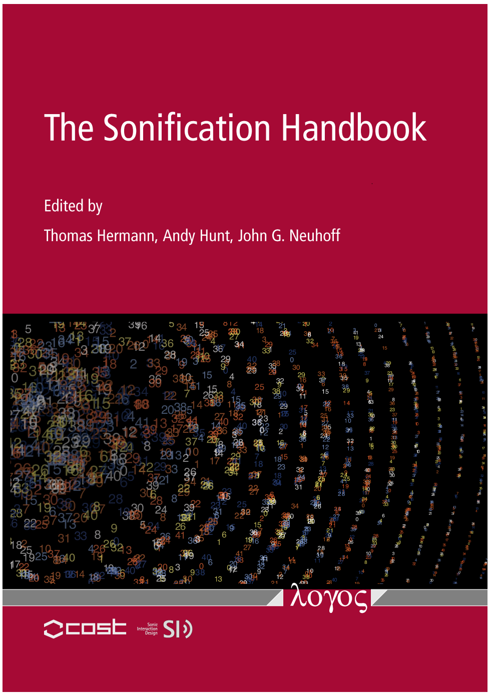

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Chapter 19

Intelligent auditory alarms

Anne Guillaume

How to make an intelligent alarm? The concept of intelligence is in the overall approach of an alarm system as part of an integrated workstation and taking into account the sound environment. The sound design is of course an important step to allow immediate identification of the hazard through a mental representation of the sound, quick learning, easy discrimination and memorization.

Reference:
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Media examples: http://sonification.de/handbook/chapters/chapter19

Chapter 19

Intelligent auditory alarms

Anne Guillaume

19.1 Introduction

When perceiving a sound-producing event, a person will try to find the meaning of the sound and locate where it comes from. Sound is used as a cue for identifying the behavior of surrounding sound producing objects, even if these objects are beyond the field of vision (McAdams, 1993). This spontaneous attribute probably corresponds to the most primitive role of auditory perception, which is to be warned of danger and prepare for counteraction. Because of this, for example, hikers can seek shelter as soon as they hear thunder, even if it is not yet raining. The sound of thunder plays the role of a natural alarm. This alerting function of sound signals is widely used in everyday life, and is also extensively used in the workplace, which is what we are interested in. In this case, the sound is no longer directly linked to the source of danger; the alarm is a synthetic sound, triggered to attract the operator's attention and result in a suitable reaction. This sound must distract the operator from the main task, and provide relevant information. Three kinds of information must be passed along:

- first, an indication of how serious the failure is, by helping the listener to perceive how urgent the situation is.
- The second type of information must provide clues about what triggered the alarm, using a customized sound iconography. This information must be transmitted while minimizing the attentional resources elicited by operators to manage alarms (Schreiber and Schreiber, 1989).
- A third type of information could be delivered concerning the location of the fault. For instance, in aeronautics and in road safety a rapid localization of the threat is of vital importance. Different studies effectively show that 3D sound enables a reduction in reaction times during search for a visual target (Begault, 1993; Bolia et al., 1999; Flanagan et al., 1998; Todd Nelson et al., 1998).

However, until the late 1980s, the detailed characteristics of sound alarms tended to be neglected. Alarms were installed here and there, without any real thought as to their acoustic features, or how to integrate them into a system of alarms. Operators started to complain about the mismatch between the properties of sound alarms and their purpose. This opened up a new field of investigation on how to design sound alarms, supported by an experimental approach.

In order to better understand the challenges and outcomes of research on this topic, the concept of the sound alarm will be described. Next, the perception of urgency will be addressed through considering the acoustic characteristics of sound sequences. A more cognitive approach to the problem helps in conceptualizing the many factors to be examined when designing an alarm.

Furthermore, an alarm cannot be designed in isolation, but as a component in a system of alarms customized to a specific environment. An ergonomic survey of the workstation is a prerequisite, prior to the development of any alarm system. Such a survey helps to prioritize emergencies. An intelligent alarm system is the final phase in the development, adapting its functionality whilst in use by the operator. The design of sound alarms is a complex task because of the many requirements imposed by their function, their context and operators' expectations.

19.2 The concept of auditory alarms

Hearing is a primary alert sense, and so sound alarms aim at alerting operators of any change in the state of the system they are interacting with. According to Schreiber and Schreiber (1989), a system of alarms must have five properties:

1. announcing any anomaly as quickly as possible, without its detection being hindered by false alarms or alarms of lesser importance,
2. making the localization and identification of new alarm messages as easy as possible,
3. minimizing any interference with other signals,
4. minimizing efforts devoted to its management, notably in critical moments, and
5. giving accurate information on the problem's cause.

Auditory alarms are an essential complement to visual alarms, which usually provide more information. This complementary effect of auditory alarms is due to the fact that they are effective in all directions in space, whatever the position of the operator's head and/or eyes: the operator can concentrate on the main task without the requirement to systematically scan a control panel. If this was the case, the visual system would soon be overloaded, since visual information is processed in sequence. Auditory alarms are also very useful when the operator is absent-minded or in a state of rest. In fact sound alarms have the advantage of increasing the probability of an operator reacting to emergency conditions and of reducing reaction time. Sound alarms are used to attract the operator's attention toward the relevant visual information during critical situations. In aeronautics, they have two additional advantages: they are economical in space compared to visual displays and they take advantage of the fact that audition offers a fairly good resistance to relative hypoxia[1] (in downgraded conditions) (Doll and Folds, 1986).

Sound alarms can be placed in one of two categories: speech or non-speech. The advantage of non-speech alarms is that they attract attention more effectively than speech alarms, which may be intertwined into the communication flow, and thus be unheard. Reaction time is shorter with non-speech alarms than with speech alarms (Simpson and Williams, 1980; Wheale, 1982). On the other hand, speech alarms provide more information, but the message delivered must be simple and concise. These two types of alarm may be associated in one system: non-speech to alert, speech to convey information, or even a possible solution. Under heavy workload, adding a non-speech signal to a speech alarm may be useful, because it helps to discriminate the speech alarm from the flow of speech-based information flooding the operator. However, depending on the context, speech-based alarms are not always suitable. For example, in intensive care units, delivering the message through speech might generate a considerable amount of stress for the patient. This was also the case, under specific operational conditions, for aircraft pilots during the Vietnam War (Doll and Folds, 1986). In those cases, it is essential to pay great attention to the sound design of non-speech alarms, to make sure they are well-suited to their application.

19.3 Problems linked to non-speech auditory alarm design

A number of specific organizations, such as intensive care units (ICU), are equipped with many alarms (examples of alarm sounds in operating room are **S19.1**, **S19.2**, **S19.3**, **S19.4**, **S19.5** and **S19.6**[2]). Their purpose is to help reduce the staff's workload during periods of intense activity. In reality, these alarms are often ill-adapted to this purpose: either too numerous, too loud or inaudible, or not adapted to the degree of urgency they are supposed to convey. Sometimes, in an ICU, up to twenty or thirty alarms are dedicated to monitoring a single patient, and from one patient to another relatively identical sound alarms can indicate very different problems. (Arnstein, 1997; Montahan et al., 1993; Stanford et al., 1985; Meredith and Edworthy, 1994).

ICUs are just one example. The problem of ill-adapted sound alarms can also be encountered in the monitoring systems of industrial facilities (Lazarus and Höge, 1986), or in aeronautics. In the latter environment, this problem is relayed perfectly by a pilot's report quoted by Patterson (1990). The pilot reports he was destabilized by several sound and visual alarms being activated simultaneously, making it impossible for him to react suitably, in this critical moment when he was supposed to analyze and manage the problem which triggered the alarms. This problem, noted by Wheale et al., (1979), Patterson et al., (1986), Sorkin et al., (1988) results from alarms being layered upon each other as the need arose, rather than having an all inclusive system designed in the first place. Sound levels are usually at maximum loudness, according to the "better safe than sorry" principle (Patterson, 1990). Very loud alarms are thus installed, to make sure they are perceived. However, the end result is to make

[1] Hypoxia: Hypoxia is defined as inadequate oxygen supply to the cells and tissues of the body. The major risk is brain hypoxia. In aeronautics, the main cause of hypoxia is altitude. Different technologies have been implemented to compensate for the altitude-related hypoxia, but it is important to warn the operators when a failure of these systems occurs.

[2] the alarm causes are explained on the website

them more harmful than helpful. They prevent any communication between team members, and disturb operators' cognitive activity.

19.4 Acoustic properties of non-speech sound alarms

In order to better meet operator's needs, many criteria come into play. These prerequisites are context-dependent, of course, but are quite identical in generic terms (James, 1996):

- sounds must be unique in the surrounding sound environment;
- sounds must be easily discriminated from one another;
- the sound warning must convey the right level of urgency, in relation to a degree of priority;
- the sound warning must be sufficiently audible to be detected, but should not be deafening, or prevent communication among team members.

19.4.1 Sound spectrum and intensity

A sound alarm must be designed while taking into account its surrounding sound environment. Taking into account the spectral content and noise level of ambient noise, the spectrum and sound level of alarms should be selected to interfere as little as possible with communications between crew members, yet to be sufficiently salient to be perceived reliably without being confusing or disturbing. An example from aeronautics, a very noisy environment, will help to clarify this design goal. Patterson (1982) developed a model in which the masking threshold was predicted for a large number of spectra. In this study, Patterson recorded the spectra of various helicopters flying at different speeds and altitudes, right at the position where the pilot's ear was located. He then obtained data indicating in which frequencies the greatest part of the cabin's sound energy was concentrated. The alarm's spectral content was then chosen to avoid being masked by the frequencies dominating cockpits. An alarm with at least four harmonic components scattered throughout the spectrum runs a lower chance of being masked by environmental noises than an alarm concentrating its entire energy on a single harmonic. Alarm intensity must be determined in relation to the threshold at which the different components of its spectrum are heard above the noise. To be sure the alarm is heard (100% detection), at least 4 of its spectral components must be 15dB above their specific audible threshold. Exceptions to this rule can be made, notably when background noise requires components to be above 85 dB.

19.4.2 Perceiving the urgency

Intensity is undoubtedly the most important factor to convey the sense of urgency (Loveless and Sanford, 1975). The louder the signal, the stronger the perception of urgency. This might be explained by the fact that the danger is perceived to be in the immediate proximity of the participant (Ho and Spence, 2009). However, in noisy environments (industry, aeronautics), or in critical environments (intensive care units, operating rooms), this parameter can only vary along a narrow scale: if the signal is too weak, it will go undetected. If it is too loud, it will become painful and distract the operator (Patterson et al., 1986). Therefore, even though intensity plays a major role, it must be systematically controlled. Given that the spectral content and intensity of alarms are set according to the noise level, the idea is to try, as much as possible, to define alarms with acoustic characteristics linked to the operator's perception of a given urgency.

Edworthy et al., (1991), Hellier et al., (1993), and Hellier and Edworthy (1999) studied the effects of sound parameters in non-speech alarms on the psychoacoustic perception of these alarms' urgency. Notably, these authors tried to identify the connection between spectral and/or temporal properties of acoustic signals (see section 3 for definitions) and the possibility of quantifying and predicting the urgency level perceived by listeners. Their starting point is Patterson's alarm design (1990). For Patterson, the alarm is designed with a structural hierarchy (see Fig. 19.1): the base unit is a 100 to 300 ms long pulse. This pulse is repeated several times, at different pitches and/or intensity, using different tempi. The resulting sound, made up of these consecutive components, is a sound burst. This burst is about 2s long, and is perceived as a rhythmic atonal melody. The combination of bursts makes up the entire alarm (hear sound examples **S19.7**, **S19.8**, **S19.9** and **S19.10**). The alarm provides for silences between bursts, to give the crew time to communicate and react adequately. Edworthy et al.'s study (1991) shows that the faster the rate, the higher the pitch and the more irregular the harmonics, the greater the perceived urgency. Authors have come to the conclusion that it is possible to design sound alarms with a predictable perceived urgency. This approach demonstrates the role of low level factors in determining the perception of urgency.

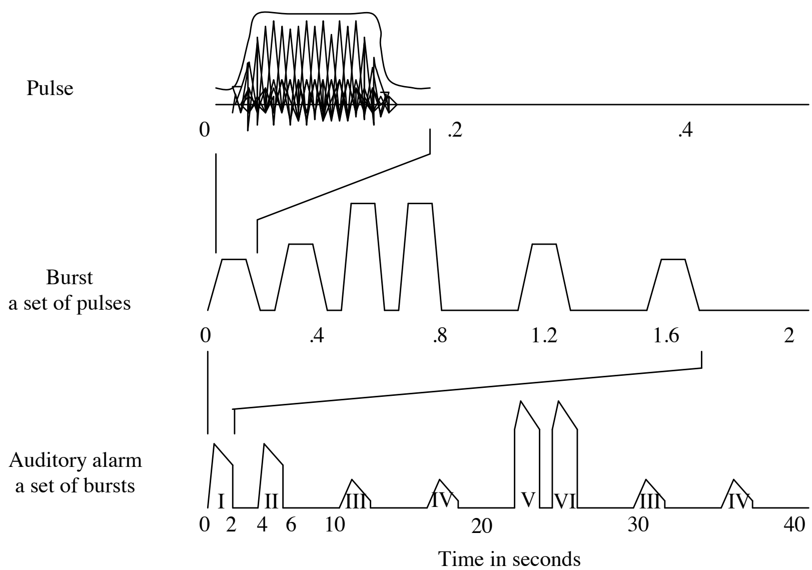

Figure 19.1: Design of alarms according to Patterson. The alarm consists of bursts that consist themselves in sets of pulses.

Alarm systems designed with these principles in mind were successfully tested in real-life conditions, either in noisy conditions (Haas and Casali, 1995), or under a moderate workload (Edworthy et al., 2000). However, the urgency of these alarms seems to no longer be perceived when the workload is more severe (Burt et al., 1995). Principles described by Edworthy appear to be relatively robust, but whether they still hold true under a significant workload is not clearly established. Bear in mind that sound alarms are usually triggered when situations become stressful.

19.4.3 Understanding the message of an alarm

Other authors recommend setting up a correspondence between the alarm's acoustic characteristics and the acoustic properties linked to the message: for example, imitating a heartbeat in order to monitor heart function (Fitch and Kramer, 1994). The message associated with the alarm is then easily identified and can help direct the operator's reaction. However, in some cases, the sound sequence is too close to the operator's everyday sound environment, and is no longer perceived as an alarm. Because it is a commonplace sound, it no longer conveys a sense of urgency (Stanton and Edworthy, 1999). This kind of approach can even be counterproductive, and disturb situational awareness. For example, the rotation of a helicopter rotor can be simulated by a sound sequence with varying intensity and tempo. If intensity or tempo decrease, it means that the rotor is slowing down, and that the helicopter is falling. But if these two parameters in the sequence change simultaneously, this means a decrease in the urgency level which goes totally against signaling a dangerous flight situation (Edworthy et al., 1995). Such an approach should therefore not be generalized but applied only on a case by case basis. It often applies to monitoring a critical physiological parameter through sound: for example, in the operating room, the conventional pulse oximeter 'beep' which gives heart rate through its rate and oxygenation level through its pitch, or respiratory sonification as described by Watson and Sanderson (2004). Sanderson et al., (2004) investigated the effectiveness of sonification to support patient monitoring. They showed that sonification triggered the fastest response, that visual displays resulted in the most accurate response and that sonification coupled with visual displays led to the slowest performance. Since Loeb and Fitch (2002) and Seagull et al., (2001) found no speed advantage when using sonification alone, the contribution of sonification with regards to its modalities requires further investigation. Sonification probably demands a learning phase. One of the main advantages of sonifying physiological signals in the operating room would be to provide the operator with information while performing surgery on the patient (and thus unable to access any external visual information). Sonification could provide the operator with a continuous stream of relevant information, to be consulted when the need arises, and interpreted according to context (Sanderson et al., 2005). However this approach should be very rigorous in order that these auditory displays add information rather than noise (Sanderson et al., 2009).

19.5 A cognitive approach to the problem

The alternative to the psychophysical approach could be to look for a link between the alarm's acoustic properties and the mental representation connected to the problem requiring action. The idea is to try and find whether the problem should be dealt with through the characterization of perceptive invariants conveying different degrees in the perception of urgency, or whether the approach should be broadened to consider that the notion of urgency is an abstract concept requiring the idea of a mental representation. This mental representation in turn may be modulated by the higher centers, according to a person's experience and surrounding context. Guillaume et al., (2003) carried out a series of parallel experiments (i) on signals designed according to the indications of Edworthy et al., (1991) to convey the perception of increasing urgency, or (ii) on real-life alarms recorded in military aircraft. When testing signals defined in (i), the results obtained validate Edworthy et al.'s findings. Sequences with increased pitch, fast tempo and irregular harmonics are perceived as having a greater urgency. However, the same results are not always obtained in the case of real alarms (ii). A number of sequences are classified as non-urgent, although their acoustic properties should have led listeners to perceive them as very urgent. These observations seem to demonstrate that different complex processes are involved in urgency perception. These processes seem to differ, depending on whether or not the sequence evokes a mental representation in the subject's mind. In cases where a mental representation may exist, hearing the sequence brings the mental representation to mind immediately. Judging as to whether or not this is an emergency depends on the association made by subjects between their mental association evoked by the sequence, and the emergency linked to it (Guillaume et al., 2003). According to Logan (1988), making this automatic depends on acquisitions stored in memory, and thus on representations which may be evoked when hearing various sequences. Automatic information processing (Schneider and Schiffrin, 1977) calling on a subject's personal experience probably comes into play when deciding whether a sound is perceived as conveying urgency or not, and allow for a fast and effective reaction. Furthermore, this activity is not attention-consuming, and may contribute to making the judgment on the urgency of a sound signal more robust, even under heavy workloads. On the other hand, in cases where no mental representation can be invoked, urgency is solely judged from the acoustic properties of the sound sequence, and context. This alternative is more attention-consuming, which would explain why the capacity to discriminate different emergency levels under heavy workloads tends to decrease. In such cases, listeners can determine the urgency of the alarm as theoretically planned, when their attention is focused on the task at hand. But if the hearer is busy doing another attention-consuming task, the acoustic characteristics of the sequence can no longer be properly analyzed, and the difference in urgency implied by the alarms presented is no longer perceived. Such an interpretation could help explain Burt et al.'s findings (1995) which show that the urgency of alarms is no longer perceived under high workload.

The cognitive approach involves searching for the mental representation of the cause for the alarm, and thus has a strong impact on the alarm's sound design. Designing the most relevant signal to evoke in as many minds as possible the same mental image requires implementing a very strict methodology to select the most representative sounds and to verify that choices made actually meet requirements.

Auditory icons (i.e., environmental sounds, see chapter 13) are good candidates for alarms which evoke mental representations. The challenge is then to find the more representative auditory icons for an event or a situation (McKeown et al., 2010). The association may be direct. The signal has a unique referent relation. For instance, if an aircraft is the target of a missile, the warning in the target aircraft could be rapid gunshots. More often the association is indirect. That means that the signal has more than one referent relation. In fact an indirect association may involve a real network of referent relations. For instance, the auditory icon associated with the lane departure warning in a car could be a horn, a car crashing, or knocking glasses.

A further improvement would be to use earcons (see chapter 14) dedicated to a specific threat. The design of these earcons could associate the cognitive and the psychophysical approaches. This would be done by slightly changing the acoustic characteristics of an environmental sound in order to render it more or less urgent. The challenge is that the modified sound should keep its referent in order to rapidly evoke the nature of the danger.

19.6 Spatialization of alarms

In order to improve the take up of information by operators in complex systems, new man-machine interfaces are presenting spatialized alarms. Information is presented in 3D sound, enabling operators to locate the virtual sound source rapidly and intuitively and direct their attention in this direction. This property of hearing is used to orient the direction of the gaze and/or the reaction of the operator. But, the act of localizing sources can also be favorable to segregating auditory streams. Thus, if two alarms go off at a short interval from one another, they are easier to segregate if they seem to be coming from different locations.

Determining the direction (given by its azimuth and elevation) of a sound by a subject depends on static and dynamic cues. Among the cues of static localization, the auditory system uses three types of cue:

(a) interaural intensity differences (IIDs) between the signals received by the two ears;

(b) interaural time differences (ITDs) – differences in phase and arrival time;

(c) spectral cues dependent on the shape of the pinna and of the head.

The first two cues are called binaural cues because they relate to the difference in information coming into the right and left ears. The third cue is "monaural" because it depends solely on information from one ear (Moore, 1997).

For binaural cues, auditory localization can be achieved by comparing the sound signals perceived by each ear. This comparison involves the differences in intensity, time and phase. The IIDs are due to the partial diffraction of sound waves in such a way that a signal reaching the ear opposite the source is weakened, and thus less intense compared to the signal coming into the ipsilateral ear. The ITDs correspond to both a difference in phase and a difference in time of the arrival of the signal between the two ears. The amplitude of interaural differences depends on the position of the source in relation to the listener. The interaural differences of phase and intensity vary according to source frequency. Differences in phase are only pertinent for low frequencies. On the contrary, IIDs are only a factor with high frequencies. They are linked to the head's diffraction properties. This diffraction only occurs for signals with wavelengths smaller than the cranial diameter. Diffraction does not occur for low-frequency signals, but diffraction by the head becomes apparent at 1500 Hz, and then increases as the frequency grows. The third spatial cue is monaural. It is determined by the treatment of information coming from one ear, independent of the other ear. This information is extracted from the resonance and reflection properties of the pinna (Blauert et al., 1998). The pinna modifies the spectrum of incident sound, depending on the angle of the sound's incidence in relation to the head. It thus supplies useful information for discerning elevation and for improving front-back discrimination.

Thus, the head and the pinna together form a complex filter, dependent on the direction of sound. This role as a filter is often characterized by measuring the spectrum of the sound source and of the spectrum of the sound reaching the ear canal. The relationship between the two measurements (normally recorded in dB) gives the head-related transfer function (HRTF). The HRTF varies systematically with the direction of the sound source in relation to the head, and is unique for each direction of space (Searle et al., 1975). The spectral modulations produced by the head and the pinna can be used to discern the location of the source. The most pertinent information supplied by the pinna is obtained for sounds that have a large spectrum of frequencies. High frequencies, above 6000 Hz, are particularly important since only these high frequencies present wavelengths that are short enough to interact with the pinna.

Spatialized sound, or 3D sound, is a technology that aims to present an acoustic stimulation via headphones in such a way that the listener perceives it as coming from a precise point in space. It is a much more ecological[3] technique than classic stereophony, in which sound, although lateralized, seems to come from the inside of the head when listening to headphones.

The application of HRTFs to a sound presented via headphones reproduces the characteristics of the sound that would come to each ear from a sound source near the subject. The subject virtually perceives this source in a spatialized way.

The rendering is optimal on the condition that the HRTFs used by a subject are the HRTFs measured on that same subject (known as personalized HRTFs) (Middlebrooks, 1999). However, for cost reasons in terms of availability, team-expertise level, complexity of material, and infrastructure involved, supplying each individual with personalized HRTFs is not very realistic. In order to spread 3D sound technology to as many people as possible, the solution would be to use "nonindividualized" HRTFs, generally manufactured from a head dummy. However, when subjects achieve a localization task with HRTFs different from their own (which is like listening through someone else's ears), their performance is not as good as with their own personalized HRTFs (Middlebrooks, 1999 Wightman and Kistler, 2005).

It is possible to improve 3D sound perception by adding dynamic cues, which can be achieved by following a subject's head movements with an appropriate device. The benefits are substantial in terms of realism and precision, particularly in the front-back dimension, but the latency time must be short enough when sending signals during the time when the head is moving (Brungart et al., 2004). This requires sophisticated and expensive equipment, and can only be considered in certain workplace setups, such as the cockpit of a fighter aircraft (Bronkhorst et al., 1996; Nelson et al., 1998).

19.7 Contribution of learning

Low level acoustic properties influence the perception of urgency, as clearly demonstrated by Edworthy et al., (1991), then Hellier et al., (1993). However, other factors come into play and may influence the perception of urgency. The influence of these factors may be such that

[3]In the Gibsonian acceptance of the term

in some cases they may reverse the ranking of urgency that would have been expected by the analysis of the acoustic properties. (Guillaume et al., 2003).

It seems that the perception of urgency is in fact a judgment on the urgency of the situation, developed out of the mental representation evoked by the alarm and the context. This mental representation might result from two phenomena.

The first phenomenon is linked to learning. The mental representation evoked comes from professional experience or from acculturation. All subjects living in a given society have mental representations of alarms. These representations are acquired throughout life, through continuously associating these sounds to the notion of alarm, i.e., potential danger to others or to oneself (ambulance siren, fire brigade siren, fire alarm, anti-theft alarms etc.). For most people, these mental representations make up a database stored by the brain in memory. When activated by a sound, the judgment on perceived urgency is brought on by associating this sound with its emotional content. The cognitive processes implied range from identifying the source to judging the urgency associated with the mental representation evoked, taking context into account. In the work environment, a number of alarms are typically learnt, and this will supplement and/or reinforce the mental representations associated with the notion of alarm. A sound will be strongly associated to a specific cause, and to its urgency, allowing for faster and more appropriate motor reactions. Such acquired alarm sounds are abstract sequences, where the mental representation is built up through learning. This is the case most often found in the workplace, where operators connect the abstract sound they perceive to the origin of the alarm.

The second phenomenon relies on the fact that some sequences spontaneously evoke a mental representation, such as environmental sounds. Stephan et al., (2006) have shown that strong pre-existing associations between the signal and the referent facilitate learning and retention of auditory icon/referent pairings. This corresponds to Stanton and Edworthy's (1999) approach, mentioned earlier. These authors carried out a number of experiments on alarm design for an intensive care unit. They compared the alarm recognition performance of a well-practiced team with that of a team of employees new to the job. The alarms were either existing alarms on resuscitation equipment, or new alarms specifically designed to be more easily linked to the situation having triggered the alarm in the first place ("representational" sequences). Results show that for the experienced team, the old alarms are the most easily recognized, while the opposite is true for the freshman team, who recognize the new alarms better. However, both subject groups consider that the existing alarms are more suitable than the new ones ("representational" sequences). This result might be explained by the fact that even though the new alarms have a clearer connection to the failure they do not directly evoke emergency situations, because they are not connected to danger in everyday life.

Graham (1999) also carried out an interesting experiment. He compared the reaction time obtained to stop, using the brakes, in a driving simulation task. Operators hear either a horn, or tires screeching, or two more traditional sound alarms, i.e., a 600Hz tone, or a verbal alarm. The shortest reaction time is obtained with the horn and the screeching tires, the horn getting a slightly faster reaction time. The horn is an abstract alarm drivers are so familiar with that it is often considered as an environmental sound. The connection between horn and driving reaction is strongly established. As to the screeching tires, this is an environmental sound linked to a mental representation which evokes danger while driving.

Generally speaking, in the case of abstract alarms, connection with urgency is not direct, and only comes through learning. This connection is obtained when the subject knows what the alarm means and reacts accordingly. The confusion experienced by the different teams comes from the fact that the same alarm can be used for problems having different levels of seriousness.

In the case of "representational" alarms, learning is also highly important. Of course, making the connection with the cause of the alarm is easier, but the sound sequence in itself does not necessarily bring the notion of danger to mind, and consequently does not evoke the necessity of an urgent reaction in everyday life. Yet it is this notion of danger which helps the operator to react in the work environment. The motor reaction adapted to the sound sequence will be acquired by learning.

In both cases, the connection between the sequence and the cause of the sound is less direct than it would be in the everyday environment. Allocating a specific urgency to the alarm will thus gain more attention, notably from people who are not familiar with these alarms. In a second stage, learning will help reinforce the link between the alarm and the subject's appropriate reaction, coming from perceiving both the cause of the emergency and its urgency. Thus the difficulty in defining an alarm lies in finding a link, as direct as possible, between the alarm and its original cause, in order to minimize the attention allocated by the subject to "decode" the alarm.

19.8 Ergonomic approach to the problem

In order to evaluate the cause and the actual level of urgency of the alarms, a preliminary ergonomic approach is required, studying operator activity to pinpoint operators' real needs. Observing and questioning operators is the only way to obtain a realistic assessment of the degree of urgency associated with an alarm. Sanderson and Seagull (1997) carried out observations focused on variation in anesthetists' responses to alarm across different phases of surgery in varying kinds of surgical procedure. They observed that alarms do not function simply to warn of problems, but instead are used as tools with varying functions depending on type and phase procedure. They classified anesthetists' responses to alarms into four categories:

1. **correction or change** the alarm induced an action to correct an unexpected event;
2. **expected or intended**: the alarm indicated a state of affairs and no actions were required;
3. **ignore**: the alarm was an artifact and no action was needed;
4. **reminder**: the alarm was a reminder to initiate an expected action.

They pointed out that many more alarms were ignored than were the basis for corrective actions, and that the ignored alarms mainly took place during induction and emergence phases for which the context was quite different from the maintenance.

Similarly, Guillaume et al., (2005) carried out an ergonomics survey to assess the respective importance of the various alarms used in the operating room. Anesthesia procedures were observed in different operating rooms in order to classify the auditory signals. For each auditory signal, the team of anesthetists explained its meaning, the consequences for the patient or the monitoring systems, and whether they needed to interact with the patient, the monitoring equipment, or the warning signals.

The categories were represented in four sets:

1. Signals indicated a clinical problem. There was a vital risk for the patient. At least one physiological parameter was out the range of normal values;
2. Functioning signals reminded the anesthetist to act on the monitoring system;
3. Technical signals indicated a failure in the functioning of the monitoring equipment;
4. Interfering signals included auditory signals that originated from other parts of the operating room.

This classification aimed to allow a graded level of urgency to the alarms. As spectrum analyses were also performed on each warning signal, the authors pointed out that similar spectra were observed for alarms belonging to different sets (and thus with different levels of urgency). The use of a functional classification as described by Sanderson and Seagull (1997) or Guillaume et al., (2005) could help with the implementation of a realistic grading of the urgency level of the auditory alarms, that would result in a gradation of the acoustic properties of sound spectra. The conception of a well-designed alarm system requires an excellent knowledge of the application as well as practical experience that can be acquired by an ergonomic approach.

19.9 Intelligent alarm systems

Intelligent alarm systems generally use artificial intelligence for the automatic diagnosis of problems. These computerized systems collect information on system status from sensors and use artificial intelligence to organize this corpus of data into a data stream helping to diagnose the problem. The underlying assumption is that automatic diagnosis will reduce the time lag between the occurrence of a problem and its correction, by minimizing the time required to identify the problem (Westenskow et al., 1992). This approach to problem diagnosis also allows for the prioritization of problems. Being able to grade failures onto a scale is essential. A single failure may have side effects impacting system operation, and trigger off additional alarms. This, in turn, can result in several alarms going off simultaneously, confusing the operator, unable to decide which problem should be dealt with first (i.e., “cascading alarms”) (Sorkin, 1988; Stanton, 1994). Under stress, the operator may choose to focus on a secondary problem and overlook the main failure, wasting precious time. Bliss and Gilson (1998) report the high-profile incident at the Three Mile Island nuclear power facility that underscored this problem. They cited Sheridan (1981) who noted that when detection of system failure is automatic, the sheer mass of display activity in the first few minutes of a major event can completely disturb the operators. For instance, at one loss-of-coolant incident at a nuclear reactor, more than 500 annunciators changed status within the first minute. Problem prioritization allows the system to trigger off only the one alarm corresponding to the main failure. The operator’s attention is then directed to the real problem. Complex algorithms come into play to diagnose the problem and manage priorities within the system (Zhang and Tsien, 2001). This engineering approach helps to limit the number of alarms which may be triggered simultaneously and reduces false alarms.

It also reduces sound nuisance and the stress associated with it. It also decreases the operator's cognitive workload, by drawing attention solely to the main problem. This approach supplements the sound design approach, which requires in-depth work on the properties of acoustic signals to achieve the quickest information processing possible (see Figure 19.2). In this framework, the content of the sound signal may be supplemented by the signal's presentation mode, notably through the use of 3D sound. In aeronautics, 3D sound is being widely investigated (Begault, 1993; McKinley et al., 1994; Nelson et al.,1998; Bolia et al.,1999; Brungart et al., 2003) to save that extra few seconds which in turn will help to save the aircraft by immediately directing the pilot's attention to the threat at hand. To summarize, we could define the concept of an intelligent alarm as the alarm that takes all these approaches into account.

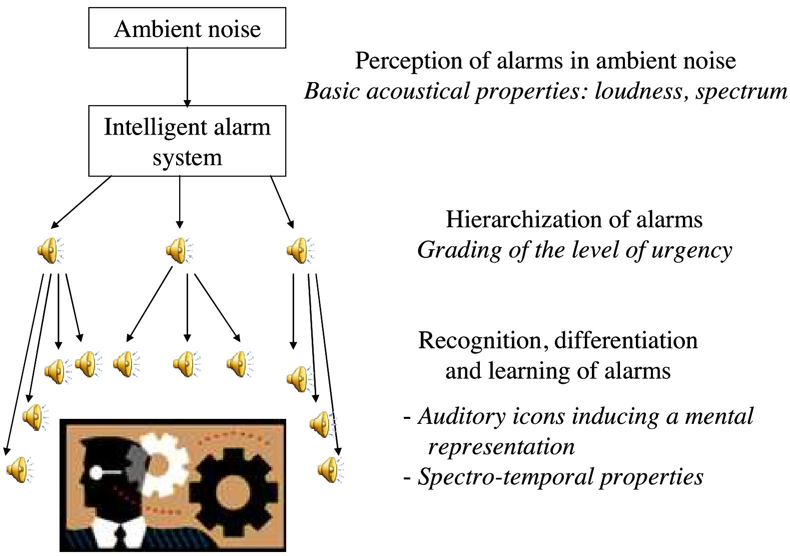

Figure 19.2: General scheme of an intelligent alarm system.

19.10 Conclusion

The complex issue of designing what can be called "intelligent sound alarms" requires bringing together multi-disciplinary teams, taking into account engineering, ergonomics and sound design aspects. The information-providing content of alarms has to convey the problem's degree of urgency and root cause. Psychophysical and cognitive approaches must be considered together, to evoke a mental representation while allowing the modulation of the degree of urgency perceived. Furthermore, reducing the attention consumed to manage alarm systems requires an ergonomic study of operators' real needs and the application of artificial intelligence in the management of the system of alarms.

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