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Respiratory protective devices — Human factors —

Part 7: Hearing and speech

Appareils de protection respiratoire — Facteurs humains —

Partie 7: Discours et audition

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 94, *Personal safety — Personal protective equipment*, Subcommittee SC 15, *Respiratory protective devices*.

This first edition of ISO 16976-7 cancels and replaces the second edition (ISO/TS 16976-7:2019), which has been technically revised.

The main changes as follows:

— requirements more specified.

A list of all parts in the ISO 16976 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

For an appropriate design, selection and use of respiratory protective devices, basic physiological demands of the user should be considered. The function of a respiratory protective device, the way it is designed and used, and the properties of its material can affect communications: either speech or hearing or both.

This document belongs to a series of documents providing basic physiological and anthropometric data on humans. It contains information about hearing and speech associated with wearing respiratory protective devices.

Respiratory protective devices — Human factors —

Part 7: Hearing and speech

1 Scope

This document contains information related to the interaction between respiratory protective devices and the human body functions of hearing and speech.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1999, *Acoustics — Estimation of noise-induced hearing loss*

ISO 16972, *Respiratory protective devices — Vocabulary and graphical symbols*

IEC 61672, *Electroacoustics — Sound Level Meters*

3 Terms and definitions, and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO 1999, ISO 16972 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Terms and definitions

3.1.1
hearing
manner in which the brain and central nervous system recognizes and interprets *sounds* (3.1.5)

3.1.2
ototoxicity
damage to *hearing* (3.1.1) from overexposure to drugs or toxic substances

3.1.3
noise
unwanted *sound* (3.1.5)

3.1.4
presbycusis
gradual sensorineural *hearing* (3.1.1) loss due to natural ageing

3.1.5
sound
form of energy that moves through media in waves of pressure

3.1.6
sound pressure
local pressure deviation from the ambient atmospheric pressure caused by a *sound* (3.1.5) wave

Note 1 to entry: The sound pressure is measured in pascals (Pa).

3.1.7
RMS sound pressure
deviation from the ambient atmospheric pressure caused by a sound wave at an instant in time over a given period of time

3.2 Abbreviated terms

SPL sound pressure level

NIHL noise induced hearing loss

TWA time-weighted average

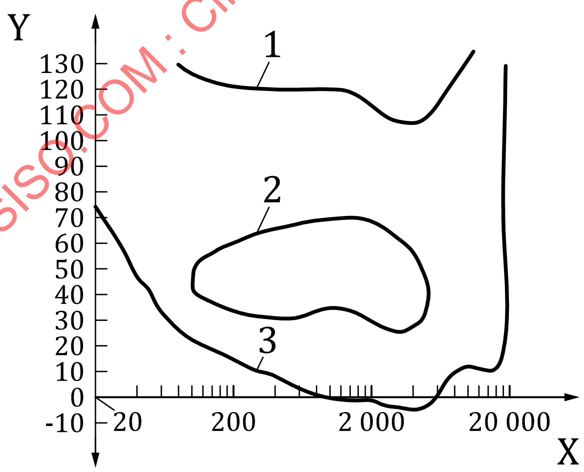
STI speech transmission index

SII speech intelligibility index

RMS root mean square

4 Range of hearing and speech

Humans with normal hearing can usually hear sound pressure waves in a frequency range of about 20 Hz to 20 000 Hz, but the ear is most sensitive to frequencies from 500 Hz to around 4 000 Hz and declines dramatically in sensitivity as frequencies drop below 500 Hz. Figure 1 depicts the frequency response and sound pressure level response of human hearing and speech. The frequency range is affected by ageing as explained further in 7.3.



Key

X logarithmic sale of frequency in Hz

Y sound pressure level, in dB

1 pain threshold

2 range of speech

3 hearing threshold

Figure 1 — Range of human hearing and speech

5 Measurement of sound pressure

The measurement of sound pressure is carried out using a sound level meter which shall meet the requirements of IEC 61672.

The sound pressure level (SPL) is the logarithmic ratio of the sound pressure to a reference sound pressure and is expressed in decibels (dB) by Formula (1):

$$L_p = 20\log_{10}\left(\frac{p_{RMS}}{p_0}\right) \tag{1}$$

where

L_p	is the sound pressure level, in dB,
p_{RMS}	is the root mean square (RMS) sound pressure, in Pa,
p_0	is the sound reference pressure, in Pa.

In air, the reference sound pressure is 20 µPa. That reference is based on the average human threshold of hearing at a frequency of 1 000 Hz.

When measuring sound pressure level as it relates to human perception, weighting factors, as given in IEC 61672, are used to represent human loudness perception at different frequencies. The most common is the A weighted sound measurement which approximates the human loudness perception at 40 phon (40 dB at 1 000 Hz) and is expressed as dBA. Examples of some typical sound levels are:

library:	40 dBA;
normal conversation:	60 dBA;
traffic noise:	80 dBA;
metal shop:	100 dBA;
siren:	120 dBA;
jet engine:	140 dBA.

A perceived difference in sound level occurs at approximately 3 dB, and a perceived doubling of sound volume occurs with a 10 dB increase in sound pressure level.

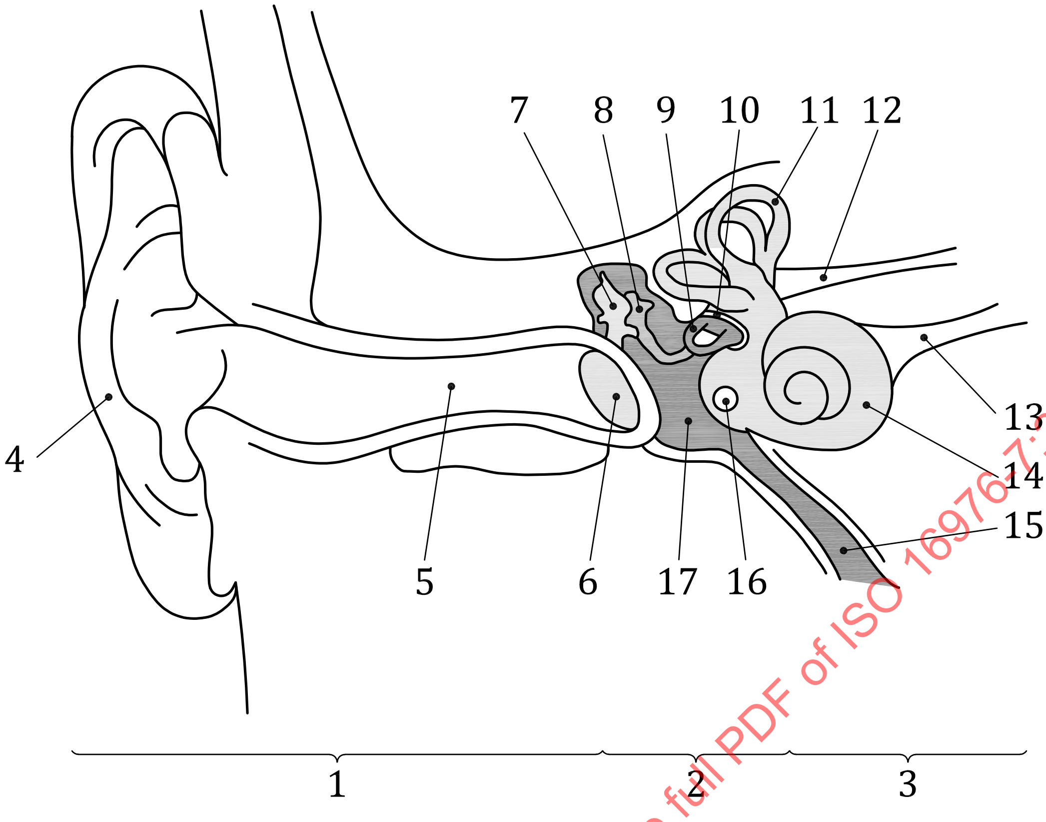
Another sound weighting is the C-weighting, which approximates the human loudness perception at 100 phon.

6 Physiology of the ear

6.1 General

The human ear is the sense organ that detects sounds and changes the pressure waves into a signal of nerve impulses that is sent to the brain. The ear not only receives and converts sound but also plays a major role in the sense of balance and body position.

As shown in Figure 2, the ear is usually described in three sections: the outer ear (key 1), middle ear (key 2) and inner ear (key 3).



Key

1 outer ear
2 middle ear
3 inner ear
4 pinna
5 external auditory channel
6 tympanic membrane
7 malleus
8 incus
9 stapes
10 oval window
11 semi-circular canals
12 vestibular nerve
13 cochlear nerve
14 cochlea
15 Eustachian tube
16 round window
17 tympanic cavity

Figure 2 — Physiological ear terms

6.2 Outer ear

The outer ear is the most external portion of the ear. The outer ear includes the pinna (also called auricle), the ear canal, and the very most superficial layer of the ear drum (also called the tympanic membrane). In humans, the only visible portion of the ear is the outer ear. The outer ear does help get sound (and imposes filtering), but the ear canal is very important. Unless the canal is open, hearing will be damped. Ear wax (cerumen) is produced by glands in the skin of the outer portion of the ear canal. The outer ear ends at the most superficial layer of the tympanic membrane.

The pinna helps direct sound through the ear canal to the tympanic membrane (eardrum).

6.3 Middle ear

The middle ear, an air-filled cavity behind the ear drum (tympanic membrane), includes the three ear bones or ossicles: the malleus (or hammer), incus (or anvil), and stapes (or stirrup). The opening of the Eustachian tube is also within the middle ear. The three bones are arranged so that movement of the tympanic membrane causes movement of the malleus, which causes movement of the incus, which causes movement of the stapes. When the stapes footplate pushes on the oval window, it causes movement of fluid within the cochlea (a portion of the inner ear).

In humans the middle ear (like the ear canal) is normally filled with air. Unlike the open ear canal, however, the air of the middle ear is not in direct contact with the atmosphere outside the body. The Eustachian tube connects from the chamber of the middle ear to the back of the pharynx.

The arrangement of the tympanic membrane and ossicles works to efficiently couple the sound from the opening of the ear canal to the cochlea. There are several simple mechanisms that combine to increase the sound pressure.

— The first is the "hydraulic principle". The surface area of the tympanic membrane is many times that of the stapes footplate. Sound energy strikes the tympanic membrane and is concentrated to the smaller footplate.

— A second mechanism is the "lever principle". The dimensions of the articulating ear ossicles lead to an increase in the force applied to the stapes footplate compared with that applied to the malleus.

— A third mechanism channels the sound pressure to one end of the cochlea and protects the other end from being struck by sound waves. In humans, this is called "round window protection".

6.4 Inner ear

The inner ear includes both the organ of hearing (the cochlea) and a sense organ that is attuned to the effects of both gravity and motion (labyrinth or vestibular apparatus). The balance portion of the inner ear consists of three semi-circular canals and the vestibule. When sound strikes the ear drum, the movement is transferred to the footplate of the stapes, which presses into one of the fluid-filled ducts of the cochlea. The fluid inside this duct is moved, flowing against the receptor cells of the cochlear nerve, which fire. These stimulate the spiral ganglion, which sends information through the auditory portion of the eighth cranial nerve to the brain.

7 Hearing loss

7.1 Conductive hearing loss

Abnormalities such as impacted ear wax (occlusion of the external ear canal), fixed or missing ossicles, or holes in the tympanic membrane generally produce conductive hearing loss. Conductive hearing loss may also result from middle ear inflammation causing fluid build-up in the normally air-filled space. In some cases, conductive hearing loss is reversible.

7.2 Ototoxicity

A number of drugs in clinical use and some substances at the workplace (e.g. styrol) are considered "ototoxic" and have the potential to cause damage to hearing as a side effect, especially in combination with noise exposure. Hearing loss caused by ototoxic drugs can be reversible or permanent.

7.3 Presbycusis

Hearing loss caused by natural aging affects the higher frequencies making word recognition difficult, see Clause 8. It is permanent.

7.4 Noise induced hearing loss (NIHL)

NIHL is caused by exposure to sound levels or durations that damage the hair cells of the cochlea. Initially, the noise exposure may cause a temporary threshold shift, that is, a decrease in hearing sensitivity that typically returns to its former level within a few minutes to a few hours. Repeated exposures lead to a permanent threshold shift, which is an irreversible sensorineural hearing loss. Hearing loss has causes other than occupational noise exposure. Hearing loss caused by exposure to nonoccupational noise is collectively called sociocusis. It includes recreational and environmental noises (e.g. loud music, guns, power tools, and household appliances) that affect the ear the same as occupational noise. Combined exposures to noise and certain physical or chemical agents (e.g. vibration, organic solvents, carbon monoxide, ototoxic drugs, and certain metals) appear to have synergistic effects on hearing loss[3][4][5][6][8][9][11][12]. Conductive hearing losses, as opposed to sensorineural hearing losses, are usually traceable to diseases of the outer and middle ear.

7.5 Other types of hearing loss

For more information on other types of hearing loss, see ISO 1999.

7.6 Other effects of noise

Noise exposure is also associated with nonauditory effects such as psychological stress and disruption of job performance[11][12][13] and possibly hypertension. See References [14] to [26]. Noise may also be a contributing factor in industrial accidents[27][28][29][30].

7.6.1 General

Hearing loss from long term exposure to noise has been recognized as a hazard. The effects of noise can include increased stress, cardiovascular function (hypertension, changes to blood pressure and/or heart rate), annoyance, sleeping problems, and mental health. In the workplace, non-auditory effects of noise also include problems with oral communications.

7.6.2 Effects on the wearer

7.6.2.1 Physiological

The physiological effects can be temporary or permanent.

Examples of temporary physiological effects are

— the spontaneous response to loud noise, where muscles are required to protect the auditory senses,

— the muscle tension response, where muscles tend to contract in the presence of continuous loud noise,

— the respiratory reflexes, where the respiratory rhythm tends to change when noise is present,

— changes in the heart beat pattern, and

— changes in the diameter of the blood vessels, particularly in the skin.

7.6.2.2 Performance

Examples of the performance effects would be the

a) speech intelligibility.

The presence of noise interferes with the understanding of what other people say, including hearing safe work instructions. This exchange includes for example face-to-face talks, telephone conversations, audible danger/warning signals, and speech over a public address system.

In order to be intelligible the sound level of speech shall be greater than the background noise at the ear of the listener. People with otherwise unnoticeable hearing loss find it difficult to understand spoken words in noisy surroundings.

In a noisy work environment, people are able to converse with difficulty at a distance of one meter for a short time in the presence of noise as high as 78 dB(A). For prolonged conversations, the background noise level shall be lower than 78 dB(A).

In a work environment with a low background noise level not exceeding 55 to 60 dB(A) people often can talk at distances of 2 m to 4 m comfortably, see Table 1.

Table 1 — Speech communication versus level of background noise

Communication	(50 to 70) dB(A)	(70 to 90) dB(A)	(90 to 100) dB(A)	(100 to 130) dB(A)
Face-to-face (unamplified speech)	Raised voice level at distances up to 2 m	Very loud or shouted voice level at distances up to 50 cm	Maximum voice level at distances up to 25 cm	Very difficult to impossible, even at a distance of 1 cm
Telephone	Satisfactory to slightly difficult	Difficult to unsatisfactory	Use press-to-talk switch and an acoustically treated booth	Use special equipment
Intercom system	Satisfactory	Unsatisfactory using loudspeaker	Impossible using loudspeaker	Impossible using loudspeaker
Type of earphone to supplement loudspeaker	Any	Use any earphone	Use any in muff or helmet except bone conduction type	Use insert type or over-ear earphones in helmet or in muffs; good to 120 dB(A) on short-term basis
Public Address System	Satisfactory	Satisfactory to difficult	Difficult	Very difficult
Type of microphone required	Any	Any	Any noise-cancelling microphone	Good noise-cancelling microphone
NOTE The information given in this table has been compiled from the data in Reference [3]. Although this is an old reference, no recent information was found that would change these examples.				

b) annoyance.

In noisy environments, people generally prefer to reduce the noise loudness, avoid it, or leave the noisy area if possible. The same noise could be annoying to some people but acceptable to others. There is no definite relationship between the degree of annoyance or unpleasantness of noise and the risk of adverse health effects. For example, very loud music may be pleasant to one group of people and annoying to another group. Both groups will be equally at risk of hearing loss.

Besides loudness of sound, several other factors contribute to annoyance. Table 2 lists examples of such factors.

Table 2 — Factors that affect individual annoyance to noise

Areas of concern	Factors
Primary acoustic factors	Sound level Frequency Duration
Secondary acoustic factors	Spectral complexity Fluctuations in sound level Fluctuations in frequency Rise-time of the noise Localization of noise source physiology
NOTE The information given in this table has been compiled from the data in Reference [3]. Although this is an old reference, no recent information was found that would change these examples.	

Table 2 *(continued)*

Areas of concern	Factors
Non-acoustic factors	Adaptation and past experience How the listener's activity affects annoyance Predictability of when a noise will occur Is the noise necessary? Individual differences and personality
NOTE The information given in this table has been compiled from the data in Reference [3]. Although this is an old reference, no recent information was found that would change these examples.	

c) job interference.

Depending of the type of activity, noise can severely affect efficiency of a task performance. The following examples will illustrate this point.

— A noisy environment could create a hazard, since audible alarms might not be heard.

— A noisy environment interferes with oral communication and thus, interferes with the activity.

Further information can be found in References [10] to [25]. Noise can also be a contributing factor in industrial accidents[26][27][28][29].

8 Noise exposure limits

8.1 Workplace exposure levels and durations

Occupational noise exposure should be controlled so that worker exposures are less than the combination of sound exposure level (SPL) and duration (T), as calculated by Formula (2) and as shown in Table 3.

$$T\,(\text{min}) = \frac{480}{2^{(\text{SPL}-\text{TWA})/3}} \tag{2}$$

where TWA (Time-Weighted Average) noise exposure limits vary with jurisdiction, but are usually accepted to be 80 dBA or 85 dBA for an eight hour work shift using a 3 dB exchange rate, i.e. the duration halves for every 3 dB increase in sound pressure level (SPL).

Table 3 — Maximum exposure duration (*T*)

SPL	Maximum duration for TWA = 85 dBA			Maximum duration for TWA = 80 dBA		
dB	h	min	s	h	min	s
80	25	24		8	0	
81	20	10		6	21	
82	16	0		5	2	
83	12	42		4	0	
84	10	5		3	10	
85	8	0		2	31	
86	6	21		2	0	
87	5	2		1	35	
88	4	0		1	16	
89	3	10		1	0	
90	2	31			47	37
91	2	0			37	48
92	1	35			30	0

Table 3 *(continued)*

SPL	Maximum duration for TWA = 85 dBA			Maximum duration for TWA = 80 dBA		
dB	h	min	s	h	min	s
93	1	16			23	49
94	1	0			18	54
95		47	37		15	0
96		37	48		11	54
97		30	0		9	27
98		23	49		7	30
99		18	54		5	57
100		15	0		4	43
101		11	54		3	45
102		9	27		2	59
103		7	30		2	22
104		5	57		1	53
105		4	43		1	29
106		3	45		1	11
107		2	59			56
108		2	22			45
109		1	53			35
110		1	29			28
111		1	11			22
112			56			18
113			45			14
114			35			11
115			28			9
116			22			7
117			18			6
118			14			4
119			11			4
120			9			3
121			7			2
122			6			2
123			4			1
124			4			1
125			3			<1
126			2			<1
127			2			<1
128			1			<1
129			1			<1
130			<1			<1
131			<1			<1
132			<1			<1
133			<1			<1
134			<1			<1
135			<1			<1

Table 3 *(continued)*

SPL	Maximum duration for TWA = 85 dBA			Maximum duration for TWA = 80 dBA		
dB	h	min	s	h	min	s
136			<1			<1
137			<1			<1
138			<1			<1
139			<1			<1

Where the noise exposure is composed of two or more periods of noise at different levels, the total noise dose (D), which is the actual exposure relative to the amount of allowable exposure and for which a dose of 100 and above represent exposures that are hazardous, can be calculated as given in Formula (3):

$$D = 100\left(\frac{C_1}{T_1} + \frac{C_2}{T_2} + ... + \frac{C_n}{T_n}\right) \tag{3}$$

where

C_n indicates the total time of exposure at a specific noise level;

T_n indicates the duration for that level as given in the table above.

Incremental doses can be summed using the following tables.

As an example, calculate the dose for an employee who is subjected to 92 dB for 2 h, 87 dB for 4 h and 82 dB for 2 h.

From Table 3, T_{n} for 92 dB is 1 h 35 min (1,58 h), for 87 dB, 5 h 2 min (5,03 h), and for 82 dB, 16 h.

Therefore,

$$D = 100\left(\frac{2}{1,58} + \frac{4}{5,03} + \frac{2}{16}\right) = 100(1,27 + 0,80 + 0,13) = 220\,\%$$

Using Table 4 below,

D = 126 + 79 + 13 = 218 %.

The difference is caused by rounding.

Table 4 — Percentage of total dose based on 85 dBA TWA

SPL (dBA)	Duration of exposure h 1/4	1/2	1	2	4	8	10	12
105	318	636						
104	252	504	1 008					
103	200	400	800					
102	159	317	635					
101	126	252	504	1 008				
100	100	200	400	800				
99	79	159	317	635				
98	63	126	252	504	1 008			
97	50	100	200	400	800			
96	40	79	159	317	635			

Table 4 *(continued)*

SPL (dBA)	Duration of exposure h							
	1/4	**1/2**	**1**	**2**	**4**	**8**	**10**	**12**
95	32	63	126	252	504	1 008		
94	25	50	100	200	400	800	1 000	1 200
93	20	39	79	158	316	632	789	947
92	16	32	63	126	253	505	632	758
91	13	25	50	100	200	400	500	600
90	10	20	40	79	159	318	397	477
89	8	16	32	63	126	253	316	379
88	6	13	25	50	100	200	250	300
87	5	10	20	40	79	159	199	238
86	4	8	16	31	63	126	157	189
85	3	6	13	25	50	100	125	150
84	2	5	10	20	40	79	99	119
83	2	4	8	16	31	63	79	94
82	2	3	6	13	25	50	63	75
81	1	2	5	10	20	40	50	60
80	1	2	4	8	16	31	39	47
79				6	13	25	32	38
78				5	10	20	25	30
77					8	16	20	24
76					6	13	16	19
75					5	10	13	15

8.2 Peak limit value

Exposure to impulsive noise is regulated by national regulations and is generally accepted not to exceed 137 dBC or 140 dBC.

9 Speech and hearing difficulties

Speech as shown in Figure 1 encompasses a range from about 100 Hz to 5 000 Hz. Various phonemes are comprised of different frequencies even though they may share a similar sound. Plosives like “pa”, “ka”, “tee”, “bee” and “dee” range from low to medium frequencies. Fricatives like “sss”, “vee” and “zee” are mostly high-frequency sounds.

Vowels are mostly medium- to low-frequency sounds. Thus, communication problems due to hearing loss will be dependent on the frequency of the loss. If hearing loss is in the high-frequency range, as it usually is with presbycusis, fricative sounds will be easily confused.

Further affecting the ability to hear speech with high-frequency loss is the fact that there is a difference in the frequency range between male and female voices: males use frequencies down to about 100 Hz while females’ lower limit is about 250 Hz.

The ability to understand speech is compounded by many factors in addition to hearing loss. One major issue is masking due to the background noise. The noise spectrum and speech-to-noise ratio are very important to understanding speech. Another factor is distortion caused by reverberations, muffling, echoes, or just plain variations in pronunciations or dialect. This arena is far too complex for this document.