REVIEW

Auditory warnings in noisy environments

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Auditory warnings are used throughout industry, transport, and the medical world. Despite the fact that auditory warnings frequently have to compete with intense and complex noise backgrounds, their use is widespread. This article reviews research and practice in the area of auditory warning design and implementation with particular emphasis on noisy environments. Auditory and visual modalities as warning senses are compared, and ergonomic methods of producing warnings which are acoustically tailored to their environments are reviewed. Developments in design approaches are reviewed with examples of both traditional types of warnings and digital, contemporary warning styles. Other issues such as false alarms and the minimisation of warning numbers are briefly considered.

Keywords: Auditory warnings; alarms; communication; ergonomics

Introduction

It is no surprise that in an increasingly hazard-aware and litigious society, the role of warnings has become more and more important. Warnings now appear in just about every aspect of our working and social lives. In occupational settings there are many environments where people are often engaged in difficult and demanding tasks but where their attention must from time to time be diverted to other, more important and urgent tasks. This is typically achieved through a system of auditory warnings. Examples of such situations include aviation, control rooms, and medicine. In all three cases warnings need to command attention without causing startle and annoyance. They also need to convey information about the task or situation requiring attention, and often these warnings have to compete with a great deal of other sensory stimulation impinging on the observer at the time. One particular problem of relevance here is that auditory warnings may have to compete with a complex, noisy background. The use of warnings is on the increase for a number of reasons, not least of which is that it is technically easy to provide warnings, and the legal consequences of not doing so make the over-abundance of warnings an attractive proposition for any manufacturer who fears being sued due to inadequate warning provision. However, such overabundance does not necessarily improve either performance or safety. In this article the use of auditory warnings in the workplace is reviewed, with the aim of providing guidance and technical information as well as background literature.

Auditory warnings - why use them?

Auditory warnings are often used in noisy environments such as factory floors, control rooms, aviation, vehicles and medicine, and usually they need to be fairly loud in order to ensure that they can be heard above ambient noise. Given the myriad problems associated with exposure to loud noise over long, and even short, periods of time (Smith, 1998), which of course include not only auditory problems but others such as cardiovascular problems (Babisch, 1998) and a whole range of cognitive and performance problems (World Health Organisation, 1993; Smith, 1993; Edworthy, 1997), it is something of a contentious issue as to whether auditory warnings should be used at all. However, there are number of reasons why the safest solution in many noisy environments is to provide yet more auditory stimulation. Primarily, research shows that hearing is our primary warning sense; that is, a sound which is loud enough will be heard, and we can do nothing about blocking out that sound. For vision, the obvious alternative, we need to be looking at the right place at the right time and can more easily ignore visual stimulation. Several research studies (e.g. Wogalter & Young, 1991; Wogalter et al, 1993) show that when visual and auditory warnings are directly compared, compliance rates are much higher to auditory warnings. Additionally, in many noisy environments people frequently move about, meaning that any warning presented visually is likely to be missed if the observer is not in the right place at the right time. Even in work environments where there is little movement (e.g., flying) it is often the case that the pilot's visual sense is so overloaded that the provision of yet more visual information is likely to be useless.

Ergonomics can indeed provide us with the background information which will allow the appropriate modality to be chosen in any specific environment. Deathridge (1972) provides us with a comprehensive table which guides us in the selection of an appropriate modality for information presentation (Table 1).

Since our hearing and our vision functions much as it did in 1972, the guidance is mostly relevant today. However, there have been some advances in technology which now allow auditory warnings to be used where only visual would have sufficed before. For example, there have been significant developments in speech technology which means that both digitised and artificial speech can now be used to

Table 1. Comparison of auditory and visual presentation modes (from Deathridge, 1972)

Use auditory presentation if:	**Use visual presentation if:**
The message is simple	The message is complex
The message is short	The message is long
The message will not be referred to later	The message will be referred to later
The message deals with events in time	The message deals with locations in space
The message call for immediate action	The message does not call for immediate action
The visual system is overburdened	The auditory system is overburdened
The receiving location is too bright or dark-adaptation integrity is necessary	The receiving location is too noisy
The person's job requires moving about	The person's job allows them to remain continually in one position

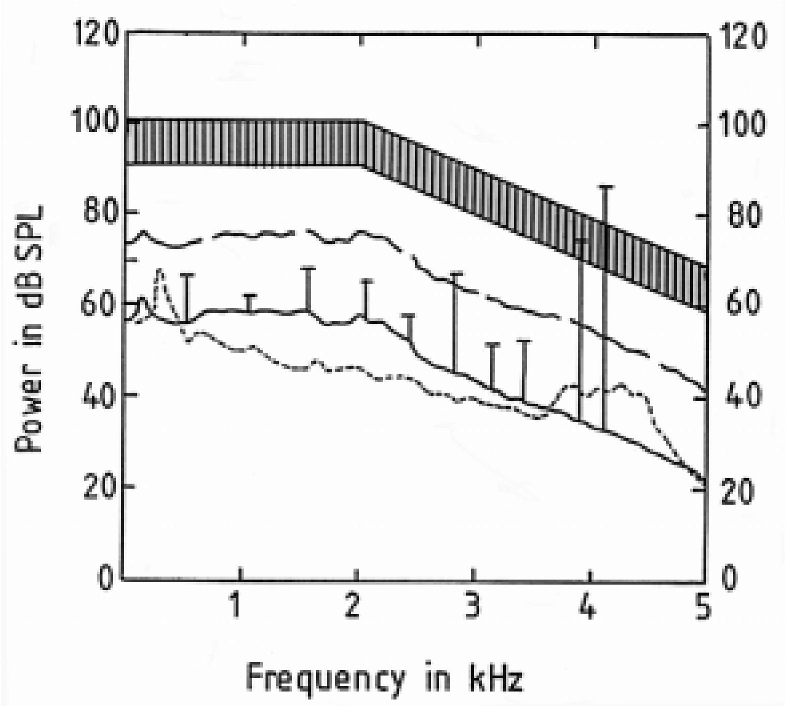

Figure 1. Noise spectrum, threshold, appropriate band for auditory warning components and components of a single auditory warning for a BAC 1-11 aircraft (from Patterson, 1982)

communicate many problems. This will increase the likelihood that auditory presentations might be used to convey long and complex information, for example. Also, the development of auditory head-up displays (these are displays that are now quite commonly used in aviation, which display the user's instrumentation directly in the line of sight, with accompanying binaural auditory cues) means that sound can be used to locate information in two- and three-dimensional space. Finally, recent advances in auditory warning design means that it is possible to convey rather more than could traditionally be conveyed through arbitrary auditory signals such as bells, buzzers, and 'bleeps'. It is worth noting also that although the visual and the auditory modalities are the two primary modalities through which warnings are most frequently conveyed, other forms of stimulation can also work well in the warnings arena, particular tactile (e.g. Sorkin, 1987) and olfactory warnings (e.g. Hatem & Lehto, 1995).

Auditory warnings for noisy environments

Audibility

Many of the situations in which auditory warnings are deemed necessary possess complex, and sometimes quite intense, noise spectra. Three such examples include factory floors where loud machinery may be in use (and where operators are likely to be wearing ear defenders), the cockpit of a helicopter and the flight deck of an aircraft. In all three of these examples it is possible to get some idea of what the typical ambient noise spectrum looks like, as it is not likely to vary greatly on a day to day basis. However, since both the level and spectrum of aircraft noise will vary as a function of speed, height, and current activity, these variables need to be taken into account in some way. In other areas where auditory warnings are used such as hospital wards, noise levels can fluctuate quite significantly. As the detectability of auditory warnings will be determined by the ambient noise over which they will need to be heard, typically a worst-case spectrum should be used although care must be taken to avoid auditory warnings which are excessively loud. It may also be possible to implement warnings which vary in their loudness level depending on the prevailing loudness level in that environment.

The detectability of any sound in a given noise environment will be determined by masked threshold, and will thus depend upon the action of the auditory filter. The auditory filter thus serves as the basis for two expert systems for predicting and assessing the audibility of warnings. Patterson's guidelines for auditory warning implementation (Patterson, 1982) are based on his model of the auditory filter (Patterson 1974; 1976; Patterson & Nimmo-Smith, 1980). An alternative approach from Laroche et al (1991) is based on Zwicker & Scharf's model of the auditory filter (Zwicker & Scharf, 1965). Both approaches are reviewed briefly here.

Figure 1 shows the noise spectrum of a fixed-wing aircraft, together with threshold and auditory warning calculations for that environment. The lowest solid line shows the spectrum of level-flight noise (when the plane is flying normally, at a reasonable speed, and not carrying out any specialised manoeuvre), which is the most typical noise spectrum. The dashed line illustrates a noise spectrum for other, more rare, flying conditions. The solid line above the lowest solid line shows auditory threshold in level-light noise as predicted by Patterson's model. The solid, shaded area above this is the appropriate band for auditory warning components. The lower of these lines is 15dB, and the upper line 25dB, above masked threshold. At 15dB above threshold auditory warnings are hard to miss, and by 25dB above threshold there is nothing to be gained by making warnings yet louder. Indeed, there is much to be lost because as the absolute level of the warning rises, so does the risk that warnings will become aversive. Aside from the associated auditory problems, a major risk is that warnings that are excessively loud will be switched off and thus rendered useless. In practice, it is just as important to ensure that warnings are not excessively loud as it is to ensure that they are loud enough to be heard above ambient noise.

The shaded band in Figure 1, the appropriate band for auditory warnings as determined by the model, suggests that different components need to be at different absolute levels of loudness in order to be subjectively equal in loudness. Thus in this example a component which is appropriately loud at a low frequency would be too loud if presented at the same level in the upper regions of the spectrum as there is less ambient noise in that region. The vertical lines in Figure 1 show the levels of the 10 individual components of a firebell typically used in this environment. When compared with the appropriate band for components, it can be seen that all but two components will be inaudible. Of the two that are audible, one is in the appropriate band and the other is too high. This will result in a warning which is unnecessarily shrill. It will be easily masked because if there is suddenly a lot of noise around the frequency of the audible components, the noise will mask those components; other components at different frequencies will not be able to compensate, because they have been shown to be inaudible. A warning such as this firebell will typically also be hard to localise, which may not be a problem in this application but could be a problem in other environments where the operator is moving around. Patterson's guidelines have been implemented in a number of projects including the design of auditory warnings for helicopters and for hospitals. Both projects are described in detail elsewhere (Edworthy & Adams, 1996).

A second expert system for assessing auditory warnings is that developed by Laroche et al (1991). The central principle of this approach is to model the excitation pattern that would occur

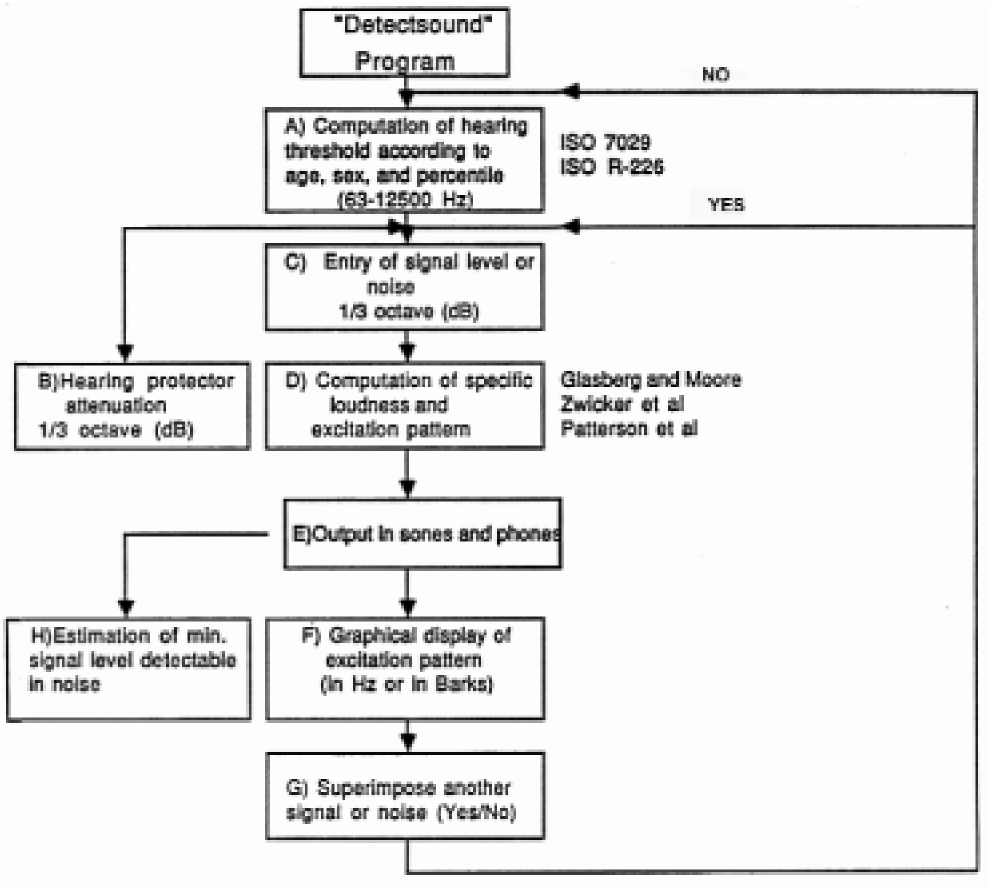

Figure 2. Flow chart showing stages of the 'Detectsound' process (from Laroche et al, 1991)

at the ear if particular sounds and noises are presented. The system is based on Zwicker & Scharf's model of the auditory filter (Zwicker & Scharf, 1965) which is validated for a larger range of frequencies, and higher sound pressure levels, than is Patterson's model. The model, called 'Detectsound', which is marketed as a set of programs, models the functioning of the ear when it detects warning and other sounds. The main stages of the process are shown in Figure 2. The first stage is to take account of how the hearing of individuals will be affected by age and sex. Attenuation due to the wearing of hearing protective devices is also taken into account here. The second stage is to calculate the transmission factor, if necessary. The transmission factor is a function of the way sound is transmitted from the outer to the inner ear, which varies non-linearly as a function of frequency. Thus a correction may be necessary here, depending on the frequencies concerned. The third stage, a central stage, is the calculation of the excitation levels that would be produced at the ear, given the sound or noise that is currently being evaluated. This involves the modelling of the auditory filter, which can be conceived as a bank of individual filters operating at different centre frequencies which, when taken together, mirror how the ear would filter that same sound. The fourth stage involves the calculation of the actual loudness levels involved, while the final stage involves the calculation of total loudness and the superimposition of noises and sounds. Here, the excitation pattern of one sound can be compared with another. The excitation pattern that would be produced by the ear in response to each of the sounds can be effectively viewed as a visual pattern. These patterns can be superimposed graphically. If one pattern completely covers another when they are viewed together, then the covered sound will be inaudible. So a sound whose excitation pattern visually occludes another on a graph will, in practice, mask the occluded sound auditorily.

Comparisons between sounds can be carried out systematically using this technique. For example, the excitation patterns produced by noise can be compared with those produced by specific warnings, in order to see if any specific warnings will be masked by the background noise. Warnings can be directly compared, showing whether or not specific warnings will mask one another; and warnings can be compared with other sounds, to see if either will be masked by the other.

A study by Momtahan et al (1993) made exactly these sorts of comparisons when looking at the alarms in an operating theatre and a recovery room in a Canadian teaching hospital. The study took a series of recordings of ambient noise, warnings, and other sounds typically heard in that environment and made a number of meaningful comparisons using the 'Detectsound' software. This study revealed a number of interesting findings. It was found, for example, that many alarms would not reach masked threshold, if heard with specific other sounds. In particular, an orthopaedic drill could potentially mask the majority of warnings used in the same environment. The group of alarms which could be masked included important alarms such as the cardiac monitor, ventilators and other anaesthesia equipment.

Both Patterson's and Laroche et al's thorough and analytical approaches to the detectability of warning signals highlight some of the problems which currently exist. One of the major problems is that warnings are either too loud or too quiet, whereas if a proper empirical approach is taken, they could be tailored appropriately to the noise environment. Another problem which produces an acoustic by-product is that there are often too many warnings in a single environment, which brings with it two major problems; the first is that warnings are more likely to mask one another, and the second is that in order to be heard, the tendency is to make each warning louder and louder so that the problem of excessive noise is exacerbated. However, there are certain styles of warning, and warning design protocols, which will minimise the impact of this problem and these will be considered later.

Other acoustic issues

Two important issues, which will be touched on here, are that of localisability of warning sounds and the impact of the use of hearing protection devices. Both are highly theoretical and complex areas (e.g. Blauert, 1983; Wilkins & Martin, 1984; Jones & Broadbent, 1987), but there are some simple and important aspects of both of these issues which need to be borne in mind in relation to auditory warnings.

The localisability of auditory warnings is an important issue. Although the localisability of the firebell shown in Figure 1 is probably not an issue of great importance because it is heard in a confined space, if the same sound were used as a back-up (reversing) alarm on a lorry then localisability would be a central issue if it needs to be heard by pedestrians who may be standing anywhere in the vicinity. In general, localisability will be improved by having several audible components in the warning sound, preferably with a fairly low fundamental frequency. It is of some concern that the most ubiquitous type of warning sound is the continuous tone, often a sinusoid (thus having only a single component) which, as well as all the other disadvantages associated with such a tone, is very hard to localise. Such sounds are simply inappropriate acoustically as warning sounds.

Another important issue to bear in mind is that in many environments in which auditory warnings are used, ear muffs or ear plugs (or both) are used. While generally it is advocated that noise reduction policies are a better answer to occupational noise problems than the use of such devices (Jones & Broadbent, 1987), the use of such devices inevitably continues. Some hearing protectors can actually improve the localisability of sound, certainly for hearing-impaired listeners (Abel, 1993; Abel et al, 1993; Abel & Hay, 1996), and in certain frequency regions the audibility of wanted information (such as speech) can be improved in relation to unwanted information (Jones & Broadbent, 1987). To some extent the particular brand of device worn can have an impact on the perception of warning signals, so when these are used it is probably best to consider the impact on a case-by-case basis.

Design

Before the days of digital technology the types of auditory warning available for use was restricted to horns, bells, buzzers, sirens and the like. The types of sounds that can now be designed is, however, more or less unrestricted. Warning sounds can range from modified traditional warnings, to 'tune-like' warning sounds, through sound images representing actual sounds made by actual objects and events. However, it is more than likely that not all of these sounds will work as warning sounds. Additionally, improved speech technology means that the use of speech warnings is a much more attractive prospect than would have been the case a few years ago. It is true to say that there is no agreed design type that is more suitable than any other, and that this is an area where much research is needed. However, there are a number of interesting design protocols which alleviate many of the problems associated with traditional auditory warning design and implementation. Some of these will be reviewed in the following sections.

Speech versus nonspeech

Several studies have directly compared the use of speech warnings with the use of nonspeech warnings (e.g. Simpson & Williams, 1980; Hakkinen & Williges, 1984) and these studies appear to show some advantage for speech warnings. However, we have to bear in mind that such studies typically compare newly-developed speech systems with potentially out-moded nonspeech systems, so that the comparison is hardly a fair one. Indeed one of the studies compares a newly-developed speech warning system with a nonverbal system consisting solely of single tones. Single tones provide no information as such, so it is not surprising that a speech warning system would out-perform such meagre nonverbal signals. That aside, the great advantage of speech over nonspeech is that, if it is intelligible, its meaning should be unambiguous. However, it is more difficult to produce intelligible speech warnings for a complex noise environment than it is to fit a nonspeech warning to the same noise spectrum. In addition, the very lack of ambiguity in speech might be a problem. For example, a discreet nonverbal warning is a hospital ward will attract the attention of those trained in its meaning without causing undue concern for both the patient and his or her relatives. Speech warnings in this environment are likely to cause more problems than they solve. Finally, many workplaces are multi- or bilingual which reduces the viability and effectiveness of an exclusively speech-based warning system.

One design compromise is to design warning sounds which mimic speech in some way, but which retain their nonverbal nature. For example, a set of warnings designed to illustrate proposed new operating theatre warning standards (Patterson et al, 1986) included one or two warnings which mimicked the temporal pattern of the warning word itself. For example, the warning sound for 'Cardiovascular' contained 6 pulses, the same number as the word itself, and the pitch pattern consisted of three pulses at one pitch followed by three at a lower pitch. This warning is very easily learned and retained.

However, while such design protocols appear to produce easily-learned warnings, we need to bear in mind that, used to excess, confusion may occur. Indeed, just as important as appropriate design is the issue of keeping the number of warnings to a realistic level; such a goal becomes more elusive as it becomes technically easier to arm equipment with alarms and warnings for every conceivable fault, and where manufacturers are increasingly aware of the risk of legal consequences if they fail to warn users of potential problems which might develop in the use of that equipment.

Warning Design Protocols

The number of auditory warnings in use is likely to increase in the future, thus it is important to design warnings so that they perform the function for which they are designed, without causing undue stress and annoyance. Whereas the central design tenet thirty years ago was to design alarms which, by their very nature, cause startle and annoyance, the more ergonomic approach taken today is to design warnings which attract attention to a problem without causing undue startle and annoyance. The distinction between auditory warnings and alarms is defined elsewhere (Edworthy & Hellier, in press). Auditory warnings should also allow people to communicate in order to identify the problem at hand, which traditional alarms typically do not do. It makes no sense in many situations to aggravate an already stressful situation by increasing the level of arousal of the recipient so far that they are then unable to deal with the problem in hand. Alarming sounds are appropriate under some circumstances (for example, burglar alarms) but generally they are not. Thus more recent approaches to auditory warning design focus on the need to communicate without overwhelming, and on the need for communication.

Traditional warning sounds

Traditional warning sounds such as bells, horns, klaxons, sirens and the like possess a number of undesirable acoustic qualities. Typically they are too loud for the application in which they will be used; they are usually continuous once activated, which gets in the way of speech and other communication (e.g. firebells); and they are often irritating and aversive. However, they do have the advantage that they are known to be warnings both within and across cultures (Lazarus & Hoge, 1986). It has also been shown that traditional warnings are particularly salient when heard among other sounds (Ballas, 1993). As there is much evidence to show that the essence of a sound can be retained without having to retain all parts of the sound (e.g. Solomon 1959a; 1959b; 1959c; Warren & Verbrugge, 1984) then it follows that it might be possible to retain the essence of some traditional warning sounds while editing out the more irritating qualities. It is possible, for example, to digitise and edit a bell sound into a new sound which still sounds like a bell, and then to use this sound in more up-to-date, ergonomic design protocols. In particular, the design protocol outlined by Patterson would allow such a resynthesis.

'Patterson'-style sounds

Along with his guidelines for setting appropriate levels for auditory warnings, Patterson set out a design protocol which overcomes most of the problems associated with more traditional types of warning. The design is set out in Figure 3. The diagram is in three sections, as is the design procedure. The first step is to design a pulse of sound lasting (usually) less than 500ms in length. This pulse contains all the important acoustic information which will later aid localisation and be resistant to masking. The pulse would typically have a fairly low fundamental frequency (below 1000Hz) and would possess a number of harmonics. The amplitude envelope is also shaped so that the sound does not initially come on at full level, so as to avoid startle. This pulse is the building

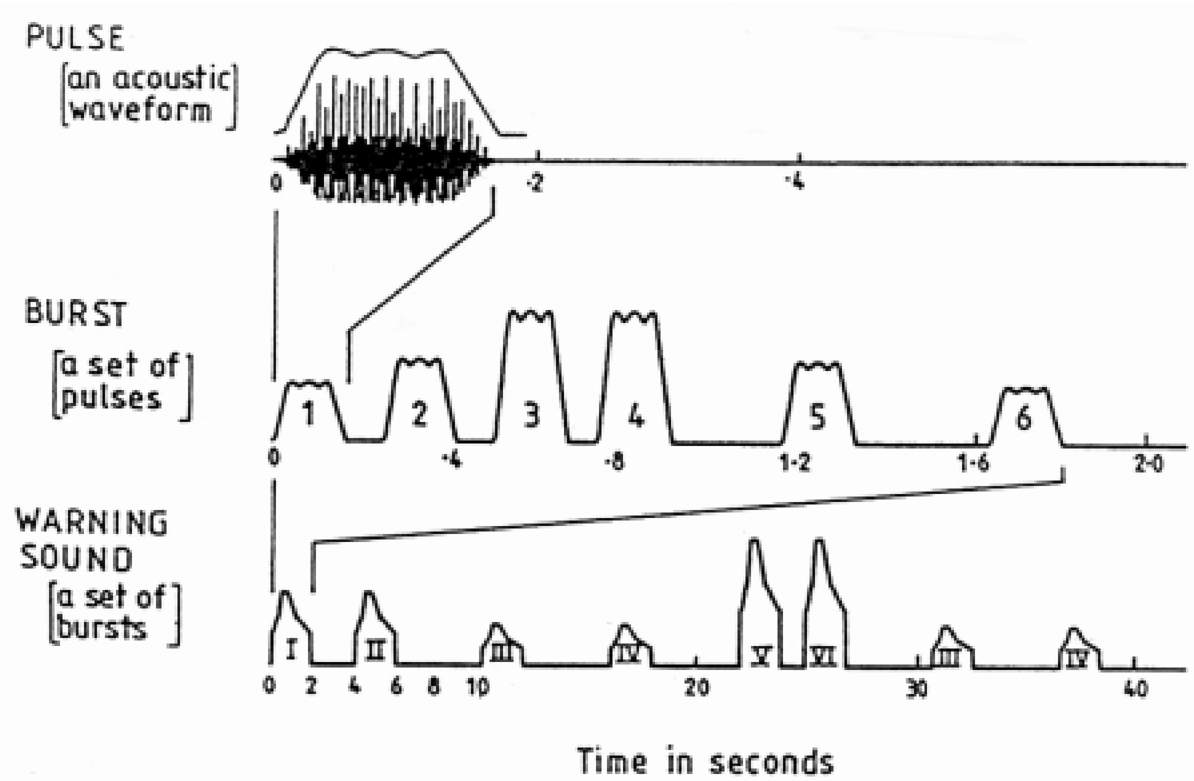

Figure 3. Diagram of the three stages of construction of a Patterson-style warning. The top section shows the pulse, the basic unit of sound. The middle section shows the burst, the 1-2 second melody-like structure. The bottom section shows the course of a complete warning, consisting of bursts varying in urgency, interspersed with silence. Time is shown in seconds underneath each section. The size of the units in the middle and lower sections gives a rough guide to amplitude.

block of the whole warning. The next design stage, shown in the centre of Figure 3, is to design a 'burst' of sound typically lasting one or two seconds. This burst consists of the pulses played several times, possibly varying the pitch and the time intervals between each of the pulses. Thus in effect a short melody-like sound is constructed. The final stage of construction, shown at the bottom of Figure 3, is to construct a complete warning which consists of bursts of sound played at different levels of urgency, with time intervals between them to allow communication. The precise ordering of the bursts will depend on the situation, for example if the situation is very urgent then two attention-getting bursts might be played, followed by a brief pause, followed by two bursts more urgent than the first; for a situation which is less urgent, it may be enough to get attention with two bursts, and then drop into a less urgent form of the burst so that communication can continue over the top of the warning, as shown in Figure 3.

This design protocol overcomes virtually all of the problems associated with traditional warnings. First of all, if the design guidelines are followed in full then warnings will be at an appropriate level of loudness. Secondly, the acoustic information in the pulse will allow localisation and will be resistant to masking. Thirdly, the burst is designed to provide enough stimulation to attract attention without being aversive. A fourth feature is that the design protocol allows the urgency of the warning to be manipulated by the designer at the level of the pulse, burst and warning (Edworthy et al, 1991;

Hellier et al, 1993). And finally, an integral part of the warning is the use of silence, so important in situations where danger is at hand and communication is vital.

This design protocol has been used in the design of a number of sets of warnings, including helicopters and medicine (Lower et al, 1986; Patterson et al, 1986). Full details of these projects can be seen elsewhere (Edworthy & Adams, 1996).

Stanford & McIntyre's approach

Stanford & McIntyre (1985, 1988; McIntyre & Stanford, 1985) explored the possibility of using radically different alarm sounds for the purposes of anaesthesia monitoring. The sounds proposed were based on vowel segments put together in different ways to signify different risks. Similarly to Patterson, the building block of their sounds were small units rich in harmonic content and made into larger units of sound. These warnings were tested in a number of ways, and among the most important results was that it was shown that these warnings were detectable at very low signal-to-noise ratios, as low as -24dB, much lower than that which could be achieved using the traditional sounds with which these warnings were being compared. From an occupational point of view then these warnings would not need to be played at such as high level in order to be heard, which is significant in itself. The results of the testing also showed that the new warnings were preferred to the old. This too is important because if warning sounds are disliked, they are likely to be turned off and then not reactivated in waiting for the next occurrence of the problem.

Auditory images

The design protocols outlined above involve the use of abstract, or semi-abstract, sound. A school of thought also exists which suggests that it might be better to use real, everyday sounds as warning sounds (e.g. Gaver, 1993). Thus, for example, one answer to designing a flood warning might be to use the sound of water rushing into a container. If designed well, the sound itself can give information about how fast the water is rushing in, how close the container is to being full up and so on. There are several logical reasons for this. First of all, when we listen to everyday sounds our primary response is to identify the object or event making that sound. In addition, we do not need to learn the meanings of everyday sounds in the way that we might need to learn the precise meaning of abstract sounds. There is certainly much scope for the use of such sounds in providing feedback and monitoring information (e.g. Gaver 1989; Rauterberg, 1998), although currently there is less evidence to show that such sounds will work well as warning sounds. It needs to be borne in mind that we may well listen to warning sounds in a different way to other sounds in specific environments (Ballas, in press), and the temptation might be to provide many such sounds because of the ease of learning and recognising them. If large numbers of such sounds are used, they may cease to be effective as warning sounds. Furthermore, the masking of one sound by another, and the overloading of the operator with excessive sound will always be a potential problem, no matter what sounds are used.

Other Issues

False alarms

At least as important as proper ergonomic design of warnings is the issue of false alarms. From an acoustic point of view, false alarms provide information of no use whatsoever and serve to increase the noise levels within that environment. From an occupational point of view, they will, over time, lower performance on the task as there is evidence to show that people will match their response level quite accurately to the false alarm rate (Bliss et al, 1995). For example, alarms which are accurate for 90% of the time will produce response rates close to

100%, as people will respond in accordance with the warning's accuracy, and slightly above. If a warning is only 10% accurate, then once people have learned this they will respond only 10% of the time. Thus from an occupational point of view false alarms are costly both in terms of annoyance and performance.

Number of auditory warnings

One of the most intractable problems with the way auditory warnings are typically implemented is that the number in use in a specific environment tends to mushroom very quickly, so that tens, even hundreds, of warnings are potentially possible in a single environment. Aside from the masking and annoyance problems that will ensue, people are unable to differentiate between such large numbers of alarms, and there is the additional problem that there is a strong chance that they will cease to function as alarms if large numbers are used. There are a number of ways of reducing the number of alarms without compromising safety, however. One way is to restrict the use of individually different alarms to top-priority situations only, using specific sounds only to signal the category of risk thereafter. Thus only a single sound might be used to signal all second-priority situations, a different sound to signal third-priority situation and so on. For risks other than those requiring immediate action, there will be time for the operator to seek out more information from, say, a visual display. Such a design procedure has been used for military helicopters (Lower et al, 1986; Edworthy & Adams, 1996).

An alternative way of reducing the number of alarms in use is to focus on functions rather than equipment. For example, medical equipment is always changing, along with the alarms that support this equipment. The people who the equipment is designed for, however (the patients), do not change and so it makes much greater sense to assign specific alarms to specific medical functions or situations than to pieces of equipment. Kerr (1985) has shown that it is possible to include nearly all likely medical events within six medical risk categories. Thus there is no real need to have more than 6 warnings in the hospital situation, although in practice there are hundreds. Sample warnings to accompany this rationale have been designed (Patterson et al, 1986) and the standardisation of such a system through the British Standards Institute (BS EN 475) and the International Standards Organisation (ISO 9703) continues.

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