Fort Lauderdale, Florida, USA
inter-noise 99
1999 December 06–08

SOUND EXPOSURE AND SPEECH INTELLIGIBILITY IN ROYAL NETHERLANDS AIR FORCE CHINOOK HELICOPTERS

Sander J. van Wijngaarden & Herman J.M. Steeneken
TNO Human Factors Research Institute
PO Box 23
3769 ZG Soesterberg
The Netherlands
{vanwijngaarden, steeneken}@tm.tno.nl

INTRODUCTION

In many types of aircraft and vehicles, high ambient noise levels are a known threat to the audiological health of aircrew members. Direct speech communication is generally impossible under such conditions, which means that crewmembers have to rely on some type of intercommunications system.

Within the Netherlands armed forces, the standards upheld for peacetime noise exposure are taken from national working conditions legislation, based on the international standard ISO-1999 [1]. The equivalent continuous A-weighted noise level is restricted to a maximum of 80 dB during 8 hours daily; higher levels are acceptable if exposure times are reduced to half the time for every 3 dB above an A-weighted level of 80 dB.

In the CH-47D Chinook helicopter during stationary flight, A-weighted noise levels up to 111 dB are observed. Chinook loadmasters even have to operate at higher noise levels, during complicated manoeuvring or when working outside in the rotor downwash. Indications exist that within the US Army, which has already had Chinook helicopter operational for decades, a considerable percentage of Chinook aircrew members have acquired substantial hearing loss due to noise exposure [2].

Very high noise levels also make speech communication using intercommunications systems a non-trivial task. Even when using relatively good quality earphones and noise-cancelling microphones, the signal-to-noise ratio at the tympanic membrane, which effectively determines speech intelligibility, is limited by the occurrence of high ambient noise levels [3]. Speech intelligibility in RNLAF Chinook helicopters was reported by many crewmembers to be marginal.

Sound exposure and speech intelligibility depend on several factors, first of which is the nature and strength of the ambient noise. Secondly, the acoustic insulation offered by the helmets (earmuffs) is very important. Other factors are the characteristics of (noise cancelling) microphones and earphones, and the intercom channel characteristics. All of these factors were considered in an effort to optimise speech communication and hearing protection in the CH47 D Chinook helicopter. In this paper, a selection of the results obtained in this research is presented.

CH47 D CHINOOK AMBIENT NOISE

The CH47 D Chinook helicopter is a relatively large and powerful cargo helicopter, equipped with twin rotors, that is capable of lifting heavy loads internally and externally. Naturally, the ambient noise in the Chinook helicopter is very much dependent on the exact measurement location and the manoeuvres taking place at the time of the measurement. A-weighted sound levels are always in the range of 100 up to 115 dB for practical locations.

The most dominant noise sources are located to the rear of the aircraft, in the cargo area. This is where the most frequent working stations of the loadmasters are. Therefore, loadmasters are expected to be at greater risk due to the high noise levels than the pilots are. Noise spectra (measured in 1/3 octave bands) are given in figure 1 for representative positions in the aircraft during straight and level flight.

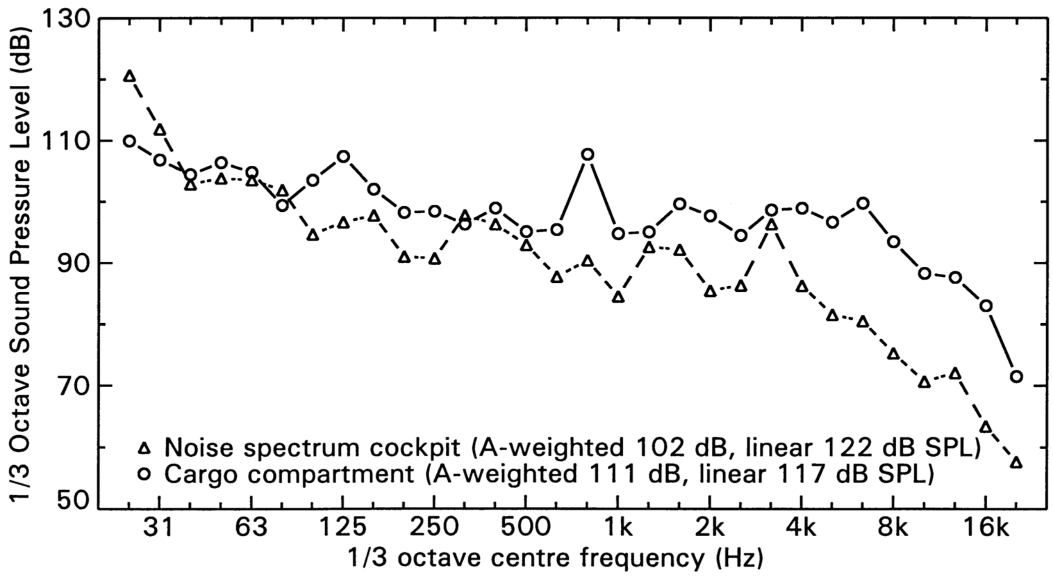

Figure 1. Chinook 1/3 octave band noise spectra (level re 2.10^{-5} pa, in cockpit and cargo compartment, during straight and level flight.

The spectra in figure 1 are considered sufficiently representative of most situations occurring in practice. The RNLAF CH47D Chinook ambient noise was investigated in more detail by the Netherlands Aerospace Laboratory NLR [4]. A fine-grained analysis of the ambient noise was made in that study, identifying separate noise sources. The findings of that study correspond well with the measurements given in figure 1. However, the level of detail of that study is beyond the scope of this paper.

PERSONAL PROTECTION EQUIPMENT

Model of sound attenuation with air crew helmets. Sound attenuation of an air crew helmet is principally provided by earmuffs, integrated in the helmet system. The outer shell of the helmet offers only negligible protection against noise.

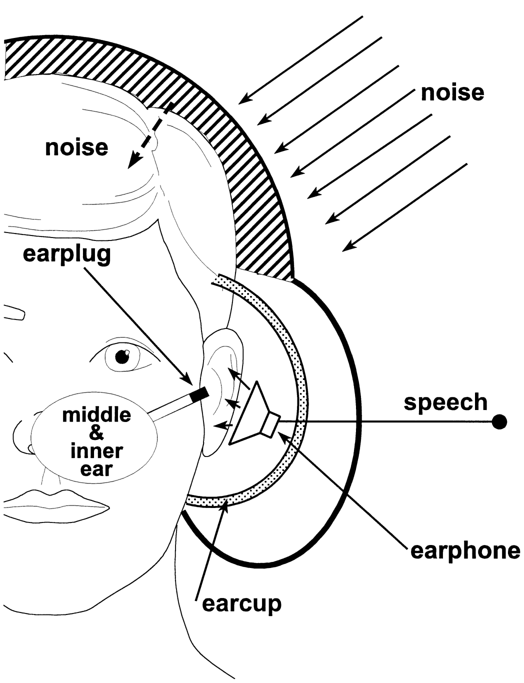

Figure 2. Model of sound attenuation of a helmet system.

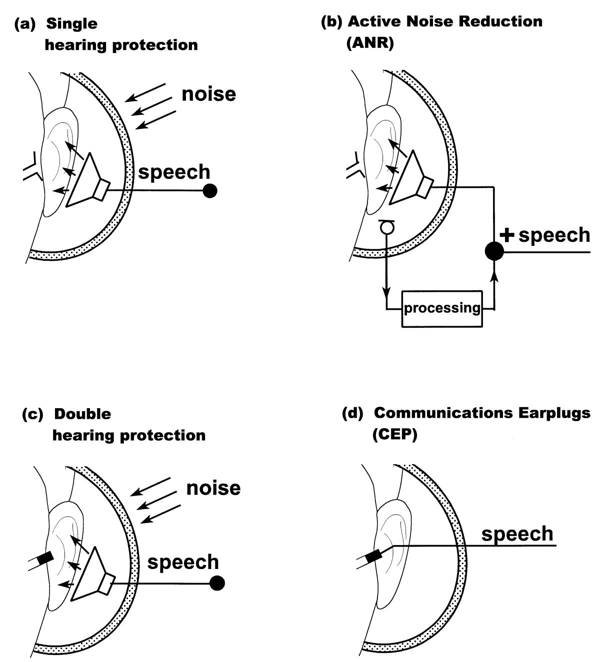

Figure 3. Four hearing protection configurations based on figure 2.

In figure 2, a model of the sound attenuation of a helmet system is given. Helmet and head are separated by a soft (personally customized) liner. The helmet is secured to the head with straps at the neck and chin. The construction of the helmet presses the earcups or earmuffs against the head. The earcups are fitted with seals to minimize acoustic leakage. In the earcups, telephones are integrated to present the intercom sound. To obtain the required sound attenuation, several options based on the above helmet model are available. Four options, which will be treated further in this paper, are given in figure 3.

If the sound attenuation of the earmuffs is insufficient, additional attenuation may be obtained by inserting earplugs in the ear canal. Such plugs will also attenuate the intercom sound produced by the telephones (figure 3c).

If the sound attenuation of earmuffs and earplugs is large, alternative sound conduction paths may become important. Since the helmet is rather intimately coupled with the skull, structureborne vibrations of the helmet, induced by the ambient sound, may be transmitted through the skull to the middle ear, becoming perceptible to the subject.

Original situation. Originally, RNLAF Chinook crews were equipped with a standard type of helmet, used frequently in military and civil helicopters throughout the world (referred to further in this paper as helmet A0). No additional sound attenuation devices were used (figure 3a).

The standard helmet was found to provide insufficient hearing protection. Using a standard method to calculate the continuous equivalent A-weighted sound level at the ear [5], involving the ambient noise spectrum and the attenuation characteristics of the helmet, the sound exposure due to the ambient noise was found to exceed the limits for an 8 hour working day. The allowed A-weighted value of 80 dB was exceeded under normal circumstances by 4 dB (cockpit) to 12 dB (cargo compartment). Especially the latter value was a problem, since effectively the duration of flights would have had to be limited to 30 minutes daily or less.

Helmets and ANR systems. In laboratory experiments, sound attenuation and speech intelligibility were determined for five types of helmet systems. Also, five types of Active Noise Reduction (ANR) systems were evaluated. Active Noise Reduction is based on the principle that a sound may be cancelled out by adding the same noise in anti-phase [6]. ANR requires a sense-microphone inside the earmuff and control electronics (figure 3b).

Earplugs. Another method to improve upon the attenuation of earmuffs alone, is by using earplugs. The obvious disadvantage of earplugs is the attenuation of desired sounds (intercom) as well as noise (figure 3c). If the level of the intercom sound is sufficiently high, this need not be a problem; speech intelligibility is determined by the speech-to-noise ratio, rather than the speech level in itself. However, the attenuation of earplugs tends to be quite frequency-dependent, causing a type of shaping of the spectrum of the speech signal that may degrade speech intelligibility. The effect on speech intelligibility is minimal if the attenuation characteristic is ‘flat’, i.e. the attenuation is approximately equal for all frequencies occurring in speech.

Communications EarPlugs (CEP’s). An earplug-based option that does not have the disadvantage of attenuation of earphone sound, is to use earplugs with integrated earphones (figure 3d). This concept was introduced by the US Army Aeromedical Research laboratory [7] and is called Communications EarPlug (CEP). Four sample sets of the US Army CEP prototypes were made available to the Royal Netherlands Air Force for experimenting purposes, and subjected to a series of sound attenuation and speech intelligibility measurements.

INFLUENCE OF NOISE ON SPEECH COMMUNICATION

When using an intercommunications system, the quality of this system is a determining factor for the speech intelligibility that is realized. Particularly bandwidth, electronic noise and dynamic behavior of the system largely determine the overall intelligibility of intercom speech.

The ambient noise influences speech intelligibility in two ways: speech is mixed with ambient noise at the microphone (talker position), and again at the earphones (listener position). Hence, optimization of speech intelligibility requires investigation of both microphone and earphone/earcup configurations.

The selection of a suitable type of noise-canceling microphone has considerable impact on speech intelligibility [3]. However, to emphasize the interaction between speech intelligibility and hearing protection, this paper is focussed on the influence of noise at the listening side of a speech channel.

An efficient and standardized physical measurement method that predicts speech intelligibility is the Speech Transmission Index (STI) method [8,9,10]. This method assumes that the intelligibility of a transmitted speech signal is related to the preservation of the original spectral differences between the speech sounds. Using an artificial test signal, resembling speech in terms of modulations and frequency spectrum, STI-values may be measured. The obtained STI-value (in the 0–1 range) is a good predictor of subjective speech intelligibility. The method is quite suitable to measure speech intelligibility degradation due to ambient noise at the listening side of an intercom channel. The test signal is applied to the earphones, and recorded back using a miniature microphone near the ear canal entrance.

Speech intelligibility under noisy conditions is determined largely by the speech-to-noise ratio. Hence, speech intelligibility and sound exposure can never be studied independently, since the overall sound exposure of crewmembers depends as much on the earphone sound level, as on the sound level at the ear due to ambient noise. Crewmembers generally respond to high ambient noise levels by adjusting intercom volume controls to high sound levels, potentially increasing the overall sound exposure even further. In the next section, the relation between speech intelligibility and sound exposure will be explored further.

RESULTS

Sound exposure due to the ambient noise. Ignoring the influence of the intercom system on the overall sound exposure, the equivalent continuous A-weighted sound pressure level due to the *ambient noise only* may be calculated. This calculation requires knowledge of the ambient noise spectrum (figure 1) and the joint (frequency-dependent) sound attenuation of all hearing protective devices used by a crew member (figure 3).

There are basically two categories of methods to perform sound attenuation measurements with hearing protectors: objective measurements (based on physical measurements of sound levels) and subjective measurements (using the hearing threshold of subjects as a reference). Both types of measurements were used. The objective method used is known as the “Microphone In Real Ear” or “MIRE” method [11]; the subjective method is described in standard ISO 48690-1 [12]. Both methods yield a reliable estimate of the mean sound attenuation of the hearing protector under test, as well as of the statistical spread (standard deviation).

Since the actual sound attenuation of a hearing protector is subject-dependent, so is the resulting sound exposure. Suppose the mean sound attenuation is used, given the population of Chinook crew members, leading to a calculated equivalent A-weighted level of 80 dB (exactly the limit for an 8 hour working day). This means, since the *mean value* was used, that only 50% of the population will actually be within exposure limits. In (standardized) exposure calculations, the standard deviation is subtracted from the mean, leading to a larger percentage of the population that is protected according to exposure limits [1,5].

Sound attenuation of hearing protective devices. In figure 4, measured sound attenuation characteristics are given for five types of helmets, marked A-E, without ANR (configuration 3a). Figure 5 shows attenuation results of some of the same helmet types as in figure 4, now *with* ANR (ANR types marked 1-5). Helmet A0 (0 meaning no ANR) is repeated as a reference.

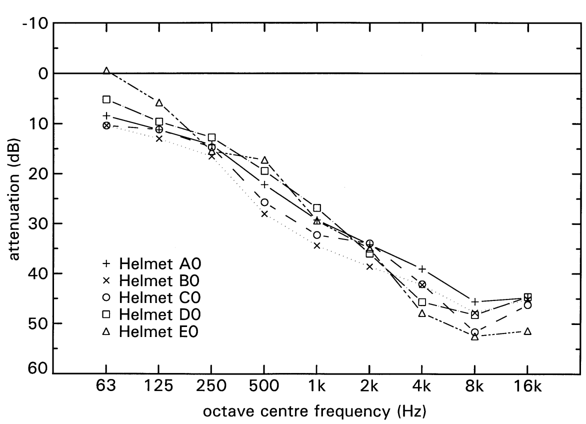

Figure 4. Sound attenuation of five types of air crew helmets (MIRE method, 4 subjects). Measured with 1/3 octave resolution.

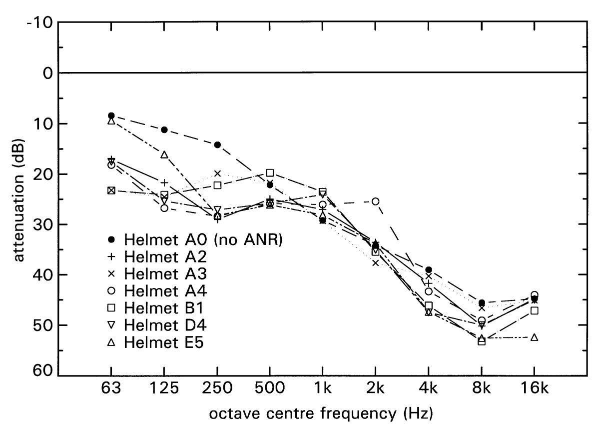

Figure 5. Sound attenuation of five types of ANR systems with several air crew helmets (MIRE method, 4 subjects). Measured with 1/3 octave resolution.

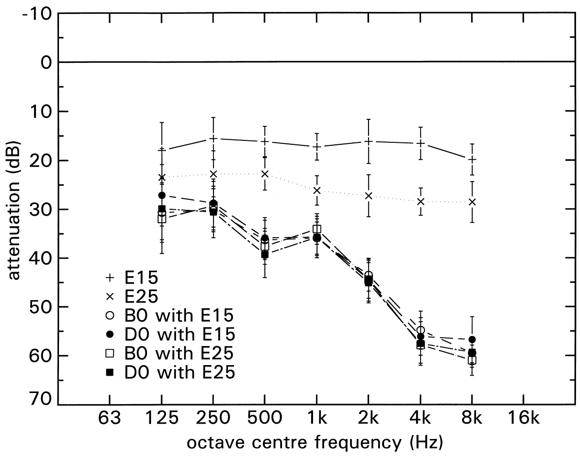

Figure 6. Sound attenuation of two types of earplugs (E15 and E25), with and without helmets (ISO-4869-1 method, 16 subjects). 1/1 octave resolution.

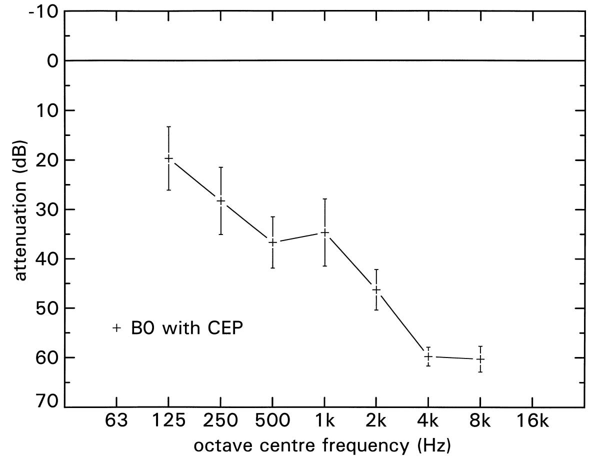

Figure 7. Sound attenuation of Communications Earplugs, with helmet B0 (procedure of ISO-4869-1 method, 4 subjects). 1/1 octave resolution.

In figure 6 sound attenuation measurement results are given for two types of custom molded earplugs (E15 and E25) with a ‘flat’ frequency characteristic. Also, overall sound attenuation curves are given for both types of earplugs *combined* with helmets B0 and D0. Finally, in figure 7 joint attenuation results are given for CEP’s with helmet B0. Although the measurement procedure used to obtain figure 7 was in fact identical to the procedure described by ISO 4869-1, the number of subjects was only 4 instead of the usual 16. Figure 7 should be regarded as an indication of sound attenuation, and may not be used to base noise exposure calculations on.

Figures 4-7 clearly show that the application of ANR or earplugs enhance the overall sound attenuation. ANR proves to be effective, mainly for frequencies below 1000 Hz, which is a well-known fact for ANR systems [6]. The earplugs offer additional protection over a far wider frequency range. It is interesting to observe that, although there are differences in individual earplug and helmet attenuation curves, the *joint* attenuation of helmet-earplug combinations appears to approach a certain limit (figures 6 and 7). The local minimum in attenuation at 1 kHz is readily noticed in all helmet-earplug attenuation curves. The most probable cause of this effect is helmet-bone conducted sound; this is an effect similar to regular bone conduction of sound [13], but enhanced by the helmet structure, that is intimately coupled with the skull bones. The attenuation of the earplugs is partly ‘bypassed’ by this parallel conduction path.

Calculated sound exposure due to ambient noise. If figures 4,5 and 6 are used to calculate the A-weighted sound pressure level at crew members’ ears due to ambient noise, the results of table I are obtained. Table I shows that many of the improvements on the original situation in the RNLAF Chinooks, still offer insufficient attenuation to reach equivalent A-weighted levels below 80 dB. The best results are obtained using earplugs.

Table I. Continuous equivalent A-weighted sound levels at the tympanic membrane, due to ambient noise (dB).

	Cockpit	Cargo comp.
Helmet A0	84	91
Helmet B0	81	88
Helmet C0	84	90
Helmet D0	85	91
Helmet E0	87	93
Helmet + ANR A2	77	85
Helmet + ANR A3	80	86
Helmet + ANR A4	77	87
Helmet + ANR B1	82	91
Helmet + ANR D4	77	87
Helmet + ANR E5	78	86
Helmet + Earplugs B0 & E15	69	78
Helmet + Earplugs D0 & E15	71	79
Helmet + Earplugs B0 & E25	69	79
Helmet + Earplugs D0 & E25	69	78

Table II. A-weighted earphone sound pressure levels (dB) for STI=0.60 and STI=0.35 (cargo compartment).

	STI=0.35	STI=0.60
Helmet A0	85	97
Helmet B0	76	89
Helmet C0	77	94
Helmet D0	79	90
Helmet E0	82	91
Helmet + ANR A2	80	88
Helmet + ANR A3	77	88
Helmet + ANR A4	83	95
Helmet + ANR B1	79	89
Helmet + ANR D4	78	88
Helmet + ANR E5	75	85
Helmet + Earplugs B0 & E15	70	79
Helmet + Earplugs D0 & E15	68	77
Helmet + Earplugs B0 & E25	69	77
Helmet + Earplugs D0 & E25	66	74

Speech Transmission Index measurements. STI measurement results for the various alternatives are given in Table II. The STI target for normal operations is 0.60; the worst-case acceptability limit is STI=0.35, corresponding to 50% intelligibility of redundant sentences. Table II gives calculated sound levels at the tympanic membrane *due to the earphones*, that is sufficiently high to achieve STI=0.60, respectively STI=0.35 in the cargo compartment. Comparison between tables I and II shows that even when the ambient noise is attenuated to levels below 80 dB(A) at the tympanic membrane, the overall sound exposure may still be increased by the intercom sound.

Clearly, the lowest possible sound exposure is obtained when using earplugs. This is, in fact, the only of the investigated options that allows for equivalent A-weighted levels lower than 80 dB in the cargo compartment. The application of ANR has, at best, a small positive influence; in real Chinook practice, all of the tested ANR systems showed periods of instability , momentarily increasing sound exposure and causing severe annoyance.

CONCLUSIONS

Of the investigated hearing protection options for the RNLAF Chinook helicopter, the combination of helmets and custom molded earplugs clearly showed the best results; using earplugs, an maximum sound attenuation is obtained, that appears to be limited by helmet-bone conducted sound. The sound exposure when using a helmet-earplug combination will allow a maximum daily exposure time of 8 hours.

In the Chinook noise environment, ANR systems did not show a considerable improvement on conventional helmets; this is explained by the relative strength of high-frequency components in the noise spectrum, for which ANR does not offer additional attenuation. In fact, *reduced* attenuation by applying ANR was sometimes obbserved.

Communications earplugs offer roughly the same sound attenuation as conventional earplugs, according to a limited set of measurements. The advantage of CEP's is the production of earphone sound at the most efficient location, behind the earplug in the ear canal. In principle, this will allow better speech intelligibility at moderate sound levels.

With all options except the earplug-helmet combination, care must be taken to avoid a significant contribution of the intercom sound to the overall sound exposure.

REFERENCES

[1] ISO 1999 2nd edition (1990). *Acoustics – Determination of occupational noise exposure and estimation of noise-induced hearing impairment.* Geneva: International Standards Organization.

[2] "Communication and Noise Hazard Survey of CH-47D Crewmembers," J.E. Ribera, B.T. Mozo, K.T. Mason, & B.A. Murphy, USAARL Report No. 96-02, Alabama U.S.A.: U.S. Army Aeromedical Research Laboratory (1995).

[3] "Speech transmission quality and hearing protection in the CH 47D Chinook helicopter," S.J. van Wijngaarden, J.A.Verhave & H.J.M. Steeneken, TNO Rep.No. TM-97-A042, Soesterberg The Netherlands: TNO Human Factors Research Institute (1997).

[4] "Interior noise levels of the RNLAF Boeing CH-47D Chinook.," J.M.G.F. Stevens & H.M.M. Van der Wal, NLR contract report CR 97562 L, Amsterdam, The Netherlands: National Aerospace Laboratory NLR (1997).

[5] "On the problem of combining the intersubject induced hearing loss,"G.F. Smoorenburg, Hearing Conservation Conference, OES Publications, Lexington, KY, USA: Anderson Hall, University of Kentucky (1992).

[6] "Personal Active Noise Reduction with integrated Speech Communication Devices: development and assessment," H.J.M. Steeneken & J.A.Verhave, AGARD conference proceedings 596 "Audio effectiveness in aviation", Neuilly-sur-Seine France: AGARD (1997).

[7] "The Communications EarPlug: A logical choice for voice communications in aircraft," B.T. Mozo & J.E. Ribera, AGARD conference proceedings 596 "Audio effectiveness in aviation", Neuilly-sur-Seine France: AGARD (1997).

[8] "A physical method for measuring speech transmission quality,"H.J.M. Steeneken & T. Houtgast, *J. Acoust. Soc. Am.*, **67**, 318-326 (1980).

[9] IEC 60268-16 2nd edition (1998) Sound system Equipment "Part 16: objective rating of speech intelligibility by speech transmission index", Geneva.

[10] "Mutual dependence of the octave-band weights in predicting speech intelligibility," H.J.M. Steeneken & T. Houtgast, *Speech Comm.*, **28**, 109-123 (1999).

[11] "Assessment of hearing protector performance in impulse noise. Feasability study part II: Methods," G.F. Smoorenburg, A.W. Bronkhorst, W. Soede, & A.J.C. de Reus, Rapport IZF 1993 C-32, Soesterberg: TNO Technische Menskunde (1993).

[12] ISO 4869-1 Acoustics-Hearing Protectors-Part 1. *Subjective method for the measurement of sound attenuation.* Geneva: International Standards Organization (1990).

[13] "In search of the bone-conduction threshold in a free sound field," J. Zwislocki, *J. Acoust. Soc. Am*, **29** (7), 795-804 (1957).