3 are for high priority system-detected non-conformance events (e.g. divergence from a predicted route), and P4 are for low priority system-detected non-conformance events (e.g. overdue position report). On-screen visual alerts convey information about the type of event within the priority category. At the same time as the new auditory alerts were introduced, the visual alert scheme was improved, so that P1 alerts appear with yellow text on red background (instead of just yellow text), P2 alerts as red text on yellow background (instead of just red text), and P3 and P4 alerts are simply yellow text (no change made).

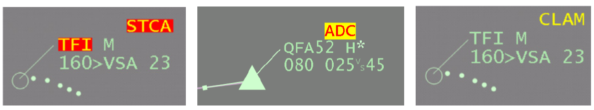

Figure 2. *Examples of on-screen visual alerts (P1, P2 and P3 from left to right). The color scheme for P4 is the same as for P3.*

3.2. Supplementary alerts

When the priority alerts were first trialed in air traffic control simulators, communication, information and feedback alerts retained the 1.7 kHz pure tone, which made these events seem more urgent than high priority events. Therefore some supplementary alerts were created for text communication receipt (CPDLC), receipt of meteorological data (AIF), keyboard input error, and timer. These are simple and relatively unobtrusive, and have a different character to the priority alerts to avoid confusion. The CPDLC and AIF alerts are a pair of tones. The keyboard error alert is a rapid downward complex tonal sweep. The timer alert, which tells an operator that a pre-set time has elapsed, is reminiscent of a clock tick. Currently the CPDLC and keyboard error alerts are not implemented due to a software limitation.

4. ISSUES ENCOUNTERED IN THE DESIGN OF THE ALERT SCHEME

4.1. Audibility, Loudness and Stress

A key design criterion for alerts for air traffic control consoles is stress minimization. The purpose of an alert is to convey the information represented, including its urgency, but not to induce stress in the operator, which might reduce the effectiveness of their reaction to the alert. This seems somewhat paradoxical, since high urgency is associated with stress, and some of the signal characteristics that convey urgency are also associated with emotional arousal and annoyance. To some extent this is addressed by selecting signals that convey high urgency within the calm context of an operations room, even though they would not convey such urgency in a busy and noisy context. Furthermore, some signal parameters that are used to control urgency provoke greater annoyance than others – for example, sharpness dominates the sensory unpleasantness models of Zwicker and Fastl [13], and so may be inappropriate as an urgency indicator in a low stress work environment.

Patterson finds that sudden attacks in auditory alerts produces a startle effect – the operator's response is dominated by muscle tensing and other reflex effects rather than a rational response [4, 5]. However, the envelopes advocated by Patterson were not favored by the air traffic control specialists who were involved in alert selection. We can point to two issues that may argue against these envelopes: (i) our alerts were substantially quieter than those designed by Patterson (he was concerned with flight deck environments); and (ii) the fade-in envelope advocated by Patterson may produce a 'looming effect', where the sound seems to represent something rapidly approaching the person [14], which may induce an instinctive stress reaction.

A design question for this type of situation is whether an auditory alert must always be audible to the operator, and also whether it must be always be audible to the supervisor. The answer must weigh the cost and benefit associated with levels of audibility: loud alerts will assure audibility, but will induce annoyance, stress and distraction; quiet alerts will not degrade the work environment, but may fail to draw attention to a critical event. In this case we have prioritized audibility in the same way that events are prioritized.

We monitored the sound pressure levels in three active operations rooms over a period of 1 week, and found that L_{90} rarely exceeds 50 dBA and L_{10} rarely exceeds 60 dBA. (These are the levels exceeded 90% and 10% of the time, measured using 'fast' integration over a contiguous succession of 15 minute periods.) Hence the alert level at the operator's position is at least 10 dB above L_{90} (and P1 is 10 dB above L_{10}) when the volume control is set to its default position of 3. However, the measurements show a regular daily cycle of background noise, so that for several hours per day the noise levels are much lower. In this situation the controller may reduce the alert levels. They may also increase the alert levels in busy times.

One of the major benefits of the new alert scheme is a reduction in the overall sound level produced by multiple alerts in a large operations room. This is achieved through a combination of decay envelopes (rather than the constant tone) yielding lower equivalent sound pressure levels, and through the redesign of auditory alert triggering. In particular, some low priority events are represented only by a visual alert for the first 60 seconds, and then by an auditory alert if the visual alert is unacknowledged by that time.

4.2. Localization

The design of localizable alerts when the direct path between loudspeaker and ear is broken is an interesting challenge. Nevertheless, it is not difficult to improve on the localizability of a 1.7 kHz pure tone. Operators usually wear a one-earpiece headset, leaving the other ear free to provide spectral directional cues (e.g. for front-back discrimination). Distance perception may be at least as important as direction perception in this situation, and the provision of high frequency complex spectral content in the audio signal should benefit both direction and distance perception. Considering that an operator normally uses the one console, it may be possible over time to learn something of the spectral and temporal (e.g. direct-to-reverberant ratio) features of the consoles around them (including their own).

The inclusion of high frequency content without having overly sharp alert sounds was achieved through concentrating it in the attack portion of the pulse envelope, which also should support temporal localization cues. By way of compensation for the loudspeaker position (under the desk), the priority alert sound-files have strong high frequency content in their attacks.

4.3. Audio System Considerations

This project is an instance of audio signal design for a very limited audio system. Initially we thought that we could apply linear systems principles in compensating for the loudspeaker's frequency response. Hence the loudspeaker's spectral magnitude response was measured both on axis, and with it positioned under a desk in a similar situation to the air traffic control console installation. An inverse filter was devised, and this appeared to work when we played candidate alerts through the console loudspeaker in an audio studio environment. However, it was immediately evident in the first simulator trial that the spectral compensation was inadequate, with the lowest frequency alert being too quiet, and the highest frequency alert too loud. At this point we realized that the whole audio system of the air traffic control console needed to be taken into account, not just the loudspeaker and its under-bench position.

A series of measurements were then made using a simulator console, in which we prepared the alerts, loaded them onto the system (which took about 15 minutes), and measured each one at the operator's head position (the level taken was the maximum A-weighted sound pressure level, with 'fast' or 125 ms temporal integration) by generating triggering events in the simulator software. The alerts were then edited and the process repeated. To complicate things, the console software has a 5-level stepped volume control, so alerts were measured at the various volume levels. The effect of the volume control appeared to be non-linear, meaning that some alerts would show larger changes in sound pressure level than others for a given volume control change. This effect may have been due to an impedance mismatch between the sound-card and loudspeaker.

These complexities provide a reminder of the importance of *in-situ* measurements, as well as operator trials. The audio system appeared to be simple, and certainly did not include any esoteric components. But in fact, the system's behavior was non-linear and difficult to measure, model and compensate for.

4.4. Alert sound

The alert scheme advocated by Patterson has a synthetic quality, since the sound is generated from a set of very simple rules. Earlier it was noted that one possible problem with that scheme is the looming effect. The artificiality of the sounds might be regarded as a more general limitation. The designers of the alert sounds that are the subject of this paper both have substantial musical backgrounds, and felt that a more naturalistic sound quality would contribute better to the sound environment of an operations room. The use of percussive attacks, harmonic spectra, and exponential decays imitates the acoustic response of many struck damped resonators, and we consider this to be helpful in maintaining a positive acoustic work environment.

Another way in which our priority alert sound design is distinctive is the large pitch range spanned between the highest and lowest priority levels (about one-and-a-half octaves). This is in contrast to many other schemes, where the range may be a few hundred hertz in the high frequency range.

5. EVALUATION

As reported previously [1], the results of formal evaluation of the new alerts in simulator trials prior to implementation were overwhelmingly positive. Preliminary results in the post-implementation review (February-March 2006) are summarized here. These results are based on structured interviews with 42 controllers based in six air traffic control centers (in the cities of Adelaide, Brisbane, Cairns, Melbourne, Perth and Sydney). Ratings were made on a seven point scale ranging between -3 (unacceptable) to +3 (excellent). Mean results for the various centers differed markedly, as shown in Figure 3.

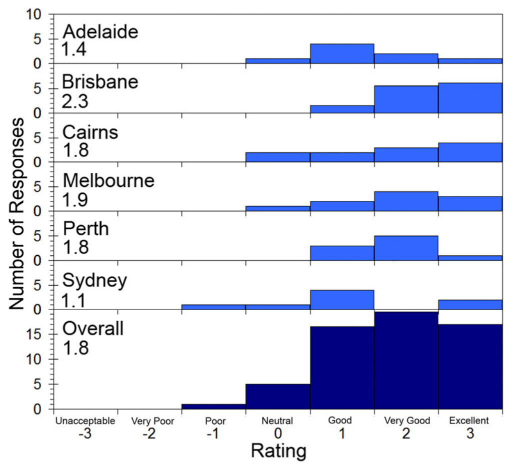

Figure 3. *Response distribution for the question, "Indicate the overall effectiveness of the presentation of alarms in notifying controllers of the urgency or criticality of a triggering event (i.e. to what extent can you tell if an alarm is high or low priority?)". Mean ratings are given on the left.*

Due to the different air traffic conditions and air traffic controlled by each center, the number of P1 alarms experienced was far greater in the small centers at Adelaide, Perth, and especially Sydney, and this explains the centers' different rating distributions. Frequent P1 alarms resulted in feelings of desensitization and annoyance in these centers. Software changes are being examined to reduce the number of these alarms. Hence, these variable results do not reflect on the alert sounds themselves, but demonstrate clearly adverse effects of frequent high urgency alarms in a control room. This effect is also seen in Figure 4, which shows the rated effectiveness of the four priority alert sounds.

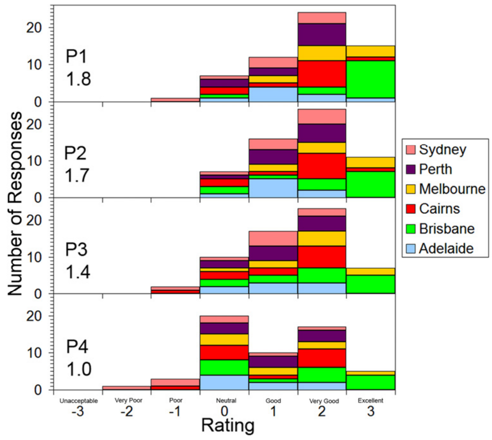

Figure 4. *Response distribution for the question, "Indicate the overall effectiveness of the new aural alarms for each priority level". Mean ratings are given on the left.*

It can be seen in Figure 4 that the rated effectiveness of the alert sounds is simply related to their priority level, with the exception in Sydney, where the large number of P1 alarms reduces its effectiveness. The term 'effectiveness' may be influenced by many factors – including perceptual prominence, the appropriateness of the meaning communicated by the sound, and the ability to distinguish alert sounds. When asked to indicate how well these can be differentiated (using both visual and auditory alerts), the mean rating was 1.5 (between Good and Very Good). Figure 5 shows ratings of each of the priority auditory alerts in conveying appropriate urgency.

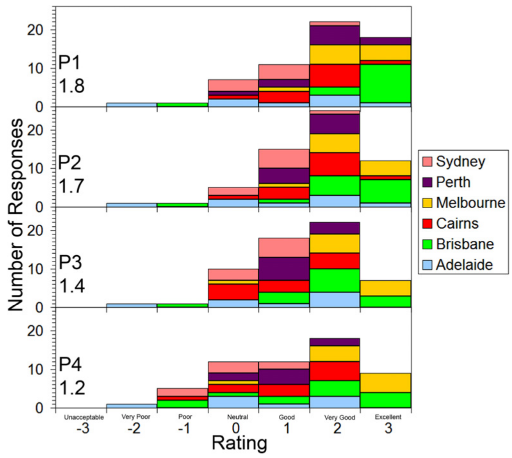

Figure 5. *Response distribution for the question, "Rate the ability of the tones to convey priority or urgency". Mean ratings are given on the left.*

6. CONCLUSIONS

This paper outlines some issues arising from the design, testing, implementation and review of auditory alerts for air traffic control consoles. The alert scheme was initially very well received by operators, and continues to be positively evaluated after seven months of operation. The detrimental effect of frequent high urgency alarms is the biggest issue raised by the post-implementation review. A more detailed analysis is beyond the scope of this brief paper.

7. ACKNOWLEDGMENTS

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