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Acta
OTO-LARYNGOLOGICA

SUPPLEMENT 320

Methods for assessing high frequency hearing loss in every-day listening situations

By

Gunnar Aniansson

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STOCKHOLM, SWEDEN

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DOKTORSGRAD KOMMER ATT OFFENTLIGEN FÖRSVARAS
I AULAN, SAHLGRENSKA SJUKHUSET
TISDAGEN DEN 11 JUNI 1974 KL. 9 F. M.

By

Gunnar Aniansson

GÖTEBORG 1974

ACTA OTO-LARYNGOLOGICA
SUPPLEMENT 320

From the Department of Otolaryngology (Head: Professor G. Herberts, M.D.)
and the Department of Audiology (Head: Ass. Professor G. Lidén, M.D.)
Sahlgren's Hospital, University of Göteborg, Sweden

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Gunnar Aniansson

GÖTEBORG 1974

Translated by
L. James Brown

Statistical adviser
Martin Härnqvist

Printed in Sweden, Gotab, Kungälv 74.13412

To my wife Amelie, my daughter Helena and my sons
Gustav, Johan, Per and Hans.

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CHAPTER 1

INTRODUCTION

In view of the fact that as much speech intelligibility can be conveyed in the frequency band over 1900 Hz as below 1900 Hz (French & Steinberg 1947) it was thought worthwhile to assess the importance of a hearing loss above 2000 Hz.

High frequency loss above 2000 Hz because of presbycusis and/or the effect of noise is very common in a population living in an industrialised country with a long average life expectation.

According to Spoor's (1967) compilation of 8 publications on presbycusis, of all the men who were above 70 years and who had not had noisy occupations, 25 % had a hearing loss of at least 47, 52 and 60 dB at 3000, 4000 and 6000 Hz, respectively.

A permanent threshold shift of the frequencies above 2000 Hz because of the effect of noise is very common among workers with noisy occupations. In Heijbel's (1962) investigation of 1953 workers in heavy industry (automobile and tractor engine factories, including foundries) 70 % of the men in the 30–39 year age group and 80 % of those in the 40–49 year age group with noisy jobs had loss of hearing owing to the noise. In Lindqvist's (1970) investigation of 2328 workers in the building industry (joiners, bricklayers, cement workers, painters) 70 % in the 36–45 year group and 80 % in the 46–55 year group had such injuries. So-called severe noise injuries (Heijbel & Lidén, 1957), i.e. hearing loss also at a frequency of 2000 Hz and even below, as well as notable loss of hearing at frequencies above 2000 Hz was noted in about 10 % of workers around 30 years and in 25 % of those in their 50s according to Heijbel. Lindqvist found severe noise injuries in 7 % of 30 year old men and 33 % of men in their 50s. In most of these cases the hearing loss could be regarded as an occupational disease, but in some cases it was due to civil or military rifle practice.

Loss of hearing at frequencies above 2000 Hz has been regarded as having little effect on speech perception. Several investigators (Fowler 1942, Sabine 1942, Fletcher 1950, Harris et al. 1956, Quiggle et al. 1957) have shown the frequency range 500–2000 Hz to be the most important for predicting speech intelligibility. Common to all these investigations however, is that they have been carried out in quiet environments.

Owing to urbanisation, we spend much of our time in noisy environments and conversation in quiet surroundings is becoming the exception rather than the rule. Kryter et al. (1962), Harris (1965a), Lidén (1965) and Niemeyer (1967) have shown in persons with sensorineural losses, that the frequencies above 2000 Hz increase in importance in relatively noisy listening situations.

In the investigation of Kryter et al. (1962) it was found that the three most important audiometric frequencies for the intelligibility of sentences and phonetically balanced English monosyllables masked by noise of 65–95 dB SPL with the same frequency distribution as speech are either 2000, 3000 and 4000 Hz or 1000, 2000 and 3000 Hz.

In Harris' (1965a) investigations with so-called every-day speech in which the test words consisted of English sentences, loss of hearing at 1000, 2000 and 3000 Hz were best correlated with loss of intelligibility of speech in English.

Niemeyer (1967) used German sentences in random noise corresponding roughly to traffic noise. He found that loss of intelligibility can occur with a sensorineural loss above 3000 Hz to 4000 Hz and is invariably with a loss above 2000 Hz to 3000 Hz.

On the other hand, Schultz-Coulon (1973), who tested German sentences in cocktail party noise on persons with high-tone loss, found that a high-tone loss above 2000 Hz had at most an insignificant effect on the intelligibility of speech.

Intelligibility of speech is examined audiologically with speech audiometry. The examination is, as a rule, made in silence. Persons with noise induced high frequency loss above 2000 Hz, have in these tests with monosyllabic words a discrimination score of 90–100 %, which may be regarded as normal. These findings often contrast with the patient's subjective symptoms of being unable to communicate when the listening situation becomes noisy or as soon as several persons talk at the same time. This observation and the above investigations induced us to study the hearing ability of normals and of persons with sensorineural loss at frequencies above 2000 Hz in quiet environments and in every-day listening situations.

It is convenient to use recordings when handling subjects in different acoustic environments. Such recorded listening situations also permit good reproducibility because of the stability of the conditions. The recordings of speech in noisy environments or in the presence of competing speech should, if it is to simulate a given listening situation, be made via an artificial head with microphones placed at the sites of the ears (Firestone 1930). It is true that this technique, especially the immobility of the head has some disadvantages compared with an authentic situation. The possibility of a listener to turn his head so as to achieve the best possible listening angles is lost (Harris 1965b). But the stereophonic recording nevertheless reproduces the important differencies in phase and intensity between the ears in binaural listening.

A persons' age and vocabulary affects his ability to understand speech, especially if the listening situation is made worse by noise and if the speech signal is more redundant i.e. consists of sentences (Farrimond 1962, Schultz-Coulon 1973). It is thus important to investigate the influence of the vocabulary factor on the test scores.

The effect of high frequency and low frequency filtered speech on the intelligibility in noise of normal hearing subjects has theoretical interest and has been included in this study.

French & Steinberg (1947) developed a method with which it was possible to predict the intelligibility of speech in different noise environments. They called this the articulation index or AI. Depending on the speech material, this index can be converted to corresponding speech intelligibility scores. This method has been used on normals in order to predict the speech intelligibility of different filtered and unfiltered speech signals in noise. The results obtained with the AI-method are compared with the observed results of listening to filtered speech. In the same way the AI was calculated on subjects with sensorineural loss listening to unfiltered speech signals in noise. A comparison was then made between the predicted discrimination scores and the results observed.

Increasing knowledge about hearing ability in every-day listening situations in persons with sensorineural loss above 2000 Hz would enable the clinicians to better understand what a loss of hearing in the tone audiogram means to the patient in every-day environments. At the same time it would make it easier, from the medico-legal point of view, to assess the social handicap of hearing loss. Further, increased knowledge of the effect of noisy environments on the communication of normals and persons with hearing impairments might be useful in designing laws and regulations concerning traffic noise.

The purpose of the present investigation has also been to demonstrate the need of a method for assessing speech discrimination in a noisy environment. It is hoped that the recordings used in this study can be utilized as a basis for a new clinical test concerning speech audiometry in every-day situations. In summary the main purpose of the present investigation is

to study if binaural earphone listening to stereophonic recordings of speech in every-day noise situations is a reliable substitute for direct listening and can be used for assessing the effect of noise on speech discrimination,

to investigate the effect of different degrees of high frequency losses on speech discrimination in different every-day noise situations,

to present a clinical test for measurement of speech discrimination in every-day noise situations.

In addition it has also been found important

to compare the intelligibility of low- and high-pass filtered speech in every-day noise situations on normal hearing subjects and

to present a method for predicting speech discrimination in every-day noise situations from tone audiograms and by calculation of the articulation index.

CHAPTER 2

FACTORS INFLUENCING SPEECH DISCRIMINATION

Beside the hearing acuity of the listener, speech discrimination depends on a number of different factors. The most important are:

- The possibility of binaural hearing.
- The possibility of speech-reading by the listener.
- The listening efficiency of the listener, i.e. a factor difficult to control and affected by, among other things, motivation, training, intelligence and age of the listener.
- Characteristics of the speaker.
- Presence or absence of noise masking speech and/or competing speech.
- Local acoustic conditions, particularly the reverberation time.
- Distance between listener and speaker.
- Verbal material.

These factors are further described below.

Binaural hearing

The superiority of binaural over monaural listening to speech is well known in the function of threshold sensitivity (Shaw, Newman and Hirsh, 1947). It is also well established that binaural speech discrimination in the presence of noise or competing speech is significantly better than monaural discrimination in a given situation (Koenig 1950, Hirsh 1950, Pollak & Pickett 1958, Nordlund & Fritzell 1963, Carhart 1965 and Harris 1965 b). This can be explained by the difference in amplitude and/or timing (phase) in the two ears (Licklider 1948).

The recording of speech in noisy environments or in the presence of competing speech should as is mentioned in the introduction, be made via an artificial head with microphones placed at the sites of the ears (Firestone 1930) if it is to simulate a given listening situation.

The head shadow gives the differences in interaural intensity, while the difference in distance from the sound source to each ear (microphone) gives differences in time (phase) in the two ears (microphones). The artificial head should have no auditory canals so that the effect of the auditory canal has an influence only when the recording is presented via the earphone.

Speech-reading

The possibility of speech-reading increases speech discrimination in unfavourable listening situations as shown among others by Neely (1956).

In the present investigation the effect of speech-reading was intentionally excluded because it varies from one test person to another. One might very well imagine that persons with a hearing impairment and persons used to conversing in noisy environments are better versed in speech-reading. If this ability makes itself felt, the discrimination of speech in the presence of different sorts of noises will be less well correlated with the tone audiogram.

Listening efficiency

Discrimination of speech depends also on a number of factors difficult to control, factors which are known under the blanket name of listening efficiency. This consists of, among other things, motivation and training (Zwislocki et al. 1958), but also age and vocabulary effect a person's ability to understand sentences correctly (Farrimond 1962). Persons used as controls should therefore not be only age matched but also as homogenous as possible in respect of their vocabulary.

In 1959 Corso, in an investigation of a population in a rural area without industry, showed that hearing was poorer among the men than among the women in each of four age-groups between 18 and 49 years. Similar results have been reported by Hinchcliffe (1959) in the 18–24 year age group. A difference in the tone audiogram between the sexes was found to be independent of age and was most marked in the higher frequencies. As a rule, only insignificant differences were found between the right and the left ear in a given individual. According to Corso (1959), the audiometric standards should be specified independently for men and women. In the present investigation comparisons were made only between men.

The speaker

It must be expected, as shown by Dreher & O'Neill (1957), that speech will be easier to understand if the speaker himself is in the same noisy environment as the listener who is to hear the speech signal.

This is partly because the speaker raises his voice somewhat but also due to a tendency to pronounce the test words somewhat slower. In the above investigation, however, the difference in vocal effort at 70 dB(C) of white noise, compared with quiet environments, was only 3 to 6 dB and by no means so large as at an ambient noise level of 90–100 dB(C). As for the duration, each spondee was 0.1 sec longer at 70 dB(C) white noise than in a quiet environment. Gardner (1964), who used noise with a spectrum similar to community noise, found an increase in vocal effort by 0.36 dB for every dB increase of noise, when 58 dB(C) was used as a starting point. In the present investigation the word lists were recorded by a speaker in a quiet room and presented to the listener at a level independent of the noise level. The levels of the community noise were however between 60 and 70 dB(C). For this reason it can be assumed that the above mentioned factors only slightly interfered with the results of the tests.

Noise masking speech and competing speech

The dominating environmental noise is that produced by road and air traffic. Extensive measurements of noise have been made in several countries. Today we know the average curves which show the level and distribution of frequencies of environmental noise during different parts of the day in different types of residential areas (Bonvallet 1951, Meister & Ruhrberg 1953, Ronge 1955, Stevens & Baruch 1957, Cederlöf et al. 1961, *Samhällsplanering och Vägtrafikbuller* 1972 and others). A noise spectrum that slopes downward at a rate of 5 dB per octave is, according to Stevens & Baruch (1957), representative of the outdoor background noise in residential areas in a community with different forms of traffic and industrial activity.

Since communication by speech occurs mainly indoors, when assessing the speech-masking effect of environment noise one must take into account the reduction in noise on its passage through windows and to the sound absorption of the noise in the room. A normal closed window attenuates the noise by 20–25 dB(A) *(Samhällsplanering och vägtrafikbuller* 1972).

The maximum permissible noise in living apartments according to the present laws and regulations in Sweden takes into account only the noise from sources within the house and gives no fixed limits for noise entering from outdoors *(Svensk byggnorm* 67). There is at present no legal maximum noise limit outdoors, but such rules are expected within the next year or so.

Several authors have shown that speech discrimination decreases if the primary signal is accompanied by a meaningful secondary signal, so-called competing speech (Miller 1947, Carhart 1965 and others).

In every-day situations in a given flat or house there is not only traffic noise but also other noises, such as competing speech from the radio, TV and other persons.

Acoustic properties of the room

The length of the reverberation time notably influences speech perception (Knudsen 1929, Steinberg 1929, Knudsen & Harris 1950, Thompson et al. 1961, Moncur & Dirks 1967 and others). The optimal length of the reverberation time for good acoustic conditions varies with different room volumes and room types.

The reverberation time is different for different frequencies. It is often given as a mean for the values of 500, 1000 and 2000 Hz. This is however a relatively crude measure compared with the reverberation time curve as a function of frequency. And generally speaking it is difficult to find two rooms or halls with the same acoustic properties and the same reverberation time curve, even if the mean of the different frequencies is the same. The results of experiments performed in a certain locality are thus influenced by the locality in question.

Due to the integration properties of the ear, the early reflexions of a speech signal contribute to the understanding by increasing the level of the useful speech signal. The later reflexions have a disturbing effect simular to the effect of background noise and reduce speech discrimination. These findings have been used by Meyer (1954) who further has defined the acoustic quality in a room or hall in terms of *Deutlichkeit* (Definition). It is expressed as the energy of direct sounds and early reflexions (within 50 msec) in relation to the total amount of sound energy which reaches the listener.

Distance between listener and speaker

The longer this distance the lower the signal level. When listening outdoors in free field without reflecting walls and in the absence of wind, the sound pressure level falls by 6 dB for each doubling of the distance. Indoors the sound that is reflected will play a relatively important role in the amplification of the speech signal. With an absorption area of 16 m^2 in a locality (as in the present investigation) the direct sound pressure level produced by a point source is equal to the reflected sound pressure level already at 0.56 m from the source of sound and at greater distances the reflected sound pressure level is higher than the direct. The sound pressure level there falls only from e.g. 65 dB 1 m from the speaker to 62 dB at a distance of 3 m according to our measurements. In smaller rooms the speech level thus falls relatively slowly with increasing distance.

Verbal material

In order to avoid undue smoothing out of differences in the results of tests between groups of normals and persons with impaired hearing and between simulated listening situations, the test material should be selected to reveal also relatively small differences and should thus be relatively difficult. In 1948 Egan elucidated the relative differences in difficulty between English speech tests. The tests that may be chosen are, in decreasing order of difficulty, logathomes (nonsense words), monosyllables, spondees, sentences and numerals. Monosyllables are only slightly easier than logathomes. The choice thus remains between logathomes and monosyllables.

The vocabulary should include all phonemes in the Swedish language. Lidén & Fant (1954) devised 25 phonetically balanced lists, each consisting of 50 monosyllables. After clinical tests in which the commoness of the word in every-day speech was also considered, it was found that 6 lists were of equal difficulty (Lidén 1954). These lists are still used for evaluation of speech discrimination in silence. Lidén's and Fant's lists were revised and recorded anew in 1966 by Bertil Johansson (personal communication) into 12 phonetically balanced lists with monosyllables. These were found to be of equal difficulty when tested on normals in silence (Johansson 1966 pers. comm.). They are, however, easier than Lidén's lists (Fransson, Hasselrot, Lindström and Lundborg 1969).

In order to avoid a memorising effect, a given subject should not hear the same list of words more than once (Miller et al. 1951, Thwing 1956). It is therefore an advantage to have a large number of lists of equal difficulty if various test situations are to be examined.

Miller & Nicely (1955) have shown that consonants are masked to a varying extent by noise and Picket (1957) showed that this holds also for vowels. This means that only lists containing all phonemes in the language can be used for speech intelligibility tests in noise.

As shown by e.g. Howes (1957), Pollack, Rubenstein & Decker (1959) and Savin (1963), intelligibility of speech in the presence of noise depends on the commoness of the word in the language. This implies that it is not possible, without further examination, to be sure that available phonetically balanced lists of Swedish monosyllables are of equal difficulty when tested in the presence of noise or competing speech. Even if the word frequency factor has been taken into account in the design of the list, the frequency with which a given word is used in a language varies with time.

One way to avoid this problem was pointed out by Pollack et al. (1959), who showed that the frequency factor has no effect if the words are presented in the form of alternatives. A test with Swedish rhymes in alternative (closed response test) has been devised by Risberg (1968 pers. comm.), but was not available in the planning of this investigation. Kryter & Whitman (1965), who used Fairbanks' rhyming test (Fairbanks 1958) in modified form, have shown that alternative words are much easier as test material than phonetically balanced monosyllables. But the comparison seems only to hold for a vocabulary limited to 1,000 Pb-words. As shown by Nickerson et al. (1960) there is no difference in difficulty between the above rhyming test and the vocabulary of Pb-words limited to 200.

A fact suggesting that logathomes should be used is that they eliminate the word frequency effect as an influencing factor. There was, however, no Swedish phonetically balanced test for logathomes available at the beginning of the present investigation, but such a test has been devised in the meantime (Johansson 1971, pers. comm.).

It has, however, been claimed to be difficult to test an untrained group with logathomes (Wendt 1959).

Thus, if it is desired to choose a fairly difficult test that includes all phonemes in the language, balanced monosyllables should probably be preferred for testing untrained listeners.

Part I

CHAPTER 3

SPEECH DISCRIMINATION IN EVERY-DAY LISTENING SITUATIONS

A. Comparison between intelligibility of speech in direct listening and with ear-phones

To obtain the best possible knowledge of a person's ability to hear and understand speech, any test used for speech discrimination should include simulation of the listening situations in the every-day life of the subject. One alternative would be to make recordings of speech in noise representative of the noisy environments of various occupational groups. Another method, which was used in the present investigation, would be to use – for the recordings – an ordinary living-room, i.e. a very common listening milieu for the major part of the population and there simulate common listening situations.

To find out whether such recordings give similar or different results compared with listening directly in the recording-room but without speech-reading, a comparison was made between the two forms of listening.

Three listening situations were studied.

Subjects

The test subjects consisted of 6 male students with normal hearing. Their tone-threshold was 10 dB or better (re ISO 1964).

Methods

The following listening situations were arranged in the living-room of a 3-room flat: (Fig. 1).

1. Indoor speech with disturbing "traffic noise", closed windows. Signal/noise = –10 dB. Speech and noise spectrum are given in fig. 2.
2. Indoor speech with disturbing "traffic noise", closed windows and competing radio voice. Signal/noise = –10 dB + competing radio voice.
3. Indoor speech with three male authentic competing speakers reading newspaper text.

The spectrum of the speech signal and the three competing speakers are given in fig. 3. Concerning the methods used for measuring the noise level and the fluctuating speech signal, see below.

The floor space of the room was 20 m^2 and its volume 50 m^3. The measured reverberation time was about 0.5 sec. (Fig. 4).

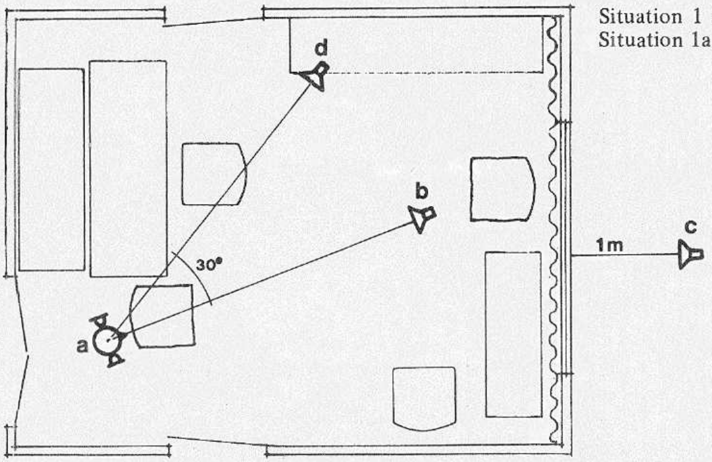
The reverberation time was measured by firing a pistol shot and recording the "bang" on a Nagra III B tape-recorder. The recording was afterwards analysed with a one-third octave analyser and level recorder. Of a number of shots, three were selected for analysis. The reverberation time of each one-third octave was determined as the mean of the 3 shots.

An artificial speaker and an artificial listening head were used for the recordings. The speaker had a directivity pattern and a spectrum, which was well in agreement with that of an authentic male voice. The artificial head had no auditory canals. The speaker and the listening head are identical with those described by Nordlund, Kihlman and Lindblad (1968).

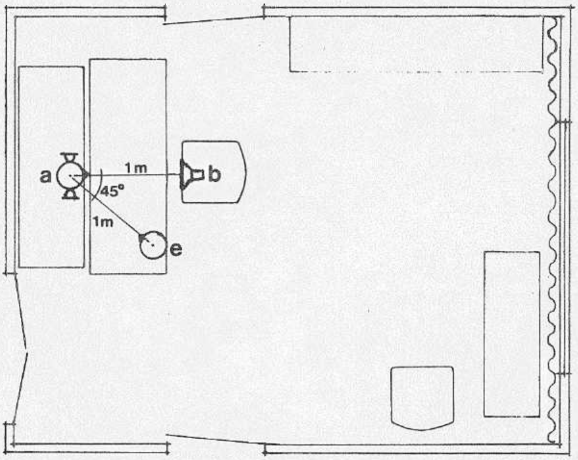
The approximate sound pressure level of the speech signal and disturbing noise, including competing speakers, was measured during recordings with a precision sound level meter (Brüel & Kjaer 2203) with the use of the decibel C-scale. The meter was set at slow. The noise was also measured in dB(A). The level of the speech signals refers to the approximate means of the speech peaks.

The test signals are recordings with a male voice of 50 Swedish phonetically balanced monosyllables each, devised by Johansson 1966. The syllables had a carrier phrase: "*Nu hör Ni . . .*". Each key-word was presented at an interval of 5 seconds. Three lists of 50 Pb-words each were used. The recordings were made via the artificial head. The speech signal, noise and competing speech were presented via separate loud-speakers. In situation 3 (see above) however, the competing

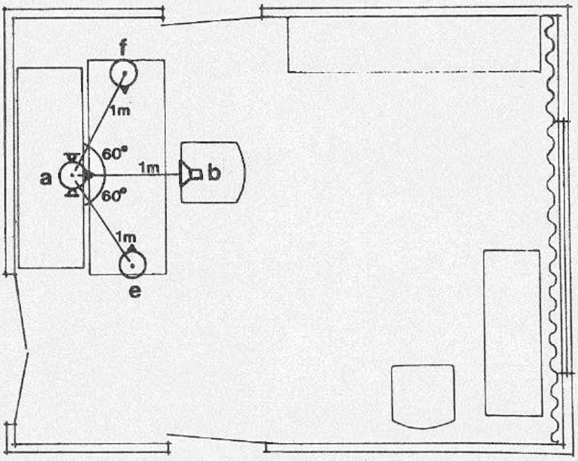
Situation 1 and 2 accounted for under A.
Situation 1a, 1b, 2a and 2 b accounted for under B.



Situation 3a accounted for under B.



Situation 3b accounted for under B.



Situation 3 accounted for under A.
Situation 3c accounted for under B.

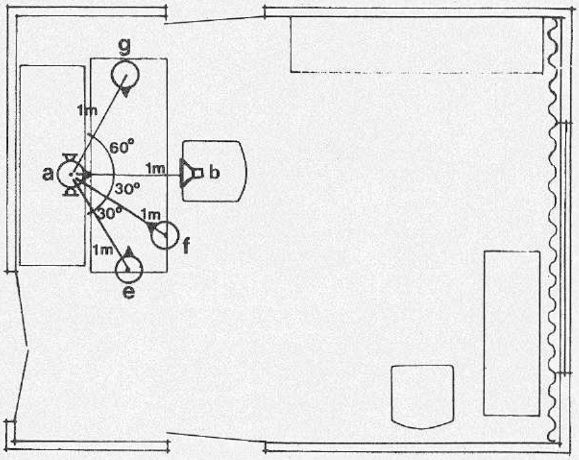


Fig. 1. Recording room with artificial head a, loudspeaker for speech signal b, noise c and competing speech from radio d and competing speakers e, f and g.

Floor surface 20 m^2. Volume 50 m^3. Total limiting surface 85 m^2.

Reverberation time 0.5 sec. Absorption 16 m^2.

In recordings accounted for under A there was a change in disposition of furniture. (See fig. 4 regarding reverberation time).

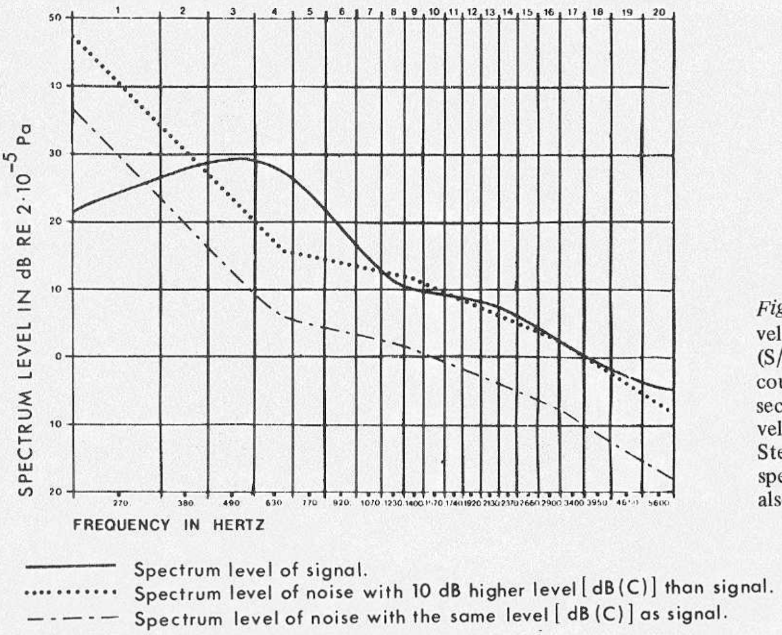


Fig. 2. Noise and speech spectrum levels in listening situations 1a and 1b (S/N = 0 dB and S/N = −10 dB) accounted for in section B. In section A the noise and speech levels are 5 dB(C) higher. French & Steinberg's (1947) division of speech spectrum in 20 bands is shown. (See also chapter 5).

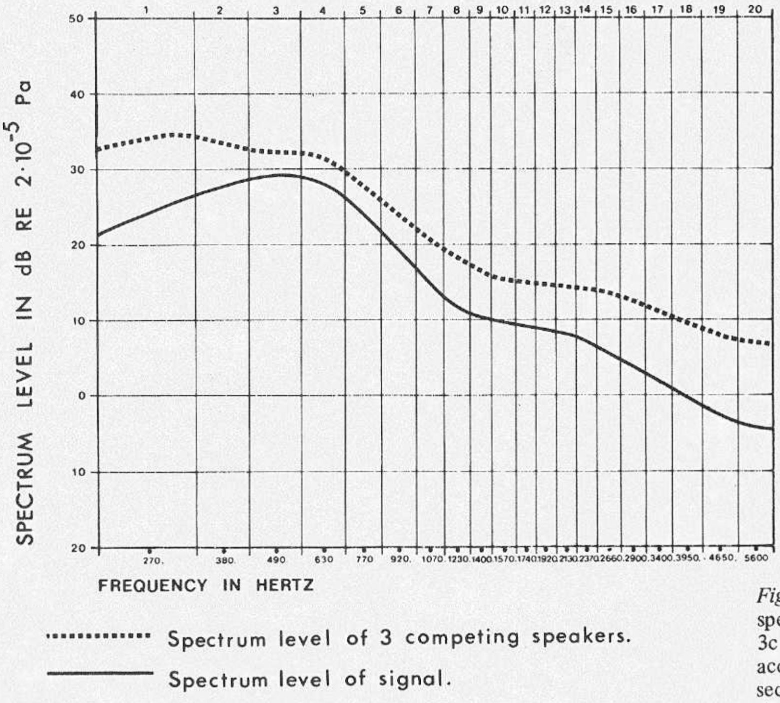


Fig. 3. Speech and competing speech spectrum levels in listening situation 3c (Signal + 3 competing speakers) accounted for in section B. In section A the level of the speech signal and each of the competing speakers were 5 dB(C) higher. French & Steinberg's (1947) division of speech spectrum in 20 bands is shown. (See also chapter 5).

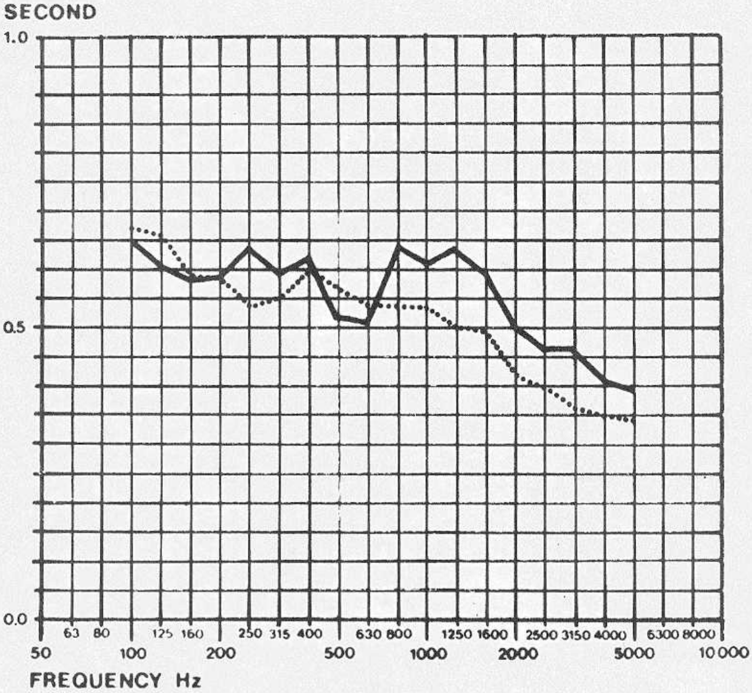


Fig. 4. Reverberation time in seconds as function of frequency.

——— For the recordings accounted for under A.

. . . . . For the recordings accounted for under B.

Difference between curves due to change in disposition of furniture from one recording time to another.

speakers were authentic and only the speech test was presented via the artificial speaker.

The speech signals used at all recordings were 65 dB(C). The competing male radio voice had the same level as the test signal. As a disturbing noise in the situation 1 and 2 an artificial community noise was used, i.e. a broad band noise with a spectrum declining 5 dB per octave. It was presented via a loudspeaker, placed about 1 m *outside* a closed window.

In the recording situation 1 and 2 the distance between listener and speaker was 3.5 m and between the listener and the competing radio voice 3.5 m. In situation 3 the only source of disturbance was the competing male speakers reading newspaper text. The distance between the loudspeaker and the listener was 1 m, as was the distance between the listener and each of the competing speakers. The level of the voice of each competing speaker was about 65 dB(C) each, measured at a distance of 1 m from the speaker. To facilitate maintenance of a steady level of the voice each speaker had a sound level meter before him. All sound levels given refer to measurement at the site of the artificial head.

Procedure

The principle of comparison was as follows: The test person's capacity to discriminate speech by listening directly in the room with both ears on a monosyllabic list of 50 words was first determined during each of the situations 1, 2 and 3. Second the test subject was replaced by the artificial head and recordings were made of the very situation that was tested. The same word material was used, i.e. the same list was used twice. Third the recordings were presented two weeks later to the same test subjects via binaural ear-phones. The individual results of the two test sessions were compared. The recordings via the artificial head in situation 1 and 2 were performed in the absence of the experimental persons, while in situation 3 the recording was made at the same time as the direct listening was going on. The artificial head was then hanging immediately over the head of the listener.

The recordings from the situations 1, 2 and 3 were presented via head-phones, of the same type as used by Nordlund, Kihlman and Lindblad (1968), to 6 normal hearing subjects in a quiet room at the Audiological department. They were

Table 1. Individual results of six normal hearing students listening to Pb-words in three different every-day listening situations in direct listening and via binaural ear-phones.

1. $S/N = -10$ *dB*

Direct listening	Ear-phones	Difference
78 %	78 %	0 %
96 %	88 %	−8 %
70 %	72 %	+2 %
82 %	78 %	−4 %
80 %	80 %	0 %
82 %	88 %	+6 %

No significant difference
at the 5 % level

2. $S/N = -10$ *dB + radio*

Direct listening	Ear-phones	Difference
56 %	64 %	+ 8 %
78 %	64 %	−14 %
64 %	60 %	− 4 %
66 %	58 %	− 8 %
68 %	68 %	0 %
68 %	70 %	+ 2 %

No significant difference
at the 5 % level

3. Signal + 3 competing speakers

Direct listening	Ear-phones	Difference
60 %	68 %	+ 8 %
40 %	68 %	+28 %
68 %	66 %	− 2 %
52 %	60 %	+ 8 %
62 %	70 %	+ 8 %
52 %	68 %	+16 %

Significant difference
at the 5 % level

listened to at the same level as during the recording.

The test subjects gave their answers in writing. All written answers were examined by one person.

Results

Direct listening and listening via binaural ear-phones to recordings made in the same listening situations were compared in the 6 normal hearing students.

The situations 1 and 2 showed no significant difference between the two listening methods.

In 3 a significant difference was found: the number of errors in direct listening was significantly larger than that with ear-phones (see table 1).

The results show that for persons with normal hearing, good agreement existed between direct listening and listening via ear-phones concerning speech in broad band noise and speech in broad band noise plus competing radio voice. In the situation with 3 competing speakers, on the other hand, better results were achieved when listening via ear-phones.

Discussion

The experiments with listening via ear-phones were carried out two weeks after those with direct listening and with the same lists of words. A certain effect of learning cannot be excluded. This effect, however, seems less likely because the test subjects had, in the meantime, taken part in other speech tests and listened to other lists with monosyllabic words of the same type that had been used. This circumstance is considered to reduce the effect of practice and memory (Stuckey 1963).

In contrast to ear-phone listening to recordings, the direct listening gives the test person a chance to turn his head to find the best listening position. In all the direct listening situations the speech signal reached the head at an azimuth of 0°. This means that the head position was nearly as good as possible, which explains why this factor obviously did not influence the results in the direct listening.

The reason given by the test subjects for the better results achieved with ear-phones in situation 3 was that they could concentrate much better when they were not distracted by the presence of the 3 disturbing speakers.

Our results agree with the findings by Nordlund, Kihlman and Lindblad (1968). They found 4–10 % higher scores in the tests achieved by listening via the artificial head compared with direct listening.

Conclusion

Binaural ear-phone listening gives an equally good or somewhat better result than direct listening.

Summary

In experiments performed on 6 students with normal hearing, two listening methods were compared with respect to intelligibility of Pb-words. The methods used were:

1) Direct listening without speech-reading.

2) Listening, via binaural ear-phone, to the same verbal material in the same listening situation as in the first test. The recording was made via an artificial head with one channel for each ear (microphone).

It was found that direct listening and binaural listening via ear-phones gave equal results in "traffic noise" with and without a competing radio voice. In the situation with three competing speakers, listening via ear-phones gave somewhat better results than in the direct listening situation.

B. Speech discrimination in every-day listening situations by normals and persons with high frequency hearing loss

This section concerns speech discrimination by normal hearing subjects and by persons with bilateral high frequency loss of hearing. The speech tests are performed in silence and in 7 different every-day listening situations. Normals and persons with different degrees of hearing loss are also compared in the different listening situations. The effect of bilateral and unilateral loss of hearing at 3000 Hz on speech discrimination in different listening situations is compared as well. Finally an assessment is made of the vocabulary capacity of the subjects.

Subjects

Only persons whose native language was Swedish were accepted in the investigation. The material consisted of 63 men, 22 normals and 41 with bilateral sensorineural loss.

The controls N (22 persons aged 28–49 years) had a hearing acuity of 20 dB or better (re ISO 1964) at 250, 500, 1000, 2000, 3000, 4000 Hz and 25 dB or better at 6000 and 8000 Hz, according to the tone audiogram.

All of the controls were employed at AB Volvo motor-car factory. They had the privilege of being routinely examined tone-audiometrically at certain intervals.

As stated in the introduction it was of special interest to examine persons with bilateral normal hearing up to 2000 Hz and 3000 Hz, respectively, but with considerable symmetric loss at higher frequencies. The test subjects were therefore selected as follows: Copies of audiograms of men below 50 years with high frequency losses were obtained from the department of Audiology, Sahlgren's Hospital, the outpatient clinics, AB Volvo and AB Götaverken, Göteborg. The audiograms were analysed and grouped in classes as below. Subjects satisfying above mentioned hearing criteria were invited to take part in the investigation. After otological investigation of the subjects' ears and after the tone audiogram had been taken, the test subjects with sensorineural hearing losses were grouped into the following classes according to the degree of high frequency loss.

L 4000: (Loss 4000 Hz). Bilateral sensorineural loss of 50 dB or more at 4000 and 6000 Hz and normal hearing (≤20 dB re ISO, 1964) at 3000 Hz and below (6 persons, aged 24–46 years).

L 3000: (Loss 3000 Hz). Bilateral sensorineural loss of 50 dB or more at 3000, 4000, 6000 Hz and normal bilateral hearing (≤20 dB re ISO, 1964) at 2000 Hz and below (22 persons, aged 25–49 years).

LU 3000: (Loss, unilateral, 3000 Hz). Unilateral sensorineural loss of 50 dB or more at 3000 Hz and at most 35 dB sensorineural loss at 3000 Hz on the other ear. Bilateral sensorineural loss of 50 dB or more at 4000 and 6000 Hz. Normal hearing (≤20 dB re ISO, 1964) bilaterally at 2000 Hz and below (7 persons, aged 35–46 years).

L 2000: (Loss 2000 Hz). Bilateral sensorineural loss of 50 dB or more at 2000 Hz and above and normal hearing (≤20 dB re ISO, 1964) bilaterally at 1000 Hz and below (6 persons aged 31–42 years).

None of the test subjects with hearing loss was above 49 years or below 24 years.

All together some 10 persons, both with and without loss of hearing, had such difficulty in giving written answers to the speech discrimination test in silence that they were not included in the above mentioned groups.

Of the normal group (N) 7 persons had been exposed to an ambient noise level of about 75–80 dB(A) during working hours. They did not use ear-plugs. Their tone audiograms and speech tests in silence were completely normal although they were taken after they had been working for 1–5 hours. The other controls were working in a less noisy environment.

None of the test subjects in the group L 4000, L 3000, LU 3000 and L 2000, whose tone audiograms and speech tests in silence had not been taken immediately before the other tests, had been working in an ambient noise of more than 67–72 dB(A) on the day of the examination.

Among those in the above groups whose tests in quiet were performed immediately before the other tests, a few had been working without ear-plugs at unknown ambient noise levels with only a few hours pause before being tested.

All the test persons were questioned regarding earlier exposure to noise and subjective impairment of hearing. At none of the examinations did any report that their hearing was worse than usual.

There was anamnestic evidence that the impairment of hearing in the 41 persons with sensorineural losses had been caused by exposure to noise in all cases.

Several probable causes of impairment of hearing were revealed, the most common of which were: work at a ship-building yard, civil and/or military rifle practice without the use of ear-plugs, military training in the artillery, work in the engine room of ships, work at saw mills, work with motor-saws, work as tinsmiths, work in industrial workshops and in the building trade.

2 persons whose sensorineural loss had been observed early in life and is possibly congenital, were excluded from the investigation. Their results, however, did not differ from those of the test persons with the same loss.

Methods and technical data

Recordings were made of 7 different simulated every-day listening situations in the living-room of a 3-room flat. The room and the equipment for simulating the listening situations and for recording and presenting the tests are the same as described in Methods under A. The arrangements of listener, artificial speaker, competing radio voice, competing speakers and loudspeaker for noise are shown in fig. 1. The measured reverberation time was about 0.5 sec. (Fig. 4).

The following listening situations were recorded:

1a. Signal/noise = 0 dB
1b. Signal/noise = −10 dB
2a. Signal/noise = 0 dB + competing radio voice
2b. Signal/noise = −10 dB + competing radio voice

Distance between artificial speaker and listener 3 m

3a. Signal + 1 competing speaker
3b. Signal + 2 competing speakers
3c. Signal + 3 competing speakers

Distance between all speakers (including signal) and listener 1 m

Speech signal, noise and competing radio voice were presented via separate loudspeakers. In the situations 3a, b, c, however, the competing speakers were authentic and only the speech signal was presented via a loudspeaker (artificial speaker). The speech signals were made up of seven different lists of phonetically balanced monosyllables of the same type as described in Methods under A. Speech signals, competing radio voice and authentic competing speakers had a level of 60 dB(C). The male competing speakers read newspaper text. The same broad band noise as described under A was used. Concerning the spectrum levels of the speech signal, noise and 3 competing speakers, see fig. 2 and 3.

All of the sound levels given refer to measurements at the site of the artificial head.

The levels of the noise during the listening situations 1a–b and 2a–b were 60 and 70 dB(C) which corresponded to 44 and 54 dB(A), as determined from simultaneous measurements. According to *Samhällsplanering och vägtrafikbuller* (1972), on town planning and road traffic noise, one should add 20 dB(A) in the appraisal of the corresponding outdoor noise levels, which holds for Swedish standard windows. Newly built houses, however, now often have special windows which damp the noise a further 5 dB(A).

In the experiments then, the indoor noise levels correspond to the following outdoor traffic noise. The values for houses with modern special windows are given within brackets.

Indoors levels		Outdoor levels
dB(C)	dB(A)	dB(A)
60	44	64 (69)
70	54	74 (79)

The recordings were presented binaurally with the same sound pressure level as when recorded.

Discrimination tests in quiet and in every-day listening situations were performed with phonetically balanced word lists. They were presented binaurally via ear-phones at the level of 60 dB(C) measured with a sound level meter set at slow.

In order to get a quick but fairly good estimation of the investigated persons' vocabulary, a psychological test devised by Dureman & Sälde (1959) was used. It is a part of a test-battery for measuring verbal understanding. The task is to choose the right synonym to a given word out of five alternatives. All together 30 words are given. The number of wrong answers is counted.

Procedure

The recordings were presented in two different rooms, both free from any notable noise from outdoors. They were small conference rooms without windows and with a background noise level of less than 25 dB(A), situated in AB Volvo's office building, Torslanda, Göteborg, and Sahlgren's Hospital, Göteborg. When the recordings were presented the sound levels were the same as those prevailing during their recording. Groups of 3–10 subjects listened binaurally with ear-phones to the recordings from the listening situations 1–3. Half a list of words (25 words) was used as a practice list preceding the real tests.

The answer was given in writing. Misspellings were ignored in the evaluation of the answers given.

The test subjects were also examined regarding their vocabulary level.

All of the controls and more than two thirds of the persons with loss of hearing were examined with tone audiometry and binaural discrimination of speech in quiet a few days before the group test. The remaining subjects with loss of hearing went through these two tests immediately before the group test.

The group test was performed either at 1,4 or 7 p.m. Both the controls and the subjects with impaired hearing were roughly equally distributed among the 3 times of the day. The group test was performed according to a special schedule.

Results

Quiet environment

All of the test subjects were examined for binaural speech discrimination in quiet. The results in the control group N and in the test subjects in the groups L 4000, L 3000 and L 2000 were analysed. The results of these group tests are given in fig. 5 and table 2 as mean discrimination scores. Fig. 5 and table 2 show that the normal hearing control group and the subjects with high frequency losses except group L 2000 discriminated more than 84 % of the monosyllabic words in quiet. The group L 2000 achieved a mean value of 61 %. Significant differences at the 5 % level were nevertheless found between the groups: N and L 4000 (6 % [4–12]), N and L 3000 (10 % [8–12]) and L 4000 and L 3000 (6 % [2–8]). (See table 3.)

The confidence invervals show that in individual cases the difference between a normal and a person in the last mentioned groups is only a few per cent.

Thus, even in the presence of a significant difference between a *group* of normals and a *group* of test subjects with sensorineural loss at frequencies above 2000 Hz, *a speech discrimination test in a quiet environment often shows only a very small reduction in discrimination ability in individual persons with high frequency hearing loss.*

Every-day listening situations

All 63 subjects (22 controls and 41 with impairment of hearing) listened to 7 lists of 50 monosyllables each in the seven different every-day listening situations described. The hard-of-hearing persons were divided into groups of 3–10. The discrimination scores of the normals and the different groups with high frequency losses are given in fig. 5 and table 2. The mean percentage of correct answers and the 95 % confidence intervals are also given.

In a comparison between the normals (N) and the group L 4000 in listening situation 1a (S/N = 0 dB) there was only a small difference in discrimination. In the two most difficult situations 2b and 3c (S/N = –10 dB + radio and signal + 3 competing speakers) the normals had a mean score of 63 % and 62 % while the group L 4000 had 53 % and 49 % respectively.

Table 2. Mean discrimination scores in per cent for 22 normal hearing subjects and 34 persons with symmetric bilateral high frequency losses in quiet and in seven different every-day listening situations. The 95 % confidence interval in parenthesis.

	n			Listening situations		
		Quiet	S/N = 0 dB (1a)	S/N = −10 dB (1b)	S/N = 0 dB + radio (2a)	S/N = −10 dB + radio (2b)
N	22	**97** (97–98)	**89** (87–92)	**69** (66–72)	**72** (68–76)	**63** (60–66)
L 4000	6	**90** (84–95)	**81** (75–87)	**55** (46–65)	**57** (51–62)	**53** (42–62)
L 3000	22	**88** (85–90)	**62** (58–65)	**38** (34–42)	**33** (29–38)	**20** (18–23)
L 2000	6	**61** (45–73)	**24** (13–32)	**7** (4–11)	**6** (2– 9)	**6** (2– 8)

	n		Listening situations		
		Signal + 1 competing speaker (3a)	Signal + 2 competing speakers (3b)	Signal + 3 competing speakers (3c)	Mean of 7 tests
N	22	**76** (73–79)	**72** (69–74)	**62** (60–65)	**72** (70–74)
L 4000	6	**61** (57–68)	**60** (56–66)	**49** (44–53)	**60** (55–64)
L 3000	22	**43** (38–49)	**38** (34–44)	**26** (24–29)	**37** (34–40)
L 2000	6	**14** (8–17)	**8** (6–12)	**5** (1– 8)	**10** (7–12)

Comparisons between N and L 3000 in the easiest listening situation 1a (S/N = 0 dB) showed that the group N had a discrimination score of 89 %, while the group L 3000 had only 62 %. In the two most difficult listening situations 2b and 3c (S/N = −10 dB + radio and signal + 3 competing speakers) the normals (N) had a mean value of 63 % and 62 % but the group L 3000 reached only a mean value of 20 % and 26 % respectively.

In fig. 5 and table 2 the total number of correct answers in all 7 tests have been added, i.e. 350 words. The results showed that the normal group for all test situations had a mean score of 72 %. The group L 3000 did not accomplish more than 37 % correct answers. The corresponding figure for L 4000 was 60 %.

A closer analysis of table 2 shows listening in every-day listening situations of increasing difficulty to imply an increasing loss of discrimination from 97 % to 72 % for normals. The corresponding values in the three groups of high frequency losses are:

L 4000 from 90 % to 60 %
L 3000 from 88 % to 37 %
L 2000 from 61 % to 10 %

In order to further elucidate the differences between the different groups in the various every-day listening situations, the mean difference in percentage of correct answers between the groups below were determined:

N and L 4000
N and L 3000
N and L 2000
L 4000 and L 3000
L 4000 and L 2000
L 3000 and L 2000

The resulting mean differences in percentage are given in table 3 with the 95 % confidence interval.

The differences among all groups mentioned above were significant at the 5 % level for all 7 listening situations and the total number of answers of all seven tests.

It is clear from table 3 that the difference between the normals (N) and the group L 4000 varied between 8 and 16 % in the different listening situations. The difference in the number of correct answers in the 7 tests (350 words) was 13 %.

Table 3 shows also that the difference between N and L 3000 varied from 28 to 43 %. The difference in the total number of correct answers in the 7 tests was 35 %.

On comparison between normals (N) and L 2000 differences of 58 to 68 % were found between the various listening situations. The total

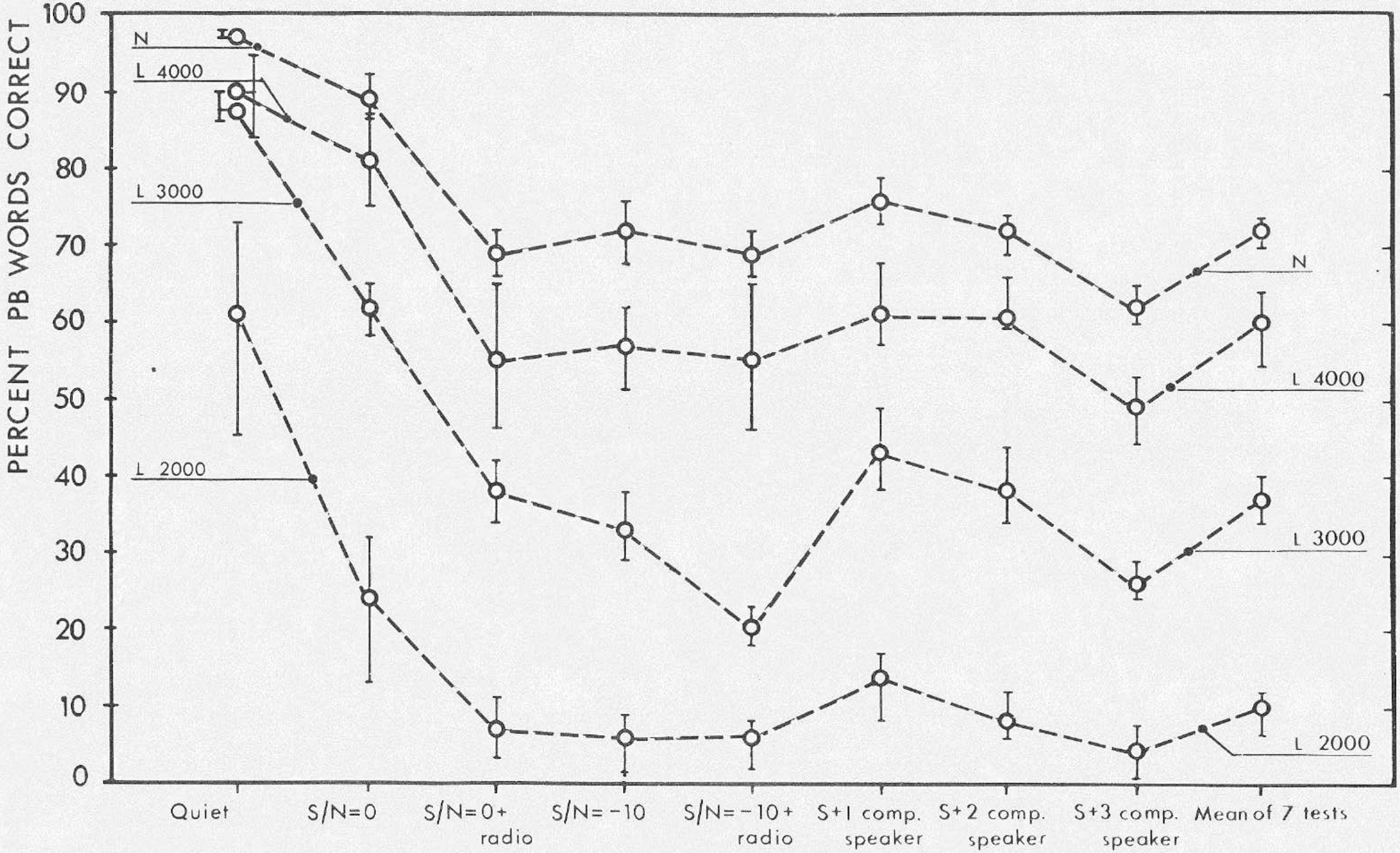


Fig. 5. Per cent correctly understood Pb-words (mean and 95 % confidence interval) for the groups: N, L 4000, L 3000 and L 2000. The results of each group in the various tests and the mean of the seven every-day listening situations is connected with a curve marked ––––

Table 3. Differences in percentage of correct understood Pb-words between groups below in different listening situations and in the sum of the seven tests. Mean and confidence interval (95 % confidence level).

	n	Listening situations				
		Quiet	S/N = 0 dB (1a)	S/N = 10 dB (1b)	S/N = 0 dB + radio (2a)	S/N = −10 dB + radio (2b)
N – L 4000	22– 6	**6** (4–12)	**8** (4–14)	**16** (8–24)	**16** (8–24)	**10** (4–18)
N – L 3000	22–22	**10** (8–12)	**28** (24–32)	**43** (38–46)	**38** (34–44)	**43** (38–46)
N – L 2000	22– 6	**33** (26–46)	**65** (58–74)	**58** (54–62)	**68** (60–74)	**58** (54–62)
L 4000 – L 3000	6–22	**6** (2– 8)	**19** (12–26)	**18** (8–26)	**24** (16–32)	**32** (24–40)
L 4000 – L 2000	6– 6	**26** (16–46)	**57** (48–68)	**49** (38–58)	**52** (44–58)	**48** (35–58)
L 3000 – L 2000	22– 6	**24** (16–38)	**38** (30–46)	**31** (24–36)	**28** (18–36)	**16** (12–20)

	n	Listening situations			
		Signal + 1 competing speaker (3a)	Signal + 2 competing speakers (3b)	Signal + 3 competing speakers (3c)	Difference in mean of 7 tests (350 words)
N – L 4000	22– 6	**16** (8–20)	**12** (6–16)	**14** (8–18)	**13** (9–17)
N – L 3000	22–22	**32** (28–38)	**32** (26–38)	**36** (32–40)	**35** (31–38)
N – L 2000	22– 6	**62** (58–68)	**62** (58–68)	**59** (54–63)	**63** (59–65)
L 4000 – L 3000	6–22	**18** (10–26)	**22** (12–30)	**22** (18–28)	**22** (16–28)
L 4000 – L 2000	6– 6	**48** (42–54)	**51** (48–58)	**45** (40–49)	**50** (45–54)
L 3000 – L 2000	22– 6	**30** (22–38)	**30** (22–40)	**23** (17–28)	**27** (23–33)

difference in the number of correct answers in 7 tests was 63 % (see table 3).

It is apparent from table 3 that there are considerable differences between the group with well preserved binaural hearing at the frequency of 3000 Hz (L 4000) and the groups with severe binaural loss of hearing at 3000 Hz (L 3000). The difference ranged between 18 and 32 %. The difference in the number of correct answers of the 7 tests was 22 %.

Comparison between L 4000 and L 2000 showed differences of 45 to 57 %. The difference in the number of correct answers in 7 tests was 50 % (table 3).

Table 3 shows that the difference between the group with sensorineural loss at 3000 Hz and above (L 3000) and the group L 2000 was 16–38 %. The total difference in the number of correct answers in 7 tests was 27 %.

Summing up, the examinations of speech discrimination in these every-day listening situations revealed that groups with bilateral sensorineural loss of 50 dB or more at frequencies of 4000 and 3000 Hz respectively and above (L 4000 and L 3000 respectively), showed a poorer discrimination of speech (13 % and 35 % less respectively) than normals in such listening situations. The group with bilateral sensorineural loss of 50 dB or more at 2000 Hz and above showed 63 % poorer discrimination than normals.

The significance of adding one competing voice to speech signal in a background of broad band noise

Addition of one competing voice in an already difficult listening situation reduces speech discrimination. To find out whether this reduction is equally large for normals as for persons with hearing loss, comparisons were made between N and L 4000 and between N and L 3000. The listening situations 1a–2a and 1b–2b were studied:

S/N = 0 dB without and with radiovoice
S/N = −10 dB without and with radiovoice

The results achieved in the groups are given in table 4.

The intervals for differences between the two listening situations S/N = 0 dB without and with radio voice were figured out in each group. There was a significant difference in size of the differences at the 5 % level between the groups N and L 3000. According to the same method of calcula-

Table 4. Difference in per cent of speech intelligibility in listening situations without and with competing radio voice. Means and 95 % confidence intervals are given.

Discrimination differences between listening situations:

	n	S/N = 0 dB and S/N = 0 dB + radio	S/N = −10 dB and S/N = −10 dB + radio
N	22	**16** (12–20)	**6** (4–10)
L 4000	6	**24** (16–32)	**10** (2–16)
L 3000	22	**28** (22–34)	**18** (12–22)

tion, no significant difference was found between N and L 4000.

Significant difference at the 5 % level in listening situations S/N = −10 dB without and with radio voice was found in the size of the difference between the groups N and L 3000.

No significant difference at the 5 % level was found in the size of the difference between N and L 4000.

The results thus show that in the listening situations S/N = 0 dB and S/N = −10 dB the groups with 50 dB loss of hearing bilaterally at 3000 Hz and above (L 3000) were significantly more disturbed than normals by a competing radio voice. The group with preserved hearing bilaterally at 3000 Hz, but with loss of hearing of 50 dB at 4000 Hz and above (L 4000), on the other hand, was not disturbed significantly more than normals in these two listening situations.

The significance of monaural and binaural sensorineural loss at 3000 Hz

To appraise the significance of preserved hearing at 3000 Hz in one ear a group of 7 persons (LU 3000) with good hearing in only one ear at 3000 Hz and about 50 dB reduction bilaterally at 4000 Hz and 6000 Hz was selected. The results in this group were compared with those of the groups L 4000 and L 3000 both having at least 50 dB hearing loss at 4000 and 3000 Hz respectively. The performances by these three groups in S/N = −10 dB and in the situation with 3 competing speakers were investigated.

Table 5. Mean discrimination in per cent for different groups of high frequency losses in two different listening situations: S/N = −10 dB and signal + 3 competing speakers.

	n	S/N = −10 dB	S + 3 competing speakers
L 4000	6	**55** (46–65)	**49** (44–53)
LU 3000	7	**54** (51–59)	**35** (28–38)
L 3000	22	**38** (34–42)	**26** (24–29)

Table 5 shows that the results achieved by LU 3000 and L 4000 in the listening situation S/N = −10 dB were in good agreement. But this was not the case for the situation signal + 3 competing speakers (see table 5), where all of those in group LU 3000 were below the lowest score for L 4000. In the situation with signal + 3 competing speakers the group LU 3000 lay roughly midway between L 4000 and L 3000.

The above comparisons indicate that in a listening situation with broad band noise, speech discrimination is good if hearing at 3000 Hz is preserved on one ear. This is, however, not the case in a listening situation like that with signal + 3 competing speakers. In this latter listening situation the group LU 3000 had a relatively greater loss in intelligibility than L 3000 and L 4000.

Influence of vocabulary level on speech discrimination

To find out whether the vocabulary level of the subject has any effect on speech discrimination, all the test subjects except those in group L 2000 were examined with a vocabulary test. Table 6 shows the sum (mean and confidence interval) of wrong answers in the normal and hard-of-hearing groups. The following groups were compared:

N with L 4000
N with L 3000 and
L 4000 with L 3000.

No significant difference at the 5 % level was found in any of the cases. The difference between the results achieved in the different groups (with

Table 6. Mean and 95 % confidence interval of sum of wrong answers in vocabulary test devised by Dureman & Sälde (1959).

	n	Sum of wrong answers
N	22	**7** (5–11)
L 4000	6	**11,5** (6–18,5)
L 3000	22	**7,5** (5–10)

the exception for L 2000 whose vocabulary level was not investigated) in the 7 every-day listening situations can thus not be ascribed to any difference in the vocabulary level of the groups.

Discussion

At present Sweden has no laws prohibiting noise above a certain level. For recreation areas near houses, i.e. playgrounds, gardens, parks and the like, in new and unexploited areas a maximum value of 55 dB(A) outdoors as equivalent noise level during day-time has been proposed by a state agency *(Samhällsplanering och Vägtrafikbuller* 1972.) The highest noise level used in the present investigation was 54 dB(A) (indoor value). The mentioned publication also specifies the maximum equivalent noise level during day-time indoors with the windows closed. It is set at a level of 35 dB(A). This is a rather stringent level and applies to houses in new building areas. But the real noise levels in built-up areas are much higher. In many cases, e.g. along busy city streets the equivalent level during day-time indoors with closed windows is 50–55 dB(A).

It might also be mentioned that when new houses with ordinary windows are planned for a maximum noise level of 35 dB(A) indoors the noise level may rise to 45 dB(A) when the window is opened. If the house fills the requirements by the use of special windows, the indoor level when the window is opened may rise to anything up to 55 dB(A) even in a new house in a new building area.

The levels studied in the investigation may thus occur also in new-built-up areas with windows open as well as closed.

It is probable that an educated and intelligent person will understand speech in difficult listening situations better than one who is less gifted. Therefore this factor may influence the results of the speech discrimination tests a certain amount. The vocabulary test measures the person's vocabulary capacity and reduction indicates a positive correlation to unexpectedly low discrimination score values. The vocabulary test is included among several other tests in a so-called intelligence test. It reflects more or less the test subject's level of education. Comparison between the scores achieved by the different groups of test subjects in this investigation showed no significant differences between them. In addition, tests with common monosyllabic words ought to be less correlated with the test person's language background than more redundant tests, e.g. sentences. Thus it might be assumed that the results of the different tests were a relatively good measure of the test subjects' ability to hear speech independently of their level of education, power of association, and ability to draw conclusions.

According to Lovrinic et al. (1968), tests with written answers may be useful but cannot be used on all persons. We also experienced this. Moreover a written test appears to give a somewhat lower average percentage of right answers which Lovrinic et al. ascribed to the fact that oral answers are more often erroneously regarded as correct than are written answers.

Certain differences in the ability of the test subjects to give written answers in speech discrimination tests must, however, be expected. Assuming that the ability to write usually varies with the person's vocabulary and level of education, this ability should be fairly well reflected in the results of the vocabulary test. As no significant difference could be found between different groups in this test, one may draw the conclusion that there is no notable difference in writing ability between the groups either.

All the normals and about two thirds of the test subjects with loss of hearing were examined with tone audiograms and speech discrimination tests in quiet, one or a few days before the speech discrimination tests in every-day listening situations. The others underwent the same tests in uninterrupted succession. It could thus be suspected that a temporary threshold shift smaller or greater on the two examination days might have influenced the results achieved by most of the test subjects.

According to findings in Kylin's investigations (1959 and 1960), which have been confirmed by Glorig et al. (1961) a temporary threshold shift does not occur in the presence of noise below 75 dB(A), and is negligible below 80 dB(A).

The majority of the test persons, i.e. all the controls and two thirds of those with impairment of hearing, were working at AB Volvo. According to the measurements, made by the company's technicians, in those parts of the factory where these persons were employed, the noise levels for the vast majority of them lay below that capable of causing a temporary threshold shift.

Of those with normal hearing, 15 were exposed to a noise level below 75 dB(A) during working hours. The remaining 7 with intact hearing were exposed to an occupational noise level of 75–80 dB(A) and did not use ear-plugs. The tone audiograms of these 7, who were normal, had been taken after 1–5 hours' work.

Of those with loss of hearing, all in groups L 4000, L 3000, LU 3000 and L 2000, were exposed in their occupation to noise levels below 75 dB(A) or had been examined with tone audiometry immediately before the other tests.

Thus it appears probable that a temporary threshold shift, if any, could not affect the correlation between the tone audiograms and the other tests.

Less than one third of the persons with impaired hearing had their hearing measured with audiometry in the Audiological department of Göteborg. These audiograms are taken during optimal conditions which may not be the case in health check-ups.

There is, however, no evidence that this first mentioned group of patients in any crucial way differed from the main part of the test persons. Most of these so-called patients were people who had requested audiometry examination for occupational or professional reasons.

A more precise method telling where the high-tone loss begins is Békésy-audiometry. With such a method there would have been a possibility to group the sensorineural losses more exactly compared with the "crude" tone audiogram. Unfortunately Békésy-audiometers were not available for this investigation.

Speech discrimination tests in quiet revealed only small differences between the normals (N) and the group with sensorineural loss at 3000 Hz and above (L 3000). On the other hand, we found large differences in speech intelligibility between these groups in the 7 every-day listening situations.

Thus a loss of hearing of 50 dB or more bilaterally at 3000 Hz and above implies a considerable impairment of perception of phonetically balanced monosyllables in every-day listening situations.

As will later be apparent (in chapter 5) the articulation index (AI) is a means of predicting the difficulty of the listening situation for persons with normal hearing. If it is assumed that AI also can reflect the increase in difficulty in the same listening situation that a loss of hearing gives, the AI in a given listening situation will vary with the hearing loss. It is assumed that the relation between the perception of sentences and monosyllables in fig. 6, which holds for the English language, is valid also for Swedish (Lidén & Fant, 1954). This means that a certain degree of intelligibility of Pb-words in a given listening situation corresponds to a certain percentage of intelligibility of sentences. It is thus possible to calculate the intelligibility of sentences instead of phonetically balanced monosyllables in the 7 every-day listening situations studied. This might be of interest because conversation seldom consists of single monosyllabic words. The intelligibility of

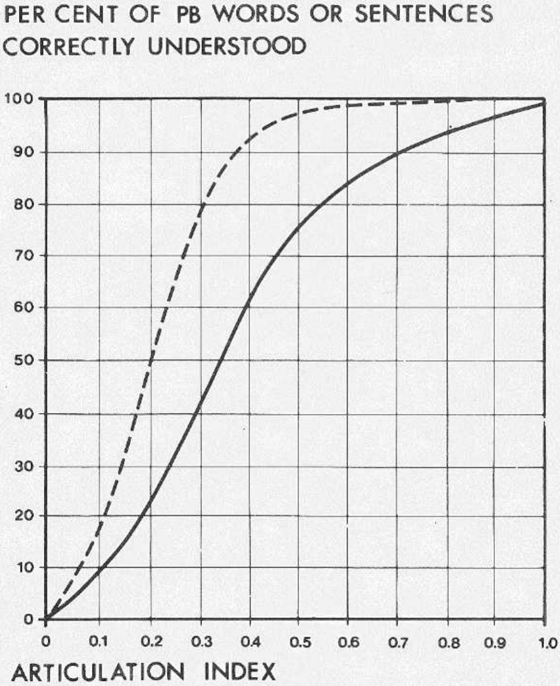


Fig. 6. Relation between articulation index and two different English measures of speech intelligibility investigated on normal hearing persons.

– – – – Sentences
———— 1,000 Pb-words (test vocabulary limited to 1,000 words)

From American National Standard, methods for the calculation of the articulation index. 1969.

every-day speech is considerably higher than what tests with phonetically balanced monosyllables indicate.

The listening situation S/N = 0 dB + competing radio voice simulates a fairly normal background noise + 1 competing voice in a room with a closed window facing the street in the centre of a town or facing a main traffic street. In this situation (2a) the group with normal hearing up to 2000 Hz and a loss of 50 dB at 3000 Hz and above (L 3000) scored 33 % intelligibility of monosyllables, while the corresponding figure for the normals was 72 %.

Assuming that these percentages of monosyllables can be converted to intelligibility of sentences according to fig. 6, persons with a loss of hearing of 50 dB or more bilaterally at 3000 Hz and above and with unimpaired hearing up to 2000 Hz (L 3000) will only understand 70 % of a conversation consisting of sentences in this situation. The corresponding figures for the normals will be 95 %. In other words, persons with normal hearing up to 2000 Hz, but with a loss of 50 dB or more bilaterally at higher frequencies will not understand one third of a conversation consisting of sentences spoken in a very common every-day listening situation, while normals will miss only 1 sentence out of 20.

In the situation with one speaker and 3 competing voices (3c) the group L 3000 heard and understood 26 % of monosyllables, while the normals understood 62 %. If, as above, we assume a correlation between sentences and monosyllables as illustrated in fig. 6, it will be obvious that a person belonging to the group L 3000 (so-called mild noise-induced hearing loss) will feel severely handicapped in such a situation. In this very common every-day situation he will understand only about every other sentence (55 %), while normals will understand 19 (95 %) out of 20 sentences.

Miller, Heise and Lichten (1951) have shown the effect of the sentence content upon the articulation scores for words in isolation. The relation is valid for normals and English (fig. 7). If we use these curves for our comparisons between intelligibility of monosyllables and sentences we will reach about the same results as with the AI-curves.

When comparing discrimination of speech between two groups in listening situations with and without a competing radio voice, it should be borne in mind that the lists used in the present investigation have not been proven to be equally difficult to understand when listened to in the presence of disturbing noise. But if it be assumed that the difference in difficulty between two lists is constant in the same listening situation, it will be possible for instance to ascertain whether the addition of a competing voice will disturb normals and persons with impairment of hearing to the same effect or not.

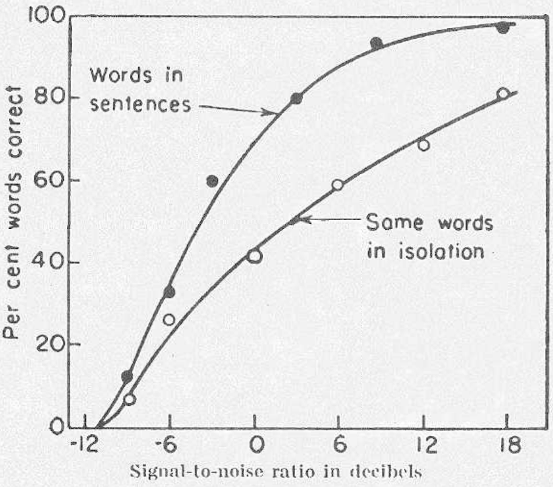


Fig. 7. Effect of the sentence content upon the articulation scores for words (From Miller, Heise and Lichten 1951).

Significant differences in the impairment in per cent correctly understood Pb-words, in the listening situation without and with one competing radio voice were seen between the normals and the group L 3000. Addition of a competing voice in an already difficult listening situation will thus lower speech discrimination by a person with preserved hearing up to 2000 Hz and a bilateral loss of 50 dB or more at higher frequencies, significantly more than that of a normally hearing person of the same age.

No such significant differences could be demonstrated between the normals and the group L 4000.

According to table 4 it is not unlikely, however, that there is a difference between these two groups. But on the basis of the small number of subjects in group L 4000 a small difference between L 4000 and N can not be proven to be significant.

The comparison made between a group with preserved hearing on one side at 3000 Hz (LU 3000) and the groups L 4000 and L 3000 (preserved hearing bilaterally up to 3000 Hz, and 2000 Hz respectively) showed that speech discrimination is correlated with the better ear in a listening situation with broad band noise, but is correlated with the worse ear in a listening situation like the one with signal + 3 competing speakers.

Here, however, a reservation must be made: at 3000 Hz only 6 of the 7 persons in group LU 3000 heard better with the right ear. In the listening situation with 3 competing speakers, 2 speakers disturbed hearing from the right side and 1 from the left. All the individual results, however, showed similar differences between the listening situation with broad band noise and the one with 3 competing speakers. Thus, it seems probable that the 3 competing speakers disturbed hearing to an equal extent on both sides. It therefore seems warranted to conclude that in calculation of correlations between tone audiograms and speech intelligibility in every-day listening situations, the evaluation of the better ear compared with that of the worse ear will vary with the listening situation.

The explanation for the worse results by the group LU 3000 in the listening situation with test signal and 3 competing voices is probably that speech intelligibility in such a listening situation is dependent on two good ears which can discriminate phase and amplitude differences from the different sound sources.

Concluding remarks

Comparison between the performance of normals and persons with high frequency hearing loss in more or less difficult listening situations have shown that the importance of high frequency loss up to now has been completely underestimated. The reason for this is the fact that speech discrimination has hitherto mostly been measured only in quiet. This is necessary for diagnostic purposes, but is hardly relevant and even misleading when used for assessing the degree of the daily hearing difficulties. Hitherto a clinical audiological test has not been available for the assessment of the social adequacy of the hearing handicapped in every-day listening situations. In this investigation the task has been to evaluate the pure auditory function in every-day listening situations. Thus a speech reading test has been excluded. The testmaterial in this investigation comprises 7 different every-day listening situations. This does not mean that all conceivable situations are covered. Tests convenient for clinical evaluation of every-day listening situations are suggested below.

Suggested clinical tests

The intelligibility of a speech test depends among other things upon psychological factors (see chapter 2). Particularly recordings with one competing voice as the only disturbance is probably partly a test of how easy the subject can avoid listening to the competing speech. Nevertheless, regarding the commoness of listening situations with one competing speaker, it can be justified to use such a test. On the other hand it appeared from the present investigation that all recordings used were suitable for testing speech discrimination in every-day listening situations.

For clinical purposes these tests should be used preferably in mild to slight noise-induced hearing losses. In such cases regular speech audiometry gives normal or close to normal discrimination scores, thus strongly contrasting to the patients' subjective feelings of hearing difficulties. The tests to be suggested should be sensitive enough to make a realistic evaluation of the patients' real hearing difficulties possible. From this viewpoint the following recordings are suggested to be used as a battery of tests: S/N = 0 dB, S/N = 0 dB + radio and signal + 2 competing speakers.

As shown by Klockhoff & Lidén (1974) the recordings last mentioned have already been found valuable in the clinical work. It should, however, be observed that the recommended tests are best suited for persons with impairments over 2000 Hz. Judging from the results in the group L 2000, lists of the type S/N = 0 dB should be used for examining persons with hearing loss at 2000 Hz and below, while the other tests might be too difficult.

Summary

The binaural intelligibility of Pb-words in quiet and in 7 simulated indoor every-day listening situations was tested on 41 persons with bilateral high tone loss and 22 normals. In every-day listening the group (L 3000) with bilateral sensorineural loss of 50 dB or more at 3000 Hz and above and normal hearing up to and including 2000 Hz scored 28–43 % less than normals. The corresponding figures for a group (L 4000) with bilateral normal hearing up to 3000 Hz and bilateral sensorineural losses of 50 dB or more at 4000 Hz and above was 8–16 %. In quiet there was a 6–10 % difference between normals and these hearing impaired groups.

Comparisons between the listening situations with and without one competing voice showed that the group L 3000 (see above) was disturbed significantly more than the normals in an already difficult listening situation, while no significant differences were found between the normals and L 4000.

Comparisons between the speech intelligibility in community noise and in a listening situation with three competing speakers showed that in a situation with community noise speech intelligibility was correlated mainly with the better ear according to the tone audiogram, while in listening situations with several competing voices the significance of binaural hearing was much greater.

The vocabulary level was appraised and comparisons showed no difference in this respect between the groups.

Based on the results of the present investigation three tests for clinical evaluation of speech intelligibility in every-day situations are suggested. These tests are primarily intended for persons with sensorineural loss above 2000 Hz.

Part II

CHAPTER 4

COMPARISON BETWEEN THE INTELLIGIBILITY OF LOW-PASS FILTERED SPEECH AND HIGH-PASS FILTERED SPEECH IN NOISE IN NORMAL HEARING SUBJECTS

As pointed out in chapter 3 B good speech discrimination in every-day listening situations requires good hearing ability up to 4000 Hz or, with less rigorous criteria, at least good bilateral hearing up to 3000 Hz. These results on hearing impaired persons agree well with Kuzňiarz's findings (1968). He found in observations on normals in white noise and in low frequency noise that filtered speech with cut-off frequencies above 2000 and 3000 Hz respectively resulted in a significant worsening of speech intelligibility compared with unfiltered speech. This difference was particularly clear in low frequency noise. No such difference could be demonstrated in silence.

A question that arises is: what is the significance of a given impairment of hearing above 2000 Hz on speech intelligibility, compared with that of a corresponding impairment below 2000 Hz?

As shown by French & Steinberg (1947), the intelligibility of nonsense syllables is equally good when all information given by the speech signal is filtered off above 1900 Hz as below 1900 Hz.

According to Hirsh (1952), the frequency range of 1500–2500 Hz is the most important for the intelligibility of English monosyllabic words. It is clear from the two latter investigations that presentation of speech to normals in quiet in differently filtered versions means that a loss at the frequencies below 500, 1000 and 1500 Hz, respectively, has the same effect on intelligibility as a loss at frequencies above 4000, 3000 and 2500 Hz, respectively.

If these results hold also for persons with impairment of hearing, listening to every-day speech, a severe loss from 500 Hz and below would imply just as large an impairment as a loss at 4000 Hz and above. In the same way a considerable hearing loss at 1000 Hz and below would have the same effect on intelligibility of speech as a considerable reduction at 3000 Hz and above.

To check this possibility we tried to find subjects with symmetric sensorineural losses at low frequencies in order to be able to compare their speech discrimination in every-day listening situations with subjects with symmetric sensorineural loss at higher frequencies. This proved unsuccessful.

Comparisons were therefore instead made between groups of normals listening to low-pass and high-pass filtered speech, in some of the listening situations described in chapter 3 B.

The investigation described in this chapter and some of those accounted for in chapter 3 B are in turn used as a basis for a theoretical calculation of the speech intelligibility in different listening situations described in chapter 5.

Subjects

The test subjects consisted of 66 male medical students with a tone threshold of 10 dB or better (re ISO, 1964) in the frequency range 125–8000 Hz. They were divided into 8 groups of 7–10 each. The groups were named according to the filter through which the signals were passed before they were recorded. The groups are given below:

Group Unfiltered	(8 persons)
Group LP (Low-pass) 3100	(9 persons)
Group LP 2300	(8 persons)
Group LP 1400	(7 persons)
Group HP (High-pass) 950	(8 persons)
Group HP 1500	(10 persons)
Group HP 2000	(8 persons)
Group HP 2600	(8 persons)

Technical data and equipment

The verbal material consisted of 3 lists of 50 monosyllabic phonetically balanced words per list. Of the 7 recordings in every-day listening situations used in chapter 3 B, three were selected viz. numbers 1a, 2a and 3c (S/N = 0 dB, S/N = 0 dB + competing radio voice and S + 3 competing speakers). These 3 recordings were re-recorded through the above mentioned 7 filters. The frequency curves were shaped with a Krohn-Hite filter type 3323 having a slope of 24 dB per octave. By recording the lists twice through the filter, the resulting slope/octave increased to 48 dB.

The speech material was presented to the normal test persons with the aid of a two-channel amplifier with a VU meter and attenuator for both channels. A distribution box for 10 pairs of ear-phones (Telephonic type TDH-MX 41 AR) was used.

Procedure

8 groups, each consisting of 7–10 male medical students, with normal binaural hearing according to the tone audiogram, listened to the above mentioned recordings 1a) S/N = 0 dB, 2a) S/N = 0 dB + radio voice and 3c) Signal + 3 competing speakers. The sound pressure levels of signal and noise were 60 dB(C) (before filtering). The competing radio voice and the voice of the competing speakers had a sound pressure level of 60 dB(C) (before filtering). As is apparent from the grouping of the subjects, one group was examined with unfiltered lists, while each of the remaining 7 groups listened to a filtered version. None of the test subjects took part in more than one group.

The recordings were listened to groupwise in a conference room with no window and with a noise level below 25 dB(A). The recordings were presented at the same sound pressure level as during recording. Binaural listening with ear-phones was used and the answers were given in writing. The test persons had their tone audiogram taken immediately before the group listening test.

Results

The results obtained in the 8 groups of students including one group listening to an unfiltered version, are given in table 7 and fig. 8, 9, 10.

In a comparison between groups LP 2300 and HP 1500 it was found that in the situation S/N = 0 dB, the means and the intervalls in both groups were very similar. In the situation S/N = 0 dB + competing radio voice, the loss of the high frequencies in a comparison between the same groups above gave a somewhat larger reduction in speech discrimination than did a loss of the low frequencies, but the difference was not significant at the 5 % level. In the situations S + 3 competing speakers, a loss of the lower frequencies showed a larger reduction, but the difference was not significant at the 5 % level.

In a comparison between LP 3100 and HP 950 the results obtained in the two groups in all 3 listening situations, agreed well and showed no significant difference at the 5 % level between the two groups in any of the listening situations.

The results thus show that the effect of filtering off frequencies above 2300 causes roughly the same reduction of speech discrimination as filtering off below 1500 Hz and filtering off above 3100 Hz has the same effect as filtering off below 950 Hz.

Table 7. Three recordings of Pb-words in every-day listening situations re-recorded through different filters and presented via binaural ear-phones to eight groups of students with normal hearing. The mean percentage of correct answers in the group and the confidence intervals (95 %) are given.

	S/N = 0 dB	S/N = 0 dB + radio voice	3 competing speakers
Unfiltered	94 (90–98)	74 (66–82)	64 (62–68)
LP 3100	85 (78–90)	67 (57–75)	57 (47–64)
LP 2300	74 (62–88)	42 (36–54)	48 (38–52)
LP 1400	45 (32–54)	18 (6–26)	17 (8–30)
HP 950	82 (76–86)	64 (58–74)	50 (46–54)
HP 1500	76 (62–81)	52 (48–58)	41 (37–48)
HP 2000	48 (40–56)	38 (26–54)	33 (28–36)
HP 2600	15 (4–34)	8 (2–12)	10 (6–18)

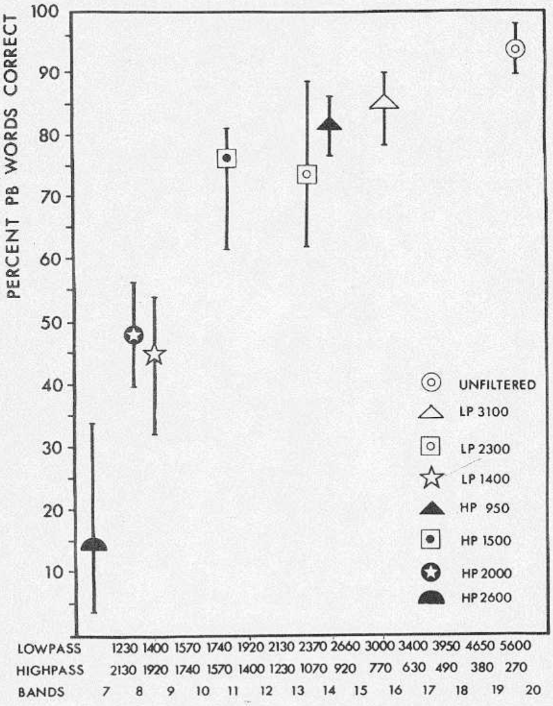


Fig. 8. S/N = 0 dB

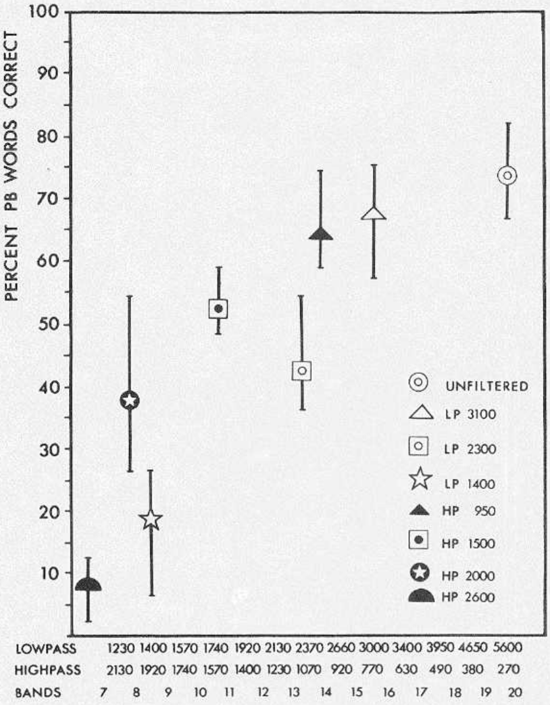


Fig. 9. S/N = 0 dB + radio

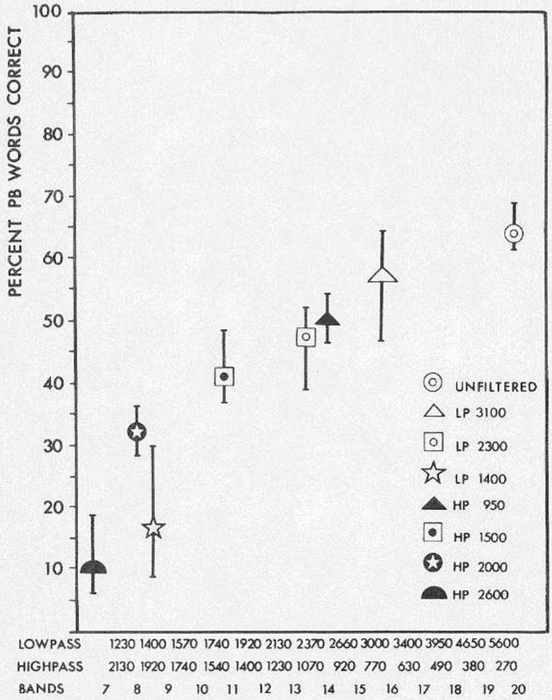


Fig. 10. Signal + 3 competing speakers

Fig. 8, 9 and *10.* Per cent Pb-words correctly understood in listening situations:

S/N = 0 dB (Fig. 8)
S/N = 0 dB + radio (Fig. 9)
Signal + 3 competing speakers (Fig. 10)

French & Steinbergs' division of speech spectrum in 20 bands, each of which equally important for speech discrimination, are placed along X-axis (see also chapter 5).

Discussion

The results of comparisons between high-pass and low-pass groups show that low-pass filtering of speech at 3000 Hz has the same effect on speech intelligibility as high-pass filtering at 1000 Hz on normal hearing subjects. The results lend further support to the conclusion in chapter 3B that normal hearing in a frequency range up to at least 3000 Hz is important to speech intelligibility in every-day conditions.

These results are found in normal hearing students. When it comes to the problem of what effect a hearing loss at various frequencies means for speech intelligibility the answer can not be given yet. It will probably be easier to obtain a clearer insight into this problem when a sufficiently large number of speech audiograms recorded in every-day situations and the corresponding tone audiograms of persons with sensorineural loss become available.

Summary

The recordings: 1a) S/N = 0 dB, 2a) S/N = 0 dB + radio and 3c) Signal + 3 competing speakers, accounted for in chapter 3 B were presented to 66 normal hearing medical students divided into 8 groups. In one group the verbal material was presented unfiltered, while the other 7 listened to filtered versions.

A comparison was made between the groups of students that listened to the recordings with reduced information at the lower frequencies and groups with reduced information at higher frequencies. It was found that filtering off above 2300 Hz gave roughly the same speech discrimination as filtering off below 1500 Hz and filtering off above 3100 Hz means just as much as filtering off below 950 Hz.

CHAPTER 5

SPEECH DISCRIMINATION PREDICTED FROM TONE AUDIOMETRY AND ARTICULATION INDEX

French & Steinberg, (1947), developed a method with which it was possible to calculate an index for the intelligibility of speech from purely physical measurements. They called this Articulation Index or AI.

For better understanding of the articulation index it is necessary to recall some characteristics of a speech signal. Speech has an irregular wave form with a high peak factor. In other words, the peak instantaneous sound pressures are high, compared with the long term (60 sec) rms (root mean square) sound pressure. This means that if the rms level is measured every 1/8 second of the acoustic wave it will encompass a range of nearly 30 dB. French & Steinberg found that a speech signal having a long term rms sound pressure level of −12 dB relative to the rms sound pressure level of the noise (white noise) will be barely detectable. The explanation of this is the dynamic nature of the speech signal with peaks about 12 dB over the rms sound pressure level.

Thus the minimum contribution to intelligibility is made at a signal-to-noise ratio of −12 dB. They also found a maximum in speech intelligibility at a signal-to-noise ratio of +18 dB and more. This means that there is a range of 30 dB in the signal-to-noise ratio between a speech intelligibility of 0 % and 100 %.

In order to calculate an index for the intelligibility of speech French & Steinberg (1947) divided the speech frequency range in 20 bands, each of them of same and equal importance for speech discrimination. In each of these 20 bands the difference is measured between 1) the longterm rms speech level + 12 dB and 2) the rms noise level (or between speech peaks and the rms noise level). Differences above 30 dB are counted as 30 dB. Each band can contribute with at most one 20th part of 1, i.e. 0.05 (if there is a difference in the band of 30 dB or more) and the sum of all 20 bands can give an articulation index between 0 and 1.

The AI-values calculated from physical measurements are afterwards converted to estimated speech intelligibility scores with the use of curves of the type shown in fig. 11, valid for English speech material. The Swedish articulation index function for different verbal material has not yet been measured. But according to Lidén & Fant (1954) there is no reason to expect it to differ appreciably from the American data.

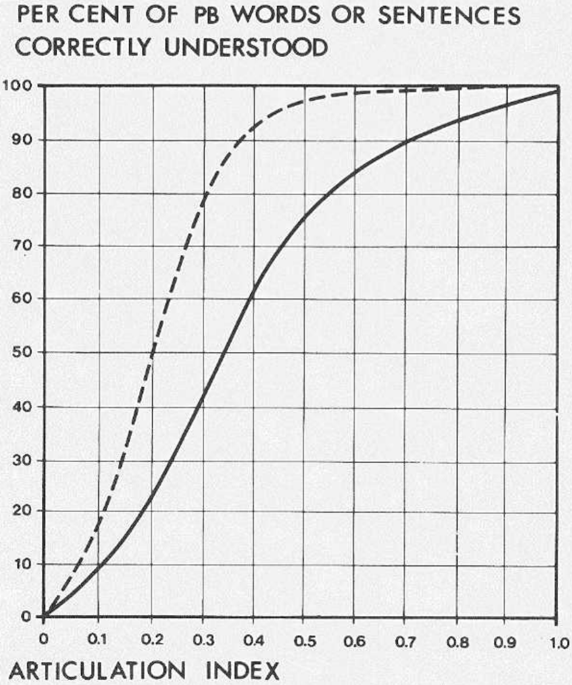


Fig. 11. Relation between articulation index and two different English measures of speech intelligibility investigated on normal hearing persons.

– – – – Sentences
——— 1,000 Pb-words (test vocabulary limited to 1,000 words)

From American National Standard, methods for the calculation of the articulation index. 1969.

Calculation of the articulation index for predicting speech intelligibility in communication systems and noise environments has been used for many years. This method has not yet been used in audiology, but it may open new avenues. It seems conceivable that the discrimination loss of a hard-of-hearing subject listening in noise theoretically might be calculated from the articulation index and the AI-function shown in fig. 11, but there may be limitations. According to Stevens & Baruch (1957) and Kryter (1962), the AI-calculation may not always be valid for abruptly ending spectra. Nevertheless, it seems worthwhile to test the above mentioned hypothesis. With this purpose in mind a group of normal hearing subjects listening in every-day noise situations to filtered speech (accounted for in chapter 4) had their discrimination scores theoretically computed from articulation index calculations and the AI-function in fig. 11. These results have then been compared with the observed discrimination scores accounted for in chapter 4.

In the same way a comparison was made between observed discrimination scores of hard-of-hearing subjects (accounted for in chapter 3 B) and their computed scores.

Further a comparison has been made between the observed scores of the normal hearing subjects listening to filtered speech (thus simulating different degrees of hearing loss) and the hard-of-hearing subjects whose hearing loss had "cut-off" frequencies corresponding closely to those used in the filtered speech groups.

Subjects

The subjects consisted of two groups.

In the first group the same 66 normal hearing subjects were used as described in chapter 4. They listened to the monosyllabic word list in listening situation 1 a) (S/N = 0 dB) accounted for in chapter 4. As mentioned in chapter 4, this was re-recorded through the following seven filters (the unfiltered version was included for comparison):

LP 3100 HP 1500
LP 2300 HP 2000
LP 1400 HP 2600
HP 950 Unfiltered

The group of subjects are named according to the filtered version they listened to.

The second group of subjects consisted of the same subjects used in chapter 3 B, i.e.

22 normal hearing persons, N
6 described as L 4000
22 described as L 3000

These groups of subjects were exposed to the listening situations 1a and 1b (S/N = 0 dB and S/N = −10 dB) accounted for in chapter 3 B.

Equipment and procedure

The articulation indices of the above mentioned groups and recordings were calculated according to American National Standard . . . 1969. The one-third octave band method was used. This method is derived from the 20-band method described above. The form for the calculation is shown in table 8 and fig. 12 from which it is obvious that the AI is derived from the speech peak-to-noise difference in 15 one-third octave bands. Differences above 30 dB are counted as 30 dB. This measure is afterwards multiplied by the particular weighting-coefficient of the band. The sum of the 15 products then gives the AI.

The spectrum of the speech signal was measured in the following way: The peak rms value for each of the 50 key-words in a word list in each of the 15 above mentioned one-third octave bands was measured with the aid of a Brüel & Kjaer audiofrequency spectrometer 2112 (integration time 100 msec) and a Digital Equipment Lab 8/e computer, and the arithmetic mean of each of the bands was calculated. This was done on 4 lists of words. Since the peak rms spectrum level curves proved to be practically identical, no further measurements were made for the other word list.

The spectrum level of noise in listening situation 1a (S/N = 0 dB) and 1b (S/N = −10 dB) accounted for in chapter 3 B was measured with the same equipment. The noise spectrum levels were not considered to give any upward masking.

The AI-values were corrected for a reverberation time of 0.5 sec. by subtracting 0.05 (American national standard . . . 1969).

In calculating the AI-contribution in the 48 dB/octave slope in the filtered lists the level of audibility for sounds with a continuous spectrum was taken into consideration. This means that when the curve for audibility crosses the 48 dB/

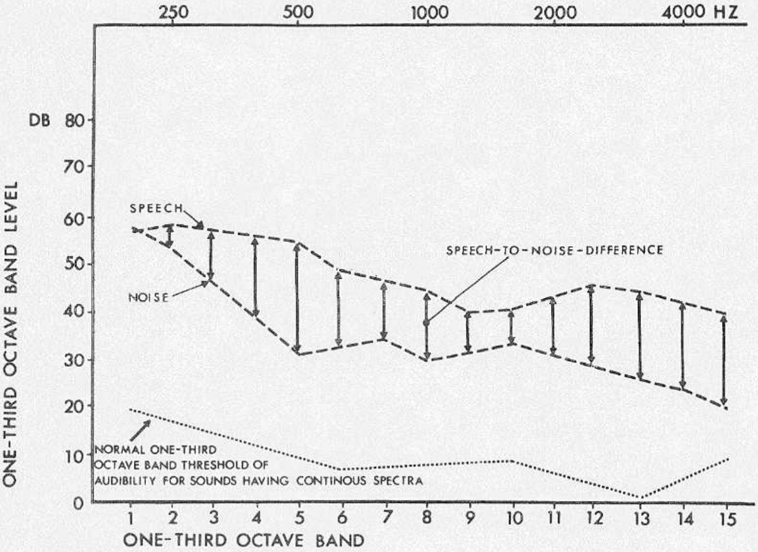


Fig. 12. The speech-to-noise difference in each of the 15 one-third octave bands is calculated and listed in the form shown in table 8.

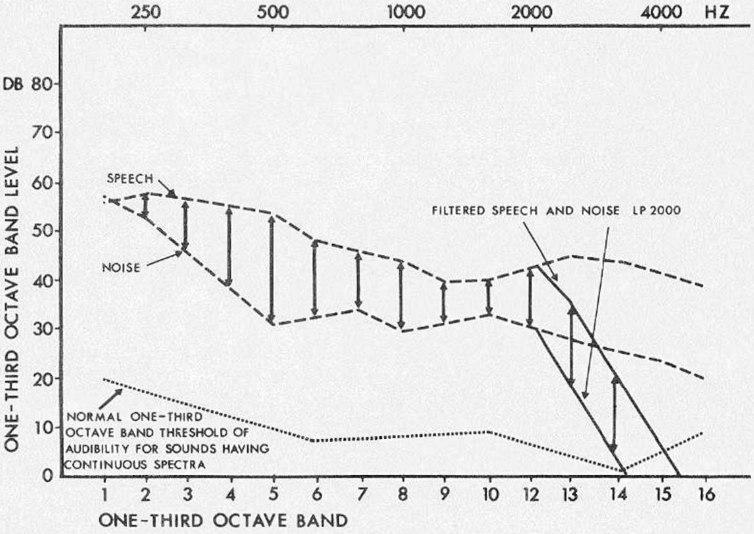


Fig. 13. The speech-to-noise difference in each of the 15 one-third octave bands is calculated and listed in the form shown in table 8. As an example a low-pass 2000 Hz recording is given. Observe that when the normal curve for audibility crosses the 48 dB/octave slope for speech no more AI-contribution is possible.

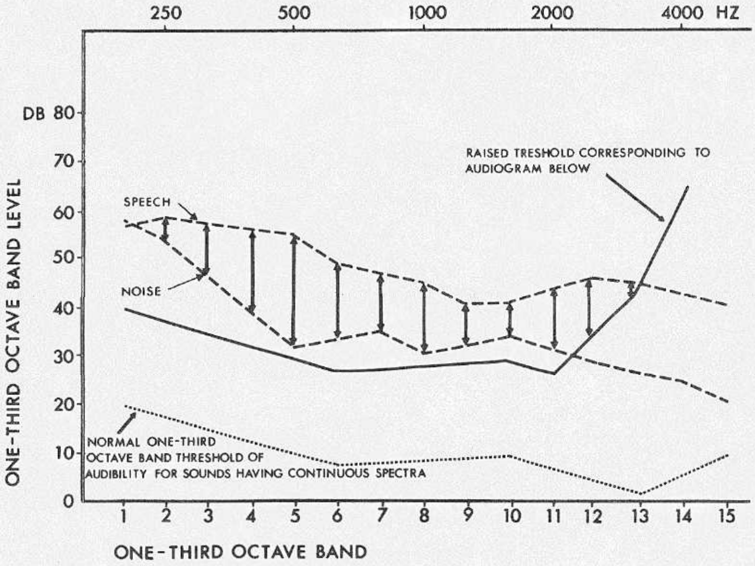


Fig. 14a. The speech-to-noise differences in the 15 one-third octave bands is calculated and listed in the form shown in table 8. As an example the raised threshold of audibility for the high-tone loss according to the presented audiogram in fig. 14b is given. Observe that when the raised threshold of audibility crosses the speech curve no more AI-contribution is possible.

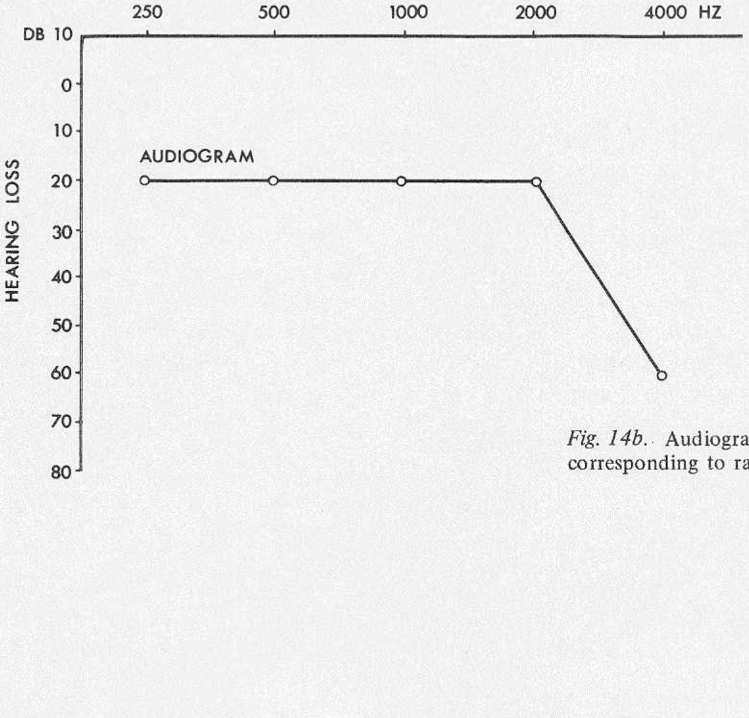


Fig. 14b. Audiogram showing binaural tone-thresholds, corresponding to raised threshold of audibility in fig. 14a.

Table 8. Articulation index calculation form for one-third octave bands from Methods for the calculation of the articulation index (American National Standard 1969). The speech-to-noise differences shown in fig. 12, 13 and 14 are meant to be listed in column 2. The sum of the fifteen results in column 4 then gives the articulation index.

Col 1 One-Third Octave Band (Hz)	Center Frequency (Hz)	Col 2 Speech-to-noise Difference in dB	Col 3 Weight	Col 4 Col 2 x Col 3
180– 224	200	....	0.0004	....
224– 280	250	....	0.0010	....
280– 355	315	....	0.0010	....
355– 450	400	....	0.0014	....
450– 560	500	....	0.0014	....
560– 710	630	....	0.0020	....
710– 900	800	....	0.0020	....
900–1120	1000	....	0.0024	....
1120–1400	1250	....	0.0030	....
1400–1800	1600	....	0.0037	....
1800–2240	2000	....	0.0038	....
2240–2800	2500	....	0.0034	....
2800–3550	3150	....	0.0034	....
3550–4500	4000	....	0.0024	....
4500–5600	5000	....	0.0020	....

octave slope for speech no more AI-contribution is possible. (See fig. 13.)

In the AI-calculations for the hearing impaired groups L 3000 and L 4000 (accounted for in chapter 3 B) it was assumed that the groups L 3000 and L 4000 had full information up to 2000 Hz and 3000 Hz respectively and no information from 3000 Hz and 4000 Hz respectively and above. The AI-contribution for the frequencies between none and full information was interpolated with the assumption that the hearing level was 20 dB at 2000 Hz and 3000 Hz respectively, and 60 dB at 3000 Hz and 4000 Hz respectively. (See fig. 14.)

The threshold of audibility for sounds having a continuous spectrum corresponds to a normal audiogram (0 dB hearing loss) in fig. 13. In fig. 14 this threshold corresponds to the given audiogram.

Results

Comparison between computed and observed speech intelligibility in experiments with filtered speech

Table 9 gives the articulation indices for listening situation 1a (S/N = 0 dB) and re-recordings through different LP- and HP-filters. For comparison the unfiltered version also is given. Discrimination scores computed from the AI-calculation and the AI-function in fig. 11 are also given. In table 9 a comparison is made between computed and observed discrimination scores for Pb-words in the experiments with filtered speech. As can be seen, the observed and the computed values agree surprisingly well.

In fig. 15 the observed mean values of the discrimination scores accounted for in table 7 and 9 are plotted as a function of AI. The curve for 1000 English Pb-words in fig. 11 is also inserted (the expected values). Fig. 15 shows that our results agree well with those expected, though the

Table 9. Articulation indices (AI) computed for listening situation 1a (S/N = 0 dB) and different LP- and HP filtered versions with the corresponding computed discrimination scores according to the function in fig. 11. Comparisons is made with observed results (95 % confidence interval within brackets).

	AI	Discrimination scores computed	 observed
Unfiltered	0,67	88	94 (90–98)
LP 3100	0,60	84	85 (78–90)
LP 2300	0,48	73	74 (62–88)
LP 1400	0,38	58	45 (32–54)
HP 950	0,54	80	82 (76–86)
HP 1500	0,45	70	76 (62–81)
HP 2000	0,34	50	48 (40–56)
HP 2600	0,26	35	15 (4–34)

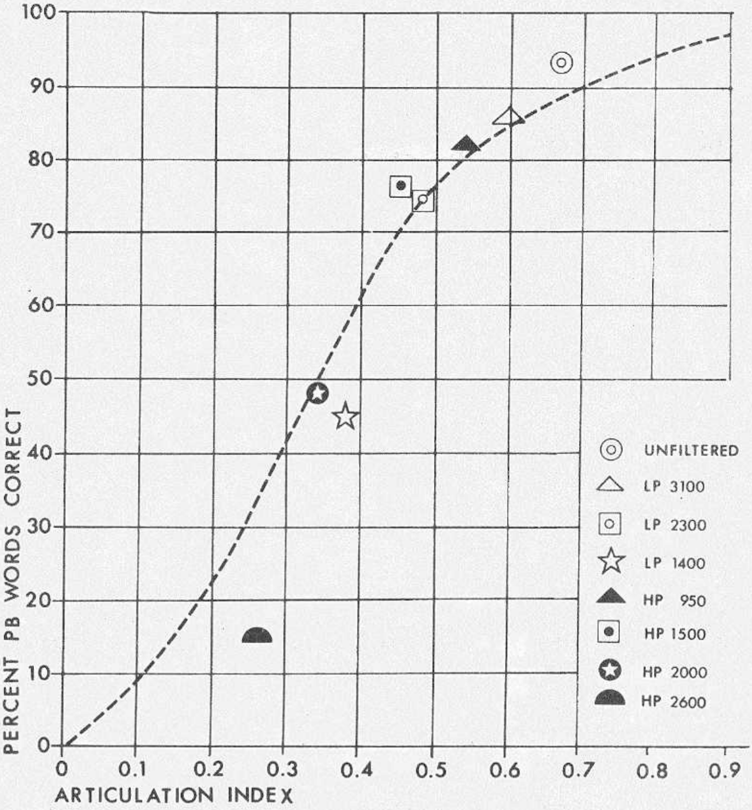


Fig. 15. Mean per cent correctly understood Pb-words as function of articulation index (AI) for the groups given in the figure in recording S/N = 0 accounted for in chapter 4. Comparison is made with the curve for speech discrimination of English Pb-words as function of AI.

verbal material used consisted of Swedish Pb-words.

Comparison between computed and observed speech discrimination in groups with sensorineural loss

AI-calculations were made for the groups N, L 4000 and L 3000 (accounted for in chapter 3 B) in the listening situations 1a and 1b (S/N = 0 dB and S/N = –10 dB).

Table 10 gives the calculated articulation indices for the above mentioned experimental groups. In table 10 a comparison is made between observed and computed discrimination scores for the normal and the hard-of-hearing groups in the two listeningsituations. In the easy listening situation (S/N = 0 dB) there is a very good agreement between the computed and the observed results in all groups.

In fig. 16 the mean values of the results, for the normal and hard-of-hearing groups (L 4000 and L 3000) in listening situations 1a and 1b (S/N = 0 dB and S/N = –10 dB, are plotted for comparison with the AI-function of English monosyllabic words. The highest AI for each group is the recording S/N = 0 dB and the lowest S/N = –10 dB. Fig. 16 shows that our observed results agree well with those expected in S/N = 0 dB.

Comparison between discrimination scores in normals listening to low-pass filtered speech and subjects with sensorineural hearing loss

In fig. 17 the results of the low-pass groups from fig. 15 are shown together with the results of the groups with sensorineural loss and their controls from fig. 16. The recording is S/N = 0 dB for all groups. There is a good agreement between the sensorineural groups and the low-pass groups.

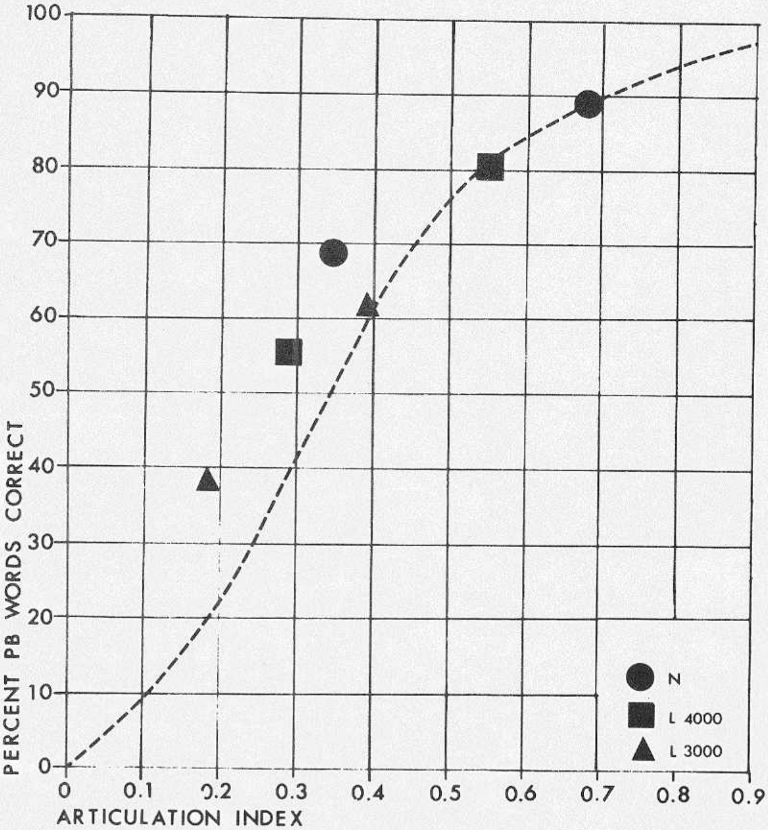


Fig. 16. Mean in per cent correctly understood Pb-words as function of articulation index (AI) for the groups given in the figure in S/N = 0 dB (highest AI for each group) and S/N = −10 dB. Comparison is made with the curve for speech discrimination of English Pb-words as function of AI (for normals).

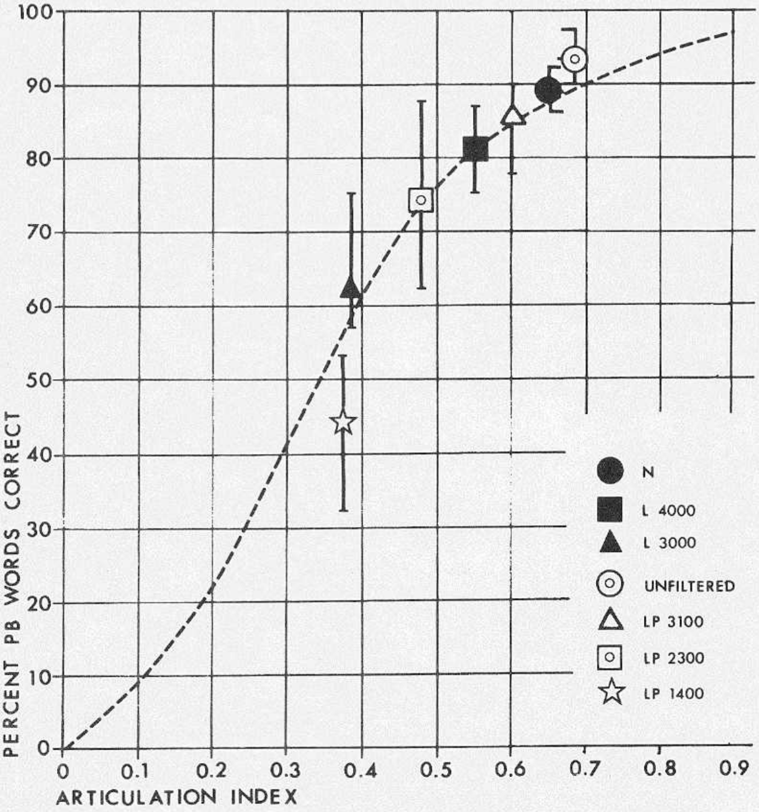


Fig. 17. Per cent (mean and 95 % confidence interval) correctly understood Pb-words in S/N = 0 dB as function of AI for the groups given in the figure. Comparison is made with the curve for discrimination of English Pb-words as function of AI (for normals).

Table 10. Articulation indices (AI) computed for listening situations: S/N = 0 dB and S/N –10 dB (1a and 1b accounted for in chapter 3 B) for normals and hard-of-hearing subjects. Comparison is made between the computed and observed discrimination scores.

S/N = 0 dB

	AI	Discrimination	
		computed	observed
N	0,67	**88**	**89** (87–92)
L 4000	0,55	**81**	**81** (75–87)
L 3000	0,39	**60**	**62** (58–65)

S/N = –10 dB

	AI	Discrimination	
		computed	observed
N	0,34	**53**	**69** (66–72)
L 4000	0,29	**40**	**55** (46–65)
L 3000	0,19	**21**	**38** (34–42)

Discussion

The results obtained with the filtered word list (S/N = 0 dB) and the performance by the controls in S/N = 0 dB, show only small differences, if any, between our results and those expected according to the estimated scores for 1000 English Pb-words as a function of AI. This supports the opinion that the Swedish articulation index does not differ notably from the English index.

Fig. 16 and 17 show that our mean results for the sensorineural groups agree well with those expected in S/N = 0 dB. Table 10 and fig. 16 show that the correlation is not so good between the computed and the observed results in S/N = –10 dB for the groups N, L 4000 and L 3000. One explanation to this might be that for one reason or another there is a smaller difference between S/N = 0 dB and S/N = –10 dB than is indicated by the speech-to-noise difference. That this hypothesis might be right is shown by the fact that all three groups in S/N = –10 dB are scoring higher to about the same extent.

Fig. 17 indicates further that normals listening to filtered speech might substitute subjects with sensorineural high frequency loss in experiments in this field.

On the other hand, fig. 17 shows that there is a relatively wide spread of the individual results in the groups. This means that even if it is possible theoretically to calculate the speech intelligibility for subjects with sensorineural impairment, it is difficult to predict the individual speech intelligibility exactly with aid of tone-audiometry and AI. Individual tests of speech in every-day noise are thus still necessary to obtain correct information about individual handicaps. The prediction of the speech discrimination from tone-audiometry and articulation index might, however, be used as a method for checking the relevance of a particular individual result. Deviation from expected values might indicate retrocochlear lesions or malingerings.

Summary

Articulation indices were calculated for different groups of subjects and listening situations accounted for in chapter 4 and 3 B. These AI-values correspond to estimated speech intelligibility curves. Lacking a Swedish articulation function, comparisons was made with the curve for the intelligibility of 1000 English Pb-words as a function of AI. These estimated scores were then compared with our found results. There was good agreement both in the groups of students tested with filtered speech and the groups with sensorineural losses. This means that speech intelligibility for groups consisting of individuals with approximately the same sensorineural hearing loss can theoretically be calculated from the articulation index.

GENERAL CONCLUSIONS

For any control investigation of speech intelligibility in every-day listening situations a reliable laboratory method is required. The observations made in this study indicate that binaural ear-phone listening to stereophonic recordings made via an artificial head is a reliable substitute to direct listening.

Using this approach the importance of high frequency hearing loss on speech discrimination was studied. The observations indicate that the effect of such high frequency hearing loss on speech discrimination has hitherto been underestimated. Good discrimination in every-day listening situations requires bilateral normal hearing up to 3000 Hz. On the basis of these observations an audiological test is suggested for evaluation of the hearing handicapped in the every-day listening situation.

Investigations in normals show that reduced information in the frequency band above 2300 Hz and above 3100 Hz gives roughly the same decrease in every-day speech discrimination as reduced information below 1500 Hz and below 950 Hz, respectively.

It is possible to estimate discrimination scores for every-day listening situations from the tone audiogram and the articulation index. This estimate may be used to predict an individuals performance. We suggest that such a prediction could be used to detect inconsistencies in individual subject's performance.

GENERAL SUMMARY

The effect of high frequency hearing loss on speech intelligibility in seven different every-day listening situations have been analysed. Different every-day listening situations have been simulated and recorded in the living-room of a three-room flat. As disturbances, use was made of community noise with and without addition of a competing radio voice and one up to three competing speakers. Recordings of these listening situations, as well as a speech test in quiet, were presented to 22 persons with normal hearing and 41 with sensorineural losses. The results obtained in the various groups were compared with each other.

The validity of the test methods was checked by comparing the results of the binaural listening via ear-phones with the results of direct listening in the recording room. Six students with normal hearing served as test subjects. The results of the listening via ear-phones to recordings of speech in community noise gave equal results as direct listening (without speech reading). When the speech signal was disturbed by three competing speakers the ear-phone listening gave significantly better results than the direct listening.

Good discrimination of speech in quiet was found to require normal hearing ability up to 2000 Hz. Good discrimination of speech in every-day listening situations, however, requires bilateral normal hearing up to 3000 Hz.

Addition of a competing voice to an already difficult listening situation causes a significantly larger fall in the speech intelligibility by a person with severe loss of hearing bilaterally at 3000 Hz and above than by a person with normal hearing.

There is evidence that in listening situations with several competing speakers, speech intelligibility is correlated more closely than hitherto supposed with the loss of hearing of the worse ear, while in continuous noise the correlation is best with the better ear.

The test persons language background did not influence the intelligibility of Pb-words in every-day noise in this investigation.

Clinical tests for the evaluation of the speech intelligibility in every-day listening situations are suggested.

In addition a comparison is presented between the intelligibility of high-pass and low-pass filtered speech, in every-day noise situations by normal hearing subjects. It was found that reduced information above 2300 Hz and above 3100 Hz gave roughly the same speech discrimination as reduced information below 1500 Hz and below 950 Hz respectively.

Finally a method is presented for predicting speech discrimination in every-day noise situations from tone audiograms and by calculations of the articulation index. The computed discrimination scores according to this method are compared with the observed scores. In the investigated listening situations there was a farely good agreement. This means that this method might be used for checking the relevance of the result of the suggested clinical test.

ACKNOWLEDGEMENTS

The present investigation was carried out at the Audiological Department of the Ear-, Nose- and Throat clinic, Sahlgren's hospital, University of Göteborg, Sweden.

I beg to express my sincere gratitude to:

Professor Gösta Herberts, head of the Department of Otolaryngology, for constructive criticism; my teacher ass. professor Gunnar Lidén, head of the Audiological Department for critical advice and guidance as well as for laboratory facilities; professor Gunnar Fant, head of the Department of Speech Communication, the Royal Institute of Technology, Stockholm; professor Tor Kihlman, head of the Department of Building Acoustics, Chalmers University of Technology, Göteborg and Arne Risberg, research engineer at the Department of Speech Communication, the Royal Institute of Technology, Stockholm, for expert advice on the technical planning of the investigation; Göte Björkman, research engineer at the Audiological Department, and Björn Lundquist, *civ.ing.*, Svensk Akustikplanerings AB, Göteborg for invaluable technical help, fruitful discussions and advice; AB Volvo, and in particular doctor Lennart Dahlberg, for most generous cooperation; AB Götaverken, and in particular doctor Paulus Tomsic, for smooth cooperation and most generous help; Martin Härnqvist, *fil.kand*, Department of Mathematics, Chalmers University of Technology, Göteborg, for help with the statistical analyses; Lars Johansson, *civ.ing.*, for technical help and for placing his flat at my disposal for the performance of the recordings and tests; Ruth Andreasson, for untiring help with the tests and secreterial work; Maria Huhta and Birgitta Lindahl, for careful drawing of the illustrations and Astrid Callgard and Rigmor Joelsson, for typing the manuscript and excellent secreterial assistance.

The study was supported by grants from the Insurance Company Folksam, the Medical Faculty, University of Göteborg, Götaverken Shipyard Company and the Swedish Board for Technical development project -72-1500/u 1170.

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APPENDIX

For the statistical calculations in this work Wilcoxon's test and Hodge-Lehmanns method were used.

Wilcoxon's test was introduced in 1945. It is a so-called non-parametric test of hypotheses of differences between distributions of two variables (two sample case) and of hypotheses of the mean value of a distribution (one sample case). An example of the latter is Wilcoxon's test for paired differences. That it is non-parametric means essentially that in the method we do not assume anything about the distribution we intend to compare, but only consider those observations we have made of the two variables. In many test situations it may be advantageous to use this type of test, if there is reason to suspect that the underlying distributions need not to be of a certain type, e.g. normal. In the case with normal distribution Student's t-test is the one most commonly used, but an advantage of Wilcoxon's test is also that it is almost as good as the t-test, even in the case where we *know* that we are dealing with normal distributions. In addition, the test can be used even when the number of observations is small.

Hodge-Lehmann's method (1963) for point and interval estimation is based directly on the Wilcoxon test and thus has the same advantages as the latter. In this investigation we used point estimation of the mean of a variable and interval estimations of it.

The confidence levels of the intervals given are at least 95 %. The "parametric" correspondence of these confidence intervals are in the case of normal distribution, the intervals that are based on the t-test, for which reason the above comparison in effectivity holds also here.

ACTA OTO-LARYNGOLOGICA · SUPPLEMENT 320

Printed in Sweden, Gotab, Kungälv 74.13412