The effect of using personal hearing protectors on communication in a	<b>Jean-Sébastien Niel</b> <b>Gwenolé Nexer</b> December 2013
noisy environment.	
This study will investigate the impact of the protective device and mainly its effects on intelligibility in a noisy environment. Through a subjective test on 22 individuals, we observed an increase of about 20% of recognized words with hearing protectors with uniform response compared with hearing protectors with non-uniform response at the same levels of attenuation.	
	<b>Protection against noise</b> E-130-1
	Hearing Pretech.com

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# **1** Introduction

# 1.1 Foreword

# 1.1.1 The need to hear warning signals, and to communicate amid noise

In an industrial environment, various warning alarms are present. They differ based on their purpose:

- a warning alarm whose purpose is to prevent workers from imminent danger (e.g., fire alarm, reverse signal of a vehicle, etc.)
- a warning signal requiring action; it can alert the worker about an action to be performed (phone ringtone, completion of a machine's cycle, etc.).

The following three terms indicate the stages of intelligibility of the signals:

- 1. Perceive: hear a signal without being able to recognize it.
- 2. Recognize: identify the signal, as a voice for example; we recognize the voice of a woman, but without understanding the meaning of the words.
- 3. Understand: identify the message and understand its meaning.

When the noise level is too high, there is saturation of the ear. Our auditory system, including the cochlea, is saturated and unable to properly process the information received. Our ability to recognize and understand the signals is reduced.

Wearing suitable hearing protection devices (PICB) generally helps in better intelligibility by reducing the noise level, thus avoiding the saturation of the cochlea (Casali J. G., 2000 [1]).

The 2005 European standard EN 458 states: "When the recognition of sounds such as verbal messages and warning signals is essential, it is best to use personal hearing protection with a low frequency flat spectrum." This may appear logical but it seems important to prove it, as well as to estimate to what extent.

### 1.1.2 Objectives of the study

The objective of this study is to assess the impact of hearing protection devices on intelligibility during communication in noise. In order to do this, this document presents the main mechanisms involved in the transmission of speech from a speaker to a listener in a noisy environment. We will also attempt to quantify the impact of the roll-off slope of the hearing protection device on intelligibility, mainly by using a subjective test.

We will compare the results observed during a subjective test with an objective intelligibility index, the STIr. In case the STIr does not reflect the observed reality, we will seek to model the observed results to calculate a proxy indicator.

## **1.1.3** Assess the uniformity of hearing protection devices

The attenuation data of hearing protection devices are obtained after being measured by a testing laboratory, on a panel of trained subjects. This is the average attenuation obtained on the subjects (which is subtracted from the standard deviation) that specifies the attenuation of the hearing protection device. The attenuation is measured for each center frequency of octave bands of 63 Hz to 8000 Hz in decibels.

ISO 4869-2 standard (Estimation of weighted sound pressure levels A when using personal hearing protection devices against noise) defines the calculation of SNR and HML for the European Commission.

The SNR is the total attenuation coefficient (Single Number Rating), which is a weighted average of the attenuation at all measured frequencies. The SNR reflects the power of the acoustic filter.

The HML values are the weighted averages of high frequency (H), medium frequency (M) and low frequency (L). The HML values reflect the uniformity of the filter.



Given below is an example of two filters:

Figure 1: three different views of the attenuation of two hearing protection devices. A presentation by frequency and average HML immediately shows a difference between the two, while the average SNR is identical.

It is observed that the attenuation reflected by the SNR is identical. However, there is a significant distortion of the audio spectrum with the filter shown in red; the slope of the red curve is largest.

In this study, we chose to synthesize the uniformity of a hearing protection device with a single indicator: its slope, with Slope = H - L.



# Protection slope (H-L)

#### **1.1.4** Assessment of intelligibility in a noisy environment

**The intelligibility of speech** reflects the transmission rate of speech from a source (speaker, loud-speaker, etc.) to a listener.

Historically, the first measurements of speech intelligibility are the subjective **measurements** done on speakers and listeners. (Campbell test 1910, Fletcher & Steinberg 1929, Fairbanks, Modified Rhyme Test, Diagnostic Rhyme Test). These methods are difficult to implement and cause objectivity and reproducibility problems. In general, intelligibility is measured in the percentage of messages (words, sentences, etc.) that are correctly transcribed by the auditor.

**Objective and predictive measures of speech intelligibility** help in assessing intelligibility without using test subjects. There are several indices, including the articulation index (**AI**), speech transmission index (**STI**) or the speech interference level (**SIL**.). The AI can predict the score obtained from subjective measures, usually observed from speech and noise levels. The SIL is measured from the level of ambient noise, vocal effort of the speaker, use or non-use of a hearing protection device, and the mother tongue. The STI helps take into account the disruptive elements such as noise and reverberation of a transmission channel, as well as elements related to the persons involved, such as gender, vocal effort or the distance between the persons. The SIL and STI are described in the standard NF EN ISO 9921, 2004.

Figure 2: Slopes (H-L) of hearing protection devices that have the same SNR

# **2** Communication in noise

# 2.1 Elements to be considered

Speech recognition is related to a multitude of parameters, of which the main ones are as follows:

#### - Ambient noise

- Sound intensity
- Spectrum
- Variation in stationary/non-stationary time

#### - The useful signal emitted by the speaker

- Clarity of the message
- Spectral range (gender, vocal effort)
- Perception of one's own voice and regulation of the spectral content/sound level
- Customized hearing protection devices (amplifies the perception of one's own voice)

#### - The listener

- Hearing thresholds
- Masking effect specific to the individual
- Capacity to reconstruct the message
- Fluency in the language/culture
- Mental substitution (context)
- Lip-reading ability
- Use of hearing protection devices

#### - Setting the environment

- Distance between the persons
- Message reception angle, due to the directivity of the head
- Location of the noise
- Acoustics of the environment (reverberation, etc.).

# 2.2 Type of noise

The noise can be stationary or non-stationary:

**Non-stationary noise:** The spectrum varies over time. Noise sources can be punctual. In a sentence, for example, one part of the message will be more altered by the noise than other parts.

**Stationary noise:** Ambient noise whose spectrum does not vary over time; the worker is exposed to such noise for the entire duration of message transmission.

#### The following is a spectrogram of industrial noise:



Figure 3: Spectra of two stationary industrial noises recorded in a car factory, from the Noisex 1990 database, thesis data (Le Cocq C., 2011 [20])

# **2.3** The speaker/properties of the useful signal

# **2.3.1** Vocal effort in relation to the noise

#### 2.3.1.1 Lombard Effect

The Lombard effect, named after Étienne Lombard, is a phenomenon of change in human pronunciation (fundamental frequency, sound intensity, articulation, and increase in vowel duration). In a noisy environment, the speaker naturally adapts his voice to be better understood.

The graph below shows the relationship between the **vocal effort range** (equivalent continuous sound level of the speech at 1 meter) and the **ambient noise level** in the position of the speaker, as defined by ISO 9921.



Figure 4: Relationship between the equivalent continuous sound level of the speech at 1 meter and the level of ambient noise, extract of ISO 9921 standard

The more the speaker must raise his voice (mainly a person who is not wearing hearing protection devices in a noisy environment), the more the spectral content of the message is distorted, and therefore the intelligibility of the message is altered. (Hétu, R., 1994 [2], Pickett, J., 1956 [3]).

#### 2.3.1.2 Deformation of the voice

Several speech levels have been defined by Kryter (1985 [5]) and Webster (1979 [4]). We find that a loud voice level is at about 74 dB. Shouting or maximum voice level cannot be sustained for a long time by an individual without using an amplification system.

We also find that these levels are identified at very short distances of one meter or less; as the distance between people increases, the sound level decreases.

Loudness of voice	Overall level - dB(A)
Maximum	88
Shout	82
Very loud	74
High	65
Normal	57
Soft	50
Whisper	40

Table 1: Loudness of voice associated with different levels of speech in dB (A) measured at 1 m in front of the speaker (Webster, 1979 [4])



Table 2: Long term average speech spectrum for different voice levels of a man, measured at 1 m in front of the subject (Webster, 1979 [4])

The frequency band of a man's voice is wider than the frequency band of a woman's voice. There is also a difference in vocal effort in a noisy environment based on gender.

Voice level	Men	Table 4 Women
Normal	58	55
Stable	65	63
Loud	76	71
Shouting	89	82

Table 3: Speech level of speakers, men and women in a quiet environment, measured at a distance less than one meter (Kryter 1985 **[5]**)

#### 2.3.1.3 Effect on intelligibility

The impact of voice effort on intelligibility was assessed by Pickett (1956 [3]). The graphs below show the relationship between speech intelligibility, voice effort, and the signal to noise ratio.

We note that whispering or shouting (and hence a distorted voice) results in a significant decrease in intelligibility in three different signal/noise settings tested. Naturally, the signal to noise ratio has a direct impact on intelligibility.



*Figure 5: The graphs show the relationship between speech intelligibility, voice effort and the signal to noise ratio. Taken from Pickett (1956 [3])* 

# 2.3.2 The effect of using hearing protection devices

#### 2.3.2.1 Modification of the voice

By wearing a hearing protection device, the speaker's hearing of his environment is reduced. However, he perceives his own voice at a louder level. This effect is due to the phenomenon of occlusion that increases the perception of physiological noise and changes the perception of the voice.

Therefore, it is possible that the speaker naturally compensates his vocal effort based on the perception of his own voice, modified by wearing hearing protection devices. Suter (1992 [6]) has reviewed a number of studies on this subject.

Howell and Martin (1975 [7]) have found that when a speaker wears earplugs, the reduction in vocal effort is about 4 dB. However, this observation is valid only for high noise levels (93 dB), and not in a quiet environment (54 dB). Hörmann, Lazarus-Mainka, Schubeius, and Lazarus (1984 [8]) subsequently confirmed these results. ISO 9921 provides that the vocal effort of the speaker decreases by 3dB with hearing protection devices.

With the vocal effort decreased, speech intelligibility for a listener is reduced (Kryter 1946 [9], Robinson and Casali, 2000 [10], Gelfand, 2004 [11]).

Howell and Martin (1975 [7]) observed that this loss of intelligibility is not solely due to the reduction of vocal effort. They suggested that individuals wearing hearing protection may also speak less clearly. On the other hand, Martin et al. (1976 [12]) evaluated the spectral differences in voice quality of speakers with and without earplugs. Their spectral analysis is reproduced in Figure 8 which shows significant differences between levels of expression in conditions with and without earplugs (about 2-3 dB (A)). However, they have noticed no significant difference in the frequency plane.



Figure 6: Average levels per octave band for ambient noise levels of 67-95 dB (A). The speakers have nonoccluded ears (solid line) or are wearing earplugs (dotted line). (Martin, Howell, & Lower, 1976 [12]).

#### 2.3.2.2 Speed of speech of the speaker:

Hörmann, Lazarus-Mainka, Schubeius and Lazarus (1984 [8]) have also noticed that for high noise levels (92 dB (A)), speakers wearing earplugs articulate more quickly; pauses between words and sentences are reduced by about 25%. The rate of exchange of information, which is a measure of the listener's reaction time, decreases with an increase in noise levels and when the speakers and listeners wear hearing protection devices.

# 2.4 Listener/Signal reception

#### 2.4.1 Use of hearing protection devices and hearing loss

Wearing hearing protection devices, especially those for non-uniform responses, may increase problems of intelligibility for people with hearing disorders.

The hearing protection device can reduce the sound signal to a level below the listener's hearing thresholds. The following graph, whose data is taken from Lazarus (1983 [13]), shows the effect of wearing a hypothetical hearing protection, attenuating the signal and noise for a subject with normal hearing and for a subject with hearing disorders.



Figure 7: Effect of a hearing protection device on the signal and noise for a subject with normal hearing (blue curve) and for a subject with sensory-neural hearing loss (orange curve). The green lines represent the signal and noise in the ear of the subject without the hearing protection device. Data taken from Lazarus (1983 [13]).

It is understood here that the phenomenon is considerably aggravated if the hearing protection device attenuates much higher frequencies, which is often the case.

### 2.4.2 Masking effect:

Masking occurs when the threshold of audibility of one sound (masked) increases due to the presence of another sound (masking). Masking takes place when two sound signals reach the cochlea of the listener simultaneously. A high intensity masking signal at a given frequency causes a more or less significant masking of sounds with low intensity on neighboring frequencies, according to the amplitude and frequency of the masking signal. Masking phenomena are complex and the overall theory of masking introduced by Fletcher in 1937 is no longer considered.

There are many mechanisms involved in masking. One of them is the "line-busy" phenomenon. In the presence of high noise, neural coding of the signal will be sought. The refractory period of neural discharge does not transmit the information of both noise and signal at the same time. The masking signal occupies the line of neurons.



*Figure 8: The masking rate produced by different pure tones and for various levels of the masking signal. Adapted from Ehmer (1958 [21]).* 

It is observed that the effect is produced from the frequency of the masking sound. This asymmetry reflects the behavior of our inner ear where low tones tend to mask high tones.

Industrial noise generally has a strong power at low frequencies. The masking effect caused by this noise thus covers almost the entire audible spectrum and changes the ability to perceive, recognize, and understand the speech signals.

Using hearing protection devices decreases both the masking signal and the useful signal, where a decrease in the level of masking noise results in a reduction of the masking effect.

Nevertheless, we have seen that hearing protection devices generally have a non-uniform attenuation. The attenuation is often much higher for high frequencies. Reducing the masking effect caused by wearing hearing protection devices is thus less beneficial, especially if the listener suffers from hearing loss. (Tran Quoc and Hétu, 1996 [14]).

## 2.4.3 Reconstructive capacity of the message

Intelligibility is quite evidently linked to the clarity of the received signal that depends on the speaker, the environment, and the listener, but we also need to consider the ability of the listener to interpret the messages.

The interpretation of messages is directly related to fluency in the language itself and knowledge of vocabulary contained in the messages. We generally note reduced intelligibility for the same message if the speakers and listeners are non-native and fluent in a second language (ISO 9921).

In case the signal is significantly degraded, mental substitution may intervene. This is an interpretive strategy, notably used by deaf people to understand the gist of a conversation without distinguishing more than a quarter of the words.

In case the speakers are face to face, lip reading (maxillofacial) may also occur. The ability to recognize words on the lips depends on the experience of the subject and context of discussion.

The issue of visual cues in face-to-face communication was studied by Rink (1979 [15]). Rink observed that in a noisy environment, listeners with hearing disorders or normal hearing performed better with visual cues, regardless of the tested protective device. Previously, Martin, Howell, and Lower (1976 [12]) had found that the presence of visual cues reduces the differences between the results obtained with occluded and non-occluded ears. For high noise levels, recognition scores are increased by approximately 30%.

# 2.5 Setting the scene

# 2.5.1 Effect of the distance between the correspondents on the intensity of the received signal:

Distance between the persons	Maximum level received by the ear, when in order to be heard, one must speak with a:								
Shout Very loud voice Loud voice Normal v									
15 cm	90 dB (A)	84 dB (A)	78 dB (A)	72 dB (A)					
30 cm	84 dB (A)	78 dB (A)	72 dB (A)	66 dB (A)					
60 cm	78 dB (A)	72 dB (A)	66 dB (A)	60 dB (A)					
120 cm	72 dB (A)	66 dB (A)	60 dB (A)	54 dB (A)					

The sound level at the listener's ear can be estimated from the strength of the speaker's voice and the distance between the persons.

Table 6: This table (without a regulating value) allows a rough estimate of the speech signal level at the ear of the listener. (Phan Chan The, (2003) [22]).

These estimates can be obtained using the following formula:

L: Level of the sound signal at the listener's ear in dB  $L_{1m}$ : Level of the sound signal at 1 meter from the listener in dB d: Distance between the persons.

This relationship is valid up to 2 meters, or 8 meters in certain conditions defined in the ISO 9921 standard. By noting the sound level of a loud voice measured at 1 meter (Webster, 1979 [4]), we can estimate the sound level perceived at other distances.

#### 2.5.2 Directivity of the head:

The angle between the signal source and the listener's head has a significant influence on his sound perception. Some frequencies are more or less attenuated based on the angle of the sound source, such as a voice.



*Figure 9: Diagram of directivity of the human head, data taken from Delétré (2001 [16]).* 

In general, lower frequencies are less affected by this directivity than high frequencies.

# **3** Methods for measuring intelligibility

# 3.1 Objective methods

#### 3.1.1 SIL method

The Speech Interference Level offers a simple method of predicting and assessing speech intelligibility in case of **direct communication** in **a noisy environment**.

The parameters considered are:

- Arithmetic average of the **noise spectrum**
- Vocal effort of the speaker
- Distance between the speaker and listener.

The SIL is a calculation of the signal to noise ratio:

 $SIL = L_{SAL} - L_{SIL}$ 

Thus, SIL = speech level - level of noise interference.

#### 3.1.1.1 Calculation of the noise interference level L<sub>SIL</sub>

In the SIL method, the noise interference level with speech ( $L_{SIL}$ ) is the arithmetic mean of the ambient noise levels of the following four octave bands: 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

 $LSIL = \frac{1}{4} \sum L_{N,OCT}$ 

#### 3.1.1.2 Estimation of vocal effort L<sub>SAL</sub>

#### 3.1.1.2.1 Taking the Lombard effect into account

We saw earlier that the vocal effort depends on the ambient noise (ISO 9921). In Figure 10, we see that the vocal effort (equivalent continuous sound level of speech) at 1 meter varies depending on exposure to ambient noise.



Figure 10: Relationship between the equivalent continuous sound level of speech at 1 meter and the level of ambient noise, in yellow; an approximation of this relationship.

We shall estimate the relationship shown in Figure 10 by

 $L_{SA1m = 0.57 \text{ X}} L_{NAS}$  + 30 (Yellow curve above)

where:  $L_{SA1m}$  is the weighted speech level at 1 meter from the speaker

and:  $\boldsymbol{L}_{\text{NAS}}$  is the weighted ambient noise level A in the position of the speaker

#### 3.1.1.2.1.1 Taking the hearing protector into account

If the noise is > 75 dB, the vocal effort of the speaker decreases by 3dB.

#### 3.1.1.2.1.2 Decrease in speech quality

If the effort is > 75 dB, the speech quality is decreased. This reduction may be taken into consideration by decreasing the vocal effort by  $0.4^{*}$ (LSAM1-75).

#### 3.1.1.2.1.3 Taking into account the distance between the speakers,

 $\mathbf{L}_{SAL} = \mathbf{L}_{SA1m} - 20 \log (r/r^0)$ 

where:

r is the distance between the speaker and the listener, in meters.  $\frac{9}{2}$ 

 $r^{0} = 1 m$ 

#### 3.1.1.2.1.4 Taking the mother tongue into account

4 dB is subtracted in case the speaker and/or listener do not communicate in their native language.

#### Example of using the SIL method:

- In ambient noise of 80 dB, the speaker has a vocal effort at 72.6 dB (Lombard effect).
- This is white noise.

This corresponds to "Bad" intelligibility, according to the ISO 9921 standard.

This indicator is simple to calculate, but it is very approximate. The main drawback of this method is the failure to take into account the spectral components of the signal and noise, whereas this information is required to assess the impact of uniformity of hearing protection devices on intelligibility. The SIL is a useful tool, but it is not adapted to our application.

### 3.1.2 STI method

The method is described in ISO 9921 and IEC 606 268 and detailed in the Basics of the STI Measuring Method, a reference document by Steeneken and Houtgast [17]:

Unlike the SIL, this method is more precise and takes into account the spectral components of the signal and noise. This method is mainly used to assess the quality of a transmission channel (room, transmission system, etc.) from the point of view of intelligibility. In addition to the parameters used by the SIL method, this method takes into account the acoustic properties of the environment (reverberations, echo, etc.).

The STI method was originally developed for carrying out **measurements**. For this purpose, a specific test signal has been developed, which, after its transmission through the test channel, was subject to a fairly complex analysis in order to determine the **actual signal to noise ratios** in different frequency bands, and to calculate the STI index.

These processes are difficult to implement. However, we can **estimate the signal-to-noise ratios by calculation** without measurement. We can also consider that in case of **direct communication**, the positions of the speaker and the listener are generally close. The acoustic properties of the environment can, therefore, have **only a limited effect** on intelligibility.

In this way, we can use this method to predict intelligibility from:

- the noise level perceived in the octave band
- the signal level perceived in the octave band
- the distance between the speakers

#### <u>Calculation from an estimate of signal to noise in an octave band:</u>

According to the STI concept, the signal to noise ratios in the range -15 dB to +15 dB are linearly related to contributions to intelligibility in the range 0-1. Therefore, we convert the real signal to noise ratio to a corresponding transmission index ( $TI_k$ ) specific to the octave band k and using the following equation:

 $TI_{k} = \frac{SNR_{kdB} - 15}{30}$ 

The revised speech transmission index is obtained as a weighted sum of modulation transfer indices for the seven octave bands with the corresponding redundancy corrections.

Stlr =  $\sum_{k=1}^{7} k = 1 \alpha_k T 1 k - \sum_{k=1}^{6} k = 1 \beta_k \sqrt{T 1 k \times T 1 k + 1}$ 

Where:

the factors  $\alpha_k$  are weighting factors of the octave;  $\beta_k$  are the redundancy correction factors.

Given below is an example of calculation of STIr

	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Noise used dBA	70.4	74.2	72.4	69.9	60	58.5	39.3
Man's voice dBA	59	67	58.3	61.7	59.9	59.3	55.1
Attenuation of the hearing protection device	8.7	9.1	12.1	19.2	27.4	31.4	39.1
Signal / noise in the ear	-11.40	-7.20	-14.10	-8.20	-0.10	0.80	15.80
TI Transmission Index	0.12	0.26	0.03	0.23	0.50	0.53	1.00
STIr	0.42						

Table 7: Example of calculating the STIr index based on the noise level and signal level in the octave band at the ear of the listener. The transmission ratios are calculated for each octave band. The STIr is a weighted sum of IT.

# 3.1.3 STI method taking into account the masking and hearing thresholds

As we have seen previously, we can use the STI without taking into account the acoustic properties of the environment. This way, the intelligibility index is calculated only from the noise spectrum, the signal spectrum, and the distance between the speakers. In other words, the STI is calculated only from the signal to noise ratio perceived by the user per octave band.

In the case of conventional acoustic filters, namely linear filters (uniform or non-uniform), irrespective of the slope of the used passive filter, the noise signal and the voice signal will go through the same filter. Thus, the signal to noise ratio would remain unchanged, regardless of the linear hearing protector used.

Example of 1000 Hz octave band on a signal to noise ratio of 20dB:



That is why the STI as defined above cannot take into account the attenuation slope of a hearing protection device.

For this, we must take into account the masking frequency and audibility threshold as described in the EN 60628-16 standard.

A very loud noise will cause a greater masking of the information supplied by the voice. Similarly, if the voice signal is too weak, the listener may miss some of the information (this signal may be below the listener's hearing threshold), regardless of the signal to noise ratio.

At the computational level, the method is to calculate the modulation index mk for each octave band from the signal to noise ratio that was previously estimated.

$$m = \frac{10^{SNR/10}}{1+ 10^{SNR/10}}$$

The auditory masking and hearing threshold result in a reduction of the modulation index:

$$m'k = mk \frac{l_k}{l_k + l_{am,k} + l_{rs,k}}$$

- Ik represents the total noise level (noise and voice) perceived by the listener
- Irs,k represents the hearing threshold factor per octave band, available with IEC 60268-16
- I<sub>am,k</sub> represents the intensity of the masking signal on the octave band

The masking effect as modeled in the STI approach does not depend on the frequency band considered, but the noise level. For example, for a sound level perceived between 55 and 65 dB, the masking slope decreases by 35 dB per octave. The total perceived noise level (noise and signal in this case) on an octave band generates a masking effect on the immediately adjacent upper octave band. In this way we can calculate lamk, the intensity of the masking signal.

From the revised modulation index m, we recalculate the effective signal to noise ratio for the listener:

SNRk= 10log [m'k / (1- m'k)]dB

	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Noise used dB(A)	70.4	74.2	72.4	69.9	60	58.5	39.3
Man's voice dB(A)	59.0	67.0	58.3	61.7	59.9	59.3	55.1
Attenuation of the hearing protection device	8.7	9.1	12.1	19.2	27.4	31.4	39.1
Signal/Noise in the ear	-11.40	-7.20	-14.10	-8.20	-0.10	0.80	15.80
TI Transmission Index	0.12	0.26	0.03	0.23	0.50	0.53	1.00
Gross STIr	0.42						
Modulation index mk	0.07	0.16	0.04	0.13	0.49	0.55	0.97
Revised modulation index mk '	0.04	0.11	0.03	0.12	0.41	0.43	0.56
Revised Signal/Noise	-13.94	-8.93	-14.92	-8.79	-1.61	-1.18	1.02
Revised TI	0.04	0.20	0.00	0.21	0.45	0.46	0.53
Revised STIr	0.33						

The new transmission indices are recalculated to obtain the corrected STI index.

Table 8: Example of calculating the revised STIr index. The modulation indices are recalculated to account for masking and hearing thresholds.

This new indicator is therefore calculated from the noise level in the octave band, signal level transmitted by a speaker in the octave band, the distance between the speakers, and the attenuation of the hearing protection device in the octave band. It allows us to take into account the signal-to-noise ratio perceived by the listener, in addition to the effects of masking and hearing threshold affected by wearing hearing protection.

# **3.2 Subjective tests**

In the field of speech audiometry, there are intelligibility tests and phonetic tests.

## 3.2.1 Phonetic tests

They are used to study the perception of phonemes.

The material used may be words (Lafon's cochlear lists) or logatomes; phonetically balanced and homogeneous lists are used for a detailed analysis.

# **3.2.2 Intelligibility tests**

These tests are used to assess the overall understanding of speech signals. We find:

→ The word test CVCEQB (3 letters - Consonant-Vowel-Consonant) Non-words

Phonetically balanced to represent the proportion in the language

→ Monosyllabic word test

Words with meanings

Phonetically balanced to represent the proportion in the language. These lists are hardly used because they are difficult

→ Dissyllabic words and ? test (Fournier's lists)

Words with meanings

Phonetically balanced to represent the proportion in the language. These lists are the most used in current practice.

#### → Sentence test

In general, sentence tests are not recommended for assessing the transmission systems, in so far as the listener's knowledge varies in terms of:

- grammar
- meaning

- syntax of the sentence influencing the results

Moreover, these lists are the easiest.

Another issue is the **construction of a large number of sentences that are phonetically representative** of speech and have a well-defined complexity.

As part of our subjective test, we will use Fournier's lists provided on CD by the Collège National d'Audioprothèse.

# 3.3 Relationship between the methods

The results of the various objective and subjective methods were compared. The ISO9921 standard proposes the table below, giving the relationship between different intelligibility indices (NF EN ISO 9921, 2004):

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Assessment of intelligibility / 22

Assessment of intelligibility <i>a</i>	Score by sentence <i>b</i> %	Score by type of words phonetically balanced with meaning c %	Score by type of words CVCEQB without meanings %	STI %	SIL d	SII d, e
Excellent	100	> 98	> 81	> 0.75	21	-
Good	100	93 to 98	70 to 81	0.60 to 0.75	15 to 21	> 0.75
				0.45 to		
Appropriate	100	80 to 93	53 to 70	0.60	10 to 15	-
Low	70 to 100	60 to 80	31 to 53	0.30 to 0.45	3 to 10	< 0.45
Bad	< 70	< 60	< 31	< 0.30	< 3	-

Table 9: Assessment of intelligibility and relationships between different intelligibility indices according to ISO9921; refer to the standard for a, b, c, d and e.



Figure 11: The relationship between STI and the subjective intelligibility tests, data taken from ISO 9921

The curves show the relationship with the STI with most subjective methods.

#### Test protocol

To evaluate the influence of using hearing protection devices on the intelligibility of communication in a noisy environment, we have implemented a subjective test.

22 subjects were exposed to stationary noisy environments with different hearing protection devices considered "uniform" and some considered "non-uniform" by the manufacturer.

A prerecorded voice signal broadcasts word lists. The subject writes down the word heard. The intelligibility score is assessed in % of recognized words.

# 3.3.1 Samples tested

We tested 6 hearing protection models A22, A26, A33, B16, B23, and B26. Hearing protection devices from range B are considered to be of uniform response, contrary to the hearing protection devices of range A.



Given below are the test characteristics of hearing protection devices:

Figure 12: Certified average attenuation of tested protective devices in the octave band

	Att. SNR	Unif. SLOPE
A22	22	17
A26	26	16
A33	33	7
B16	16	2
B23	23	-3
B26	26	-1

Table 10: SNR and slope filters

The hearing protection devices are tested by subjects in a random order. Before starting to test the hearing protection devices, the subject is trained with some lists to help in preparation.

## 3.3.2 Population

The population of subjects consists of 22 subjects, aged 21-41 years, with 6 women and 16 men with a good command of French and good hearing.

#### 3.3.3 Experimental device

The speech material is pre-recorded and broadcast on a loudspeaker at 1 meter in front of the user. Pre-recorded noise is broadcast on two lateral speakers.





Figure 13: Side view; the subject is placed 1 meter in front of the voice source. Seated, the subject writes down the word responses that he understands on a sheet of paper.

Figure 14: Top view; during the test, the voice material is being played in front of the subject, and the noise is played on two identical loudspeakers.

All noise or voice signal measurements were done in dB(A) per octave band, using an integrating sound-level meter by positioning the **microphone at the heads of the subjects.** 

Under these conditions, the test does not take into account visual cues, lip reading, or the context of playing the message.

The tests are performed in a room with enhanced soundproofing. However, the room was not designed to deal with structure-borne noise transmitted through the floor.

The bar graph below shows the ambient noise levels in the room in silence (no artificial noise added):



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Assessment of intelligibility / 25

#### 3.3.4 Voice equipment

As part of this subjective test, we selected Fournier's lists with a male voice on a CD provided by the Collège National d'Audioprothèse. These lists have the advantage of being phonetically representative of the French language. Each list contains 10 dissyllabic words with meanings. The pre-recorded words are clearly expressed with a regular speech rate.

For the entire study, we set the sound level of the voice at 70dB (A), measured at the subject's level.

To measure the voice, the pauses between words played were electronically removed in order to measure the average continuous sound level of the voice signal in the octave band at the subject level.



Figure 15: Sonometry record of the voice measured in the octave band at the subject's level. The level in dB(A) is 70.

#### 3.3.5 Noisy environments

Each hearing protection device will be tested under noisy conditions below:

It consists of a stationary noise at a dominant low frequency, prerecorded and consisting of 8 sounds between 78 and 92 dBA in total. The frequency components of the test noise are shown below:



Figure 16: Sonometry record of the test noise measured in the octave band at the subject's level. The level in dB (A) ranges from 78 to 92 dB.



Figure 17 shows the average percentage of words recognized, over 22 subjects, in different noisy environments, for each hearing protection device.

Figure 17: Average percentage of words recognized, over 22 subjects, at several noise levels. The voice signal is 70 dB (A) at 1 m, at the head level of the listener.

We observe an actual impact of the type of attenuation on word recognition. Intelligibility decreases linearly as the noise level increases.

We quickly find that hearing protection devices with uniform response have helped obtain a better intelligibility.

We also notice that regardless of the attenuation of the hearing protection device with uniform response, the intelligibility scores coincide (see graph below).



Figure 18: Percentage of words recognized at several noise levels. The voice signal is 70 dB (A) at 1 m from the listener.

#### Comparison of hearing protection devices with equivalent attenuation but different slopes:

1) The hearing protection devices B26 and A26 have the same certified average attenuation (SNR = 26dB). However, their attenuation slopes are different (16 for A26 and -1 for B26).



*Figure 19: Graph on the left: Percentage of words recognized at several noise levels for the hearing protection devices B26 and A26.* 

*Graph on the right: The rate of average attenuation in dB per octave band for the hearing protection devices B26 and A26.* 

B23 and A22 have very similar certified attenuations (23 and 22 dB of SNR, respectively). However, their attenuation slopes are different (17 for A22 and -3 for B23).



*Figure 20: Graph on the left: Percentage of words recognized at several noise levels for the hearing protection devices B23 and A22.* 

Graph on the right: Rate of certified average attenuation (CRITT) in dB per octave band for the hearing protection devices B23 and A22.

We observe **reduced intelligibility of about 20% with non-uniform hearing protection devices** for the same certified attenuation.

# 3.4 Simple modeling of the results

We seek a very simple mathematical model, similar to the observed results. The results obtained show marked characteristics. We will try to find a simple mathematical model representing these observations.

#### 3.4.1 First approximation

We assimilate the results with linear functions



Figure 21: Representation of the results in the gross form and linear form.

### 3.4.2 Second approximation

We consider the slopes of equivalent curves



Figure 22: Representation of the results in the linear form with equivalent slope

### 3.4.3 Third approximation

It is observed that the intelligibility results do not seem to correlate with the attenuation. However, by comparing the absolute values of the attenuation slopes of orientations



with the spacing of the curves (below), we see that the intelligibility <u>is very strongly</u> <u>correlated</u> to the slope (HL) of the hearing protection device.

Figure 20: To the left: Absolute values of the attenuation slopes (H - L) of hearing protection devices. To the right: Percentage of unrecognized words (for a signal to noise ratio of -10 in this example). This data is obtained from the first two approximations.

We will assume that intelligibility is only related to the slope of the hearing protection device and the signal to noise ratio.

### 3.4.4 The model

The mathematical model below provides an estimate of the observed results.

To establish this formula, we consider that the results are close to the linear functions of the fixed slope, and based on our observations, we also assume that intelligibility is only related to the slope of the hearing protection device and the signal to noise ratio.

Intelligibility (in %) = (47 - |slope|)/ 58 + 0.06 \* (10 + signal (dBA) - Noise (dBA))

We can compare (Figure 24) the gross results observed (solid lines) with the model's calculations (dotted lines) defined in the above formula:



Figure 24: Plot of raw data (solid line) and calculations with the model (dotted line)

The defined model produces fairly representative approximations of the measurements observed, considering the strong assumption that intelligibility is only related to the slope of the hearing protection device and the signal to noise ratio. Therefore, the results of certain hearing protection devices are slightly overstated (A33), and others are understated (A26).

# 4 Comparison of results with the STI

As described in Section 3.1, the STI can predict intelligibility in a given setting. It takes into account the signal-to-noise ratio perceived by the listener, in addition to the effects of masking and hearing threshold affected by wearing hearing protection.

This indicator is calculated from:

- the noise level in the octave band at the ear of the subject
- the signal level transmitted by a speaker at the ear of the subject
- the attenuation of the hearing protection device in the octave band

# **4.1 Simulation of test conditions**

We seek to compare the STI methods and our subjective test on several topics. The parameters used for calculating the STI are derived from the test conditions of the subjective measure, namely:

- The voice signal is a man's voice, the voice speed and sound intensity are regular. The average level of spoken words was measured at 70 dBA at the ear of the subject (see 4.1.4 vocal material).

- It involves low frequency dominant noise, played at levels of 78 to 92 dBA (see 4.1.5 Noisy environments)

- We use the certified average attenuation of the hearing protection devices A22, A26, A33, B16, B23, and B26.

# 4.2 Results



We observe in Figure 25 the STIr calculated per filter based on the signal:

*Figure 25: STI calculated based on the signal to noise ratio with different hearing protection devices* 





Figure 26: The relationship between the percentage of words recognized in the subjective test and the calculation of STIr in the same conditions. The red dotted curve represents the STI report and the percentage of recognized words presented in the ISO9921 standard.

Figure 26 compares the results of the two methods tested: Subjective test and STIr.

For example, take a measurement with the B23 filter. With a voice signal at 70 db (A) and a noise at 82 dB (A), over 22 subjects we obtained an average of 60% of recognized words in the subjective test. From these conditions (voice, noise, and hearing protection device) we calculate the corresponding STIr as defined in the standard, i.e. 0.25. For the B23 filter, an STI of 0.25 corresponds to an intelligibility of 60%, whereas for the filter A22, an STI of 0.25 corresponds to an intelligibility of 40%.

Note that the relationship between the two methods is different depending on the tested filter.

Although it incorporates the corrections related to masking and hearing thresholds while calculating STIr, this **STIr indicator fails to recreate our observations and the influence of the attenuation slope of the hearing protection device**.

# 5 Research of an intelligibility prediction method

We seek a substitute STIr index suitable for hearing protection devices and based on our observations.

#### Given below is a simple method in 2 steps:

- Estimate of signal to noise ratio from ambient noise (based on the ISO9921 standard and the SIL).

- Estimate of percentage of recognized words (based on our observations).

**1)** Lombard Effect (See 3.1.1.2.1 : Taking the Lombard effect into account):

Vocal effort = 0.57 \* Noise + 30

**2)** <u>Effect of the hearing protection device on the speaker</u> (See 3.1.1.2.1.1: Taking the hearing protection device into account) :

Vocal effort ' = Vocal effort – 3dB

**3)** Effect of the distance between the speakers (See 3.1.1.2.1.3 / 4: Taking into account the distance between the speakers):

Speech level at x meters = Voice effort  $' - 20 \log (x)$ 

4) <u>Calculation of the estimate of the percentage of recognized words</u>(See 4.3: Simple modeling of results)

Estimate of the % of intelligibility = (47 - |slope|)/ 58 + 0.06 \* (10 + Signal (dBA) - Noise (dBA))

# **6** Conclusion

We tried to understand the main phenomena involved in communication and transmission of information in noise, including components related to ambient noise, the signal emitted by the speaker, the listener, and configuration of the environment when the listener is wearing hearing protection devices.

The report of Suter (1992 [6]) effectively shows that in some conditions, hearing protection devices can improve speech recognition, especially in very noisy environments, when the listener is of normal hearing (Rink 1979 [15]) and is using hearing protection devices (not the speaker) (Kryter 1946 [9]). This improvement in high noise levels can be explained by the equivalent noise attenuation of the useful signal, thus reducing the risk of hearing distortion due to widening of the auditory filter, which tends to occur at high sound levels. (Coleman et al, 1984 [18]). Above 80 dB (A), there is also a non-linear increase in masking which comes into play. So in the same way, by reducing the components of noise and speech, the use of hearing protection devices must not lead to loss of spectral information, but on the contrary must reduce distortion and masking, resulting in better intelligibility. However, the situation is not always satisfactory. **Most hearing protection devices are of non-uniform response and reduce the high frequencies much more than low frequencies**. Thus, since the spectral characteristics of the signal have been modified, it allows the power of low frequencies to mask the components of high frequencies.

According to Lazarus (1983 [13]), the higher the attenuation slope per octave of hearing protection, **the greater the loss of audibility of the signal**. The phenomenon increases if the noise is at dominant low and medium frequencies, and the signal is at dominant high frequencies, even when the user of the hearing protection device is hearing impaired. In the latter case, even a high attenuation hearing protection device with relatively flat attenuation can reduce the signal **level below the hearing threshold** of the listener. This possibility is more likely with a non-uniform filter.

We tried to observe the effect of the hearing protection device, especially the effect of its attenuation slope, on intelligibility. We compared two methods of assessing intelligibility that took into account the configuration of the slope of the hearing protection device, a subjective test of word recognition in noise, and STIr, an objective method of prediction in the same conditions.

Using a subjective test on 22 individuals, we **observed an increase of about 20% of recognized words with hearing protection devices with uniform response,** compared to hearing protection devices with non-uniform response at the same attenuation levels.

The intelligibility scores in percentage of recognized words linearly decrease according to the increase in noise relative to the speech signal in dB, in the same proportions, regardless of which hearing protection device is used. Under the same conditions, the calculation of STIr does not reflect these observations; the filters do not sufficiently differ.

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# Appendix 1: attenuation values of hearing protection devices cited in the study

#### A22

Frequencies in Hz	63	125	250	500	1000	2000	4000	8000
Average attenuation (dB)	8.7	9.1	12.1	19.2	27.4	31.4	39.1	39
Standard deviation (dB)	2.6	3.6	2.5	3.3	2.6	3.3	3.3	3.3
APV (dB)	6.2	5.5	9.6	15.9	24.8	28.1	35.8	35.6
Slope: 17.4	H (dB)	29.1	M (dB)	19.1	L (dB)	11.7	SNR (dB)	22

Table 1: Attenuation values of the hearing protection device fitted with the A22 filter

### A26

Frequencies in Hz	63	125	250	500	1000	2000	4000	8000
Average attenuation (dB)	12.4	14.1	16.1	22.5	28.5	34.7	44.3	41
Standard deviation (dB)	5.1	4.6	3	2.5	3.9	3.3	3.1	4.4
APV (dB)	7.3	9.4	13.1	19.9	24.6	31.4	41.2	36.6
Slope: 16	H (dB)	31.3	M (dB)	22.3	L (dB)	15.3	SNR (dp)	26

*Table 2: Attenuation values of the hearing protection device fitted with the A26 filter* 

#### A33

Frequencies in Hz	63	125	250	500	1000	2000	4000	8000
Average attenuation (dB)	28.3	27.5	27.4	31.8	33	36	41.3	43.5
Standard deviation (dB)	5.3	3.6	3.3	3.9	3.4	2.8	4.2	3.7
APV (dB)	23	23.9	24.2	27.8	29.5	33.3	37.2	39.9
Slope: 7.4	H (dB)	34.2	M (dB)	29.8	L (dB)	26.8	SNR (dB)	33

Table 13: Attenuation values of the hearing protection device fitted with the A33 filter

# **B16**

Frequencies in Hz	63	125	250	500	1000	2000	4000	8000
Average attenuation (dB)	20.8	18.9	17.5	16	14.7	17.8	20.9	23.4
Standard deviation (dB)	3.5	3.9	2.7	3.2	2.4	3.3	4	3.5
APV (dB)	17.3	15	14.8	12.9	12.3	14.5	16.9	19.9
Slope: 1.8	H (dB)	15.4	M (dB)	13.3	L (dB)	13.6	SNR (dB)	16

*Table 4: Attenuation values of the hearing protection device fitted with the B16 filter* 

#### **B23**

Frequencies in Hz	63	125	250	500	1000	2000	4000	8000
Average attenuation (dB)	26.8	25.6	24.8	27.3	26.3	22.5	25.2	21.4
Standard deviation (dB)	4.2	2.9	2.5	2.2	1.6	2.1	2.6	3.8
APV (dB)	22.7	22.7	22.3	25	24.7	20.5	22.6	17.6
Slope: 2.8	H (dB)	20.3	M (dB)	22.9	L (dB)	23.1	SNR (db)	23

Table 5: Attenuation values of the hearing protection device fitted with the B23 filter

# **B26**

Frequencies in Hz	63	125	250	500	1000	2000	4000	8000
Average attenuation (dB)	28.2	28.2	26.8	29	28.9	29.2	24.1	30.7
Standard deviation (dB)	5.9	4	2.6	3.3	3.2	3.9	3.1	2.9
APV (dB)	22.3	24.1	24.2	25.7	25.7	25.4	21	27.7
Slope: 1.3	Н (dB)	23.5	M (dB)	24.8	L (dB)	24.8	SNR (dB)	26

*Table 6: Attenuation values of the hearing protection device fitted with the B26 filter*