How can audio technology improve working conditions?

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1.2.1 INTRODUCTION

Hearing is one of the most important human senses. The fact that we can perceive sound helps us to locate and classify sound sources and forms the basis of our speech communication. The healthy hearing system is astonishingly robust towards adverse acoustic conditions such as background noise, competing speech or reverberation. In modern societies, however, hearing deficiencies are widely spread. Recent figures estimate that about 16% of the population in industrialized countries suffer from hearing deficiencies [Shield, 2006]. Due to age-related deterioration of nerve cells in the inner ear, this percentage is much higher in older subgroups of the population (cf. Figure 1). Different estimates report that between 37% and 56% of the population aged 60 to 70 years suffer from hearing loss [Sohn, 2001; Davis, 2003; Johansson and Arlinger, 2003; Uimonen et al., 1999]. These figures gain particular importance in the light of the demographic change. Recent projections estimate a significant increase in all population groups aged 55 years or older between 2005 and 2030 and, at the same time, a considerable decrease in the younger population groups [European Commission, 2005]. This development will have a particular impact on European economies, since Europe will be the first region to experience demographic ageing. The populations in the neighboring regions Africa or Asia will start to age later given their presently considerably lower average age [European Commission, 2005]. In terms of hearing deficiencies, the demographic change will significantly increase the number of hearing-impaired people. A recent estimate expects the number of people suffering from hearing loss to rapidly increase in the following ten years and to almost double by 2030 [Shield, 2006].

The effect of ageing societies is not restricted to retired people. On the contrary, the employment rates of older workers are projected to increase massively from 40% in 2004 for the EU-25 to 47% by 2010 and 59% in 2025 [European Commission, 2007]. The increase of the proportion of older workers leads to new requirements concerning ergonomic conditions at workplaces. One important factor fundamentally related to ergonomics is acoustic communication. Both a comfortable speech communication and the perception of acoustic signals, e.g. alarm signals, are of outmost importance in modern economic processes. However, acoustic communication becomes increasingly difficult for workers with hearing impairment since part of the speech information cannot be extracted from the signal anymore.

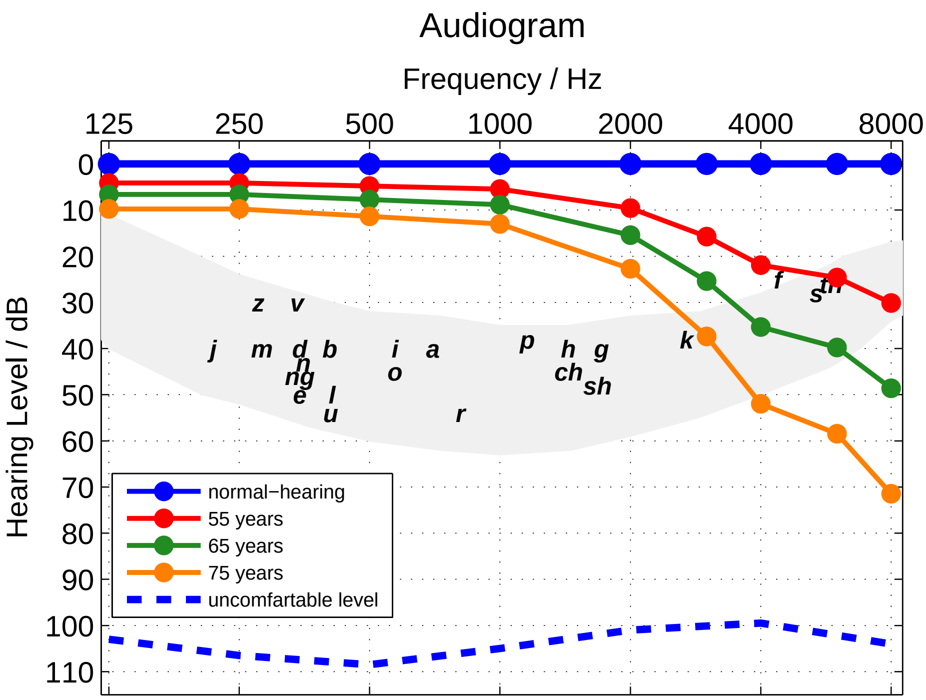

Figure 1: Audiogram of normal-hearing and hearing-impaired people suffering from age-related hearing loss [ISO 1999, 1990]. The gray area indicates the typical intensity distribution of speech across frequency. The dashed blue line indicates the level at which sounds become uncomfortably loud. Often, the uncomfortable level is similar in normal-hearing and hearing-impaired listeners.

Figure 1 illustrates this effect of hearing loss on speech intelligibility in audiogram representation. The audiogram shows the deviation from normal hearing, expressed as hearing level in decibels, as a function of frequency. The normal hearing system is able to perceive sounds in the range from 0 dB to about 110 dB hearing level, which represents the level at which sounds become uncomfortably loud. This means that all sounds between these two curves in the audiogram can be heard. Positive hearing levels indicate a hearing loss and reduce the audible range of sounds. The colored curves show average hearing losses for different age groups that have to be expected purely due to age-related loss of nerve cells [ISO 1999, 1990]. Since the curves show the mean observed hearing loss at different ages, it should be pointed out that 50 percent of the population has a stronger hearing loss when compared to this average. It can be seen that particularly at high frequencies, hearing thresholds are elevated. The gray area indicates the typical range and frequency distribution of speech. Individual speech fragments are positioned according to their principal frequency content (note that neither of these fragments consists of a single frequency alone). Given the average hearing losses, an increasing part of the speech information can no longer be perceived by older people and for example the distinction between “*f*”, “*s*” and “*th*” is no longer possible. This apparently slight impairment is often observed well before retirement age, and can have considerable consequences on communication at work. In addition to the age-related hearing loss, diseases or exposure to occupational or recreational noise (e.g. MP3-players or loud concerts) over longer periods may increase the overall hearing loss. Particular difficulty arises in non-optimal acoustic conditions. In ordinary working places such as open-office areas or factory halls, reverberation and noise from machinery or competing voices can make acoustic communication very difficult even for normal-hearing workers. In such cases, communication is often impossible for hearing-impaired workers, even though their audiogram data might indicate only small deviations from normality.

Therefore, improving the acoustic conditions at workplaces using modern technologies not only increases productivity and the quality of work for the workers, but may in fact permit older workers to work at places formerly not accessible to them due to their hearing impairments. This offers new opportunities for enterprises in terms of increased internal flexibility, i.e. the possibility to transfer workers to different workplaces, which becomes increasingly important in the face of the rapidly changing conditions of today's markets.

This paper describes current research as well as existing audio technologies to improve acoustic conditions at workplaces. The technologies comprise methods for evaluation, signal enhancement and simulation, which can be used in the design as well as in the modernization of workplaces in order to reduce the problems of the increasing portion of hearing-impaired people in modern work processes.

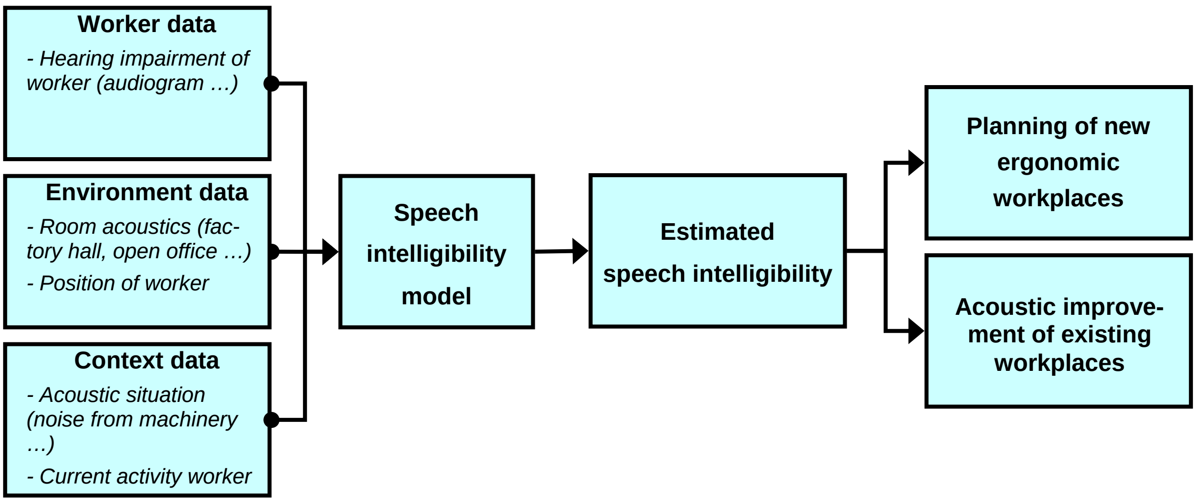

Figure 2: A model of speech intelligibility can combine information about the worker, the acoustic environment and the context to estimate how well the worker is able to communicate in the given situation. This information can be used in planning and improvement processes of workplaces.

1.2.2 Technical evaluation of acoustic working conditions

The most important aspect of acoustic communication, especially for workplaces, is whether speech can be understood properly or not. To evaluate workplaces with respect to speech intelligibility, it is – ideally – measured experimentally, directly at the workplace using the same workers normally occupying the workplace as test listeners. To ensure comparability, exactly the same conditions as typically encountered in the real working process should be ensured. Several tests were developed, which are in principle able to yield exact estimates of speech intelligibility. Naturally, such measurements involving real subjects are impracticable due to their high costs, long durations and low degree of generalization. Therefore, several technical methods were developed to predict speech intelligibility. Standardized models such as the Speech Intelligibility Index (SII, [ANSI, 1997]) or the Speech Transmission Index (STI, [IEC, 1998]) are widely used in research and applications. They account for the influence of several important factors in speech communication such as background noise, sound transmission system and reverberation. In modern workplaces, such models could be used to evaluate the ergonomic conditions with respect to acoustic communication. As illustrated in Figure 2, the models require information about the worker, the environment and the context to compute their estimate of speech intelligibility. Acoustic data about environment and context (e.g., reverberation or machine noise) can often already be estimated in planning phases of work processes by commonly used room acoustic simulation software, or can be measured at existing work places with relatively low effort. Similarly, the information about the individual worker (hearing loss, preferences) can be estimated, for example based on a company's age distribution [ISO 1999, 1990], or it can be measured with standard audiological techniques. For a given acoustic environment and context, the entire range of estimated (or real) hearing losses can be used to compute predicted speech intelligibility. This way, an easy detection of acoustically problematic working places can be achieved. In the same way, by modifying the environment or context data, the benefit from acoustic modernizations like additional damping or less noisy machinery with respect to speech intelligibility can be estimated.

In conclusion, current speech intelligibility models provide a way to easily detect and quantify difficulties in acoustic communication at workplaces, and to estimate the benefit from acoustic modifications. Thus, they can be used to create awareness for the problems of hearing-impaired workers among (mostly normal-hearing) planners and to cost-efficiently improve the acoustic conditions.

Naturally, the concept depicted in Figure 2 relies on a trustworthy estimate of speech intelligibility based on the available information. While the standardized models successfully account for the effects of background noise, reverberation and some aspects of hearing impairment, other important factors are not included in their calculations. Under certain conditions, this may lead to wrong predictions, which limits the models' applicability. Current research focuses on the development of more generally applicable models taking account of other relevant aspect like temporally fluctuating noises (e.g., [Meyer et al., 2007]), spatial distributions of different speech and noise sources (e.g., [Beutelmann and Brand, 2006]) or more detailed effects of hearing impairment (e.g., [Jürgens et al., 2009]). As a research tool as well as for practical applications, the Speech Intelligibility Prediction (SIP) Toolbox was developed at the Fraunhofer IDMT, which allows an easy comparison of standard models (e.g., SII and STI) and new, improved models (e.g., [Beutelmann and Brand, 2006]) for arbitrary acoustic situations.

1.2.3 Awareness creation through realistic simulation of the effects of hearing impairment

As described above, technical measures to quantify speech intelligibility for hearing-impaired workers can create awareness among planners of economic processes concerning the particular difficulties and needs of hearing-impaired employees. An increased awareness already during early planning periods could then lead to more ergonomic working conditions and in turn increase productivity, flexibility and quality of work. A further step towards a more intuitive impression of what it means to be hearing impaired in a difficult acoustic environment is to directly simulate the perceptual consequences of a hearing loss. While the exact effects related to different kinds of hearing impairment are still subject to current research, some relations between measurable deficiencies in hearing performance and perceptual consequences have been established. Typically, for age-related or noise-induced hearing losses, the increased threshold of hearing-impaired people is not accompanied by an equivalent increase in the uncomfortable level. This results in a reduced dynamic range in which sounds are audible. In the audiogram, this range is the area between the hearing threshold and the uncomfortable level (see Figure 1). A perceptual consequence of such a reduced dynamic range is a modified loudness perception. While soft sounds are barely audible, a slight increase in level can cause a significant increase in loudness perception. This phenomenon (referred to as 'loudness recruitment') can be very disturbing in acoustic communication at work because the optimal volume setting for a hearing-impaired worker is difficult to find, needs constant readjustments and differs from worker to worker.

Another effect related to many types of hearing impairment is a reduced spectral resolution. When two tones are heard at the same time, their spectral distance determines whether they are perceived as two distinct tones or as one auditory object. The frequency difference needed to perceive two tones is usually considerably higher in hearing-impaired listeners, i.e.

their spectral resolution is decreased. In communication situations, this can lead to a substantial loss of information since different frequencies cannot be normally distinguished.

In order to give a realistic impression of these perceptual consequences, modern hearing loss simulators include both effects of reduced dynamic range and reduced spectral resolution [HörTech, 2009]. In an online comparison, the normal-hearing user can switch on and off the simulated hearing loss for arbitrary speech (or music) signals, background noises and hearing losses. Using this tool, planners of working processes can get a feeling for the difficulties of hearing-impaired workers and take the needed precautions to ensure acoustically acceptable conditions also for hearing-impaired workers.

1.2.4 Enhancement of acoustic communication using signal processing strategies

Modern technology offers a wide range of acoustic interaction between people (via communication devices) and between people and IT products (via acoustic messages, speech recognition, etc.). However, using communication devices may be very difficult at certain workplaces. In particular, background noise and reverberation, as illustrated in Figure 3, make communication difficult already for normal-hearing people. Under these conditions, it may be impossible to use these devices for hearing-impaired people. Part of the solution to such problems can be offered by signal processing strategies, which enhance the quality of the communication signal by de-noising [e.g., Goetze et al., 2006] or de-reverberation [e.g., Goetze et al., 2008]. These algorithms remove unwanted noise and reverberation (cf. acoustic environment and context in Figure 2) from the received signal, thereby improving the audio quality and avoiding feedback in the system. The removal of noise from the combined signal of speech and noise is particularly powerful when the noise has a different spectral content from the speech signal. In many workplaces such as factories (machinery noise) or open-office areas (ventilation, typing, printer noise …) this condition is at least partly fulfilled, which offers a large potential for signal enhancement using noise reduction schemes.

Additional benefit for hearing-impaired workers can be expected if communication devices are fitted to the individual needs of a person, i.e. adjusted to the hearing loss of the individual worker. Such personalized hearing systems partly cover the functionality of a hearing aid, which may not be available for the worker or which may be impossible to wear at work, e.g. in combination with hearing protectors. Such personalized algorithms account for the reduced dynamic range (cf. Figure 1) by nonlinearly mapping the sound energy into the remaining audible range. The modified loudness perception can, thus, be partly compensated, which facilitates communication for hearing-impaired workers.

Despite improved acoustic conditions and signal quality, there may be situations for hearing-impaired (an also normal-hearing) people, in which acoustic communication is extremely difficult. Such problems have also been identified in non-occupational contexts and technical solutions have been developed, in particular in the field of ambient-assisted living. These solutions are not restricted to their original applications, and developed concepts like robust speech recognition and acoustic event detection may find applications also in modern workplaces. Acoustic events indicating alarms, incoming messages, or operational elements of machinery may be hard to detect, particularly for hearing-impaired workers. But even if they are detected, the localization or classification of the events may not be possible or error-prone. Automatic acoustic event detection can support the hearing-impaired worker, giving indications about the type of signal, its direction and intensity. Possible combinations of acoustic detection and the use of other modalities such as text messages or other visual support can be of great benefit.

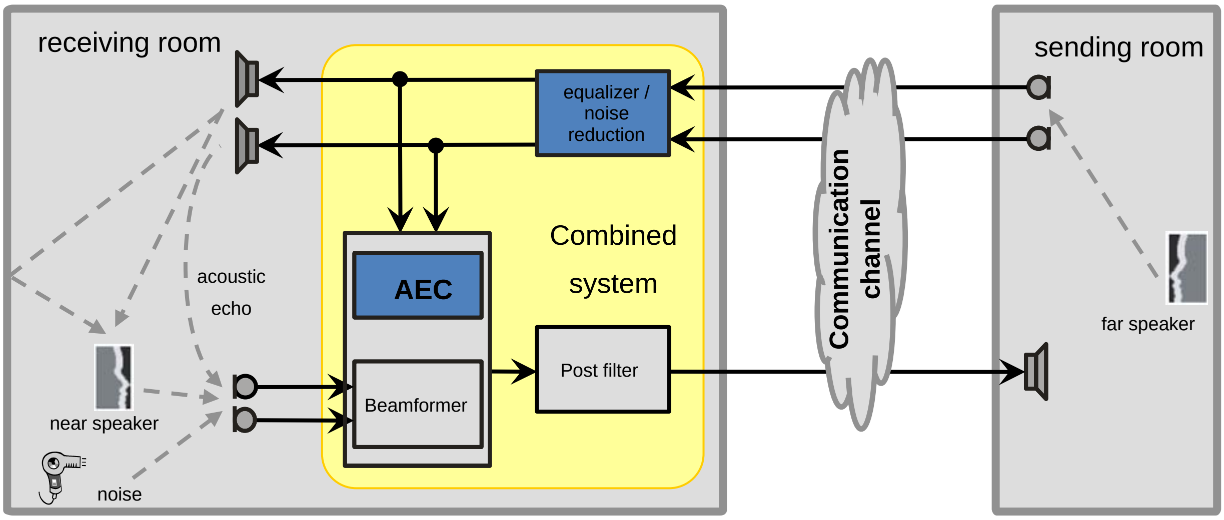

Figure 3: Illustration of the acoustic difficulties in a typical communication system. The speech of the far-end speaker is transmitted to the near-end room and is disturbed by noise and reverberation, leading to decreased speech intelligibility. In addition, the signal of the loudspeaker feeds back into the microphone. Digital signal processing strategies, such as noise reduction and acoustic echo cancelation (AEC) can help to considerably improve the signal quality and to avoid feedback in the system.

1.2.5 Summary and conclusion

The demographic aging of workers will have a considerable impact on modern work processes since more sophisticated demands will arise with respect to ergonomic conditions. As acoustic communication is a major factor in ergonomics, the increasing part of hearing-impaired workers requires particular solutions to improve the acoustic conditions at workplaces. Today, a number of technologies exist to achieve this goal. Technical methods to evaluate and quantify the difficulties of hearing-impaired can help already in planning phases to ensure good intelligibility for hearing-impaired workers. Realistic simulation techniques can create additional awareness among planners and can sensitize both managers and colleagues for the particular needs and difficulties resulting from hearing impairment. Current research focuses on the perceptual consequences of hearing loss and more accurate models will increase the applicability of models in the context of ambient-assisted working even further.

State-of-the-art algorithmic solutions can improve the audio quality in several ways. By removing unwanted noise and reverberation from the acoustic signals these technologies support communication also for normal-hearing workers, but especially for hearing-impaired workers the benefit can be substantial. The same is true for personalized acoustic signal processing. These strategies are fitted to the individual hearing loss of a worker and compensate for the deficiencies in the most efficient way. In conclusion, audio technology provides powerful tools to improve acoustic conditions for normal-hearing and hearing-impaired workers. Already today, different possibilities are applicable in realistic contexts. Current research will lead to even more accurate and comprehensive models and methods, and modern work places should make use of these opportunities. Despite these possibilities available today, the technical support for hearing-impaired workers does not have to be restricted to audio technology. Rather, multimodal interfaces using visual or textual indicators could be used in combination with audio technologies like for example acoustic event detection, which might represent a further step towards the goal of good acoustic conditions at work places.

In connection with the conference presentation, several questions were raised from the audience. The key points and responses are summarized in the following:

Question:

There are sound presentation techniques that present acoustic signals to distinct, localized positions in space, for example to individual persons in a room. Could such techniques be used to support hearing-impaired people at work?

Answer:

These techniques of highly directed sound beams are indeed interesting also in the context of ambient-assisted working. In general, a sound source directed at a particular listener can have a higher level than common public-address systems, which allows for higher signal-to-noise ratios. Especially hearing-impaired workers might benefit from increases in signal-to-noise ratio, as it was shown in several scientific studies on speech intelligibility in noisy conditions. The reason why such techniques are not widely spread yet is probably the difficult technical realization. However, should these techniques become a common way of transmitting individual information to single workers, then there may be a huge potential in combining this technique with personalized signal processing, as described before, which can be fitted to the hearing loss or preferences of the worker and basically work in the same way as a hearing aid.

Question:

You named a number of different signal processing techniques to improve signal quality. Could a combination of the different methods increase the potential advantage of these techniques?

Answer:

You are right that the full potential of these technologies lies in combined systems. For example, de-reverberation algorithms or algorithms for acoustic echo cancellation have problems in very noisy environments and work better when de-noising algorithms are used to enhance the signal quality before. In the same way, acoustic event detection will generally perform better in good acoustic conditions, and the removal of noise and reverberation will increase its performance in a way similar to human event recognition.

1.2.6 References

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Pictures / diagrams