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Auditory warning sounds in the work environment

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One of the most common auditory warnings is the ambulance 'siren'. It cuts through traffic noise and commands one's attention, but it does so by sheer brute force. This 'better safe than sorry' approach to auditory warnings occurs in most environments where sounds are used to signal danger or potential danger. Flooding the environment with sound is certain to attract attention; however it also causes startled reactions and prevents communications at a crucial point in time. In collaboration with several companies and government departments, the MRC Applied Psychology Unit performed a series of auditory warning studies. The main conclusions of the research were that the number of immediate-action warning sounds should not exceed about six, and that each sound should have a distinct melody and temporal pattern. The experiments also showed that it is possible to predict the optimum sound level for a warning sound in most noise environments.

Subsequently, a set of guidelines for the production of ergonomic auditory warnings was developed. The guidelines have been used to analyse the environments in both fixed-wing and rotary-wing aircraft, and to design prototype warning systems for environments as diverse as helicopters, operating theatres and the railways.

1. Introduction

For some time now it has been clear both to aircrew and the Civil Aviation Authority (CAA) that the auditory warning systems on civil aircraft are, to say the least, non-optimal. Briefly, the pilots complained that there were too many warning sounds, that they were too loud, and that they were confusing. The problems are illustrated in an incident report filed with CHIRP, a confidential incident reporting service provided by the Institute of Aviation Medicine at Farnborough. The following is an abbreviated version of the first few paragraphs of the report:

> 'I was flying in a Jetstream at night when my peaceful reverie was shattered by the stall audio warning, the stick shaker, and several warning lights. The effect was exactly what was NOT intended; I was frightened numb for several seconds and drawn off instruments trying to work out how to cancel the audio/visual assault rather than taking what should be instinctive actions.
>
> The combined assault is so loud and bright that it is impossible to talk to the other crew member, and action is invariably taken to cancel the cacophony before getting on with the actual problem.'

A review of the existing situation immediately revealed that all three of the pilots' complaints were justified. Some of the aircraft had as many as 15 auditory warnings; they were not conceived as a set and there was no internal structure to assist the learning and retention of the warnings. A number of the warnings produced sound levels over 100 dB at the pilot's ear and virtually all of the warnings came on instantaneously at their full intensity. With regard to confusion, there appeared to be no order among the different spectra and the different temporal patterns used in the warning sounds. Furthermore, it appeared that if two of the warnings came on simultaneously, they would produce a combined sound that would make it difficult to identify either of the conditions involved.

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The pilots' problems occur over and over again in noisy, high-workload environments where auditory warnings are used to signal danger. An extreme example of the confusion problem occurs in the intensive care wards of large hospitals. There may be as many as six critically injured patients in an intensive care ward, and each of the patients is surrounded by life-support equipment and monitors that may present 10 or more auditory warning sounds. Thus there can be more than 60 relevant auditory warnings in one ward, far more than the staff could hope to learn and remember. What is more, for reasons of economy, most of the warning sounds are high-frequency tones that differ only in their frequency and intensity. The auditory system of humans is not designed to preserve the absolute frequency or intensity of sound sources, rather it is designed to listen for changes in sounds. Furthermore, high-frequency tones are not localizable. Thus it was entirely predictable on theoretical grounds alone, that there would be significant confusions between the warning sounds in this environment (Patterson *et al.* 1986). With regard to level, excessively loud warnings are not restricted to aircraft. Warning horns and fire bells that were appropriate on steam locomotives with open cabs, are still present in the cabs of modern electric trains. Although the history of existing auditory warning systems is fascinating, the purpose of this paper is to explain how we can produce better auditory warning systems.

Before proceeding, it is perhaps worth pointing out why auditory warnings are useful and why they are necessary. Warning sounds are useful because hearing is a primary warning sense. It does not matter whether operators are concentrating on an important visual task, or relaxing with their eyes closed; either way, if a warning sound occurs it will be detected automatically and routed through on a priority line to the brain. The need for auditory warnings, in addition to visual warnings, is exemplified in an accident report which describes how a passenger helicopter descended inadvertently into the sea (Cooper 1984). Until this accident helicopters did not have auditory warning sounds. In this particular case it appears that the pilots were busy looking for landfall in fog and they simply did not see the flashing yellow light behind the control column telling them that they were descending to a dangerously low height. An auditory warning sound, as the report concludes, would almost undoubtedly have averted this accident. Thus the question is not one of whether we should, or should not, have warning sounds. Rather the question is whether we can construct sets of warning sounds that get one's attention reliably without causing startled reactions.

At the Applied Psychology Unit we began by concentrating on four problems: (*a*) what is the correct level for a warning sound, that is, the level that will render the warning reliably audible but not adversely loud? (*b*) what are the appropriate spectral characteristics to ensure that a warning is not only audible but also discriminable from other members of the set? (*c*) what are the short-term temporal characteristics that make a warning sound arresting without producing a startle response? (*d*) what are the longer-term temporal characteristics that give the warning sound a distinctive and memorable rhythm? The answers to these questions, and the guidelines that summarise the answers, form the topic of the remainder of this paper.

2. The appropriate sound level for auditory warnings

As a guideline, if a warning is to be clearly audible and draw the attention of the flight-crew reliably, the spectral components of the warning sound must be 15 dB above the threshold imposed by the background noise on the individual spectral components. Thus the problem of

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determining the appropriate range for the components of a warning sound reduces to one of finding the threshold imposed by the noise background on the components. The spectrum for background noise on the flight deck of a Boeing 727 flying at 240 knots is shown by the bottom curve in figure 1.

Threshold for any particular component is largely determined by the noise components in the same region of the spectrum as the warning component itself. It is as if the observer were listening for the warning component through an auditory filter centred at the frequency of the component; that is, threshold is determined by the amount of noise power that leaks through that filter with the warning component. After Patterson (1982), threshold was calculated as a function of frequency, at multiples of 0.01 kHz, and it is shown by the smooth curve in the centre of figure 1. As the noise spectrum is smooth, the threshold function is also smooth and follows the noise spectrum fairly closely. Note, however, that threshold does actually diverge from the noise spectrum as frequency increases because the bandwidth of the filter increases with its centre frequency.

The individual spectral components of an auditory warning must be above the threshold curve to be just audible in that noise. To be reliably audible four or more components of a warning should be at least 15 dB above auditory threshold. The lower boundary of the banded area above the threshold curve is 15 dB above threshold and so it represents the lower bound of the appropriate range for auditory-warning components. In the frequency range 1.0–2.0 kHz, the curve shows that the background noise requires the use of warning components in excess of 85 dB SPL. As this is already a high level it is recommended that the upper bound of the appropriate range for warning components should be limited to about 10 dB above the lower bound. Thus the banded region is the portion of the space in which the auditory warning components should fall.

The spectral components of the configuration horn of the Boeing 727 are shown by the dashed vertical lines in figure 1. The largest component is more than 20 dB above the

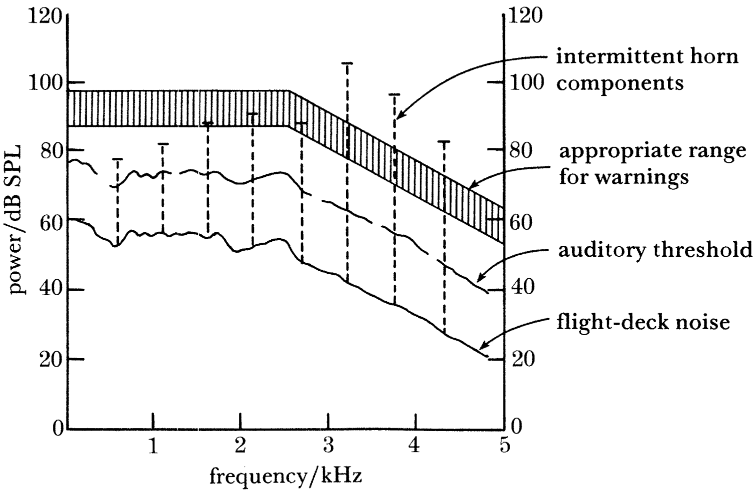

FIGURE 1. The range of appropriate levels for warning sound components on the flight-deck of the Boeing 727 (vertical-line shading). The minimum of the appropriate-level range is approximately 15 dB above auditory threshold (broken line) which is calculated from the spectrum of the flight-deck noise (solid line). The vertical dashed lines show the components of the intermittent warning horn, some of which are well above the maximum of the appropriate-level range.

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maximum of the appropriate level range. Sounds in excess of 85 dB SPL are aversive for most people, particularly in this frequency region. In a separate study (Patterson *et al.* 1985) a configuration horn was presented to two test pilots in flight at six different sound levels. They independently chose the version of the warning horn that set the main components in the appropriate-level range. There is, then, good agreement between the level that the model of auditory masking shows is required for reliable detection, and the level that the test pilots felt was appropriate.

This method of specifying the level for auditory warnings has also been used to review the loudness of the warnings on a Boeing 747 (Patterson *et al.* 1985). Eight of the eleven warning sounds had acceptable sound levels, with five of the warnings having near optimum levels. However three of the warnings were actually found to be too soft: the overspeed, landing-configuration, and take-off configuration warnings. The main spectral peak of the overspeed warning is just under the lower bound of the appropriate level range (figure 2). As the warning must be available in the loudest of the noise environments on this aircraft, the level of the warning should be increased by 8–10 dB so that it is nearer the maximum of the appropriate-level range.

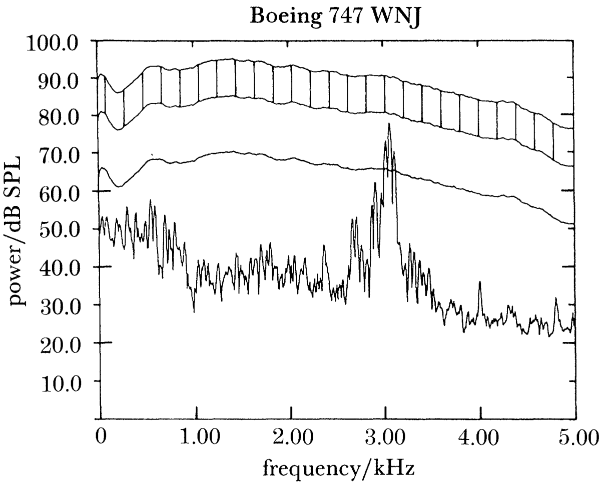

FIGURE 2. A comparison of the appropriate-level range on the flight-deck of the Boeing 747 (the vertically shaded region) and the spectrum of the overspeed warning. The warning sound level should be raised about 8 dB to ensure that it is invariably heard.

In summary, the method for setting levels can be used to design new systems or modify existing systems in an effort to maintain safe levels and avoid needlessly annoying levels.

3. THE SPECTRA OF WARNING SOUNDS

Contrary to the general conception of pitch perception, we do not hear a separate pitch for each peak in the spectrum of a sound. Rather the auditory system takes the information from temporally related components and maps them back onto one perception, namely, a pitch corresponding to the fundamental of the harmonic series implied by the related components. This property of the hearing mechanism has important implications for the design of auditory warnings. Specifically it enables us to design warnings that are highly resistant to masking by

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spurious noise sources; that is, resistant to masking by those unpredictable noise sources that might accompany the event that causes an emergency on an aircraft. Briefly, a warning sound that has four or more components in the appropriate level range, and which are spread across the spectrum, is much much less likely to be masked by a spurious noise source than one in which all of the energy is concentrated at one harmonic.

On the Boeing 747 the warning sounds chosen to represent glide slope, passenger evacuation, and overspeed problems have only one spectral peak at about 0.35, 3.6 and 3.1 kHz, respectively (Patterson *et al.* 1985). The overspeed spectrum is shown in figure 2. Some of the turbines and pumps on aircraft could produce noise in the 3–4 kHz region should they become worn, and it could make the warnings difficult to hear. In contrast, the harmonic content of the intermittent horn in figure 1 is excellent. It is very unlikely that a spurious masker could prevent its being heard, even after the level has been adjusted.

4. The temporal characteristics of warning sounds

A study was performed at APU to determine whether flight-deck warnings are confusing, that is, whether they are intrinsically difficult to learn and remember (Patterson 1982). Groups of naive listeners were taught to recognize a set of ten auditory warnings drawn from the flight-decks of a variety of current civil aircraft. The results show that the first four to six warnings are acquired quickly, but thereafter, the rate of acquisition slows markedly. There is no inherent difficulty in learning warning sounds, but beyond the first six it does require appreciatively more effort. The results of the learning and retention study cannot be directly applied to pilots on the flight-deck. They do, however, reinforce the growing belief that aircraft with sets of ten or more warnings have too many. On the other hand, the ease with which naive listeners learn six arbitrary warnings suggests that a set of six should prove entirely reliable.

A confusion analysis applied to the errors made during the learning phase of the experiment showed that warnings with the same pulse-repetition-rate were likely to be confused even when there were gross spectral differences between the warning sounds. It is important to stress that the listeners were naive and that their rate of confusion is very high with respect to the rate that might be expected to occur on the flight-deck. The results did, however, show that any potential for confusion could be dramatically reduced by employing a richer variety of temporal patterns, that is, distinctive rhythms. Subsequently, new sets of warnings for helicopters (Lower *et al.* 1986; Patterson *et al.* 1989) and have included rhythm distinctions, and learning tests on these new warning sets reveal much lower confusion rates.

Changes in sound level are useful for drawing a listener's attention, and the greater the rate of change, the more demanding the sound. However, some of the existing flight-deck warnings go from off to full on at a level over 100 dB SPL in under 10 ms. In the natural environment a rapid rise to a high sound level is characteristic of a catastrophic event in the listener's immediate surroundings. The natural response to such an event is an involuntary startle reflex in which the muscles are tensed in preparation for a blow or a quick response. Instantaneous responses often prove incorrect, and so they are specifically discouraged on the flight-deck and in pilot training. The abrupt onsets of current warnings are not justified by a requirement for fast motor responses. Patterson (1982) has suggested a rise time of 20 ms. The duration of the offset of the pulse is determined by the same factors.

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5. A PROTOTYPE ERGONOMIC WARNING SOUND

The temporal structure of a warning that might be used in a train, plane or hospital is shown in figure 3. The upper row shows the basic pulse with its rounded onsets and offsets. The middle row shows the burst, or pulse pattern, used to represent the warning. The bottom row shows the timecourse of the complete warning. The waveform within the pulse is unique to a particular warning; it carries the spectral information of the warning sound and is never altered. In this case, a burst of six pulses defines the warning sound. The basic grouping of four, clustered pulses followed by two, irregularly spaced pulses provides the rhythm of the sound which, combined with the spectral characteristics stored in the waveform, gives the sound its distinctiveness. The spacing of the pulses is varied within the burst to vary the perceived urgency.

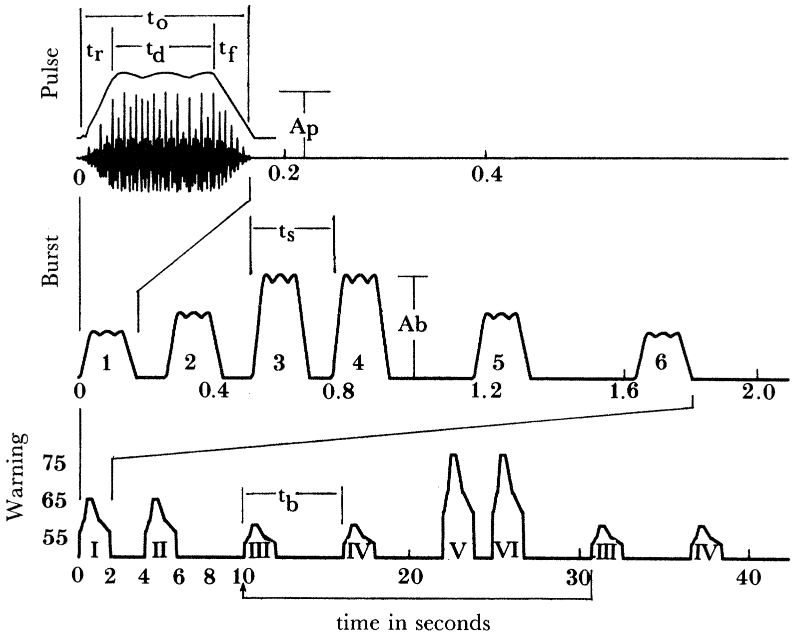

FIGURE 3. The modules of a prototype warning sound: the sound pulse is an acoustic wave with rounded onsets and offsets and a distinctive spectrum; the burst is a set of pulses with a distinctive rhythm and pitch contour; the complete warning sound is a set of bursts with varying intensity and urgency.

An arresting warning can be produced without risking a startle reaction by bringing the warning on at a comparatively low level and increasing the level of successive pulses quickly as shown in the middle row. This amplitude envelope gives the impression that an object is moving forwards rapidly and then receding slowly, and this apparent motion draws attention. At the same time, since the first pulse comes on at a moderate level, the warning does not cause a startle reaction. The basic pulse is similarly given a rounded top rather than an abrupt onset or offset to reduce the risk of a startle reaction.

The timecourse of the complete warning sound is shown in the bottom row of figure 3. The little 'houses' designated by Roman numerals, represent different versions of the burst that vary in their urgency. The height of the houses shows the relative intensity of the bursts. The spectral and temporal characteristics of the pulse (upper row) and the burst (middle row) give

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the warning sound its distinctive character. The pitch, intensity, and speed of the burst are used to vary the perceived urgency of the warning sound. A burst can be thought of as a brief atonal melody with a syncopated rhythm.

When the situation necessitates, the warning sound comes on and the first burst is played at a pitch and speed that indicate moderate urgency, and at a level that is clearly audible but not excessive, as determined by the background noise in the environment. Then the burst is repeated. At this point, it is highly likely that the warning has conveyed its message, and that further repetition of the burst in its urgent form would be needlessly irritating. At this point, then, the pitch, level and speed of the burst are lowered to reduce its perceived urgency, and it is played every 4 s or so in this non-urgent form (III and IV). With the level reduced and the time between bursts extended, one can communicate verbally in the presence of the warning without difficulty, an important advantage in an emergency. If the condition that initiated the warning sound is not alleviated within a reasonable length of time, the warning returns in its most urgent form, conveyed by a pair of bursts (V and VI) with a relatively high pitch, a fast pulse rate, and a level that overrides any ongoing speech and commands attention. Then, the warning returns to the background level to permit communication. Bursts III–VI are repeated until the condition that initiated the warning is corrected, or until someone indicates their attendance. In the latter case, the warning remains on in the background form with the urgent bursts repressed and the non-urgent bursts repeating every four seconds or so to show that an abnormal condition still exists.

6. Applications

Five sets of auditory warnings have now been developed according to the principles outlined to this point. In the case of the Civil Aviation Authority the purpose of the set was to illustrate the guidelines (Patterson 1982) and the kind of warning sounds that would satisfy a British Aircraft Standard that was being developed in response to pilots' complaints. In the case of hospitals, the purpose of the warning set was to show to British and International Standards organizations the kind of civilised, distinctive warning sounds that could be specified in a Standards document and used to replace the cacophony of buzzers and bells used currently in operating theatres and intensive care wards (Patterson *et al.* 1986). The Standards specify, and the demonstration warnings illustrate, two forms of hospital warning system. In one case there are only three sounds, each of which shows a whole category of problems and which are differentiated by their urgency. In the second form, the three category sounds are supplemented by six specific warnings all of which show urgent conditions occurring in the topmost category. The design represents an ingenious compromise that enables each authority or hospital ward to tailor the system to their own needs by adding a small number of the highly urgent warning sounds to the general set of three category warnings.

Three related sets of warnings were designed for use in helicopters (Lower *et al.* 1986). The first set was developed for the multi-role Sea King helicopter and consisted of ten warning sounds. A learning experiment was performed with helicopter pilots and it showed that the new sounds were much more resistant to confusion than those being used currently in civil airliners. The second set of warnings was produced for the Lynx helicopter and used to check the guidelines for setting the sound levels of the warning sounds. Detection levels were measured in a Lynx helicopter shell and it showed that the model of auditory masking was as accurate

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as the noise measurements that could be made beside the pilot's ear. The third set of warnings was produced for helicopters ferrying staff and supplies to North Sea oil rigs. A subset of the warnings is currently installed in more than 150 North Sea helicopters.

Finally, at the request of British Rail Research, a set of warning sounds was designed for use by trackside maintenance crews to warn of approaching trains. In this case, the aim was to preserve the correspondence between trackside warning function and the sound that British Rail already had (the PeeWee). All of the new warning sounds were constructed from components of the existing sound (Patterson *et al.* 1989). Furthermore, all four warning sounds had to be audible in the presence of no less than 46 different noise environments.

7. Conclusion

In summary, one can now design and build warning sounds that present their message with appropriate urgency and promptly fall back to permit vital communication, returning to interrupt forcefully only if there is reason to believe that the condition is not receiving sufficient attention.

The author thanks Robert Milroy and Mike Lower for their continued assistance in producing and testing the auditory warnings over the years of this project.

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Discussion

T. F. Mayfield (*Rolls Royce and Associates, U.K.*). Dr Patterson has presented what seems to be a large number of discrete tone combinations. Is it suggested that all these would be used in any one situation.

R. D. Patterson. For a discussion of the appropriate number of warning sounds, see §4.