Urgency mapping in auditory alarms: designing for the noisy ICU

Author 127

Track 10: The machine that goes 'Ping!'

ABSTRACT

Noise pollution in the ICU is a big problem with alarm fatigue as a consequence. Alarm management is needed, not only should there be less alarms, but also the acoustic quality of the alarms is of essence. Urgency mapping in alarms could prove a fruitful solution. In this paper different auditory alarm solutions which are susceptible to urgency mapping are discussed.

Keywords

Auditory alarms, urgency mapping, ICU, soundscape, alarm design

INTRODUCTION

While most hospitals pay utmost attention to the hygiene in their Intensive Care Unit (ICU), noise pollution is often neglected. In the last couple of decades the average sound pressure levels (SPL) in ICUs have increased almost 20 dBA, resulting in a SPL from 57 to 72 dBA during daytime and from 42 to 60 dBA at night (Busch-Vishniac et al 2005). To put this in perspective; these sound levels are equivalent to a vacuum cleaner at a distance of 1 meter during the day or conversational speech at 1 meter during the night.

While these sound levels may not cause direct health issues, prolonged exposure to such sound levels will cause sleep deprivation. Which consequently causes disruption of the immune system, occurrence of delirium and smaller undesirable effects such as higher levels of anxiety, stress and annoyance (Delaney 2015). To counter these possible effects, the World Health Organisation (WHO) advices sound levels with peaks below 40dBA in areas where patients are treated (Berglund 2015).

But these noise levels do not only affect the patients, it also causes a desentization of medical staff to auditory signals. In specific, a desentization to auditory alarms.

Analysis of the soundscape in an ICU found auditory alarms to be the cause of excessive noise levels in 30% of the non-patient-involved causes (Park et al 2014). These alarms are often reported to be unnecessarily urgent, loud and too numerous. Which can result in one alarm masking the other (Momtahan 1993).

This sheer exposure to a high amount of non-actionable alarms will cause alarm fatigue, which will result in unwanted behavior such as ignoring or shutting off of alarms. This can result in dangerous situations. So dangerous, that the ERCI actually have named it the biggest health technology hazard several years in a row. (Keller 2012) A summary of the problems associated with alarm fatigue can be found in table 1.

In most literature the solutions for this problem can be broken down into 3 parts: reduce the amount of false alarms, reduce the number of alarms in general (Lower 1986) and improving the acoustic quality of the alarm for the noisy environment. This paper focuses on the latter, and in specific on urgency mapping as a solution in current auditory alarm types.

METHOD

To find out how current auditory alarm solutions compare on urgency mapping in noisy environments based on their acoustic characteristics. I reviewed papers and books found via a Google scholar search, this search used combinations of the following terms: "alarm fatigue", "ICU", "auditory alarms", "urgency mapping", "sound scape", "noisy environment" and "alarm systems".

Problems	Underlying Reasons	Effects	Solutions
• High number of false alarms • Inaudibility of alarms due to competing sounds • Difficulty in differentiating between urgency of alarms • Increasing noise with increasing number of alarms	• Alarms are often used on a "better safe than sorry" philosophy. • Alarms are designed on the "principle of thresholds," leading to inappropriate use of upper and lower alarm limits and without taking into account that many threshold changes are reversible without any clinician intervention. • There is no urgency mapping (prioritizing alarms depending on the severity of the patient or equipment condition) involved in the design of alarms.	• Increased noise levels • Increased staff and patient annoyance • Decreased faith in the alarm system • Increased alarm response time • Decreased patient safety and work performance • Increase in adverse events	• Design of auditory alarms with distinct features • Design of smart alarms • Developing alarm protocols for improving alarm performance • Application of third-party alarm integration and notification systems

Table 1 Summary of problems, reasons, effects and solutions following a systematic review on alarm fatigue (Konkani 2012)

DISCUSSION

Most studies concerning alarm fatigue identified the three earlier mentioned solutions on alarm fatigue. While the first two are often elaborated broadly and seem to have already been tried in the field. It seems that a lot less is known for the improvement of the acoustic quality of the alarms. Research on this topic seems to be still in the relatively early stages. Most papers stay a bit on the theoretical side, a lot more testing often is needed to be able to conclude their topic. No specific papers were found on the subject of how the perception and the acoustics of alarms are changed in particularly noisy soundscapes. Much on this matter stays unknown.

RESULT

Several auditory alarm solutions were found which are susceptible to urgency mapping. In the next part of this paper the acoustic properties of these different solutions are discussed and the pros and cons of their use in the noisy ICU landscape. But first a general rule of thumb for designing alarms in noisy environments is provided.

General acoustic properties for urgent auditory alarms in noisy environments

In general the perceived urgency of acoustical sounds are best altered by varying sound attributes such as loudness, speed and pitch (Hellier 1993). A careful balance of these attributes will be needed in the design as not to invoke negative associations to these sounds. For example making an alarm too loud will pollute the soundscape even further and will provoke medical staff to focus on trying to shut it off as soon as possible instead of listening to the message it is trying to convey. So what is the appropriate loudness for an alarm to be distinguishable in the ICU soundscape?

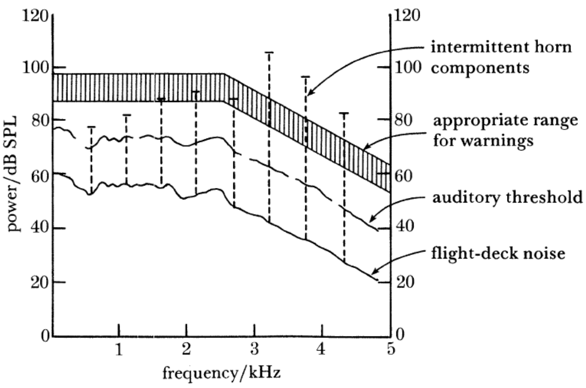

Figure 1 Auditory threshold (Patterson 1982)

Patterson stated that for any sound to be reliably audible in a noisy environment, that at least four components should be 15 dBA above auditory threshold. The upper line in the figure at 25 dBA above the auditory threshold gives the range for which the level will become excessively loud. (Patterson 1982)

Traditional warning sounds are often sound that will startle and are known across culture as 'alarm sounds'. (Lazarus 1986) Examples can be sirens, klaxons or bells. These sounds contain undesirable acoustic qualities and will rapidly become irritating. Its loudness and repetition are the only parameters that are used to indicate urgency. An advantage of these sounds is that they are very distinguishable between other sounds. (Ballas 1993)

These sounds prove to be hard to learn when there are more than 6 alarms and are easily confused. Because the human auditory system is not made to distinguish absolute frequency or intensity of sound. (Patterson 1986) Therefore, these sounds are less appropriate as an urgency mapping solution in auditory alarms.

Speech alarms prove to be more effective in urgency mapping, especially with short messages, because they can use vocal intensity to indicate urgency. Another advantage is that they can give information on the nature of the problem, thus making the warnings more unambiguous. (Graham 1999) There are a several studies that compared speech- vs non-speech warnings, which found verbal warnings to be more effective. (Simpson 1980, Edman 1982)

This can be explained by the fact that several steps in the thinking process get taken away by giving a clear command and learning of a specific sound is not needed. But it is unexplored if more complex messages might take away from reaction time, because they take longer to explain verbally.

There are some mayor issues concerning the use of verbal alarms in the ICU environment. There are studies that argue the intelligibility in noisy environments (Noyes 2006), possible complications may occur in multi-lingual work environments and especially its discreetness in front of the patients is very concerning topic.

Patterson-style sounds are based on the earlier given notion that humans are better at distinguishing sound changes than actual frequencies, Patterson provided a design protocol that overcomes most issues found in traditional type alarm sounds. This sound is divided in three modules (see figure 2) and consists of the following. A pulse with a rise time longer than 20ms and no higher than 1000 Hz to avoid startle. An rounded acoustic wave with an distinctive spectrum. The burst which is a set of pulses, each of which in a different pitch and with a characteristic rhythm. The final warning sound is expressed by a set of bursts with different intensity (Patterson 1990).

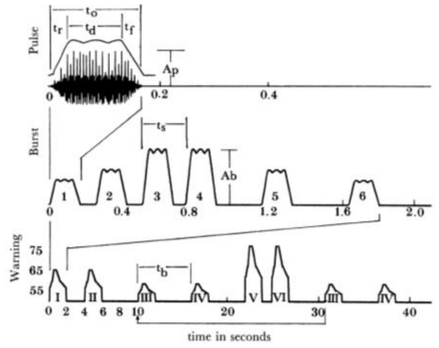

Figure 2 The modules of a prototype warning sound (Patterson 1990)

Edworthy tested this design protocol on its urgency mapping possibilities in several studies and proved its validity (Edworthy 1991)
So on the matter of urgency mapping in auditory alarms this is a good prospect in comparison to traditional warning sounds and speech alarms, however more research is needed on the matters of comprehensibility and learnability.

Auditory icons consist of everyday life sounds and metaphorical sounds. Medical icons could for example be the sound of a beating heart or a steady drip(Buxton 1994). They are thought to be more intuitive and therefore an easy to learn auditory alarm solution (Brazil 2012).
The use of everyday life sounds would make for a less obtrusive addition to the soundscape. However, they might be less easily recognized as an alarm (Gaver 1989). Another questionable point is if they are easily distinguishable in noisy environments. This is a matter that needs more research to be able to tell if this solution could be perfected for the ICU environment.

Earcons are musical sounds that are structured and grouped with principles comparable to those of computer icons. These auditory messages are designed to provide extensive information about certain objects' state and functions (Blattner 1989). An advantage to the use of earcons according to Jung, is that they can provide unobtrusive notifications to keep the soundscape 'cleaner' (Jung 2008).
But their meaning might be harder to learn (Blattner 1989). Which in a complex system as the ICU subsequently will lead to longer response times of the medical staff.
Furthermore, musical tones which at first felt ambient, may become a nuisance when people are exposed to them for a longer time. As can happen with commercial jingles for example. Besides, musical tones are susceptical to personal taste, music that one person finds unobtrusive might be perceived differently by others.
Table 2 provides a summarization of the different solutions.

CONCLUSION

Auditory alarms are inseparable from the ICU, their extra auditory stimulance next to the visual information of the machinery is essential for quick reactions of the medical staff. While they have to compete with the other noise in the soundscape, they also are a part of the problem itself. Designers need to find a way to optimize auditory alarms to be able to transfer complex messages within a noisy environment.

With the human hearing in mind, the ideal alarm would have the following characteristics: easy to localize, easy to learn and remember, able to convey enough information and is resistant to masking by other sounds in the soundscape.

Following this description, of the preceding auditory alarm solutions that are susceptible to urgency mapping, the Patterson-style sounds seem the most promising. However, there are simply too many unknowns to write off solutions such as auditory icons and earcons unquestioningly. But a lot of additional research and exploration is needed on the learnability and intelligibility of possible icons and earcons in the medical environment. I advise that future research should also look into the impact of the existing soundscape on the perception and acoustics of alarm sounds, seeing as this seems a rather unexplored topic.

Alarm solutions	Acoustic properties	Urgency mapping by	Pros	Cons	Additional research
Traditional warning sounds	Lmax=60 [dBA] Strong pitched, 'rough', near greatest hearing sensitivity (Ellis 2001)	Loudness & repetition	Distinguishable between other sounds	Hard to learn, only notification without additional information	
Verbal alarms	+18 [dBA] above ambient noise. Sounds within 300 to 3,000 Hz frequency range (Driscoll 1998)	Vocal intensity	Conveying complex information without learning,	Discreetness, intelligibility, language barriers in multi-lingual environments	Reaction time with complex messages
Patterson-style sounds	Combination of pulses, (with a rise time above 20ms, no higher than 1000 Hz, 15 dBA above ambient noise) in bursts	Combination and repetition of certain bursts.	Localizable, distinguishable		Comprehensibility & Learnability
Auditory icons	Everyday life sounds	Metaphorical meaning	Intuitive, unobtrusive	Less recognizable as an alarm, non-distinguishable in noisy environment	Comprehensibility & Learnability
Earcons	Structured and grouped musical sounds	Musically	Complex messages possible, unobtrusive	Hard to learn, different appreciation for musical tones by each individual.	Comprehensibility & Learnability

Table 2 Summary of elements concerning different auditory alarm solutions

REFERENCES

1. Ballas JA (1993) Common factors in the identification of brief everyday sounds. *J. Exp. Psych.: Hum Perc. Perf.*, 19(2), 250-67.
2. Berglund, B., Lindvall, T., & Schwela, D. H. (1999). Guidelines for community noise. In *Guidelines for community noise*. OMS.
3. Blattner, M. M., Sumikawa, D. A., & Greenberg, R. M. (1989). Earcons and icons: Their structure and common design principles. *Human–Computer Interaction*, *4*(1), 11-44.
4. Brazil, E. & Fernstrom, M. (2011) Auditory Icons. *In Herman, T., Hunt, a., Neuhoff, J., editors, The Sonification handbook,* chapter 13, 325-338.
5. Busch-Vishniac, I. J., West, J. E., Barnhill, C., Hunter, T., Orellana, D., & Chivukula, R. (2005). Noise levels in Johns Hopkins hospital. *The Journal of the Acoustical Society of America*, *118*(6), 3629-3645.
6. Buxton, W., Gaver, W., & Bly, S. (1994). Auditory interfaces: the Use of non-speech audio at the interface. *Unpublished manuscript*.
7. Delaney, L. J., Haren, F., & Lopez, V. (2015). Sleeping on a problem: the impact of sleep disturbance on intensive care patients-a clinical review.*Annals of intensive care*, *5*(1), 1.
8. Driscoll, D.P., Byrne, D.C. (1998) Acoustical considerations for effective emergency alarm systems in an industrial setting. *Poster Session, 1998 NHCA Conference, Albuquerque, NM*
9. Edman, T. R. 1982, Human factors guidelines for the use of synthetic speech devices, in Proceedings of the Human Factors Society 26th Annual Meeting (Santa Monica: Human Factors Society), 212 ± 216.
10. Edworthy, J. (1994). The design and implementation of non-verbal auditory warnings. *Applied ergonomics*, *25*(4), 202-210.
11. Edworthy J, Adams AS (1996) Warning Design: A Research Prospective. London: Taylor & Francis
12. Edworthy J, Loxley SL, Dennis ID (1991) Improving auditory warning design: relationship between warning sound parameters and perceived urgency. *Human Factors,* 33(2), 205-31., 5, 111-8.
13. Ellis, D. (2001, September). Detecting alarm sounds. In *Proc. Workshop on Consistent and Reliable Acoustic Cues CRAC-2000*.
14. Gaver WW (1989) The SonicFinder: An interface that uses auditory icons. *Human-Computer Interaction,* 4, 67-94.
15. Graham, R. (1999). Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application. *Ergonomics*, *42*(9), 1233-1248.
16. Hellier, E. J., Edworthy, J., & Dennis, I. (1993). Improving auditory warning design: Quantifying and predicting the effects of different warning parameters on perceived urgency. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *35*(4), 693-706.
17. Jung, R. (2008) Ambience for auditory displays: Embedded musical instruments as peripheral audio cues. *In Proceedings of ICAD 2008, volume 1, Paris, France, 2008. ICAD.*
18. Keller, J. P. (2012). Clinical alarm hazards: a “top ten” health technology safety concern. *Journal of electrocardiology*, *45*(6), 588-591.
19. Konkani, A., Oakley, B., & Bauld, T. J. (2012). Reducing hospital noise: a review of medical device alarm management. *Biomedical Instrumentation & Technology*, *46*(6), 478-487.
20. Lazarus H, Hoge H (1986) Industrial safety: acoustic signals for danger situations in factories. *Applied Ergonomics,* 17(1), 41-6.
21. Lower MC, Patterson RD, Rood GM, Edworthy J, Shailer MJ, Milroy R, Chillery J, Wheeler PD (1986) The design and production of auditory warnings for helicopters. 1: The Sea King. Report No. AC527A: Institute of Sound and Vibration Research, Southampton, UK
22. Momtahan, K., Hetu, R., & Tansley, B. (1993). Audibility and identification of auditory alarms in the operating room and intensive care unit. *Ergonomics*,*36*(10), 1159-1176.
23. Noyes, J. M., Hellier, E., & Edworthy, J. (2006). Speech warnings: a review. *Theoretical Issues in Ergonomics Science*, *7*(6), 551-571.
24. Park, M., Kohlrausch, A., de Bruijn, W., de Jager, P., & Simons, K. (2014). Analysis of the soundscape in an intensive care unit based on the annotation of an audio recordings). *The Journal of the Acoustical Society of America*, *135*(4), 1875-1886.

25. Patterson, RD (1982) Guidelines for auditory warnings systems on civil aircraft. Civil Aviation Authority paper 82017: Civil Aviation Authority.
26. Patterson, RD (1990) Auditory warning sounds in the work environment, Philosophical Transactions of the Royal Society of London B, 327, 485 ± 492
27. Simpson CA, Williams DH (1980) Response time effects of altering tone and semantic context for synthesized voice cockpit warnings. *Human Factors*, *22*, 319-30