

Noise and communication: A three-year update

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Abstract

Noise is omnipresent and impacts us all in many aspects of daily living. Noise can interfere with communication not only in industrial workplaces, but also in other work settings (e.g. open-plan offices, construction, and mining) and within buildings (e.g. residences, arenas, and schools). The interference of noise with communication can have significant social consequences, especially for persons with hearing loss, and may compromise safety (e.g. failure to perceive auditory warning signals), influence worker productivity and learning in children, affect health (e.g. vocal pathology, noise-induced hearing loss), compromise speech privacy, and impact social participation by the elderly. For workers, attempts have been made to: 1) Better define the auditory performance needed to function effectively and to directly measure these abilities when assessing Auditory Fitness for Duty, 2) design hearing protection devices that can improve speech understanding while offering adequate protection against loud noises, and 3) improve speech privacy in open-plan offices. As the elderly are particularly vulnerable to the effects of noise, an understanding of the interplay between auditory, cognitive, and social factors and its effect on speech communication and social participation is also critical. Classroom acoustics and speech intelligibility in children have also gained renewed interest because of the importance of effective speech comprehension in noise on learning. Finally, substantial work has been made in developing models aimed at better predicting speech intelligibility. Despite progress in various fields, the design of alarm signals continues to lag behind advancements in knowledge. This summary of the last three years' research highlights some of the most recent issues for the workplace, for older adults, and for children, as well as the effectiveness of warning sounds and models for predicting speech intelligibility. Suggestions for future work are also discussed.

Keywords: Aging, communication, educational settings, noise, warning sounds, workplace

Introduction

The effects of noise on communication impact us all, irrespective of age, sex, or lifestyle, in many aspects of day-to-day living. Noise can interfere with communication not only in industrial workplaces but also in other work settings as diverse as, for example, open-plan offices, transportation, construction, agriculture, and mining, as well as generally within buildings (e.g. residences, arenas, and schools). The interference of noise with communication can have significant social consequences, especially for persons with

hearing loss, and may in some circumstances compromise personal safety (e.g. accidents due to the lack of perception of auditory warning signals), influence worker productivity and learning in children, affect health (e.g. vocal pathology, noise-induced hearing loss), and social participation by the elderly. Indeed, many themes addressed in this paper are also of interest to the field of Noise and Performance. However, the subjects included in this review encompass the effects of noise on communication but not on performance.

This summary of the last three years' research highlights some of the most recent issues for the workplace, for older adults, and for children, as well as the effectiveness of warning sounds and models for predicting speech intelligibility. Suggestions for future work are also discussed. Developments in hearing aids are, however, not included. While the goal of much current research on hearing aids is to improve the performance in noise or competing speech, primarily by employing binaural aids with extended frequency response (up to 7.5 or 10 kHz), the benefits for persons with hearing loss remain to be broadly established.^[1,2]

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The Workplace

Hearing critical tasks

An inability to hear critical communications can be a liability in the workplace. Rather than automatically excluding potential employees with audiograms that exceed a prescribed hearing threshold, enlightened employers are considering defining more precisely the auditory performance needed to function effectively.^[3,4] Recent reviews have re-emphasized the limited ability of audiometric data to predict functional hearing abilities and the need for more direct measures of such abilities for assessing Auditory Fitness for Duty (AFFD).^[5,6] There are numerous examples of what might constitute AFFD requirements for a given environment. For example, functional hearing abilities required for new recruits by the military could include: Detection of footsteps, target identification, understanding commands, and other task-specific requirements commonly termed situational awareness. In a broad review, Tufts *et al.*^[6] highlighted the need to tailor AFFD requirements to the job, and identified several common performance considerations: 1) Sound detection and recognition; 2) Sound localization, and; 3) Speech understanding. For many workplaces the use of hearing protectors will significantly influence the performance of these tasks (see below), and needs to be considered in the assessment. Measures of speech perception in noise and of sound localization have recently been used by the Royal Canadian Mounted Police to make more informed decisions regarding AFFD for serving police officers with hearing aids.^[4] The results confirm that hearing aids can positively or negatively impact hearing abilities, with front-back sound localization being most significantly hindered.

By providing examples of successful protocols put in place to address AFFD, Laroche *et al.*,^[7] have highlighted the need to involve key players and use valid, scientifically-based tools. Future work in this field should include adapting current methodologies to deal with the effects of hearing protectors by using speech intelligibility and/or alarm detection models. Further work is also needed to include communication devices and advanced hearing protection technologies.

Hearing protection

The need to protect the ear from exposure to intense environmental noise is common to all workplaces. There have recently been at least two reviews that have noted the increasing importance of electronics, including microphones and earphones, applied to hearing protection devices (HPDs), or so-called active hearing protectors,^[8,9] and one comprehensive review of passive hearing protectors.^[10] The latter now include devices with frequency independent (i.e., “flat”) attenuation, devices in which the attenuation increases with sound pressure level (SPL) (to provide protection against impulsive sounds), devices in which the attenuation can be tailored to the application, and devices that can be fitted to individual ear canals *in situ*.

The availability of low-cost, high-performance, digital signal processors has rekindled interest in their application to active hearing protectors to improve speech communication and/or situational awareness in noise.^[9] A common assumption is that the passive attenuation of a HPD can provide overprotection from environmental noise, and so the electronics can safely *amplify* the sounds reaching the ear up to limits established for hearing protection. Such level-dependent HPDs are commercially successful but there does not yet appear to be a device capable of restoring all dimensions of situational awareness to that when a HPD is not worn. However, some can improve the audibility of sounds compared to the open ear,^[11] and some can generally improve the user’s performance compared to a traditional passive HPD.^[12-15] An alternative signal processing strategy is to employ active noise reduction (ANR), which permits, by phase cancellation, the noise at the ear to be *reduced* below that provided by the conventional passive attenuation of the HPD.^[8] By separating the sound spectrum into separate frequency sub-bands, there are more opportunities for processing speech and noise so as to improve speech intelligibility. This technique has been applied extensively to hearing aids and is being explored for hearing protectors.^[16] The application to communication headsets, in which there is a separate communication channel permitting the environmental noise and speech to be processed separately, is also beginning to receive attention.^[17]

Recent evaluations of commercial devices have found that^[9]

- 1) While active HPDs can improve speech perception in noise, the performance is largely dependent on the experimental conditions investigated and the degree of hearing loss in subject groups;
- 2) Level-dependent active HPDs with frequency-dependent amplification can significantly improve the detection of sounds in low frequency noise;
- 3) ANR can improve detection thresholds and speech intelligibility by reducing the upward spread of masking;
- 4) Source localization can be impeded in circumaural active HPDs due to the directional characteristics or position of the external microphones on the ear cups and;
- 5) User impressions of these devices are favorable except for comfort and compatibility with other safety equipment.^[15,18,19]

There is a need for more detailed manufacturer’s technical data and standardized performance tests for active HPDs, in order to predict the performance for users and select devices suitable for the job and the workplace. There is also a need for research to support more general improvements in speech intelligibility and situational awareness.

Speech privacy

Open-plan offices are becoming more common in many work settings. An important consideration for such workplaces is to provide speech privacy, that is, to prevent occupants of one workstation from being disturbed by sounds (speech or noise) from neighboring work stations.^[20] Several single number

quantities have been proposed to characterize the acoustical conditions of office spaces: The articulation index and the speech intelligibility index.^[21] In recent years, there have been renewed efforts to better understand the acoustical factors that influence speech privacy, and metrics such as the spatial decay rate of the A-weighted SPL of speech, the A-weighted SPL of speech at 4 m, and the so-called distraction distance have been proposed for this purpose.^[22]

The suitability of these metrics for predicting speech privacy and for selecting architectural features of the room (e.g., ceiling and floor absorptions, ceiling height, and screen separator height) has been studied by subjective measures of speech intelligibility in simulated offices, and by computer simulation of real office spaces.^[23] The investigation of speech intelligibility in simulated open offices found two acceptable metrics for speech privacy: The spatial decay rate of A-weighted SPL, and the A-weighted SPL of speech at 4 m (which was correlated with the distraction distance). The simulation of real office spaces using these metrics confirmed that, as expected, increases in ceiling absorption and partition height between work stations improve speech privacy.^[20,24]

Older adults

It has long been recognized that older adults disproportionately experienced difficulties understanding speech in noise compared to younger adults.^[25] This effect occurs even in those who report little difficulty understanding speech in quiet. During the last few decades, there has been considerable progress in establishing the auditory and cognitive factors that are responsible for the age-related influence of noise on speech intelligibility.^[26] Additionally, socio-emotional factors that can influence listening and social interactions, particularly for older adults, have more recently been studied.^[27,28]

Evidence for the interplay between auditory, cognitive and social factors during speech communication by older adults has been derived from four sources: 1) Speech and music perception; 2) Simulation of auditory aging by phase jittering; 3) Self-reported age-related differences in listening abilities, and; 4) Relationships between behavioral and self-reported measures of hearing with behavioral measures of memory and self-reported stigma and mood.^[27] Older adults are generally found to have degraded auditory processing of many temporal cues, from the fine structure periodicity cues to the more global cues provided by ongoing fluctuations in the amplitude envelope of the sounds.^[29,30] The relative importance of such cues depends on the task at hand (involving speech or music) and the nature of the age-related hearing loss (hair cell or neural damage). Simulation of the temporal aspects of auditory processing by jittering suggests that there may be inter-dependencies between periodicity coding and speech envelope cues. Jittering also negatively influences cognition by placing greater demands on working memory and thereby reducing working memory span. The

role of cognitive factors, especially attention, is also evident in self-reported age-related differences on the Speech, Spatial and Qualities of Hearing Scale.^[31,32] Also, strong correlations have been found between behavioral measures of hearing and cognition, and between self-reported listening abilities and socio-emotional status.

Longitudinal studies are needed to improve our understanding of the interactions between auditory, cognitive, and socio-emotional factors during everyday life. It remains to be determined whether self-appraisal is the cause or the consequence of poorer behavioral performance by older adults, and whether the auditory declines precede or follow cognitive declines.^[27] Answers to these questions could allow for the provision of better services for the treatment of difficulties communicating in noise experienced by older adults.

Children

There is a compelling societal need to maintain the effectiveness of education, both for children and adults, and interest inevitably focuses on the classroom experience. During the last 20 years there has been substantial progress in defining acceptable acoustical environments for education.^[33-36] A re-evaluation of the acoustical criteria for classrooms has suggested maximum acceptable values of environmental noise and optimum ranges of reverberation times in order to obtain acceptable intelligibility for different age groups.^[37] An equally important consideration is an acoustical environment suitable for persons with hearing loss, an issue that has been advocated by the American Speech-Language Association.^[35]

There have been numerous studies of classroom acoustics and speech intelligibility.^[38-40] In a recent study, conducted over the internet, it was found that a student's own perception of the sound environment was the best predictor of the results of hearing tests, thus providing the prospect for future population studies to be conducted in this way.^[41]

It is well documented that children require a larger speech signal-to-noise (SNR) than adults for adequate comprehension when listening in noise.^[42,43] Of current interest is the extent to which semantic clues can account for this difference. In a recent study of normal-hearing children (9 - 12 years old) listening to low predictability (LP) and high predictability (HP) sentences from the Test de Phrases dans le Bruit (TPB), a French adaptation of the SPIN test,^[44] no age-related differences were observed.^[45] However, by expanding the subject pool and SNR, and performing a cluster analysis on individual psychometric functions, two specific profiles (or clusters) could be identified. Although both clusters showed comparable gains from the provision of linguistic contextual information, the SNR at which a 50% correct score was achieved differed significantly between clusters.

The children in the second cluster required a significantly more favorable SNR than the children in the first cluster to obtain similar benefits from linguistic context. The reason for the difference in performance between the clusters was not clear. Further work is needed to investigate the benefit from linguistic contextual cues in bilingual children and those with learning difficulties.

An often overlooked consideration in classroom acoustics is the vocal effort of the teacher. A recent study monitored the vocal performance of 39 primary school teachers, 59% of whom presented with subjective, and/or objective pathological symptoms of voice disorders.^[46] The main causes of vocal pathology were found to be vocal load, smoking, and genetic predisposition, where the vocal load was defined in terms of an estimate of vocal fold vibration and phonation time. This study emphasized the need to reduce classroom noise levels to prevent health effects in teachers.

Warning sounds

Although IEC 60601-1-8^[47] advocates the use of pure tones for medical alarms, evidence suggests that tonal alarms are difficult to learn. Designing heterogeneity into alarm sets is crucial to improve alarm recognition and is correlated with ease of learning, and can assist differentiating between alarms and false alarms.^[48] It is important to appreciate that ensuring audibility, localizability, and resistance to masking effects does not guarantee the effectiveness of a warning signal in a noisy environment.^[49,50] Also, irrespective of the design, the efficacy of an alarm will always be undermined by a high false alarm rate, as it leads to scepticism about the reliability of the underlying warning system. Despite significant advances in knowledge of auditory processing and cognition in relation to alarms and auditory warning signals, the translation of knowledge into action has so far been limited. There is a pressing need to update practice and policy, particularly for medical alarms, when patients' lives can be at stake.

Audible alarms are frequently used in industry to alert individuals to the proximity of reversing vehicles. As in most applications, traditional vehicle reverse alarms involve pure tones. A broadband alarm signal has recently been proposed to reduce sound pressure nulls behind vehicles due to sound wave interference, and hence improve the audibility and ability to localize the source.^[51] The broadband signal provides some advantages over conventional pure-tone alarms: 1) A more uniform sound propagation pattern behind vehicles, and; 2) Lower SPLs to meet the requirements at the different (angular) microphone locations described in ISO 9533.^[52] Also, subjective judgments found when HPDs were not worn include: 3) Higher urgency ratings at high SNRs, and; 4) Better sound localization performance. However, some disadvantages were found: 1) Greater SNRs are required for detection, at least in environmental noises rich in high-frequency content, and; 2) Detection thresholds and urgency

ratings appear to be more severely affected by the use of HPDs with this type of alarm. In summary, the performance, while encouraging, needs to be more thoroughly analyzed from a work safety standpoint, taking into consideration the other factors such as habituation and alarm familiarity, and annoyance to bystanders.

Models for speech intelligibility

In modern electronic communication systems, speech is often corrupted by the signal processing, as well as by noise, which may introduce audible distortion and degraded intelligibility. There have been many attempts to predict the intelligibility of speech transmitted by a communication system under these circumstances, which have led to the development of numerous models.^[53-57] An improved method for predicting the intelligibility of individual words corrupted by noise or distortion has recently been described.^[58,59] The approach involves modifying a well-established model for predicting intelligibility, the Speech Transmission Index, by replacing the artificial test signal with speech and, as in the original model, focusing on the speech envelope waveform before and after passing through the communication system. In one model, the coherence between the original and corrupted speech in discrete frequency bands was used to distinguish between speech and noise. In a more complex model, the contribution to intelligibility was also adjusted for the redundancy of speech information common to nearby frequencies. The models have been used to predict the performance of subjects with normal hearing and confirmed understanding of American English, using the Modified Rhyme Test.^[60] It has been shown that only a model accounting for the coherence between the original and corrupted speech and the redundancy of speech information contained in nearby octave bands can predict the intelligibility of speech corrupted by noise, and by center clipping (i.e., distortion whereby the central part of the amplitude distribution of speech has been lost). Further development of this and related models is needed to account for the influence of a broader range of environmental noise conditions and signal processing artifacts on speech intelligibility.^[61]

Discussion and Conclusions

For persons with normal hearing, progress is being made in understanding almost all aspects of speech communication in noise and in the perception of warning sounds. It is encouraging that problems specific to persons with hearing loss are receiving increasing attention. The application of advanced electronics to hearing protectors is proceeding rapidly, with improvements in performance being achieved both for persons with normal and impaired hearing. Criteria for defining functional hearing capacity for hearing-critical jobs are gaining broader acceptance and are being extended to persons with hearing aids. In contrast, the design of alarm signals continues to lag behind advancements in knowledge of

auditory processing and cognition, though attempts are being made to implement specific alarms with desired acoustical features. The interplay between auditory, cognitive, and social factors is receiving attention for aging adults to further understanding and, ultimately, assist speech communication and hence reduce the sense of social isolation experienced by the elderly. Specific questions are being addressed concerning speech effort, and understanding speech in noise some distance from the talker when intelligibility is required, as in the classroom, or when intelligibility is undesirable, as in an open-plan office. In addition, the development of models to predict speech intelligibility under various listening conditions and with imperfect communication devices continues to support environmental and device design. Nevertheless, there remain substantial gaps in our understanding of the factors dominating the effectiveness of audible communication under the most challenging conditions, particularly for older persons and for persons with hearing impairment.

Future work should include adapting current AFD procedures to encompass the use of hearing protectors and communication devices, and research to support improvements in situational awareness for persons wearing active HPDs and hearing aids. Longitudinal studies are needed to improve our understanding of the interplay between auditory, cognitive, and socio-emotional factors influencing speech communication in noise by older adults. For children, more work is needed to investigate the benefit to learning from linguistic cues, and attention should be paid to the adverse effect of classroom noise on teachers' vocal effort. There is a pressing need to update the design of audible warning alarms to incorporate current knowledge and, finally, models for predicting speech intelligibility and alarm detection need to be developed to encompass a broader range of acoustical conditions.

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