Hearing protection and communication in an age of digital signal processing: Progress and prospects

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INTRODUCTION

The analog active noise control (ANC) technology of the 1980s-90s enabled the development of commercial, circumaural, hearing protection devices (HPDs) that are effective in reducing low-frequency environmental noise and, in many cases, in improving speech intelligibility within a built-in communication channel. The technology did little, however, to restore the user's loss of contact with the environment external to the HPD, most often evidenced by a reduction in the audibility of speech and warning sounds, as well as a reduction in the ability to localize sounds (Abel et al. 1997). Some current commercial HPDs address these issues with various forms of feed-through electro-acoustic devices incorporated into the HPD, most of which reproduce the environmental noise at the ear under some conditions. Initial evaluations of the effectiveness of such devices in quiet are encouraging (Abel et al. 2007).

The advent of inexpensive, high-performance, micro-miniature, digital signal processors has rekindled interest in the development of advanced signal processing schemes for application to HPDs. The combination of signal processing and sound field sensing are believed to hold promise for improving noise reduction and speech intelligibility in environmental noise (Davis 2002; Hornsby et al. 2001). The technology is most advanced for hearing aids (Chung 2004): its applicability to HPDs remains to be established (Chung 2007).

In this paper, the consequences of simultaneously applying ANC and digital signal processing to an HPD are considered. The performance of an HPD equipped with ANC is first described, and a basis provided for the attenuation observed. The influence of the structure of the control system on performance is stressed, and employed to introduce the expected and observed results for devices equipped with digital ANC systems. The approach provides an introduction to the more complex processing schemes that may be expected to evolve in the future. The discussion does not distinguish between an earmuff and earplug unless the effects are different. Accordingly, the source producing cancelling sound will be referred to throughout as a "loudspeaker", although for earplugs it should be considered to be an earphone.

METHODS AND RESULTS

The attenuation of an HPD equipped with ANC contains both passive and active components, the former derived from the mechanical components and construction of the device, and the latter from the electronics and electro-acoustic components. Of importance to the present discussion are the magnitudes and frequencies at which passive and active attenuation are commonly obtained. In general, the passive attenuation increases with frequency, often from as low as ~10 dB at 100 Hz, irrespective of whether the device is a circumaural HPD or an earplug. In contrast, the active attenuation reaches 10-20 dB at frequencies below 500 Hz for an ANC system mounted in an earmuff, but there will be little attenuation at higher frequencies (Zera et al. 1997). The active attenuation of earplugs may extend to ~2 kHz (McKinley et al. 2005). The overall, or total, attenuation changes little, or more commonly increases slowly, with frequency. The ability to affect the performance electronically depends on the signals selected for processing. The effects will also be influenced by the control structure of the active noise reducing system.

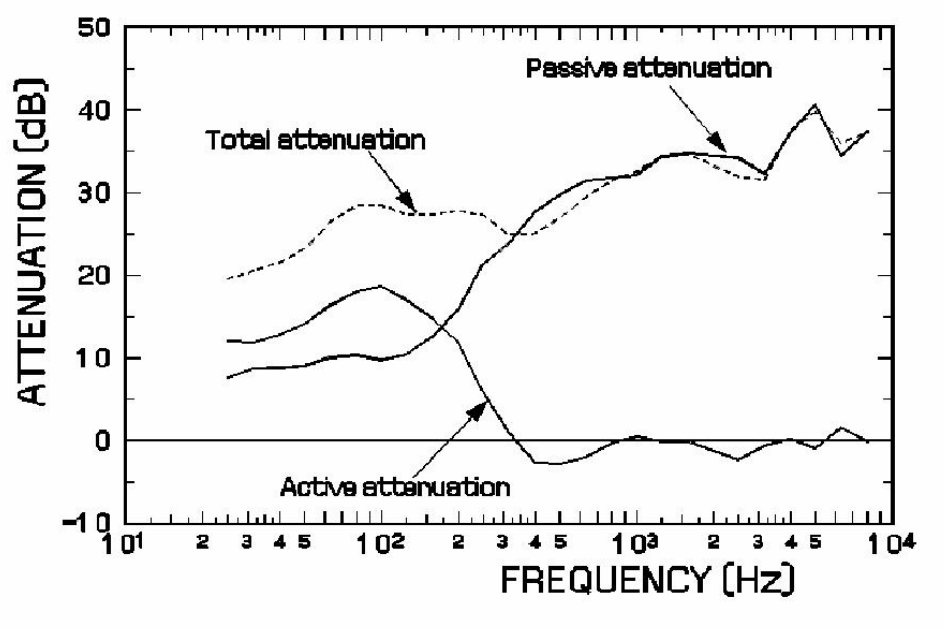

Figure 1: Passive, active and total attenuation at one-third octave-band frequencies of a circumaural HPD equipped with active noise control, when worn by human subjects. Measurements performed at the entrance to the ear canal

Active noise control for hearing protectors

The noise reduction of an HPD equipped with ANC consists of the traditional passive attenuation supplemented by that produced by the active system (Figure 1). Simplified block diagrams containing the essential elements of basic feedback, and feed-forward, active control systems for an HPD are shown in Figure 2A and 2B, respectively. The HPD contains a miniature loudspeaker, S, and one, or more, microphones (E and R). In the feedback configuration, shown by the thick lines in Figure 2A, the control filter adjusts the signal so as to reduce the sound pressure at E. An integral part of the process of sound cancellation is the transformation of the electrical signal to sound by the loudspeaker, S, the propagation of sound from S to E, and the transformation of sound into an electrical signal by the microphone, E. These elements together define the transfer function from S to E, which is termed the error path. In essence, the microphone detects the "error" in the cancellation of the environmental noise at E. Feeding back the output of the error microphone to the input of the control filter, shown by the thick lines, ensures that there is a continually updated correction to the performance of the control system.

The signal flow for the simplest feed-forward configuration is shown by the thick lines in Figure 2B. The control system employs a microphone, R, to sense the sound field external to the HPD: there is no error microphone. In consequence, the control filter must accurately reproduce the transfer function from R to S. A limitation of the “open-loop” feed-forward control structure is the lack of sensing the success of noise cancellation. This limitation is important as the transfer function, and the characteristics of the sound field enclosed by the HPD, change every time the HPD is fitted to, or repositioned on, the head (e.g., air leaks around seal between cushion and ear, or around earplug). The variability is commonly overcome by adding an error microphone, E, and the remaining elements shown by the continuous lines in Figure 2B. It should be noted that the error path is also subject to variability from the fitting of the HPD on the head, or in the ear canal (e.g., change in acoustic load impedance of loudspeaker). In practice, the transfer function of the control filter is continually adjusted to optimize performance, and is usually implemented digitally for this purpose by an adaptive filter. The algorithm to optimize the control filter requires a comparison between the signals at R and E. In the most common implementation, the signal from the reference microphone is pre-filtered by a representation of the transfer function from S to E (the error path model in Figure 2) before being compared with the signal from the error microphone. The difference between the signals is repeatedly used to compute the control filter coefficients by calculating the least mean squares error (LMS adapter in Figure 2B) (Kuo & Morgan 1996).

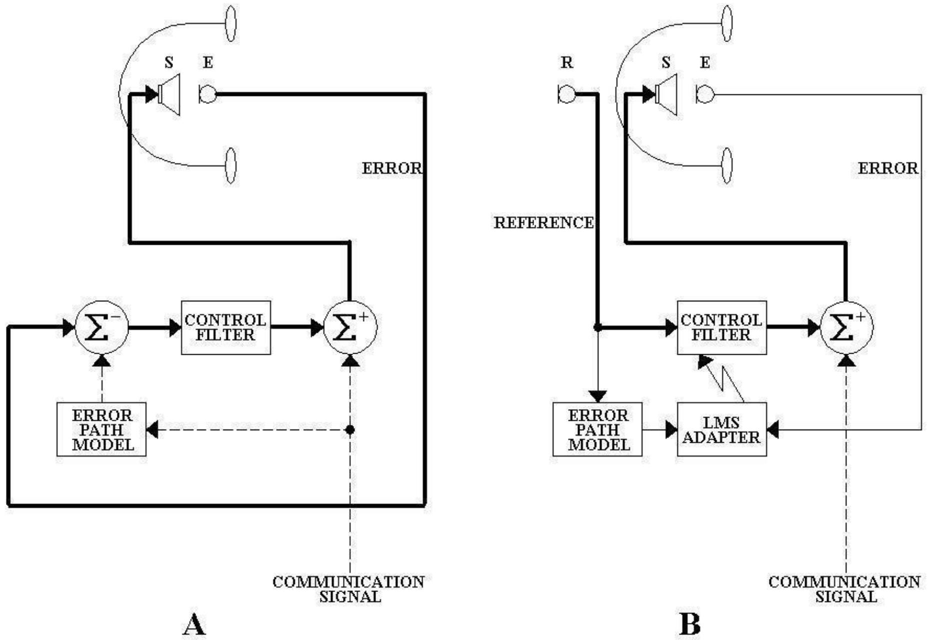

Figure 2: Basic elements of an HPD with A - feedback, and B - feed-forward, ANC and a built-in communication channel. R and E are the reference and error microphones, respectively, and S is a loudspeaker. The transfer function from S to E is represented by the error path model. An adaptive feed-forward controller involves the elements shown by the continuous lines (see text).

Active HPDs with a built-in communication channel

Communication signals have been introduced into circumaural HPDs or headsets with feedback active control systems in several ways. The most effective is shown by the dashed lines in Figure 2A, where the signal paths include signal summation (Σ^+) and subtraction (Σ^-). Note that the signal from the error microphone now contains the residual environmental noise *and* speech. In consequence, the speech sensed by the error microphone needs to be removed prior to entering the control filter. This is done by subtracting the communication signal from the error signal after first filtering it by an estimate of the error path transfer function (see Figure 2A). In this way, the filtered communication signal will approximate the magnitude of the residual speech in the error signal. A prototype communication headset equipped with such an ANC system has been demonstrated to improve speech intelligibility in noise (Steeneken 1998), as assessed by the Speech Transmission Index (STI) (IEC 60628, 1998). There are commercial variants of this system.

With a feed-forward active control system, the communication signal is also directly summed with the output of the control filter and fed to the loudspeaker, as shown in Figure 2B. Note that this method for introducing the communication signal is independent of whether the active control system is adaptive or non-adaptive. Note also that the output of the error microphone does not enter the control filter, and so cannot influence the speech signal. No compensation for the presence of speech in the error signal is thus required. In normal use, the air seal formed between the cushion of the ear muff and the head, or between the earplug and the wall of the ear canal, will attenuate the speech sounds reproduced by S reaching the reference microphone, so that there will be effectively no contamination of the control signal by speech. The intelligibility of the speech may then be expected to depend solely on the fidelity of sound reproduced by the communication channel and the speech signal-to-noise (S/N) ratio.

Implications of control structure on performance

In a feedback controller, the signal from the error microphone becomes the control signal (see Figure 2A), and so the system will attempt to cancel *all* sounds sensed by the microphone. This will include desired sounds such as speech external to the HPD or from a communication channel, or warning sounds, as well as the environmental noise. Furthermore, maintaining the stability of the feedback loop dictates all aspects of the performance. Thus, the transducers and electronics are selected to satisfy the need for maintaining stability of the feedback loop, rather than for the fidelity of sound reproduced by a built-in communication channel. The fidelity of speech reproduction is also compromised by the difficulty removing all of the residual speech from the error signal. An improvement in fidelity can usually be obtained by introducing a second loudspeaker solely to reproduce communication signals (not shown in Figure 2), which will not be restricted by feedback loop stability considerations. The need to subtract the residual communication signal from the error signal in the feedback loop, however, remains. The inherent time delay for sound to propagate from S to E introduces phase shifts in the feedback loop that restrict the maximum frequency at which active noise reduction can be obtained to ~1 kHz for earmuffs, and ~2 kHz for earplugs (McKinley et al. 2005).

In a feed-forward controller, the error signal does not enter the control filter (see Figure 2B), and only sounds that are *correlated* with the sound sensed by the reference microphone (i.e., external to the ear) will be reduced. In practice, this will limit the upper frequency of active control to ~500 Hz for earmuffs and ~2 kHz for earplugs. In contrast to a feedback controller, the noise reduction is spectrum dependent (Pan et al. 1995), with tonal sounds attenuated more than broadband sounds, and intensity dependent, the LMS algorithm giving more weight, and hence more reduction, to intense signals (Brammer et al. 1997). In addition, the desired sounds in a communication channel will not be cancelled, and the transducers and electronics may be selected for fidelity of sound reproduction (Brammer et al. 2005).

Speech intelligibility, warning sounds and spatial perception

There have been several studies of the intelligibility of speech reproduced by the communication system built into headsets with ANC. In most cases the results compare the performance of different commercial devices, without reference to the basis for the differences in intelligibility observed. Recently, the speech intelligibility of a communication headset with a feedback control structure (Figure 2A) has been compared to one with an adaptive, digital, feed-forward control structure (Figure 2B), in circumstances in which the control systems produced similar magnitudes of active noise reduction (Brammer et al. 2005). Under these conditions the two devices may be expected to provide equal improvement in intelligibility from any reduction in masking of a speech signal within the communication channel, for a given environmental noise. Even though the active noise reduction occurred mostly at frequencies below 300 Hz, the STI was generally greater for the headset with the feed-forward control structure than that with the feedback control structure. The difference was attributed to the difference in fidelity of sound reproduction by the communication channel of the headset, in particular to the flatter frequency response of the loudspeaker and its associated drive electronics. There does not appear to have been a comparison between a headset with feed-forward ANC and one with feedback ANC and a second loudspeaker for speech reproduction. Size constraints would appear to eliminate the use of a second loudspeaker for a communication earplug equipped with ANC if the device is to fit within the ear canal.

The perception of speech or warning sounds when both are external to the HPD can be expected to be similar to that of passive HPD of comparable geometry at low and moderate environmental sound pressure levels. For environmental noise with high sound pressure levels at low frequencies, an improvement in speech intelligibility from a reduction in the upward spread of masking may be expected when the ANC system is operating. This is a consequence of the frequency characteristics of the active and passive attenuation of the HPD. Reference to Figure 1 shows that there is commonly little passive attenuation at low frequencies in the absence of active noise reduction. Thus, an improvement in speech intelligibility may be obtained for noise sources with dominant frequency components at 300 Hz, and below (Buck et al. 2003). No improvement in intelligibility can be expected for environmental noise with other spectral shapes without further signal processing, and none has been observed (Nakamura et al. 2007).

Similar conclusions would be expected to apply to the perception of warning sounds. The audibility of a tonal warning sound (e.g., back up alarm) has been found to be improved when assessed by the masked threshold (Casali et al. 2004). However, the localization of the warning sound is degraded compared to an unoccluded ear when wearing any form of circumaural HPD (Abel et al. 2007). The degradation of localization when wearing earplugs is less that when wearing earmuffs, most probably due to retention of directional cues from the pinna.

DISCUSSION

More complex ANC systems have been developed for HPDs, including combinations of the basic feed-forward and feedback control structures shown in Figure 2 (Rafaely & Jones 2002; Ray et al. 2006). While these systems may be expected to combine the performance of the separate control structures, it is not apparent that they will lead to a further improvement in speech communication and in the audibility of warning sounds, or address the deficiencies in spatial perception when wearing earmuffs.

HPDs in which the signal processing amplifies low-level environmental sounds and attenuates high-level sounds, with or without ANC, address the isolation of the user from the environment. If the external sounds are reproduced binaurally by the loudspeakers, an improvement in spatial perception in the horizontal plane compared with other forms of circumaural HPDs is obtained at low noise levels (Abel et al. 2007; Carmichel et al. 2007). However, this form of automatic gain control (AGC) would not be expected to influence communication, audibility and spatial perception at high sound pressure levels beyond that of an equivalent HPD equipped only with ANC. Under these conditions the AGC is attenuating all sounds external to the HPD, and any "electronic" improvement in performance will be obtained from the ANC.

Feed-through AGC schemes that permit sounds external to the HPD to reach the ears binaurally at higher noise levels under selected conditions (e.g., for short durations) can be expected to maintain the improvement in spatial perception observed in quiet, provided the desired sounds remain audible. The accompanying increase in noise exposure, however, will need to be carefully controlled. Nevertheless, a signal processing strategy in which a predetermined sound is identified electronically causing it to be briefly transmitted to the user, together with ongoing monitoring of the overall noise exposure to ensure it remains within acceptable limits, is feasible.

More radical signal processing may, however, improve performance in intense noise. The development of earplugs equipped with ANC introduces the possibility of restoring localization associated with sound diffracted by the pinna (McKinley et al. 2005). For circumaural HPDs, some form of binaural feed-through processing, such as described, would appear necessary to restore spatial perception in the horizontal plane. Initial attempts have employed multiple microphones and signal processing to introduce head-related transfer functions (HRTFs) in an attempt to restore directional hearing, by simulating the acoustical effects of the head, ears and body (Bronkhorst et al. 2005; Johnson et al. 2004). The detection of tonal warning alarm sounds may be aided by the presence of the harmonic components of the signal (Darwin 2006).

Sub-band processing

The improvement of signal intelligibility in noise may be addressed by dividing the speech spectrum into separate frequency bands that are processed simultaneously (Moore 1995). Techniques for implementing so-called delayless sub-band processing have been described for ANC (Qiu et al. 2006), but have not yet been applied to HPDs where the overall time delay introduced by the signal processing is of critical importance. The processing time cannot exceed the time for sound to propagate from R to S for a feed-forward ANC system (Figure 2B), and this becomes extremely short for an earplug (~100us). For a feedback ANC HPD, the processing time must always be as short as possible. Introducing separate frequency bands permits the intensity within each to be calculated, and the speech S/N estimated either directly, in the case of separate environmental noise and speech within the communication channel, or from the modulation content of the frequency bands, in the case when all sounds are external to the HPD (Bentler et al. 2006). The former situation should benefit from sub-band signal processing, as it is an extension of the improvement in intelligibility already demonstrated with ANC. The benefit to the user to be gained when the speech and warning sounds are both in the environment external to the HPD remains to be demonstrated.

Nevertheless, dividing the frequency spectrum in sub-bands offers the prospect for implementing signal processing strategies for HPDs with ANC that have been developed to assist users of hearing aids listen to speech in noisy environments (Chung 2007). While the sub-band intensity modulation detection based S/N approaches have proved to be of limited benefit to hearing aid users for detecting speech in a background of many talkers or noise (Bentler 2005), they may be expected to prove beneficial for circumstances in which there is intense low-frequency environmental noise (van Dijkhuizen et al. 1997). This situation is common in HPDs, where the passive attenuation tends to emphasize low frequencies in the absence of ANC (e.g., see Figure 1). In this case the benefit in performance is again obtained from a reduction in the upward spread of masking. It should be noted that the improvement in speech intelligibility in noise observed for a hearing aid equipped with modulation detection based sub-band processing was attributed primarily to the high fidelity of sound reproduction (Alcántara et al. 2003), which suggests, again, that maintaining a flat frequency response and low distortion will remain an important consideration in ANC electro-acoustic system design.

Microphone arrays

As already noted, two, or more, microphones may be mounted on the exterior of a circumaural HPD, or helmet, and employed with signal processing to reproduce, in principle, the HRTFs lost by covering the external ear. The attempts to restore directional hearing in this way have so far not produced any advantage over a single microphone used to feed-through the environmental sound binaurally to the ears (Bronkhorst et al. 2005; Johnson et al. 2004). While the reasons for the lack of improvement in spatial perception are unclear, it should be noted that the error path will change every time the HPD is doffed and donned, or repositioned on the head, a factor that was not taken into account in either study. This mechanism would introduce errors in the reconstruction of appropriate HRTFs that may have been sufficient to offset any benefit in localization.

When attempting to listen to a talker against a background of the speech noises from other talkers, such as at a party, hearing aid users appear to derive slightly more benefit from the use of aids with directional microphones than from those with noise reduction schemes (Bentler 2005). The improvement of spatial perception of sounds external to the HPD in noise may hence be addressed by employing a microphone array to produce directional sensing of sound.

ACKNOWLEDGEMENT

This work was supported by NIOSH grant R01 OH008669.

REFERENCES

Abel SM, Giguère C (1997). A review of the effect of hearing protective devices on auditory perception: the interaction of active noise reduction and binaural technologies. Final Report for contract W7711-6-7316/001 SRV. National Defence, Canada.

Abel SM, Shelly Paik JE (2005). Sound source identification with ANR earmuffs. Noise & Health 7(27): 1-10.

Abel SM, Tsang S, Boyne S (2007). Sound localization with communication headsets: comparison of passive and active systems. Noise & Health 9(37): 101-107.

Alcántara JI, Moore BCJ, Kühnel V, Launer S (2003). Evaluation of the noise reduction system in a commercial digital hearing aid. Int J Audiol 42: 34-42.

Bentler RA (2005). Effectiveness of directional microphones and noise reduction schemes in hearing aids: a systematic review of the evidence. J Am Acad Audiol 16: 473-484.

Bentler R, Chiou LK (2006). Digital noise reduction: An overview. Trends in Amplification 10: 67-82.

Brammer AJ, Pan GJ, Crabtree RB (1997). Adaptive feedforward active noise reduction headset for low-frequency noise. In: Proc. Active 97 (pp 365-372). Budapest, Hungary.

Brammer AJ, Peterson DR, Cherniack MG, Gullapalli S (2005). Improving the effectiveness of communication headsets with active noise reduction: influence of control structure. In: RTO-MP-HFM-123 “New Directions for Improving Audio Effectiveness” (paper NBR 6-1). Neuilly-Sur-Seine, France: North Atlantic Treaty Organization.

Bronkhorst AW, Verhave JA (2005). A microphone array-based system for restoring sound localization with occluded ears. In: RTO-MP-HFM-123 “New Directions for Improving Audio Effectiveness” (paper 20-1). Neuilly-Sur-Seine, France: North Atlantic Treaty Organization.

Buck K, Zimpfer-Jost V (2005). Active hearing protection systems and their performance. Lecture NATO Series.

Carmichel EL, Harris FP, Story BH (2007). Effects of binaural electronic hearing protectors on localization and response time to sounds in the horizontal plane. Noise & Health 9(37): 83-95.

Casali JG, Robinson GS, Dabney EC, Gauger D (2004). Effect of electronic ANR and conventional hearing protectors on vehicle backup alarm detection in noise. Hum Factors 46: 1-10.

Chung K (2004). Challenges and recent developments in hearing aids: Part I, Speech understanding in noise, microphone technologies and noise reduction algorithms. Trends in Amplification 8: 83-124.

Chung K (2007). Effective compression and noise reduction configurations for hearing protectors. J Acoust Soc Am 121: 1090-1101.

Darwin CJ (2006). Contributions of binaural information to the separation of different sound sources. Int J Audiol 45: S20-S24.

Davis GM (2002). Noise reduction in speech applications. Boca Raton, FL: CRC Press.

Hornsby BWY, Ricketts TA (2001). The effects of compression ratio, signal-to-noise ratio, and level on speech recognition in normal-hearing listeners. J Acoust Soc Am 109: 2964-2973.

IEC 60268-16 (1998). Sound system equipment – Part 16: Objective rating of speech intelligibility by the speech transmission index. Geneva: International Electrotechnical Commission.

Johnson M, Carneal JP, Goldstein A (2004). Natural hearing restoration. Part II: Experimental results. In: Proc Active 2004, Williamsburg, USA.

Kuo SM, Morgan DR (1996). Active noise control systems. New York: Wiley & Sons.

McKinley RL, Bjorn VS, Hall JA (2005). Improved hearing protection for aviation personnel. In: RTO-MP-HFM-123 “New Directions for Improving Audio Effectiveness” (paper 13-1). Neuilly-Sur-Seine, France: North Atlantic Treaty Organization.

Moore BCJ (1995). Frequency analysis and masking. In: Moore BCJ (ed.): Hearing (pp 161-205). San Diego: Academic Press.

Nakamura A, Abel SM, Duncan M, Smith D (2007). Hearing, communication and cognition in low-frequency noise from armoured vehicles. Noise & Health 9(35): 35-41.

Pan GJ, Brammer AJ, Zera J, Goubran R (1995). Application of adaptive feed-forward active noise control to a circumaural hearing protector. In: Proc. Active 95 (pp 1319-1326). Newport Beach, USA.

Qiu X, Ningrong LI, Hansen CH (2006). The implementation of delayless subband active noise control algorithms. In: Proc Active 2006. Adelaide, Australia.

Rafaely B, Jones M (2002). Combined feedback-feedforward active noise reducing headset - the effect of acoustics on broadband performance. J Acoust Soc Am 112: 981-989.

Ray LR, Solbeck JA, Streeter AD, Collier RD (2006). Hybrid feedforward-feedback active noise reduction for hearing protection and communication. J Acoust Soc Am 120: 2026-2036.

Steeneken HJM (1998). Personal active noise reduction with integrated speech communication devices: development and assessment. Noise & Health 1(1): 67-75.

van Dijkhuizen JN, Festen JM, Plomp R (1991). The effect of frequency-selective attenuation on the speech-reception threshold of sentences in conditions of low-frequency noise. J Acoust Soc Am 90: 885-894.

Zera J, Brammer AJ, Pan GJ (1997). Comparison between subjective and objective measures of active hearing protector and communication headset attenuation. J Acoust Soc Am 101: 3486-3497.