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Balancing speech intelligibility versus sound exposure in selection of personal hearing protection equipment for Chinook air crews.

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Running head:
Sound exposure of Chinook air crews

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ABSTRACT

Background: Air crews are often exposed to high ambient sound levels, especially in military aviation. Long-term exposure to such noise may cause hearing damage; selection of adequate hearing protective devices is crucial. Such devices also affect speech intelligibility. When speech intelligibility and hearing protection lead to conflicting requirements, a compromise must be chosen. The selection of personal equipment for RNLAF Chinook air crews is taken as an example of this process. ***Methods:*** Sound attenuation offered by air crew helmets and ear plugs was measured using a standardized method. Sound attenuation results were used to calculate sound exposure. Also, objective predictions of speech intelligibility were calculated using the Speech Transmission Index (STI) method. Subjective preference was investigated through a survey among 28 experienced air crew members. ***Results:*** The use of ear plugs in addition to a (RNLAF standard) helmet may lead to a significant reduction of sound exposure. Using ear plugs that offer high sound attenuation, instead of using a less attenuating type, gives a little additional reduction of sound exposure, at the expense of a large reduction in speech intelligibility. Hence, it is better to use 'light' ear plugs. Better performance still is offered by Communications Earplugs, ear plugs featuring integrated miniature earphones. Results from the user preference survey correspond well with objective measurement results. ***Conclusions:*** In the case of the RNLAF Chinook, the best solution is using Communications EarPlugs in combination with a standard helmet. The Chinook case clearly illustrates that hearing protection and speech intelligibility should be treated as connected issues.

KEY WORDS

Hearing protection
Noise exposure
Speech intelligibility
Communication
Earplugs
Air crews
Speech Transmission Index

INTRODUCTION

The delivery of the first CH47 D Chinook helicopters to the Royal Netherlands Air Force in 1996 marked the beginning of a battle against noise exposure while operating this type of helicopter. In the aircraft interior, the CH47 is noisier than any other aircraft in the RNLAF (12). Since the RNLAF strives to uphold the strictest of (peacetime) national health and safety guidelines regarding noise, considerable effort was invested in limiting air crew noise exposure.

While threatening the audiological health of air crews, high ambient noise levels will at the same time cause a reduction of the intelligibility of intercom speech. When ambient noise in an aircraft interior is to be accepted as a given, which is usually the case, the selection of personal equipment (such as helmets, headsets and ear plugs) offers the best possibilities to optimize speech intelligibility and hearing protection.

More often than not, speech intelligibility and hearing protection lead to opposite requirements. While intelligibility benefits from increasing the intercom speech level, this also leads to an additional sound exposure. The use of earplugs may also have opposite effects on intelligibility and sound exposure. By using ear plugs, further attenuation of the ambient noise is obtained; at the same time, the intercom speech is attenuated, which potentially decreases speech intelligibility. For these reasons, sound exposure and speech intelligibility should always be considered as connected issues; one can not change one, without affecting the other.

Another aspect of considerable importance is *comfort*. Not only will users only accept a solution that is sufficiently comfortable; uncomfortable hearing protectors also tend to instigate tampering by users, which usually increases comfort at the expense of sound exposure. Hence, when comparing the performance of hearing protectors, a user preference survey will add valuable information to results obtained through speech intelligibility and sound attenuation measurements.

This article describes the data that was collected in search of the optimal solution for personal hearing protection equipment for the RNLAF CH47 D Chinook helicopter. It is a case study that illustrates an approach of balancing hearing protection and speech intelligibility.

THE CH47 D CHINOOK ENVIRONMENT

The RNLAF version of the CH47 D Chinook helicopter is a powerful, mid-size 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 (12).

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 the cockpit and the cargo area during straight and level flight (13).

[Figure 1 Here]

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 (11). A fine-grained analysis of the ambient noise was made in this study, identifying separate noise sources. The findings of this study correspond well with the measurements given in figure 1. However, the level of detail of this study is beyond the scope of this article

PERSONAL HEARING PROTECTION EQUIPMENT

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 Here]

In figure 2, a model of the sound attenuation of a helmet system is given. Helmet and head are separated by a soft liner, which is custom-molded or customized by means of soft pads. 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. Proper customization and helmet donning procedures are necessary to ensure optimal sound attenuation. Inside the earcups, earphones are usually integrated to present intercom or radio sound.

If the sound attenuation of the earmuffs is insufficient, additional attenuation may be reached by inserting earplugs in the ear canal. However, such plugs will also attenuate the intercom sound produced by the telephones.

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

To obtain the desired sound attenuation, several options based on the above helmet model are possible. Four options are given in figure 3.

[Figure 3 Here]

Configuration (a) is perhaps the most common among aircrews. The only protection against ambient noise is the sound attenuation offered by ear cups; speech is transferred without obstruction from the earphone to the ear canal. The overall performance in terms of hearing protection and speech intelligibility fully depends on the characteristics of the helmet, the ear seals (circumaural pads), and on the procedures that are applied for helmet customization and helmet donning.

In configuration (b), the attenuation of ambient sound is increased by application of ANR (Active Noise Reduction). ANR is based on the principle of anti-noise; the sound within the earcup is measured by means of a sense-microphone, and fed back in anti-phase through the earphone. This actively cancels out low frequencies (below approximately 1000 Hz). Unfortunately, because of theoretical and physical limitations, the effect of additional attenuation at low frequencies will be reduced by some *amplification* that ANR-systems give at higher frequencies (1000-4000 Hz). Although ANR systems are designed to reduce the A-weighted sound exposure, this will only really be effective if the noise spectrum largely consists of low frequencies. ANR is therefore typically suited for environments where low-frequency noise sources (50-1000 Hz), such as combustion engines and vehicle tracks, determine the noise spectrum. Figure 1 shows that higher frequencies form a large contribution to the Chinook noise, which makes application of ANR less effective. Furthermore, application of ANR is potentially troublesome in helicopters, since extremely low frequency sounds (such as the 11 Hz rotor fundamental in the Chinook) may cause instability (oscillation) of ANR systems. For RNLAF purposes, ANR was ruled out as on option for the Chinook after careful review and testing of the available systems (12,13).

Configuration (c) is a straightforward variation on (a); in addition to the helmet, earplugs are used for further sound attenuation. The achieved attenuation is *not* simply the sum of the attenuation of the earcup and the attenuation of the earplugs, but is usually less than that. One reason is that earcup and earplug are acoustically coupled by the air volume inside the earcup; the joint acoustic behavior is influenced by this. Another (usually more important) reason is that there is a natural limit to the overall sound attenuation. Sound is not just propagated through the earcup, then through the earplug, and into the ear canal. High noise levels will induce vibrations in the helmet, which are transferred through the bone structure of the head. Through such ‘bone conduction’ of sound, there will always be some level of noise that reaches the tympanic membrane. Hence, attenuation of sound through earcups and earplugs below this bone conduction level will *not* result in a reduction of sound exposure. Double hearing protection usually offers good protection against ambient noise, at the cost of also attenuating the intercom speech. This usually effects speech intelligibility negatively.

Configuration (d) is based on a special kind of earplug: The Communications EarPlug (CEP). This concept was introduced by Mozo of the US Army Aeromedical Research Laboratory (4). The earphone in the earcup is replaced by a miniature transducer integrated in the earplugs. This offers the same hearing protection advantages as configuration (c), but without loss of speech intelligibility. The only disadvantage is the ergonomic consideration that the necessary wires between earplugs and helmet (for the intercom signal) complicate helmet donning, and introduces the risk that communications are lost when the wires are damaged.

After an extensive market survey and investigation of more than 15 alternatives (12), a final selection was made of candidate-solutions to the noise exposure and speech intelligibility problems in the RNLAF Chinooks.

A single type of helmet was chosen for the final selection. This helmet was found in preceding measurements (12) to offer relatively high sound attenuation. The choice was also based on functionalities of the helmet not related to the noise problem (eg. night vision goggle mounts, NBC protection preparation, etc).

Two types of ear seals (referred to as I and II) were selected, both suitable for use with the standard helmet. The difference between the earseals is primarily the rigidity of the foam material that is used: earseals of type II are considerably softer than those of type I. This effects comfort, but may also influence sound attenuation.

Three types of earplugs were selected: two types of “passive” earplugs (referred to as earplugs 1 and 2), and a type of Communications Earplugs (referred to as CEP). The characteristics of these ear plug types are summarized in table I.

[Table I Here]

Earplug 1 is a type of simple disposable foam plug. Earplug 2 is a custom molded earplug; by application of acoustic filters, such earplugs can be adjusted to a variety of sound attenuation characteristics. The filter used in earplug 2 has a flat attenuation curve: all frequencies are attenuated equally, by 15 dB. This is considerably less than for the other two earplug types, hence the sound attenuation is rated ‘low’ in table I. This is a deliberate choice; theoretically, this minimizes the chance that the intelligibility of the intercom speech is reduced by these earplugs.

SOUND EXPOSURE

One of the difficulties in determining sound exposure is the natural fluctuation in noise level that nearly always occurs in practice. In aircraft, the ambient noise level is continuously changing (for example, because the aircraft changes altitude or speed); the instantaneous noise exposure varies accordingly. However, these variations are not of interest to identify the global consequences of noise exposure; we are interested in a simple measure of sound exposure that is related to a complete working day (or mission). Such a measure is the equivalent continuous A-weighted sound pressure level (L_{Aeq}).

The L_{Aeq} is defined as the A-weighted *continous* (non-varying) sound level that has the same impact in terms of sound exposure as the varying sound that we are concerned with. In other words: if the L_{Aeq} equals 80 dB, the noise exposure is the same as with a stationary noise source with an A-weighted level of 80 dB.

RNLAF noise exposure limits require that the L_{Aeq} does not exceed 80 dB during an 8-hour working day. This limit is derived from ISO-1999 (2) and Netherlands working conditions legislation. For every

3 dB above this limit, the maximum exposure time is reduced by half. Hence, if the L_{Aeq} is 83 dB, the maximum daily exposure time is 4 hours, if the L_{Aeq} is 89 dB daily exposure is limited to 1 hour. Since the RNLAF aims at maintaining the possibility of operating all aircraft for 8 hours a day with the same crew, this means that the L_{Aeq} must be no higher than 80 dB.

Although in-flight noise-dose measurements will give the most accurate estimates of the actual L_{Aeq}, this is not an efficient procedure to compare sound exposure effects of using different personal equipment alternatives. Instead, sound attenuation of these alternatives may be measured under laboratory conditions, and used (together with the ambient noise spectrum) to calculate the $L_{Aeq.}$

The sound attenuation of the earplugs (mean values and standard deviations) and earplug-helmet combinations was measured in accordance with standard ISO 4869-1 (3). This method is based on a modified Békésy procedure; the hearing threshold of a subject (16 subjects for each combination) is used as a reference for determining the sound attenuation of hearing protectors: the difference between the hearing threshold with and without protection is the attenuation of the hearing protector. For calculation of the equivalent continuous A-weighted sound pressure level (L_{Aeq}), the Assumed Protection Values (APV) is used; this is, as defined in standard ISO 1999 (2), the mean sound attenuation minus the standard deviation.

[Figure 4 Here]

In figure 4, sound attenuation as a function of frequency is given for several alternatives based on the same (standard) helmet. Although the construction of helmet and earcups are identical, considerable differences in attenuation occur for different types of earseals, and different earplugs.

When earplugs are used in addition to the helmet, the effect depends on the type of earplug. For earplug 1 and CEP, the attenuation is more or less equal for frequencies above 1 kHz, irrespective of the earplug type; the attenuation approaches an earplug-independent maximum. Using earplugs with higher sound attenuation is useless, since the level of structure-borne noise (conducted from the helmet to the skull) will exceed the level of the airborne noise at higher earplug attenuation values. This is a common finding when using high-attenuation hearing protection configurations based on helmets (13).

Earplug 2, which is specified to give only 15 dB of attenuation over the whole frequency range, apparently does not reach a maximum attenuation as earplug 1 and CEP do (figure 5). Compared to the situation without helmet, earplug 2 offers 10-20 dB of additional attenuation.

[Figure 5 Here]

Figure 5 shows that when using ‘light’ earplugs such as earplug 2, or no earplugs at all, the difference in attenuation between both types of earseals is appreciable. Based on the information in figures 1, 4 and 5, the L_{Aeq} was calculated for eight hearing protection alternatives. Results are given in table II.

[Table II Here]

To fully comply with RNLAF requirements, the L_{Aeq} values in table I should be lower than 80 dB (or, equivalently, the maximum daily exposure time should be 8 hours). Table I clearly shows that this is not possible without earplugs, or some other means of additional sound attenuation besides the helmet. When, for some reason, earplugs are not applied, the choice of the type of earseals is also of practical importance: the difference between earseals I and II in L_{Aeq} (no earplugs) is 6 dB, or a factor 4 in maximum exposure time.

Because the noise level is higher in the cargo compartment, this is the most critical location. Not all of the alternatives based on earplugs will allow for the full 8 hours of daily exposure. In fact, the choice of earseals becomes quite important. With earseal II, all of the earplugs offer sufficient sound attenuation for 8 hours of daily exposure, even in the cargo compartment.

Earplug 1 shows the best performance of the earplugs, at least in terms of sound exposure. Unfortunately, since its sound attenuation is higher than the other earplugs, it will also attenuate intercom sound more. In the next section, the effects of the different alternatives on speech intelligibility will be considered.

SPEECH INTELLIGIBILITY

Intercom speech intelligibility in the Chinook is determined by many factors, some more important than others. One of the more important factors is the ambient noise *at the microphone*. The presence of ambient noise at the microphone position will degrade the intelligibility of the speech received by this microphone.

A second factor, which has the largest influence of all, is ambient noise *at the ear*. The speech-to-noise ratio at the earphones was found to be the limiting factor for the overall speech intelligibility (12). Therefore, investigations of speech intelligibility are focused on the listening-side of the intercom channel.

For sound exposure, we were able to calculate predictions from sound attenuation measurements. For speech intelligibility, something similar is possible. Speech intelligibility may be predicted objectively through *measurements*, through the Speech Transmission Index (STI) method (1). This method yields a single 0-1 index that correlates well with many known psychophysical measures of speech intelligibility (8,10). A qualification of intelligibility related to STI, as well as the relation between the objective STI and a measure of subjective intelligibility (as measured with speakers and listeners), is given in Table III. For the subjective intelligibility the CVC-word score (percentage correct) is used. This test is based on monosyllabic nonsense words (Consonant-Vowel-Consonant, CVC).

In general, for a communication channel to be rated ‘good’, a minimum STI value of 0.60 is required. In worst case situations (e.g. maximum level of ambient noise) STI=0.35 is the lowest acceptable value. This is presumed to correspond with the 50% intelligibility level of redundant sentences.

[Table III Here]

As stated, the STI-method is a method that can be used to obtain predictions of speech intelligibility through objective *measurements*. This can be taken one step further: STI results can also be obtained through *calculations*, provided that all the necessary information is available. We need to evaluate speech intelligibility at the listening side of an intercom channel, in ambient noise, while helmets, earphones and earplugs are used. This means that for STI calculations we need the ambient noise spectrum, the frequency transfer function of the earphones and sound attenuation characteristics of helmets and earplugs. The same information was necessary for the calculation of the sound exposure, and is already available, with the exception of the frequency transfer function of the earphones. These were measured using a Head Acoustics artificial head with ear simulators, using pink noise (noise with equal energy in each octave band) as a measuring stimulus. Results from these frequency transfer measurements are given in Table IV. The frequency transfer measurements were carried out for the standard earphones that are used with the standard helmet, and for the Communications EarPlugs. Obviously, when using CEP's the standard earphones are no longer used, and STI-values are calculated using the frequency transfer of the CEP transducers.

[Table IV Here]

We indicated that the use of earplugs will potentially affect intelligibility, since these earplugs also attenuate the intercom speech. To counter the attenuation of the speech signal, the intercom volume control must be adjusted to higher speech levels. For the calculation of the results given in table V, an undistorted intercom signal of adequately high level is assumed. The necessary speech levels produced by the earphones are given, to reach STI=0.35 (worst-case minimum) and STI=0.60 (minimum for nominal conditions). The levels inside the earcup are given, as well as the levels in the ear canal; the difference is the sound attenuation of the earplug. The sound level in the ear canal is relevant, since it quantifies the contribution of the earphones to the overall sound exposure. The sound level in the earcup is also relevant, since there is a practical limit to the maximum sound level that can be produced by earphones.

[Table V Here]

All earphone levels above 90 dBA (in the table in ***bold italic*** typeface) will require modification of the intercommunications system, and the selection of a different earphone type. Above this level, the standard type of earphone used with the standard helmet suffers from signal distortion and a significant shortening of the life span of the earphone.

The earphone levels required when using earplug 1 are not realistically achievable, even if only the worst-case limit (STI=0.35) is imposed; hence, this earplug can not be expected to contribute to a solution. With earplug 2 the worst-case requirement can be met, even though the nominal requirement is not met for the cargo compartment. Since the cargo compartment is more or less a worst-case condition, this is considered acceptable.

The speech level due to CEP or earphone *in the ear canal* determines the contribution of the intercom to the overall sound exposure. The production of sound by the earphones is not continuous, but intermittent; some periods of silence will exist, in-between speech communications. Since the intercom use is frequent in the Chinook, we will assume that speech will be produced by the earphones 25 % to 50% of the time. If the level of speech due to the intercom is 80 dB(A), this means that the L_{Aeq} due to the intercom is 74-77 dB. The actual measure of interest is the combined contributions to the L_{Aeq} by both the ambient noise and the intercom.

A relatively safe rule of thumb, although computationally not completely accurate[2], is that if the A-weighted speech level in the ear canal is below 80 dB, and the L_{Aeq} due the ambient noise is below 80 dB, the combined L_{Aeq} will also be below 80 dB. By applying this rule of thumb to the results in table V, we can decide if we may assume that the overall sound exposure requirement (L_{Aeq}< 80 dB) is fully determined by the exposure to ambient noise: this is only the case if the speech level in the ear canal is below 80 dB(A).

When using the standard helmet without earplugs (especially with earseal I), speech levels above 80 dB(A) are to be expected, even if only STI=0.35 is required in the cargo compartment. This means that for the alternatives without earplugs, a proper balance between sound exposure and speech intelligibility (both meeting the minimum requirements at the same time) can not be obtained.

All of the alternatives with earplugs (including CEP) will (theoretically) allow sufficient speech intelligibility at levels below 80 dB(A). As stated above, this is not practically possible for earplug 1, which leaves earplug 2 and CEP as alternatives that meet the speech intelligibility requirements. Table V shows that CEP offers the better performance of these two alternatives.

It should be noted that the speech levels given in table V are the *minimum* levels that are required to meet STI=0.35 and STI=0.60. Air crew members tend to choose an intercom volume setting that gives the *optimum* speech intelligibility, even if a significant contribution to the overall sound exposure is the result. By comparing tables I and V, we have observed for which alternatives a balance between exposure and intelligibility in principle *can* be reached. In practice, individual crewmembers may be

[2] An accurate computation of the combined L_{Aeq} is obtained from an energetic summation of the combined contributions of the ambient noise and the intercom. This requires a more accurate estimate of the time that speech is produced over the intercom than the rough guess of 50% used here.

inclined to tip the balance in favor of speech intelligibility. This means that it is useful to choose the best alternative in terms of intelligibility, instead of choosing any alternative that meets the minimum requirements.

USER PREFERENCE

When selecting hearing protectors, user preference is a relatively important issue. Especially subjective comfort is a relevant factor. For instance, earplugs that are considered too uncomfortable will not be used in the long term; uncomfortable helmets may lead to a less tight adjustment of straps (leading to a lesser sound attenuation). The importance of proper helmet adjustment (in this case the neck strap) is illustrated by figure 6. In this case, the sound attenuation of the helmet was measured objectively, using a miniature microphone placed near the ear canal entrance.

[Figure 6 Here]

The highest sound attenuation values in figure 6 correspond to the tightest neck strap setting, and vice versa. Especially in the 4-8 kHz range, the difference in sound attenuation is considerable.
Another common observation with low-comfort hearing protectors, is that users choose to temporarily loosen or remove the hearing protectors, even when still in a high-noise environment. The impact on sound exposure, as illustrated in figure 7, can be quite dramatic.

[Figure 7 Here]

In figure 7, the maximum daily exposure time (as calculated from the L_{Aeq}) is shown as a function of the percentage of time that the hearing protector (in this case, the helmet) is removed. When wearing the helmet continuously, the maximum daily exposure time is over three hours. If the helmet is removed (or made ineffective by completely loosening all straps) only 5% of the time, the maximum daily exposure time reduces to approximately 45 minutes.
To gain insight into user preferences regarding the personal hearing protection equipment, a survey was conducted among 28 experienced Chinook crewmembers. The average number of flight hours was 700. All subjects were asked to rate four different dimensions on a 1-5 scale, ranging from bad (1) to

excellent (5). The dimensions were hearing protection, speech intelligibility, intercom sound level and comfort.

In figure 8, user responses with regard to earplug (and CEP) performance are given.

[Figure 8 Here]

Significant differences between earplug 2 and CEP are observed for speech intelligibility and intercom sound level. This is consistent with the findings of the measurements described in previous section.

Users were also asked to rate the earseal performance (figure 9).

[Figure 9 Here]

The earseals of type II, which are made of a softer material than type I, are rated significantly higher on all dimensions, including comfort. The differences found for hearing protection and speech intelligibility are consistent with the measurement results presented above.

CONCLUSIONS

The results from the user preference survey generally support the conclusions that may also be drawn from our (more objective) sound exposure and speech intelligibility measurements. Taking all factors into consideration, the alternatives offering the highest performance are based on Communications Earplugs, preferably in combination with the (soft) earseals of type II.

Evaluation of the intercom sound levels shows that the presence of intercom speech may increase sound exposure. This stresses the need to evaluate noise exposure and speech intelligibility *together* as connected issues, especially in high-noise environments.

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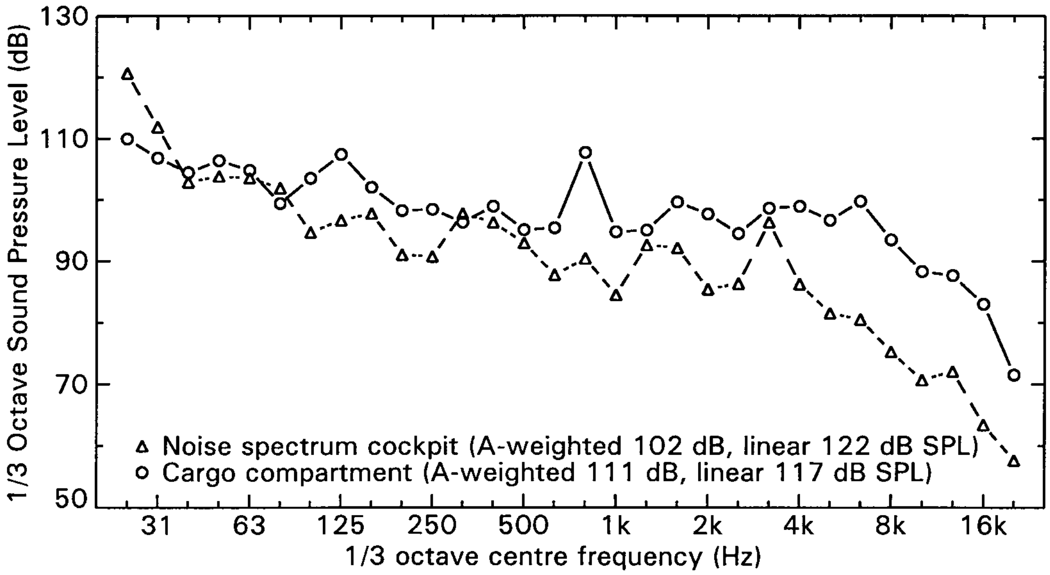
FIGURE 1


130
110
90
70
50
1/3 Octave Sound Pressure Level (dB)
31
63
125
250
500
1k
2k
4k
8k
16k
1/3 octave centre frequency (Hz)
Noise spectrum cockpit (A-weighted 102 dB, linear 122 dB SPL)
Cargo compartment (A-weighted 111 dB, linear 117 dB SPL)

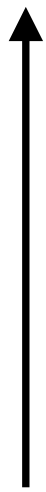


FIGURE 2

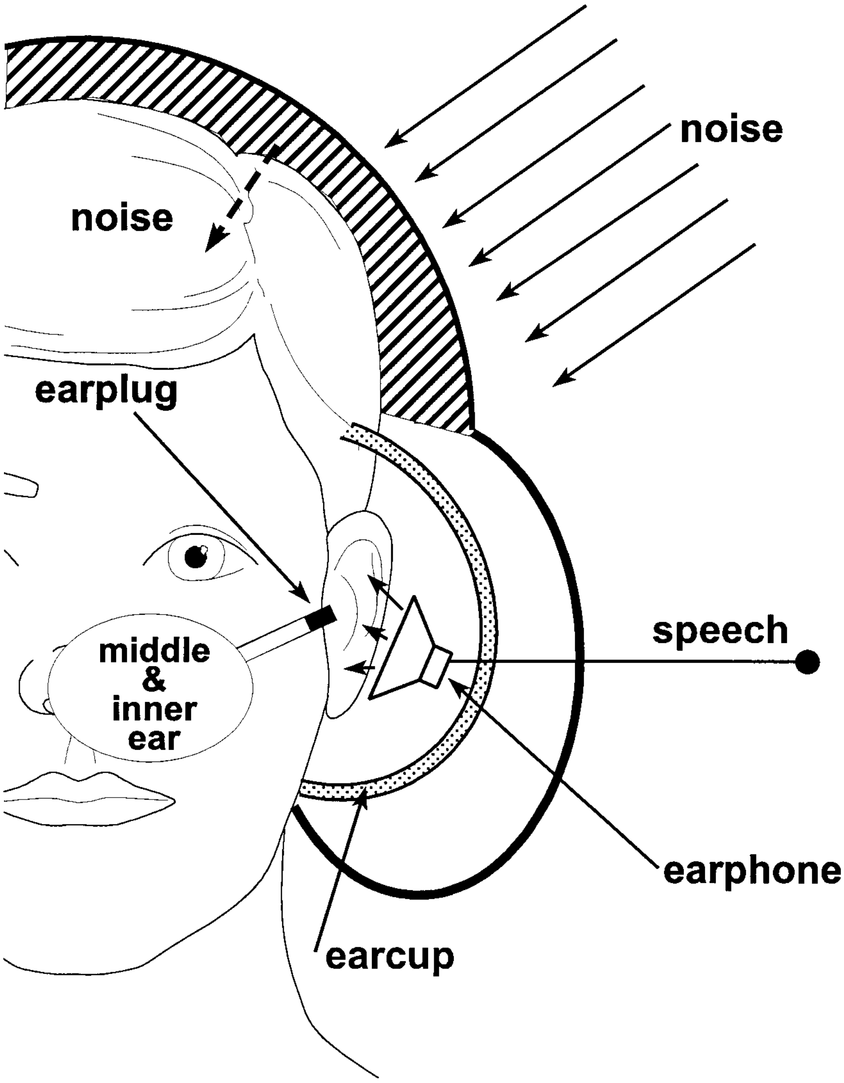

noise
noise
earplug
middle & inner ear
speech
earphone
earcup

FIGURE 3

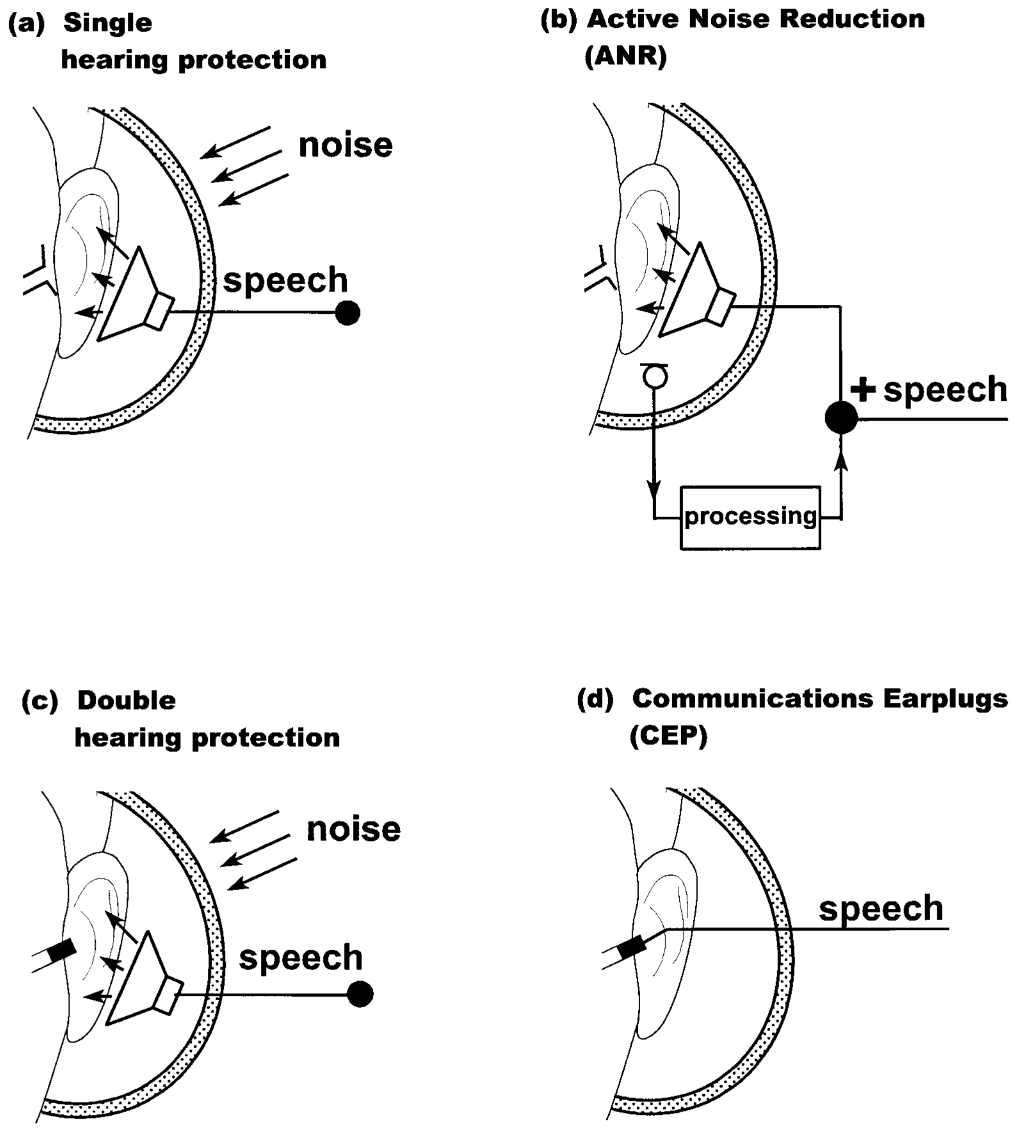
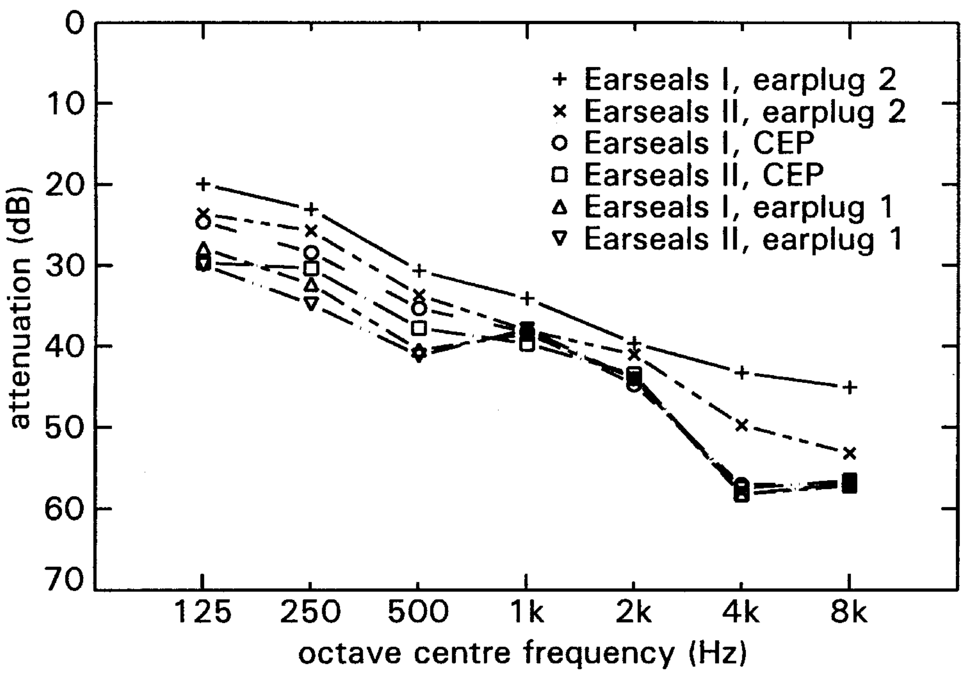

(a) Single
hearing protection
noise
speech
(b) Active Noise Reduction
(ANR)
+ speech
processing
(c) Double
hearing protection
noise
speech
(d) Communications Earplugs
(CEP)
speech

FIGURE 4



0
10
20
30
40
50
60
70
attenuation (dB)
125
250
500
1k
2k
4k
8k
octave centre frequency (Hz)
+ Earseals I, earplug 2
× Earseals II, earplug 2
○ Earseals I, CEP
□ Earseals II, CEP
△ Earseals I, earplug 1
▽ Earseals II, earplug 1

FIGURE 5

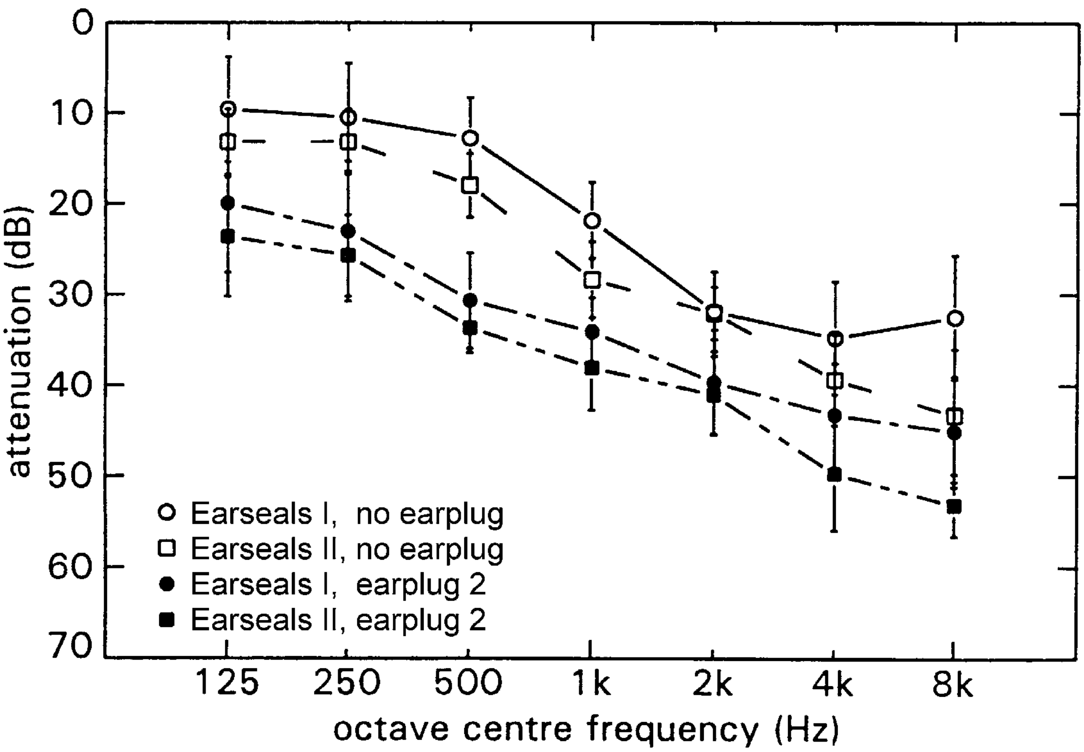

attenuation (dB)
0
10
20
30
40
50
60
70
125
250
500
1k
2k
4k
8k
octave centre frequency (Hz)
Earseals I, no earplug
Earseals II, no earplug
Earseals I, earplug 2
Earseals II, earplug 2

FIGURE 6

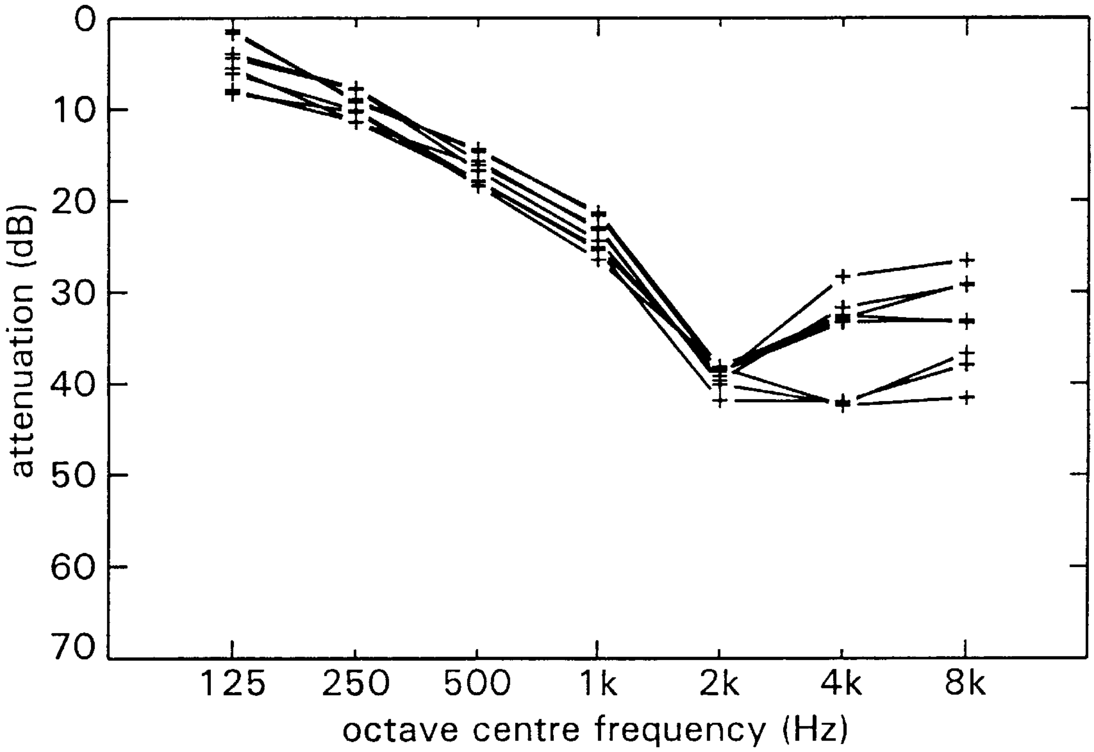

0
10
20
30
40
50
60
70
attenuation (dB)
125
250
500
1k
2k
4k
8k
octave centre frequency (Hz)

FIGURE 7

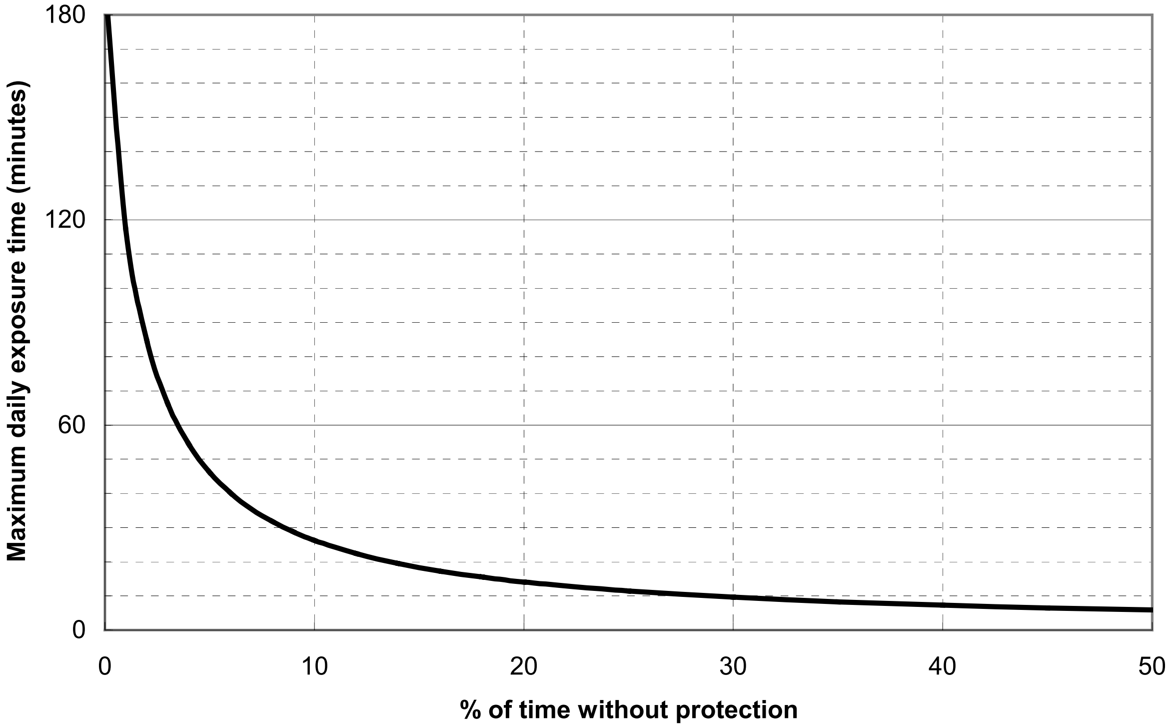

180
120
60
0
Maximum daily exposure time (minutes)
0
10
20
30
40
50
% of time without protection

FIGURE 8

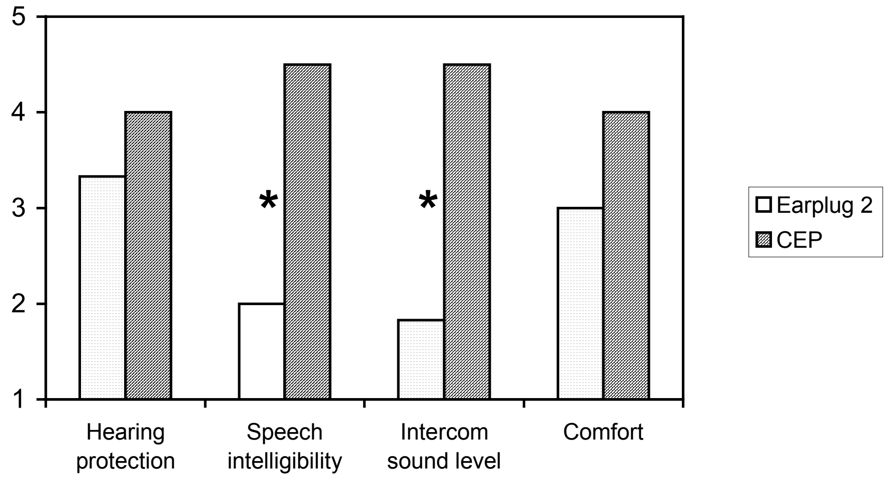
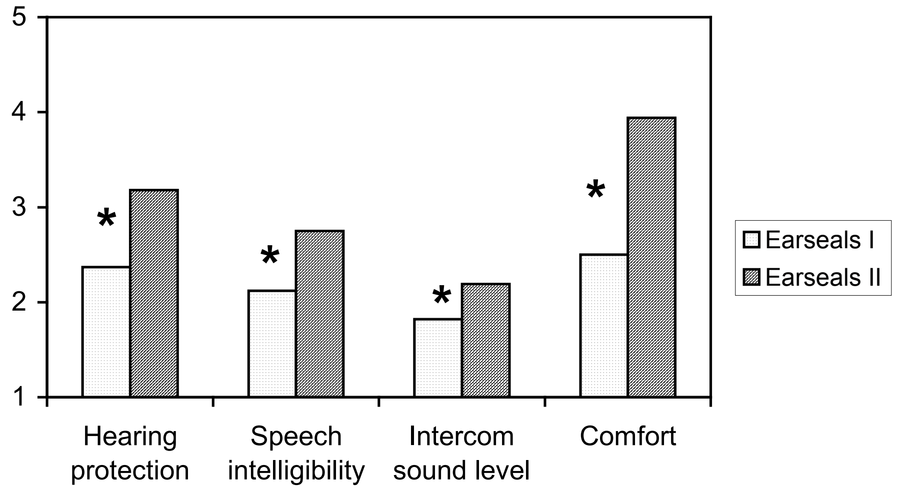

5
4
3
2
1
*
*
Hearing protection
Speech intelligibility
Intercom sound level
Comfort
Earplug 2
CEP

FIGURE 9


5
4
3
2
1
*
Hearing protection
Speech intelligibility
Intercom sound level
Comfort
Earseals I
Earseals II

LEGENDS TO ALL FIGURES

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

Figure 2. Model of sound attenuation of a helmet system

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

Figure 4. Measured sound attenuation of combinations of the standard helmet with earseals I and II, and earplug 1, earplug 2, and CEP (mean values, 16 subjects).

Figure 5. Measured sound attenuation of combinations of the standard helmet with earseals I and II, without earplugs and with earplug 2. Mean values (16 subjects) and standard deviation are given.

Figure 6. Sound attenuation as a function of octave center frequency, for different choices in tightness of neck strap adjustment (one subject, standard helmet).

Figure 7. Maximum daily exposure time (in minutes) as a function of the percentage of time without hearing protection, when using the standard helmet with ear seals II in the ambient noise field present in the cockpit (102 dB(A)).

Figure 8. User opinions (1-5 scale) on hearing protection, speech intelligibility, intercom sound level and comfort, for earplug type 2 (27 respondents, average experience 200 hours) and CEP's (6 respondents, average experience 140 hours). Significant differences (t-test, 95% confidence) between the earplug types are indicated by '***'.**

Figure 9. User opinions (1-5 scale) on hearing protection, speech intelligibility, intercom sound level and comfort, for earseals of type I (22 respondents, average experience 420 hours) and earseals of type II (19 respondents, average experience 390 hours). Significant differences (t-test, 95% confidence) between the earplug types are indicated by '***'.**

Table I. Characteristics of earplug types 1, 2 and CEP

	Intercom function	Custom molded	Sound attenuation
Earplug 1	No	No	High
Earplug 2	No	Yes	Low
CEP	Yes	No	High

Table II Equivalent continuous A-weighted sound pressure levels and maximum daily exposure times, for eight helmet-earplug combinations. Results are given for the cockpit noise spectrum (pilots) and the cargo compartment noise spectrum (loadmasters) as shown in figure 1.

Hearing protection	Cockpit, 102 dB(A)		Cargo compartment, 111 dB(A)	
(all alternatives based on the standard helmet).	L_{Aeq} (dB)	Max. daily exposure time	L_{Aeq} (dB)	Max. daily exposure time
No earplugs, Earseals I	90	45 min	96	10 min
No earplugs, Earseals II	84	3 h 15 min	90	45 min
Earplug 1 Earseals I	71	8 h	80	8 h
Earplug 1 Earseals II	68	8 h	78	8 h
Earplug 2 Earseals I	78	8 h	85	2 h 30 min
Earplug 2 Earseals II	73	8 h	80	8 h
CEP Earseals I	74	8 h	81	6 h 15 min
CEP Earseals II	70	8 h	77	8 h

Table III. Qualification and relation between STI en CVC word score

Qualification	STI	CVC word score (% correct)
Excellent	>0.75	>96
Good	0.60-0.75	86-96
Fair	0.45-0.60	65-86
Poor	0.30-0.45	32-65
Bad	<0.30	<32

Table IV. Relative frequency transfer functions in octave bands, for the earphones in the earcups of the standard helmet and the Communications Earplug.

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Earphones helmet A	-21.2 dB	-15.5 dB	-15.0 dB	-23.1 dB	-12.6 dB	-1.5 dB	-16.9 dB
CEP transducers	-6.3 dB	-7.0 dB	-9.2 dB	-9.0 dB	-3.4 dB	-7.9 dB	-26.7 dB

Table V. Predicted earphone (or CEP) levels inside the ear canal (behind the earplug) and inside the earcup corresponding to STI=0.35 and STI=0.60. All speech levels are A-weighted, in decibels re 2.10^{-5} Pa.

Hearing protection	Ambient noise level 102 dB (A) (cockpit)				Ambient noise level 111 dB(A) (cargo compartment)			
	STI=0.35		STI=0.60		STI=0.35		STI=0.60	
	Ear canal	Ear cup	Ear canal	Ear cup	Ear canal	Ear cup	Ear canal	Ear cup
No earplugs, Earseals I	74	74	82	82	81	81	91	***91***
No earplugs, Earseals II	70	70	77	77	78	78	87	87
Earplug 1 Earseals I	55	***92***	63	***100***	61	***99***	72	***109***
Earplug 1 Earseals II	55	***92***	63	***100***	61	***99***	71	***109***
Earplug 2 Earseals I	63	80	71	88	70	87	79	***96***
Earplug 2 Earseals II	59	76	67	84	67	84	76	***93***
CEP Earseals I	58	-	65	n.a.	65	-.	74	n.a.
CEP Earseals II	57	-	65	n.a.	65	-	73	n.a.